Electric Drive Inverter R&D

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Overview

Timeline

- Start – FY15
- Finish – FY17
- 17% complete

Budget

- Total project funding
  - DOE share – 100%
- Funding
  - FY15: $960K

Barriers

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

Targets Addressed

- DOE 2022 Power Electronics Targets
  - Power density: >13.4 kW/l
  - Specific power: >14.1 kW/kg
  - Efficiency: >94%

Partners

- WBG manufacturers
- Inverter component suppliers
- ORNL – Steven Campbell, Curt Ayers, Cliff White, Burak Ozpineci
- NREL – Scot Waye

Project Objective and Relevance

- **Overall Objective**
  - ✓ **Integrate wide bandgap (WBG) technology and novel circuit topologies with advanced packaging to reduce cost, improve efficiency, and increase power density.**
- **FY15 Objective**
  - ✓ **Evaluate WBG devices and develop loss models**
  - ✓ **Design, build, and test a 10 kW air-cooled inverter**
  - ✓ **Design, build, and test a 30 kW WBG-based liquid-cooled prototype.**

Milestones

Date	Milestones and Go/No-Go Decisions	Status
2014	**Milestone: NEW START**	
June 2015	Design a 10 kW WBG-based air-cooled prototype inverter using advanced packages.	**On track**
September 2015	**Go/No-Go decision: If prototype inverter meets 2022 efficiency and power density targets at 30 kW of operation, then design 55 kW liquid-cooled inverter prototype.**	

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Problem to be Addressed

State of the Art (SOA):

No WBG inverters commercially available

Problems associated with power electronics for advanced vehicle applications include:

- Low efficiency at light load conditions for inverters and converters.
- Low current density and device scaling issues for high power converters.
- Lack of reliable higher junction temperature devices.
- High cost of devices and power modules especially for WBG and advanced silicon devices.
- Low power density for the low voltage electronics and cost of inter-connects.
- Lack of adequate protection for the devices.
- High cost for low loss magnetics and high temperature films for capacitors.

Proposed Technology
Overall Strategy to Address Limitations of SOA

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 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 the 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

Proposed Technology
Specific Strategy to Address Limitations of SOA

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

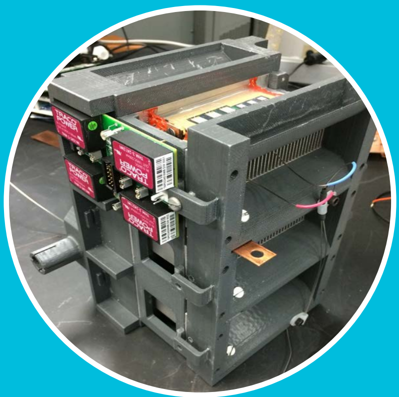
Build, test, and evaluate a 30 kW commercial-module-based WBG inverter

