Electric Drive Inverters

Madhu Chinthavali
Email: chinthavalim@ornl.gov
Phone: 865-946-1411

Oak Ridge National Laboratory
National Transportation Research Center

2017 U.S. DOE Vehicle Technologies Office
Annual Merit Review

June 6, 2017 Project ID: EDT076

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

ORNL is managed by UT-Battelle
for the US Department of Energy

Oak Ridge National Laboratory | National Transportation Research Center

Overview

Timeline

- Start – FY17
- End – FY19
- 17% complete

Barriers

- Availability and the cost of wide band gap (WBG) devices for the inverter will be barriers for achieving the DOE EDT cost target.

Budget

- Total project funding
  - DOE share – 100%
- Funding received in FY16: NA
- Funding for FY17: $1,000K

Partners

- WBG manufacturers: ROHM, CREE
- Component suppliers:SBE, ROHM, REMTEC
- ORNL team members: Jack Wang, Steven Campbell, Cliff White, Larry Seiber
- NREL – Kevin Bennion
- UTK: Saeed Anwar, Tong Wu, Fei Yang

Any proposed future work is subject to change based on funding levels

Project Objective and Relevance

- Overall Objective
  - Integrate wide bandgap (WBG) material and novel circuit technology with advanced packaging to reduce cost, improve efficiency and reliability, and increase power density of traction drive system for electric vehicles, while achieving the 2020 DOE Electric Drive Technologies (EDT) Program targets

- FY17 Objectives
  - Complete hardware development and evaluation of a 20-kW Trench SiC MOSFET-based high frequency boost converter to identify technical gaps towards 2020 power density targets
  - Simulate and evaluate state-of-the-art liquid-cooled commercial WBG module-based inverter prototype under different load conditions.

Milestones

Date	Milestones and Go/No-Go Decisions	Status
2016	Milestone: new start	
2016	Go/No-Go decision: new start	
March 2017	Go/No-Go decision: If simulation results indicate that a high frequency 20 kW, WBG-based DC-DC converter design for voltage boost applications meets 2020 EDT targets, then build a prototype.	Met
June 2017	Milestone: Develop electrical reliability evaluation methods for advanced commercial and prototype WBG devices and packages to improve the reliability of WBG-based packages for electric vehicle power electronics.	On Track
Sept. 2017	Milestone: Utilize unique capabilities and facilities to evaluate and confirm performance state-of-the-art commercial module-based, liquid-cooled all-SiC traction drive inverter to analyze efficiencies under light load conditions.	On Track

Any proposed future work is subject to change based on funding levels

Approach/Strategy

Reduce size and weight of the inverters to meet EDT 2020 targets of 13.4 kW/L and 14.1 kW/kg

WBG Reliability Analysis

(Task 1: Short Circuit Capability Evaluation)

Develop electrical reliability evaluation methods for advanced commercial and prototype WBG devices and packages to increase the safe operating area of the WBG devices

Novel System Packaging & 3D Printing

(Task 2: High Frequency DC/DC Converter)

Design low parasitic packages for high frequency operation

Design novel integrated power modules with integrated heatsinks to reduce cost through novel interconnects and process optimization

Integrated Topologies & Passives

(Task 3: Integrated Wired Charger)

Design and simulate a high frequency wired integrated charger topology to:

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

Control Algorithms & Novel Circuits

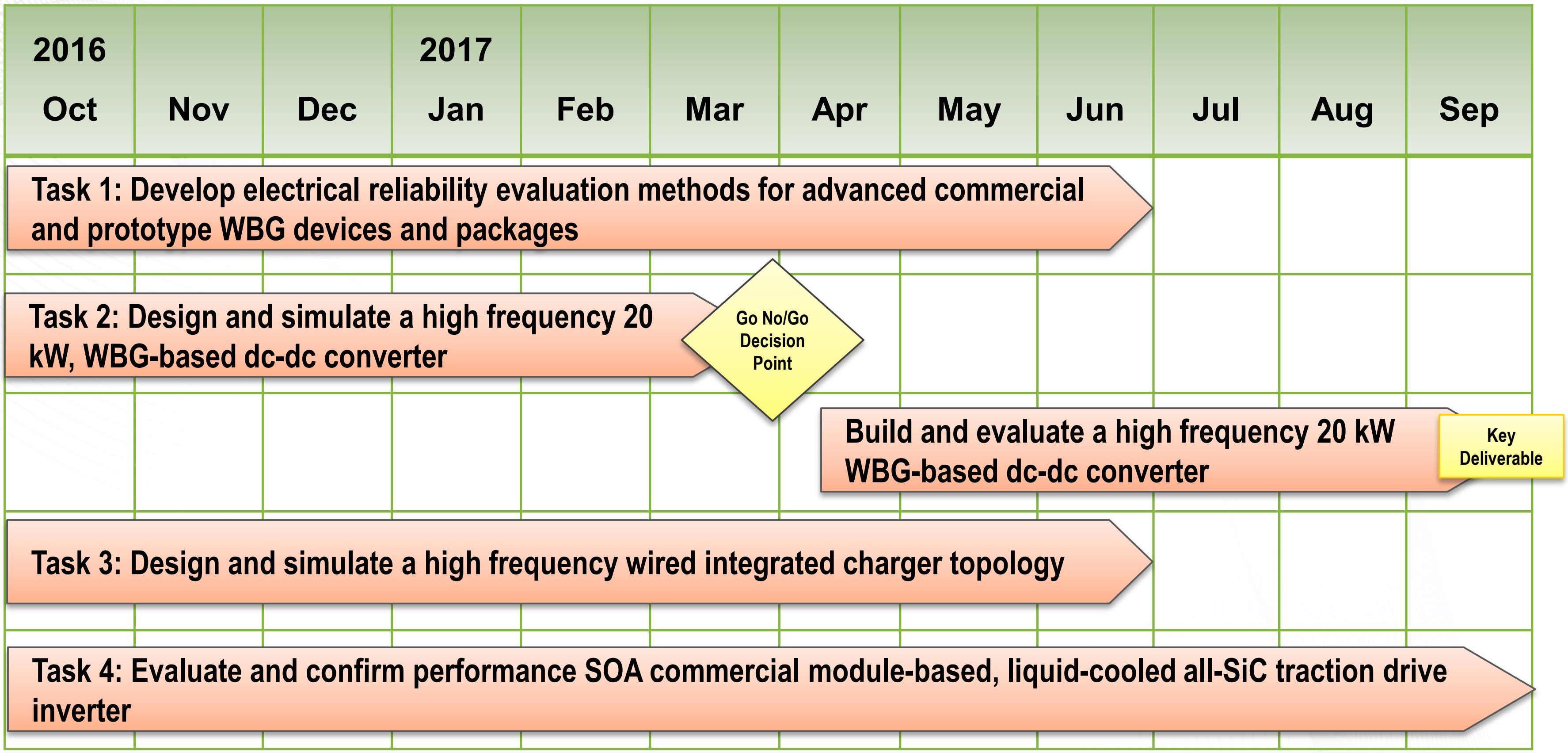
(Task 4: 30kW Inverter Performance)