- 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

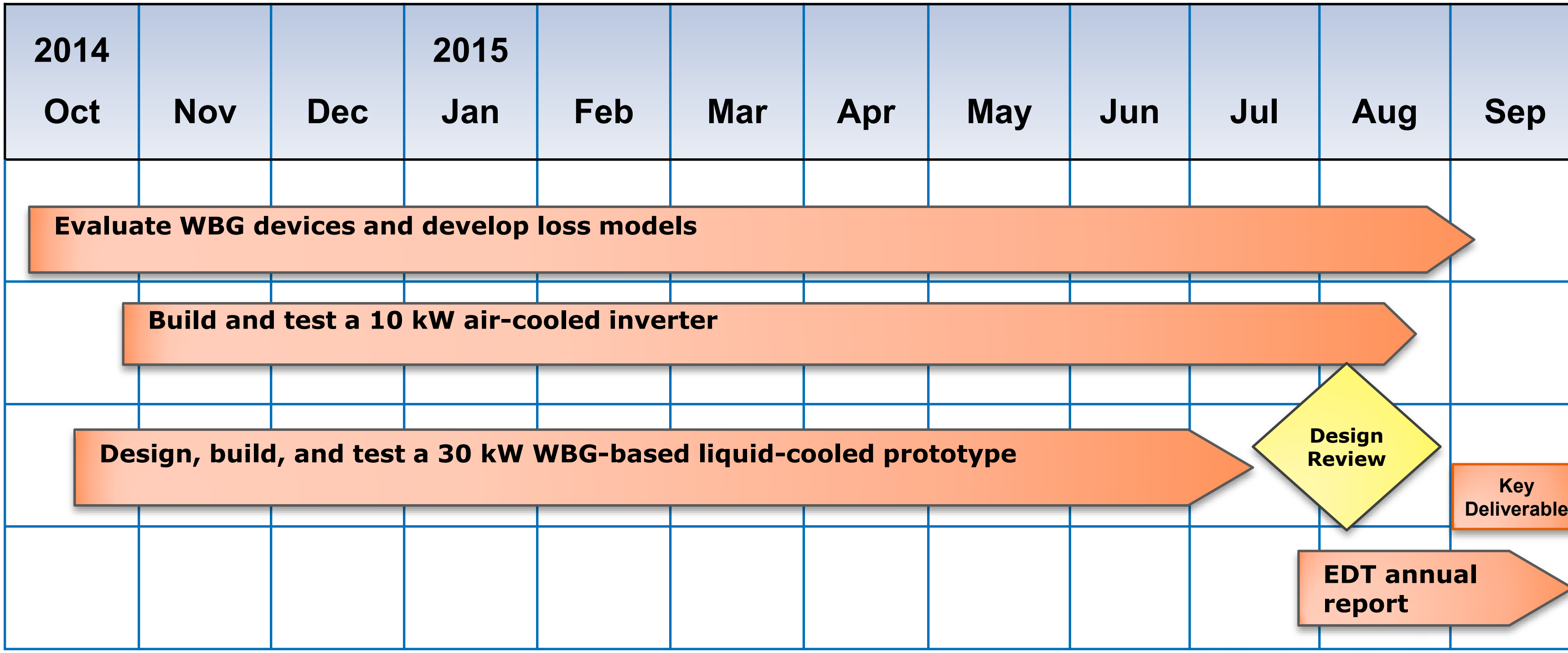


Air-cooled inverter designs

- 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 FY15 Timeline

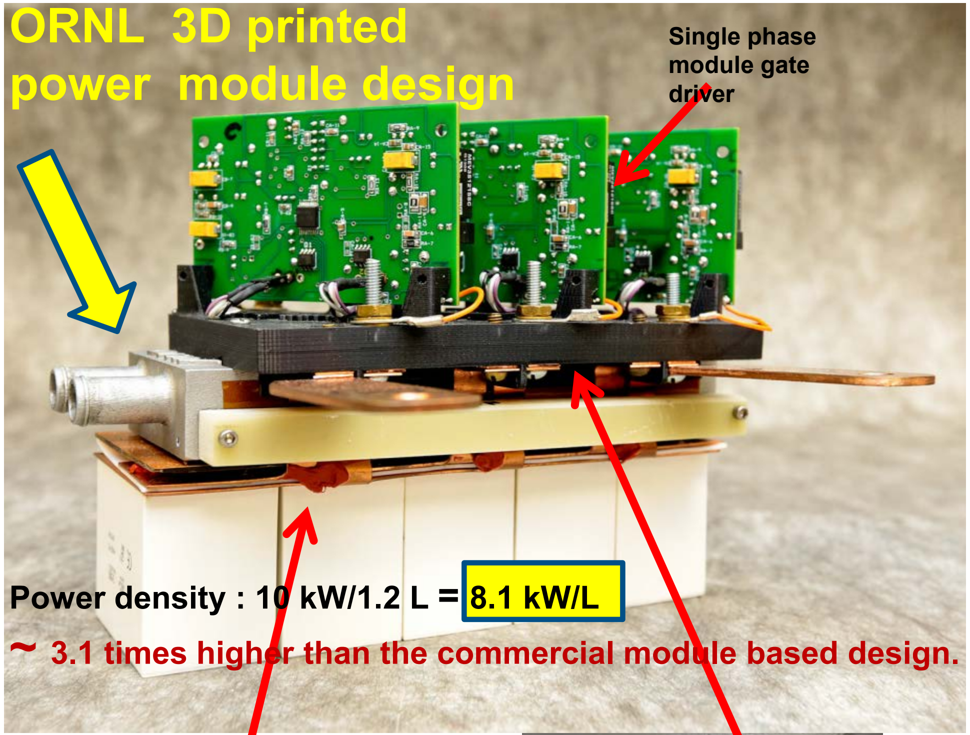


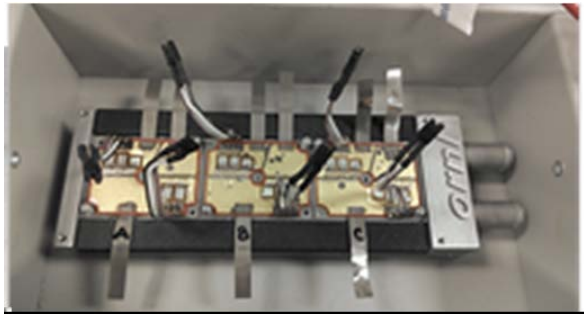
Go No/Go Decision Point: If prototype inverter meets 2022 efficiency and power density targets at 30 kW of operation, then design 55 kW liquid-cooled inverter prototype.

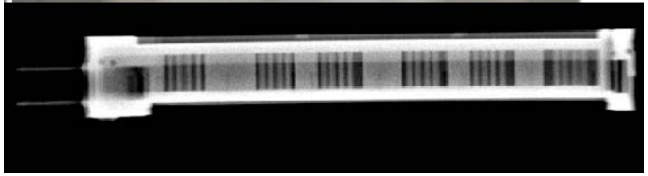
Key Deliverable: Complete design of 30 kW WBG-based liquid-cooled prototype inverter.

Technical Accomplishments - FY14
3D Printed 10 kW Inverter

Completed the build and test of 10 kW WBG inverter with *ORNL high temperature SiC 1200 V, 100 A module.*

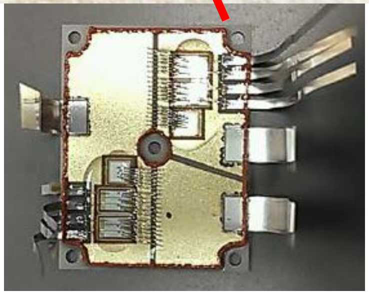






X-ray of the power module

5*40 uF caps, 900 V



1200 V, 100 A SiC MOSFET single phase module layout designed at ORNL

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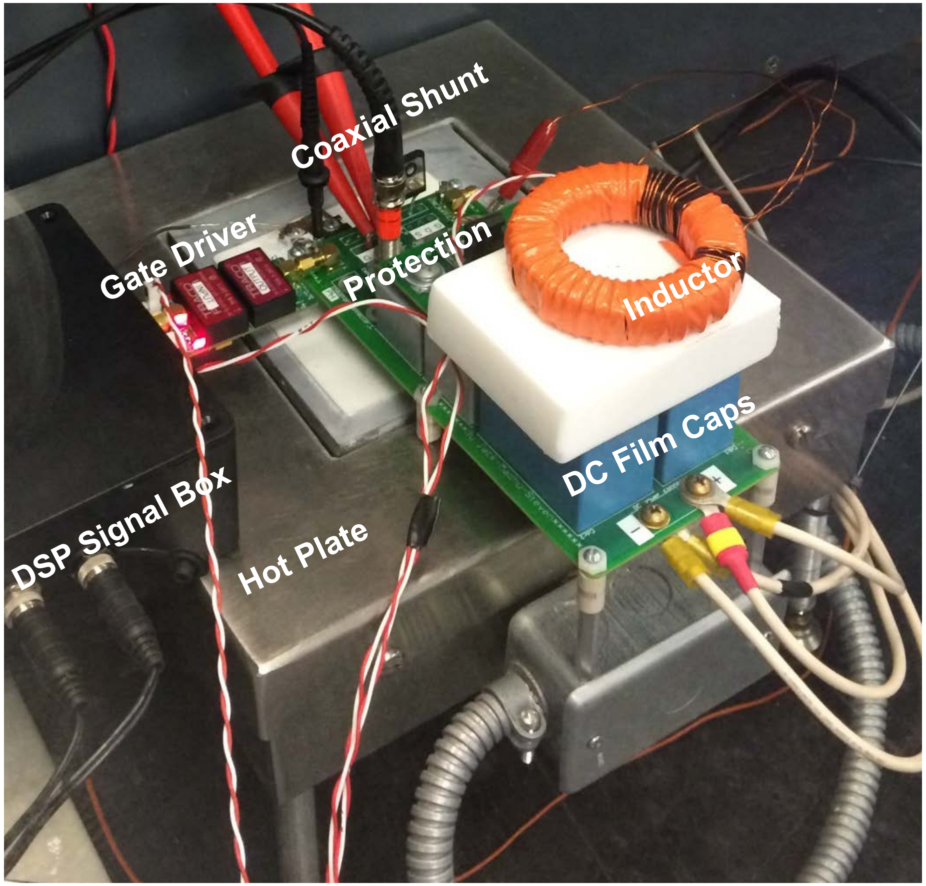
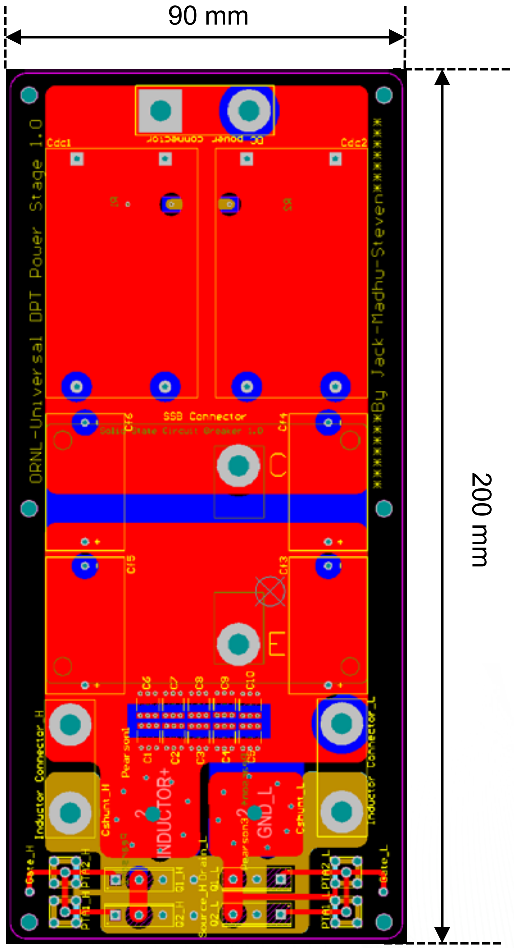
Technical Accomplishments - FY15
Upgraded Double Pulse Test Setup



Test Setup Overview



Power Stage Layout

Gate driver

- ❑ **Built-in Solid-state circuit breaker for overcurrent and short circuit protection**
- ❑ **Compatible with Si/WBG devices featuring various device packages, TO-220, TO-247, etc.**
- ❑ **Compatible with different measurement methods (shunt, Pearson, current probe)**