Evaluate issues with light load efficiencies to:

- **Increase the reliability of the system using protection circuits**
- **Design algorithms to optimize efficiency for light load conditions**

Any proposed future work is subject to change based on funding levels

Approach FY17 Timeline



Go No/Go Decision Point: If simulation results indicate that a high frequency 20 kW, WBG-based dc-dc converter design for voltage boost applications meets 2020 EDT targets, then build a prototype.

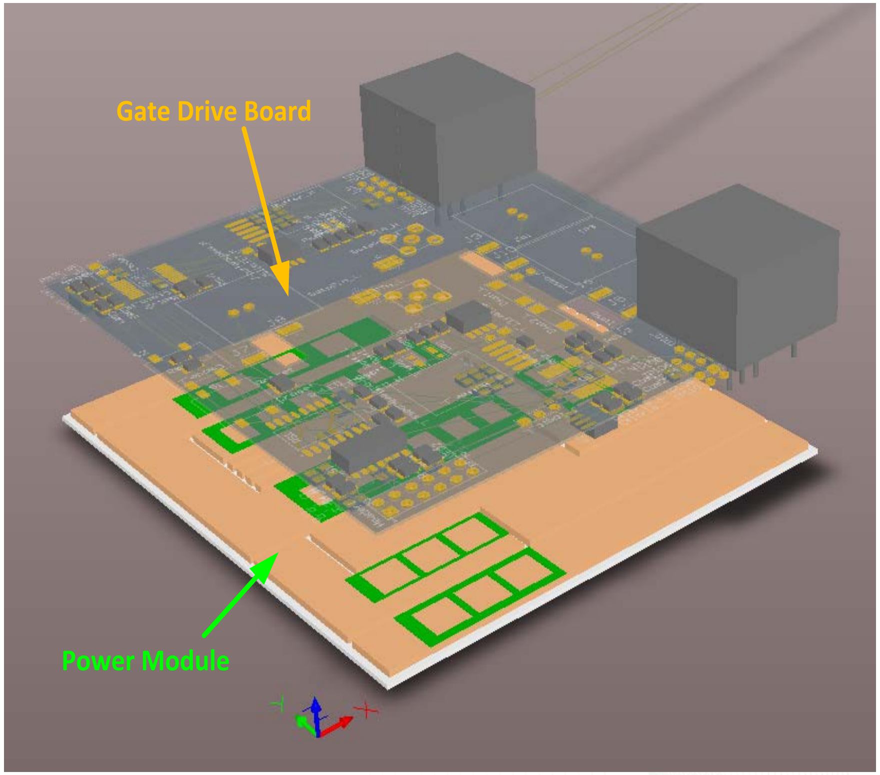
Key Deliverable: High frequency 20 kW, WBG-based dc-dc converter.

Any proposed future work is subject to change based on funding levels

Technical Accomplishments – FY17
Gate Drive/Protection Layout Design for High Frequency Boost

Advanced Features

- High driving capability (sinking/sourcing current > 30 A)
- 30% volume reduction using low-profile layout and components
- High noise immunity for high power operation up to 100 kHz switching
- Miller clamping protection function to mitigate cross-talk up to 100 kHz switching
- Fast short circuit / overcurrent protection response (<2 μs) for high power modules

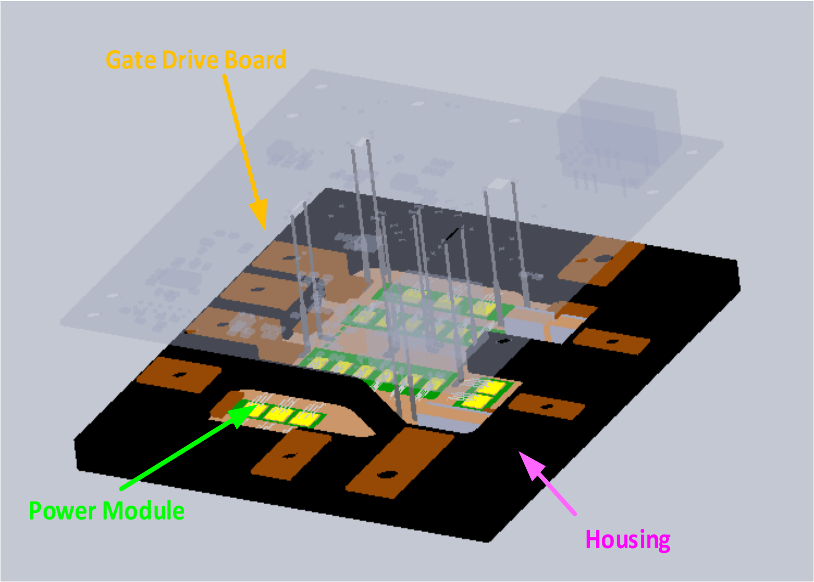


3D layout design of the gate driver

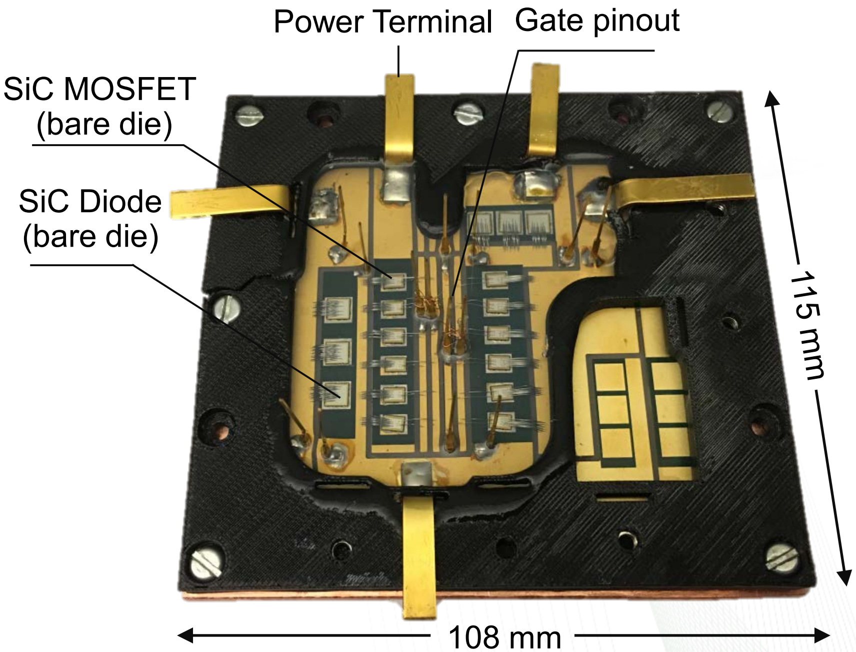
Comprehensive custom designed WBG-specific protection functions compared to SOA SiC MOSFET gate drivers

Technical Accomplishments – FY17
3D Printed all-SiC Power Module

- P-cell/N-cell concept for phase-leg power module using 1200V/55A Trench SiC MOSFETs
- Custom designed and 3D printed housing for simplified encapsulation process, reliable mechanical support, easy power terminal, and gate drive integration.



Power module 3D mechanical layout design



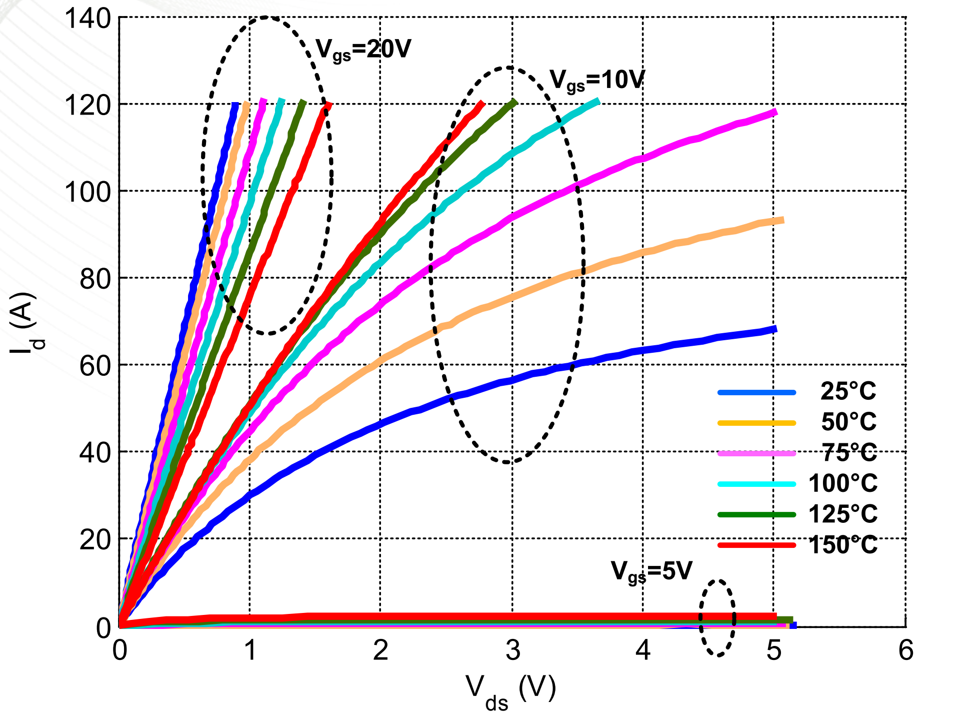
Fabricated power module

First WBG power module with integrated gate driver based on 3D printed technology