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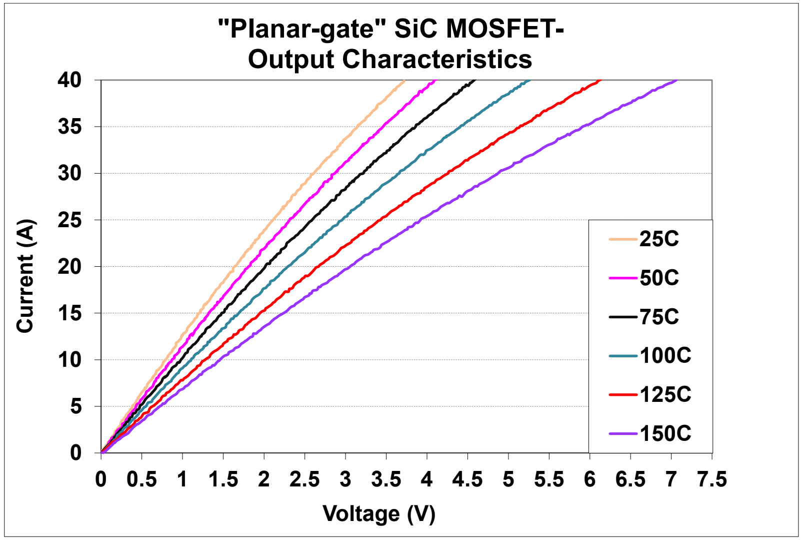
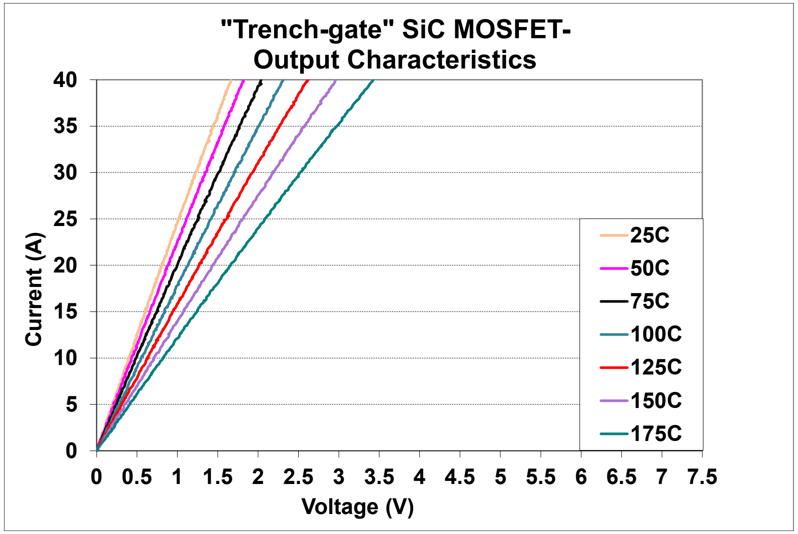
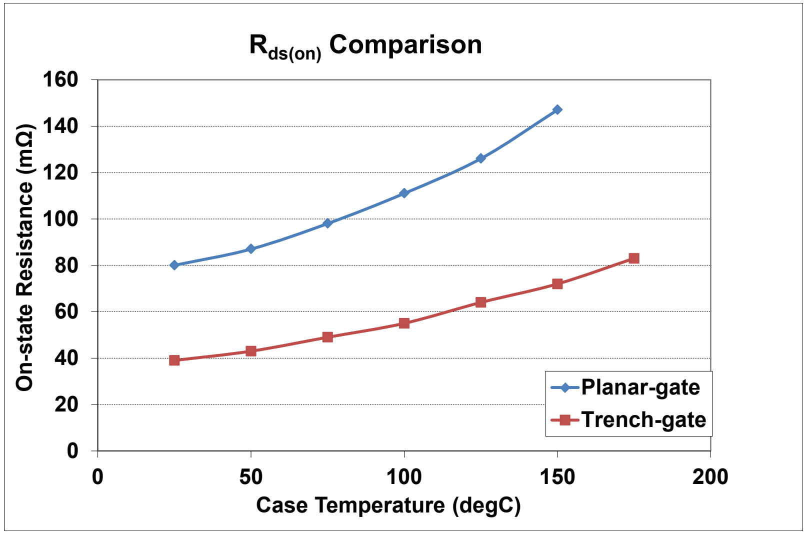
Technical Accomplishments - FY15
Static Characteristics Comparison of Planar/Trench SiC MOSFETs





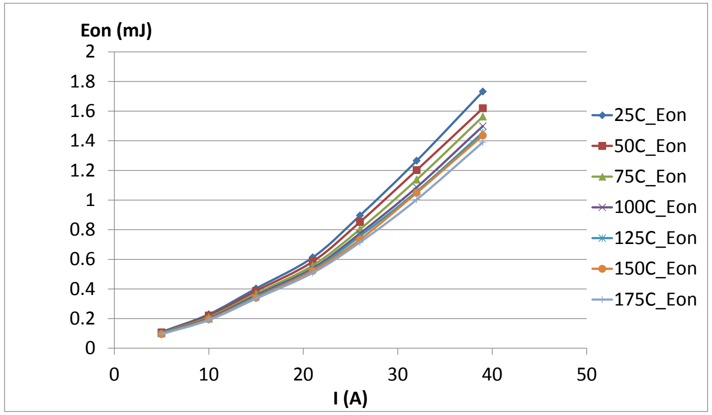


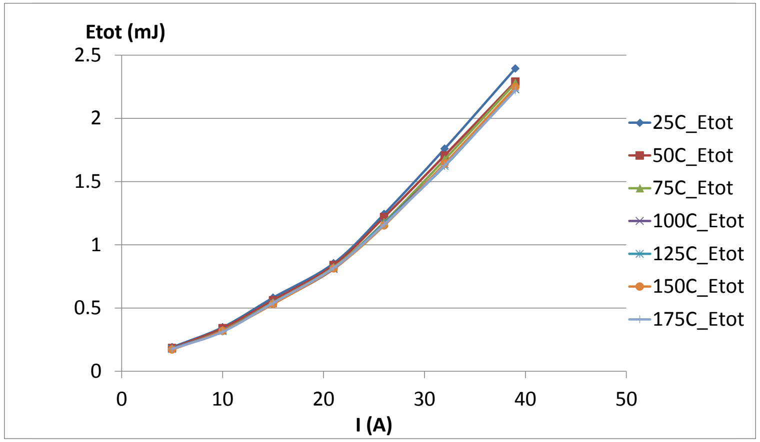
- All testing curves are obtained at V_{gs} = +20 V
- With similar voltage/current rating, the trench device presents a much lower $R_{ds(on)}$