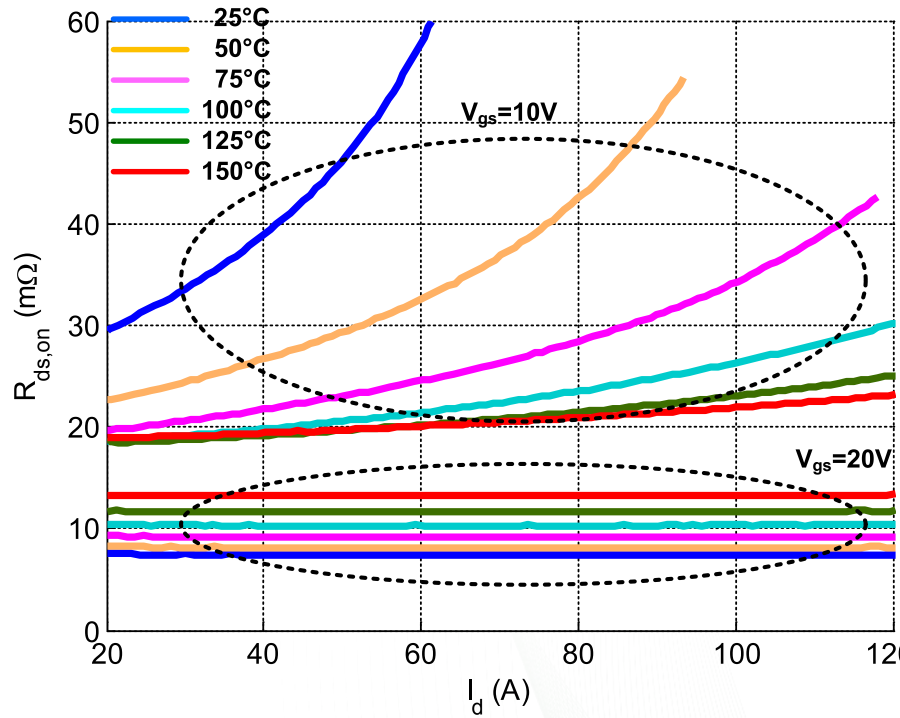
Technical Accomplishments – FY17

3D Printed all-SiC Power Module - *Temperature Dependent Static Characteristics*

- Channel resistance dominates at $V_{gs} < 10V$, and drift region resistance dominates at $V_{gs} = 20V$



Temperature dependent SiC MOSFET static characteristic



$R_{ds,on}$ vs current under different temperatures

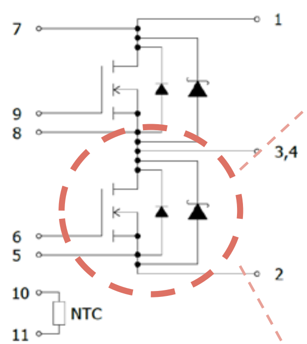
- **Positive temperature coefficient of on-state resistance $R_{ds,on}$(@V_{gs}=20V) is beneficial for current sharing under multi-chip parallel operation**
- **Low $R_{ds,on}$(@V_{gs}=20V) within a wide temperature and current range ensures low conduction loss and high power density operation**

OAK RIDGE National Laboratory | NATIONAL TRANSPORTATION RESEARCH CENTER

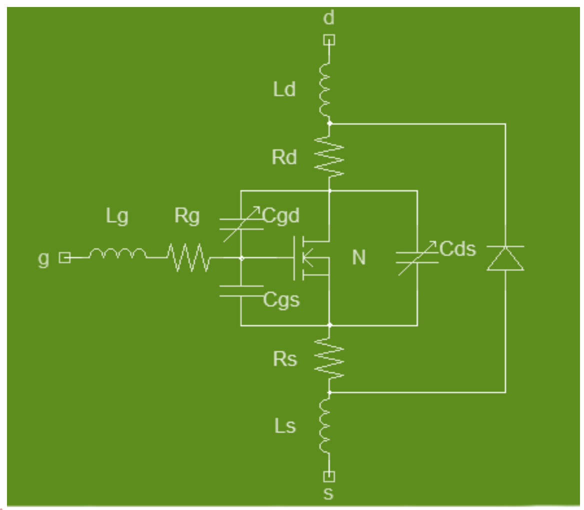
Technical Accomplishments – FY17

Integrated Device Behavioral Model for WBG Inverter Light Load Performance Simulation

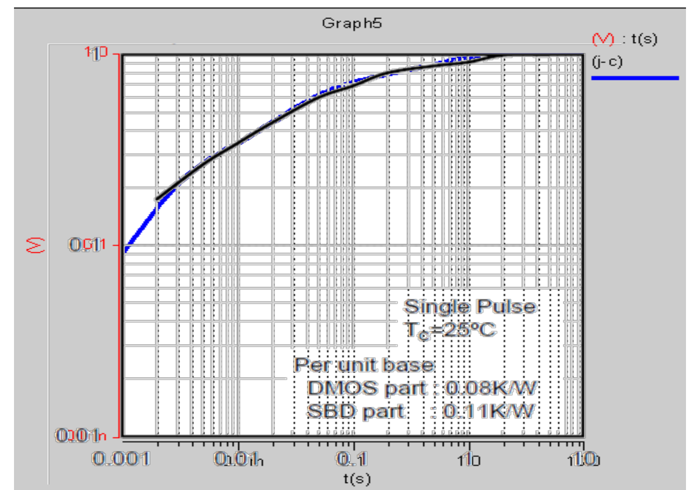
- Temperature dependent behaviors (@25°C and 125°C) were considered
- Cauer thermal parameters were evaluated using SABER thermal network tool
- Different diode and MOSFET thermal network were used because of the different die sizes



Commercial-module-based inverter (built in FY16)



Behavioral Model



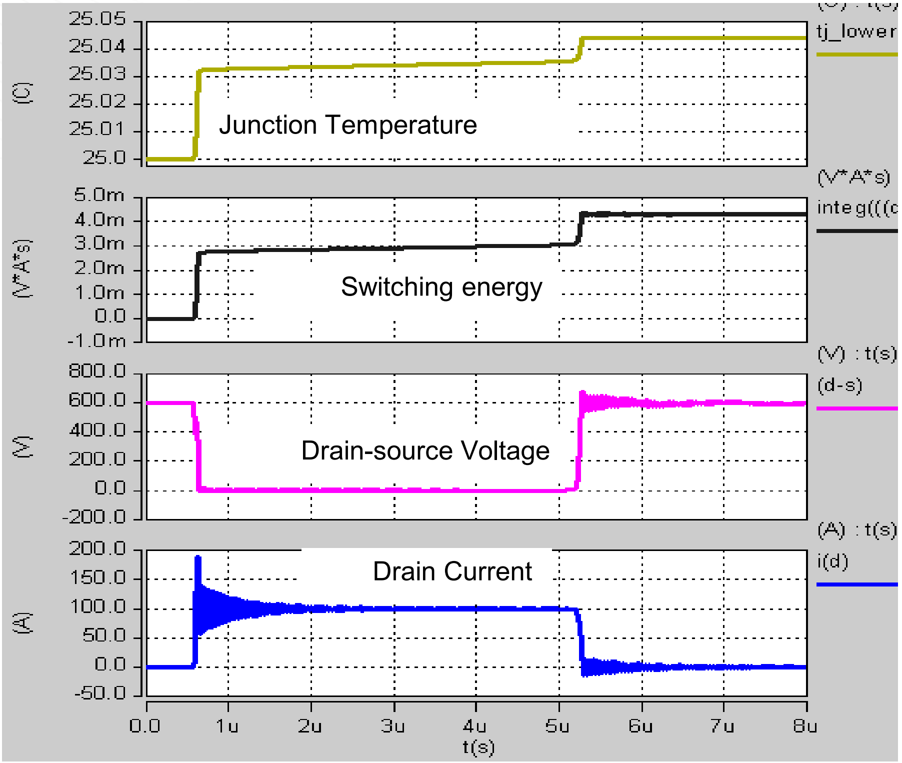
Fitted thermal impedance

Low electrical and thermal characteristic mismatch achieved (max<5%)

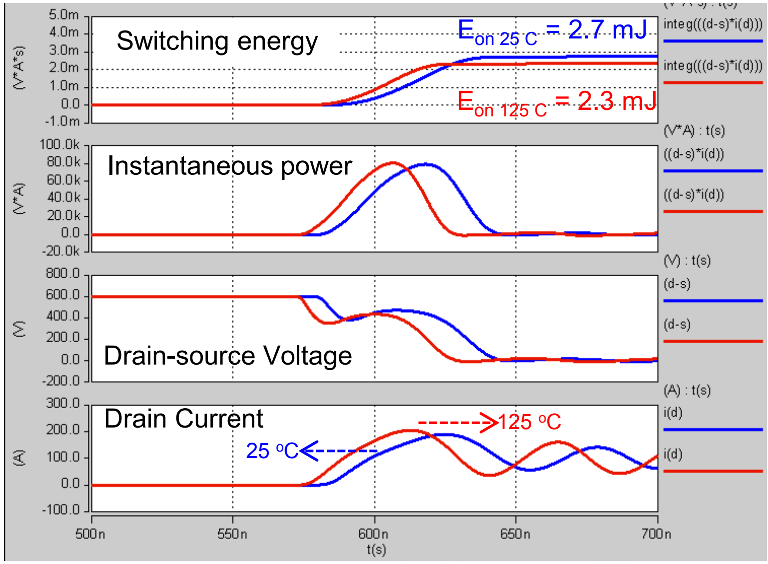
Technical Accomplishments – FY17

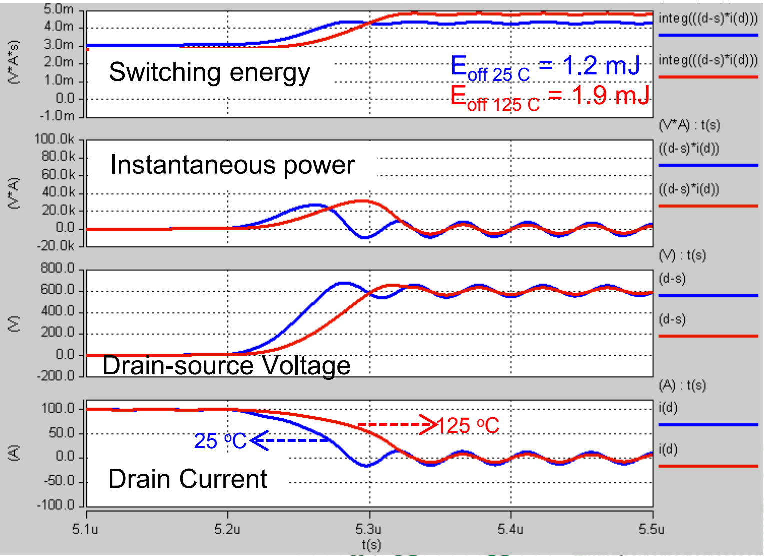
Switching & Thermal Performance Based on Developed SABER Model

- Trend of temperature-dependent switching speed matches the previous published results (lower E_{on}, higher E_{off}, and overall stable E_{tot}).
- Junction temperature rise follows the switching energy profile



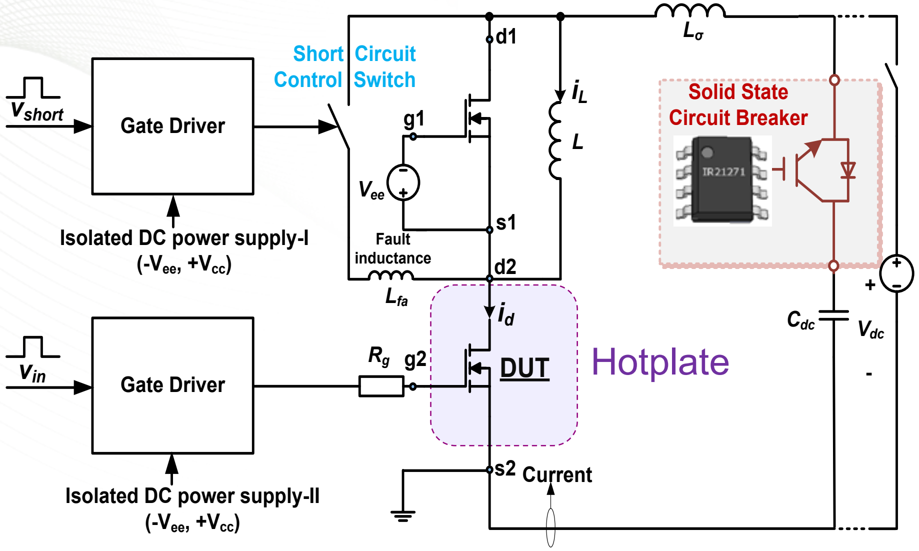
Simulated transient junction temperature rise