Technical Accomplishments - FY15

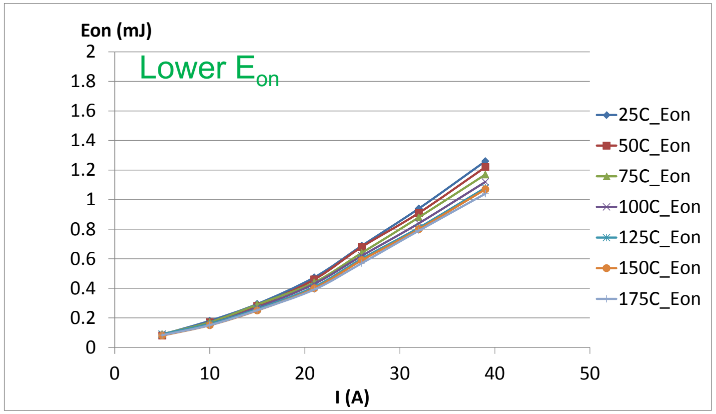
Switching Loss Comparison of Planar/Trench SiC MOSFETs @ 600 V

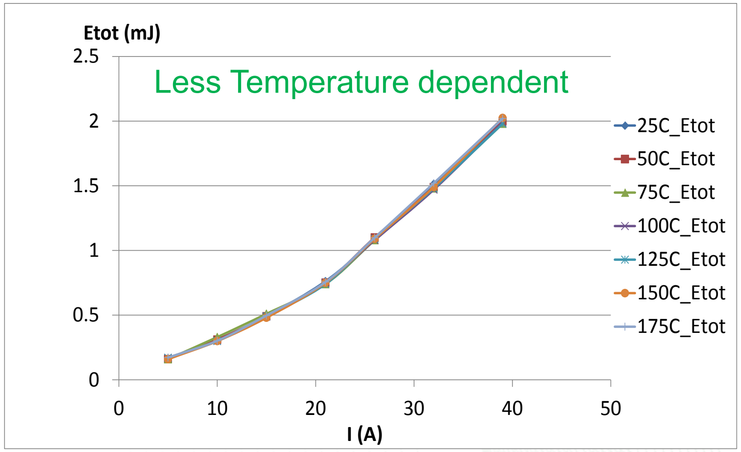
Planar-gate Device





Trench-gate Device



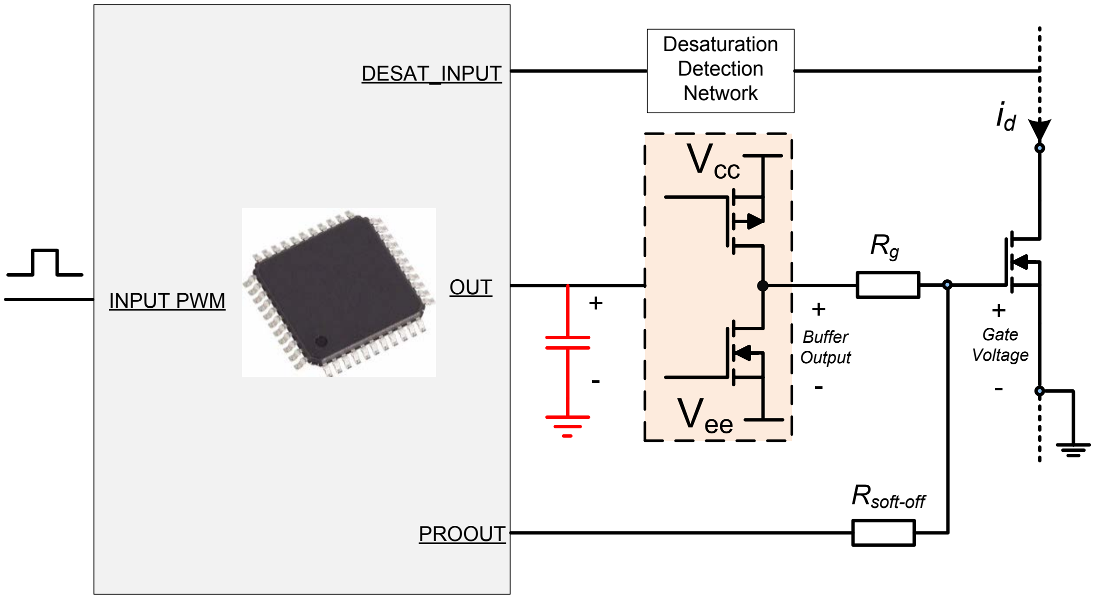


- Turn-on loss decreases with temperature, while turn-off loss increases with temperature due to faster switching speed at turn-on and slower switching speed at turn-off at higher temperature