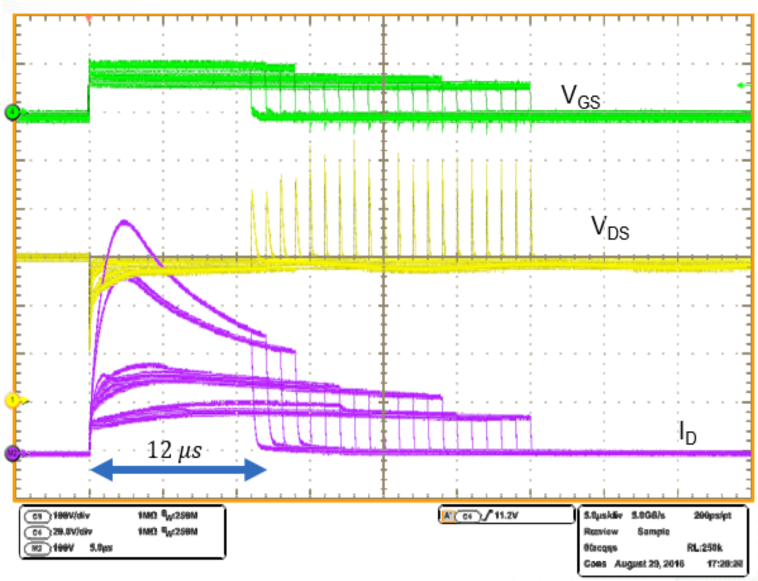


Combined device model for inverter performance prediction

Technical Accomplishments – FY17
Short Circuit Capability Evaluation



Test circuit for short circuit capability evaluation



Short circuit performance at 300V DC voltage

- Device Under Test (DUT) : 600V, 30A Trench SiC MOSFET
- Short Circuit Control Switch: Create a short circuit condition with controlled duration
- Solid State Circuit Breaker: Prevent potential damage of the test setup when DUT fails

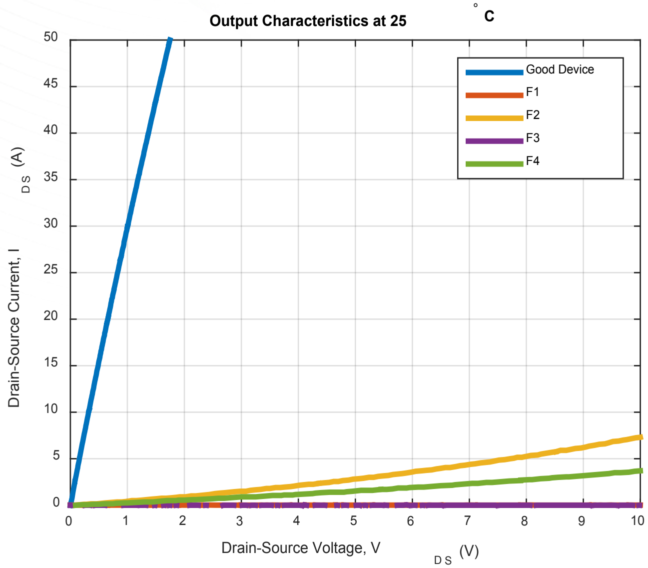
Trench SiC MOSFET fails in open circuit mode

- Short circuit duration is gradually increased form 1 μs to 30 μs.
- The device can withstand about 470 A current up to 12 μs. After that the channel degradation occurs which lead to higher channel impedance.
- The higher channel impedance further leads to reduced short circuit current.

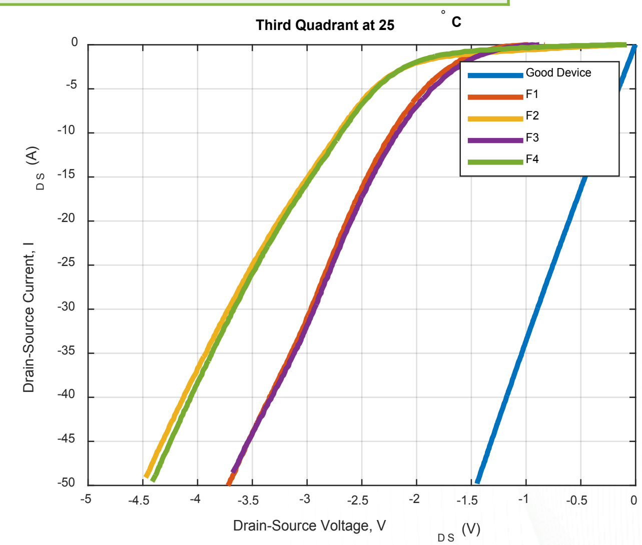
OAK RIDGE National Laboratory | NATIONAL TRANSPORTATION RESEARCH CENTER

Technical Accomplishments – FY17
Short Circuit Post Failure Analysis

Device ID	Description
Good Device	Good device sample of Trench SiC MOSFET
F1	Protected short circuit test conducted at 75°C
F2	Unprotected short circuit test conducted at 75°C
F3	Protected short circuit test conducted at 100°C
F4	Unprotected short circuit test conducted at 100°C



Output characteristics comparison among devices



Third quadrant characteristics comparison among devices

- Output characteristics show significant increase of the device on-resistance and show open circuit like behavior when 20 V gate voltage is applied.

- F1 and F3: the gate almost has no control and very low current flows through the channel.
- F2 and F4: the channel conduction is lost and body diode conducts all the current.

Desirable characteristics for highly reliable application

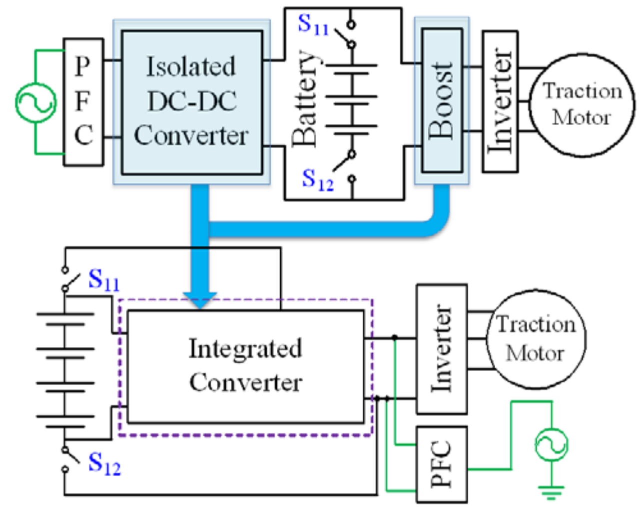
OAK RIDGE National Laboratory | NATIONAL TRANSPORTATION RESEARCH CENTER

Technical Accomplishments – FY17

Wired Integrated Charger

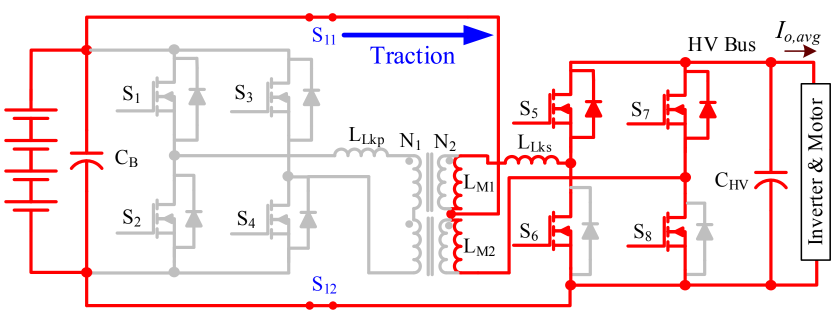
Advantages

- Share magnetics
- Share SiC power switches
- Share HV bus capacitor
- Share heat sink
- Reuse existing BMS relay for reconfiguration

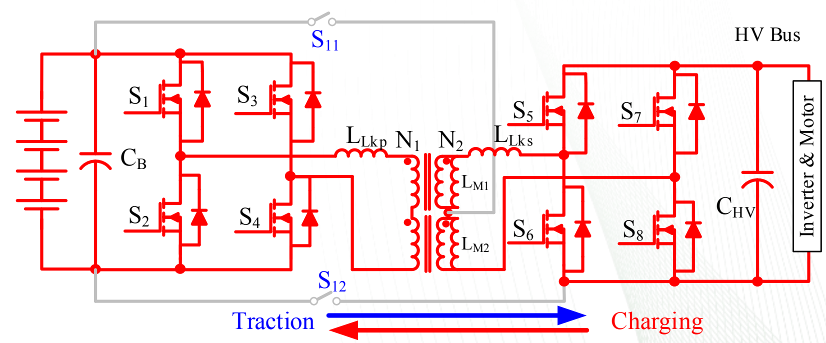


Overall concept

Operating Modes:



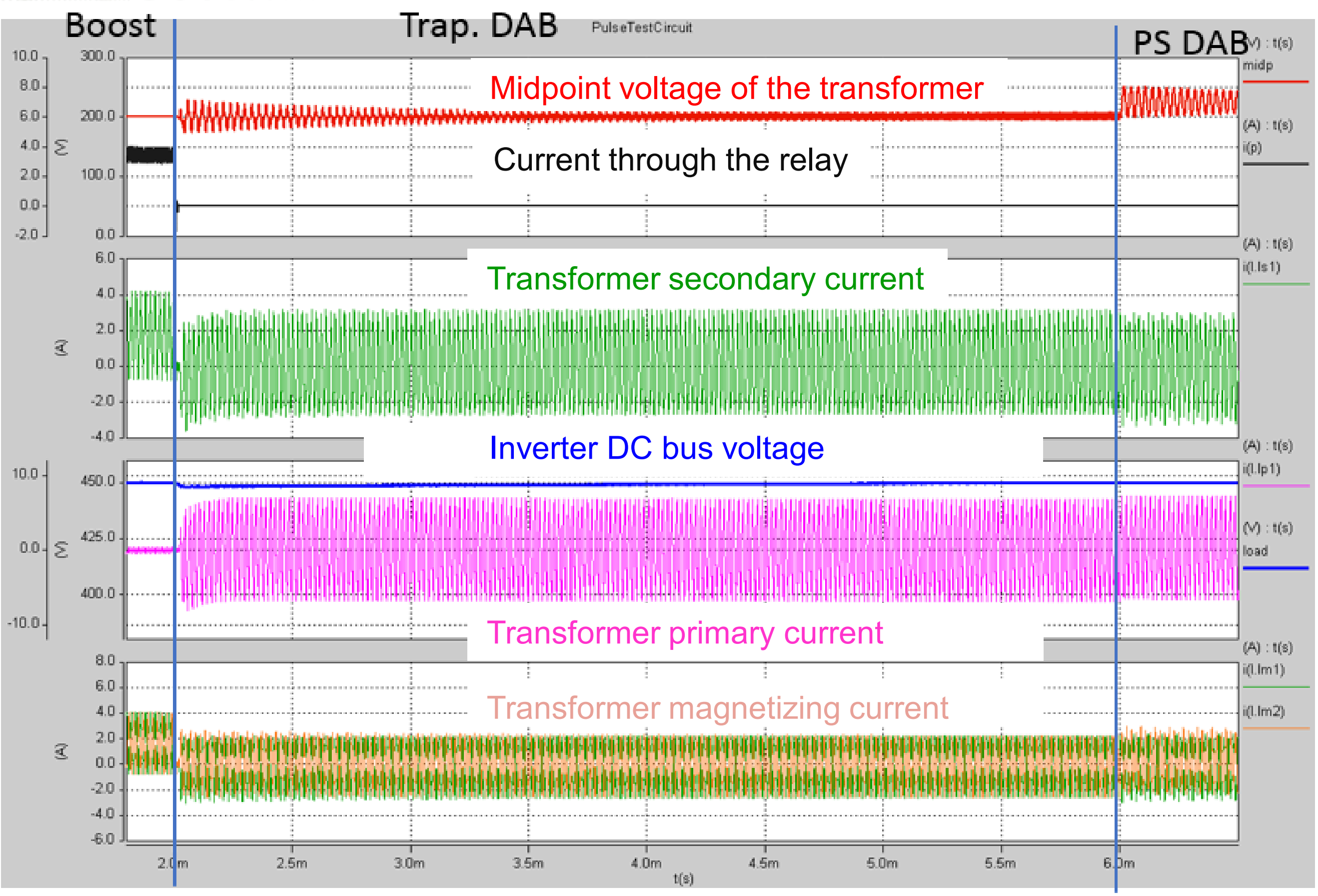
Boost configuration



Dual active bridge (DAB) configuration

Integrated topology with low component number and flexible operating modes

Technical Accomplishments – FY17
Wired Integrated Charger-Simulation of Different Operating Modes



Operating modes:

1) **Boost Mode for traction drive**

2) **DAB with phase-shift (PS DAB) modulation for charging and traction drive**

Seamless mode transition with high efficiency operation

Transition Mode:

DAB with trapezoidal (Trapezoidal DAB) modulation

- **Changing the phase shift and duty cycle simultaneously**
- **Low current / voltage stress on relay**
- **Enabling zero-voltage turn-on (ZVS) and zero current turn-off (ZCS) of the battery contactors**
- **Eliminating expensive and bulky high current/voltage rating mechanical and electronic relays**
- **No need for high inverter DC bus capacitance to hold up voltage during transition**

Responses to Previous Year Reviewers' Comments

- This project is a new start.

Reviewer comment: NA

Response/Action: NA

Collaboration and Coordination with Other Institutions

Organization	Role
WBG manufacturers: ROHM, CREE, Infineon, International Rectifier	Device prototype suppliers
Inductor/Capacitor manufacturers: SBE, KEMET, AVX	Magnetics and capacitor suppliers
Packaging material manufacturers: REMTEC, GMF, NUSIL	Custom DBC substrate, surface finishing, encapasulant, etc.
NREL, UTK	Thermal design and analysis

Remaining Challenges and Barriers for FY17

- **The power density for the current liquid-cooled boost converter designs need to be further improved to meet the targets.**
- **Parasitic inductance of the DBC substrate for the boost converter needs to be minimized to support high frequency operation.**
- **Advanced gate drive protection and control schemes need to be developed with existing components to reduce the switching loss of the traction drive inverter under light load condition.**
- **The DC link capacitor volume is a barrier to achieve the overall volume target.**

Any proposed future work is subject to change based on funding levels

Proposed Future Work

- **Remainder of FY17**
  - Complete electrical reliability evaluation methods for advanced commercial and prototype WBG devices and packages to improve the reliability of WBG-based packages for electric vehicle power electronics
  - Complete evaluation of 20 kW high-frequency boost converter
  - Complete simulation verification for the wired integrated charger topology
  - Complete evaluation and confirm performance of SOA commercial-module-based, liquid-cooled all-SiC traction drive inverter to analyze efficiencies under light load conditions

- **FY18**
  - Develop new operation schemes and gate drive techniques to improve the light load efficiency of traction drive inverter
  - Improve the power density and cost of high frequency boost converter using phase-leg modules without anti-parallel SiC Schottky barrier diodes

Any proposed future work is subject to change based on funding levels

Summary

- **Relevance:** Project is targeted toward reducing volume, weight, and cost of the traction drive inverter with improved reliability.
- **Approach:**
  - Evaluate SOA WBG device(s) to improve reliability and technical performance in electric drive inverters.
  - Develop electrical reliability evaluation methods for advanced commercial and prototype WBG devices and packages to improve the reliability of WBG-based packages for electric vehicle power electronics.
  - Simulate, design, build, and evaluate a high frequency 20 kW, WBG-based DC-DC converter for voltage boost applications.
  - Evaluate and confirm performance SOA commercial-module-based, liquid-cooled all-SiC traction drive inverter to analyze efficiencies under light load conditions.
- **Collaborations:** Interactions with WBG device manufacturers, inverter component suppliers, and packaging material supplier to maximize the impact of the inverter R&D.
- **Technical Accomplishments:**
  - Completed design and fabrication of Trench SiC MOSFET-based power module for high frequency boost converter.
  - Developed a SABER simulation behavior model (including electrical and thermal behavior) for selected commercial WBG devices for a traction drive inverter.
  - Completed design and simulation of a wired integrated charger.
- **Future Work:**
  - Complete evaluation of the 20 kW high frequency boost converter.
  - Complete evaluation and confirm performance of SOA commercial module-based, liquid-cooled all-SiC traction drive inverter.
  - Collaborate with OEMs and Tier 1 suppliers to license the technology.

Any proposed future work is subject to change based on funding levels