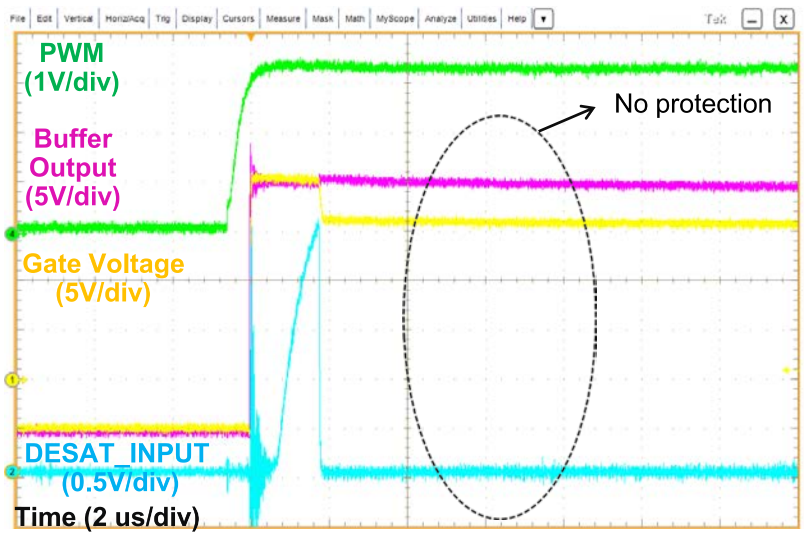
Technical Accomplishments - FY15

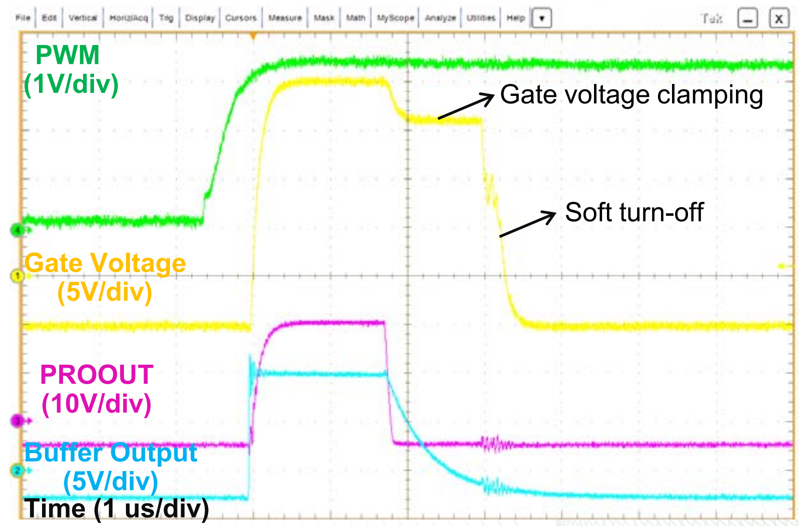
Protection Function Improvement

Block diagram for desaturation short circuit protection



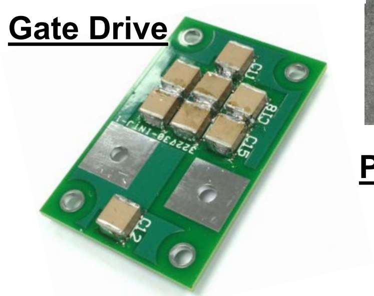
- The protection function works well if no external current buffer is adopted
- With additional buffer, protection function fails due to the residue voltage of the buffer input parasitic capacitance
- An improved method is used to overcome this issue based on the existing chip signals



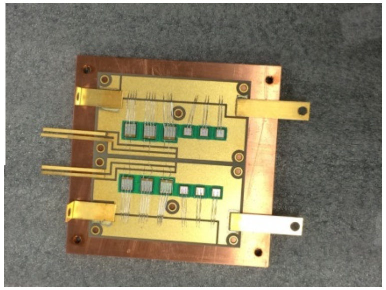


Technical Accomplishments FY15
10 kW 3D Printed Air-Cooled Inverter

Gate Drive

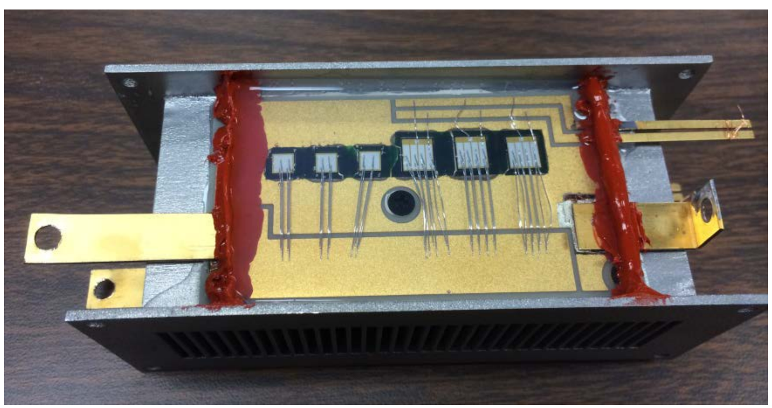


DC-side Decoupling

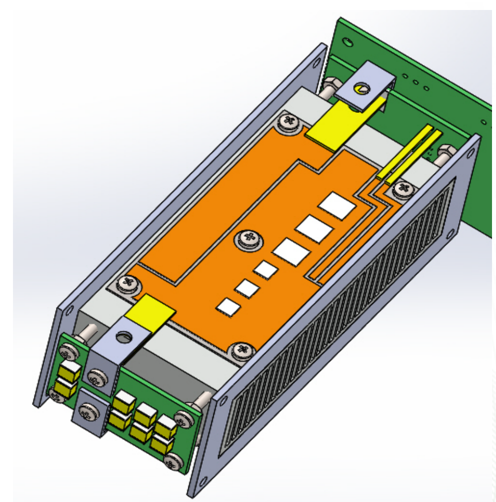


Power Module Assembly

Component	Material	Description
Switch	SiC MOSFET bare die	1200 V / 100 A, 7 mm × 8 mm Thickness: 0.18 mm Top side metallization: 4 μm Al Bottom side metallization: 0.8 / 0.6 μm Ni / Ag
Diode	SiC bare die	1200 V / 50 A, 4.9 mm × 4.9 mm Thickness: 0.38 mm Anode metallization: 4 μm Al Cathode metallization: 1.8 μm Ni / Ag
Substrate	AlN DBC	Area: 46mm × 85 mm Thickness: 12 mils Cu, 25 mils Al_2O_3 Metallization: 200 μin Ni / Au
Bonding wire	Al	Diameter: 10 mils
Die-attach	92.5% Pb-5% Sn-2.5 Ag	Thickness: 2 mil, preformed rectangular
Encapsulate	Nusil R-2188	Area: 46 mm × 85 mm, Thickness: 3 mm

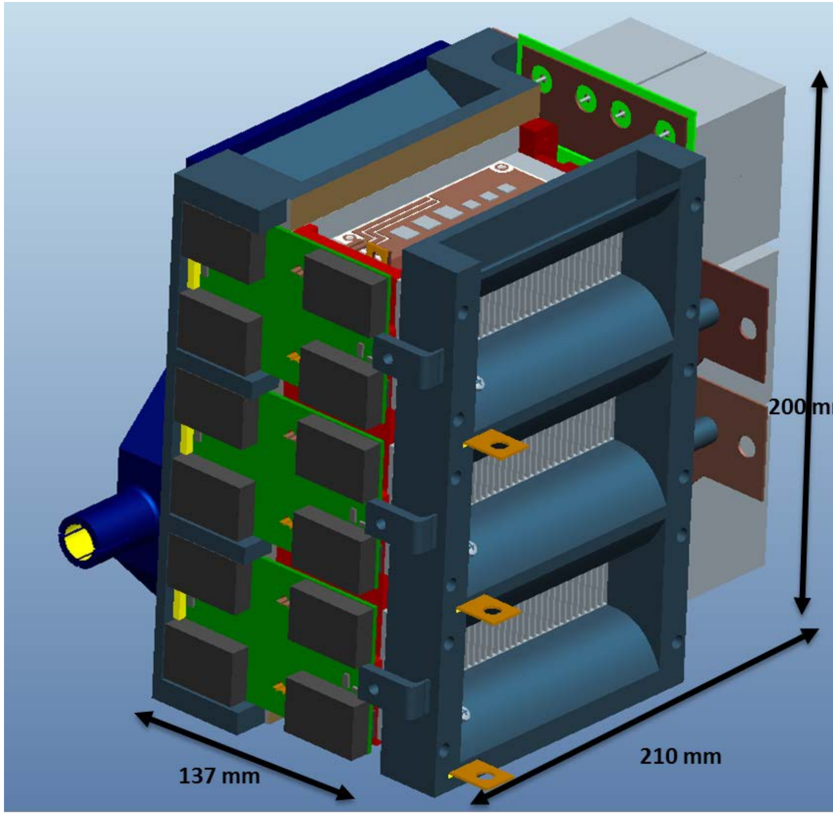


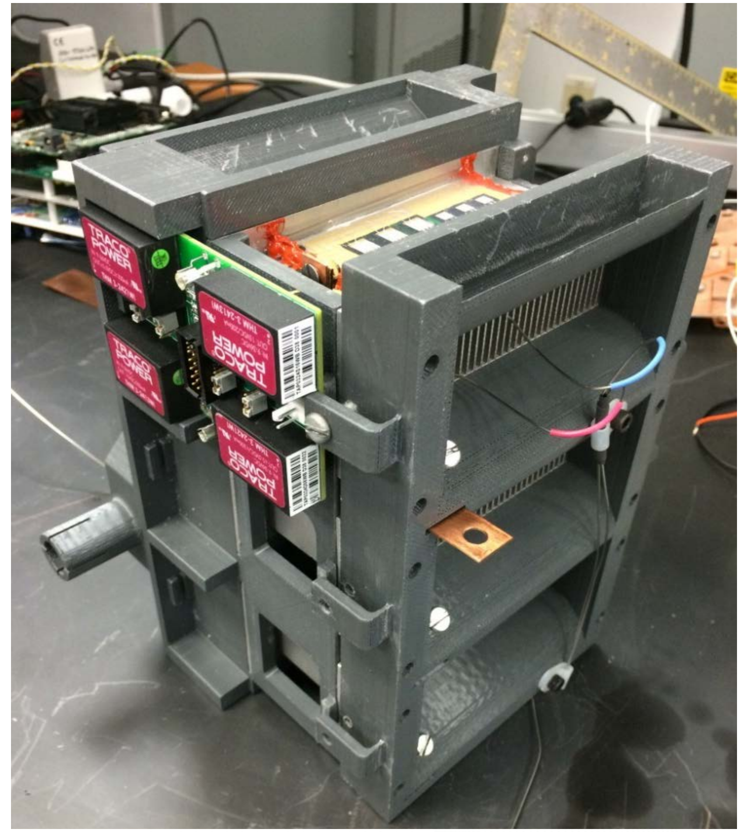
Assembled Power Module



Air Module Assembly 3D drawing

Technical Accomplishments FY15
10 kW 3D printed Air-Cooled Inverter





Three Phase Air-Cool Converter - 3D drawing

Three Phase Air-Cooled Converter - Prototype

Power density: 10 kW/ 5.8 L = 1.72 kW/L

NREL collaboration: heat sink was optimized by NREL

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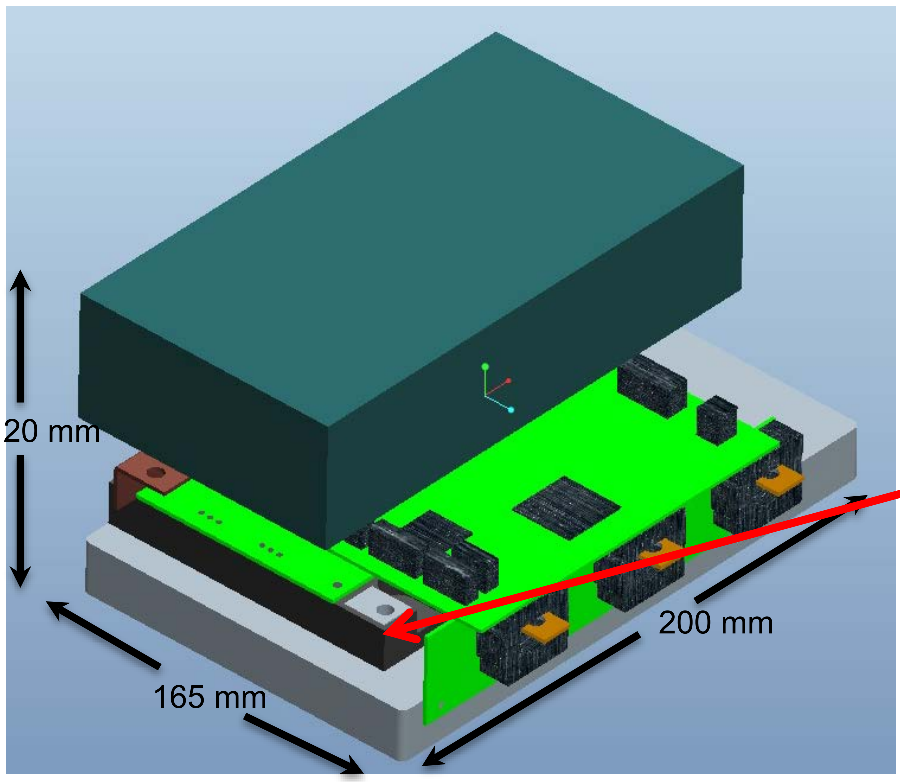
Technical Accomplishments FY15
30 kW SiC Liquid-cooled Inverter

- **Completed the inverter design using commercial SiC 1200 V, 300 A MOSFET modules.**
- **Completed the gate driver and control board design for the inverter using commercial components.**

Power density : 30 kW/ 3.96 L = 7.5 kW/L.



1200 V, 300 A SiC MOSFET commercial single phase module

Responses to Previous Year Reviewers' Comments

This project is a new start.

Partners/Collaborators

Organization	Type of Collaboration/Coordination
WBG manufacturers: International Rectifier, GeneSiC, CREE^{TM}, USiC, General Electric, Infineon, HRL.	Device prototype suppliers
Capacitor manufacturers: SBE, KEMET, AVX®	Custom capacitor suppliers
NREL	Thermal analysis

Remaining Challenges and Barriers

- The power density for the current air-cooled inverter designs need to be further optimized to meet the targets.
- The gate drive buffer with protection for multiple-device module will be a challenge; increasing the reliable operation of the inverter through advanced protection circuits.
- The dc link capacitor volume is a barrier to achieve the overall volume target.
- Reducing the cost of the interconnects for the low voltage components.

Proposed Future Work

- **Remainder of FY15**
  - Complete the testing of the 10 kW WBG-based air-cooled inverter.
  - Complete the testing of the 1200 V, 30 A, SiC trench MOSFET.
  - Complete the build and test commercial-module-based 30 kW WBG inverter

- **FY16**
  - Test the 30 kW inverter on the dynamometer to evaluate the performance of the WBG inverter.
  - Complete the design, build, and test of the protection circuits for the inverter.
  - Design, build, and test ORNL-module-based 30 kW liquid-cooled and air-cooled inverters.

- **FY17**
  - Develop, design, and test a 55 kW liquid-cooled WBG inverter with high temperature module and high temperature smart gate driver and integrate the novel protection and sense controls.
  - Design, build, and test a 55 kW WBG-based air-cooled inverter.

Summary

- **Relevance:** Project is targeted toward reducing volume, weight, and cost of the traction drive inverter.
- **WBG inverter development approach:**
  - 1st yr: WBG inverter prototypes: 10 kW ORNL air cooled inverter and 30 kW commercial-module-based liquid-cooled inverter.
  - 2nd yr: 30 kW WBG inverter prototypes: ORNL-module-based, liquid-cooled inverter and ORNL optimized air-cooled inverter.
  - 3rd yr: 55 kW WBG inverter prototype(s): ORNL-module-based, liquid-cooled Inverter and/or air-cooled inverter.
- **Collaborations:** Interactions with WBG device manufacturers, inverter component suppliers, and NREL to maximize the impact of the inverter R&D.
- **Technical Accomplishments:**
  - Completed evaluation of 1200 V, 30 A, trench SiC MOSFET.
  - Completed design, build of a 10 kW WBG-based air-cooled inverter prototype using ORNL's WBG modules.
  - Completed design, build, and test a 10 kW WBG-based liquid-cooled inverter prototype using advanced package built at ORNL.
  - Completed the design of 30 kW WBG-based liquid-cooled inverter.
- **Future Work:**
  - Design, build, and test a 55 kW WBG-based air-cooled inverter
  - Collaborate with OEMs and Tier 1 suppliers to license the technology