Highly Integrated Wide Bandgap Power Module for Next Generation Plug-In Vehicles

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Overview

Timeline

- Start – 1 January 2016
- Finish – 30 September 2019
- 67% Complete

Funding

- Project Budget $5.67 million
  - $3.79M Federal Share
  - $1.88M GM Cost Share
- 2018 funds received $0.88M
- 2019 funding planned $1.09M

Vehicle Technology Barriers

- Lower Cost Electric Drive Systems
- Higher Efficiency, long range EV
- Higher Performance and Lifetime
- Lower Mass and Volume

Project Team

- Lead:
  - General Motors, LLC
- Subrecipients:
  - Virginia Polytechnic Institute and State University
  - Oak Ridge National Lab
  - Monolith Semiconductor, Inc.
- Key Suppliers:
  - Wolfspeed (Cree Power)
- Collaborations:
  - PowerAmerica

Project Relevance

Research Focus Area: Traction Inverter

- Develop WBG semiconductor based power stage
- Technical development for key components needed for a WBG power stage: design compact gate drive, power module, high voltage capacitor, integrate commercial current sensor, use production ready GM control board

Objective

- Automotive power module with SiC MOSFET dies
- Reduce traction inverter and electric motor losses over the drive cycle and quantify efficiency benefits
- Develop technology for long range BEV's with >600V battery
- Implement selected bonding, joining and thermal management solution (low Z_{th}, long lifetime and reliability)

Address DoE Targets

- Enable inverter to meet or exceed DOE 2020 targets:
- Power Density: 13.4kW/l; Specific power: 14.1kW/kg & $3.3/kW
- Efficiency >94% (10%-100% speed at 20% rated torque)

Uniqueness and Impacts

- Compact, high temperature, low inductance automotive package

Milestones

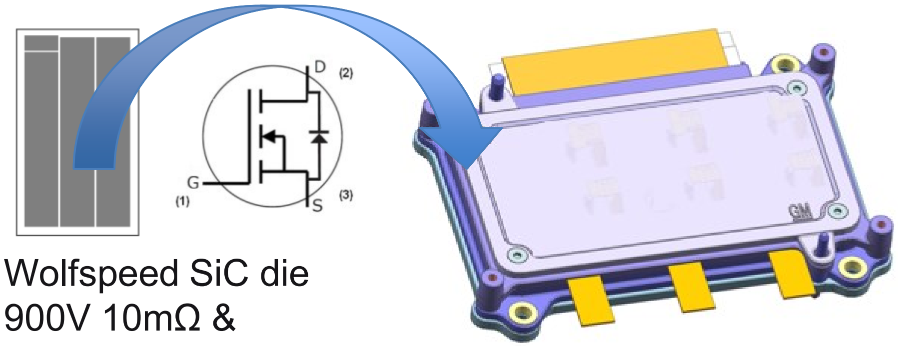
Date	2016-2018 Milestone or Go/No-Go Decisions	Status
Dec - 2016	Initial Power Module Design - Milestone	Completed
June - 2017	Power Module Detailed Design – Phase 2 Go/No-Go	Go
Dec - 2017	Prototype Manufacturing Process - Milestone	Completed
April - 2018	SiC MOSFET Final Builds and Die Tests - Milestone	Completed
June - 2018	Power Module Prototype Perf. – Phase 3 Go/No-Go	On-Track
Oct - 2018	Prototype Performance Test Completed - Milestone	On-Track
Nov - 2018	**Power module and power stage fully characterized**	**Completed**
Dec - 2018	**Performed vehicle range study**	**Completed**
Dec – 2018 to Mar - 2019	**Rescoped phase III of the project to focus more on electric drive performance and development**	**On-Track**

WBG POWER MODULE APPLICATIONS

Features

- Low conduction and switching loss
- Ultra-low parasitic inductances
- High switching frequency operation
- Normally-off device operation
- High temperature operation Tjmax=175°C
- High power high voltage power module

SiC Power Module Package

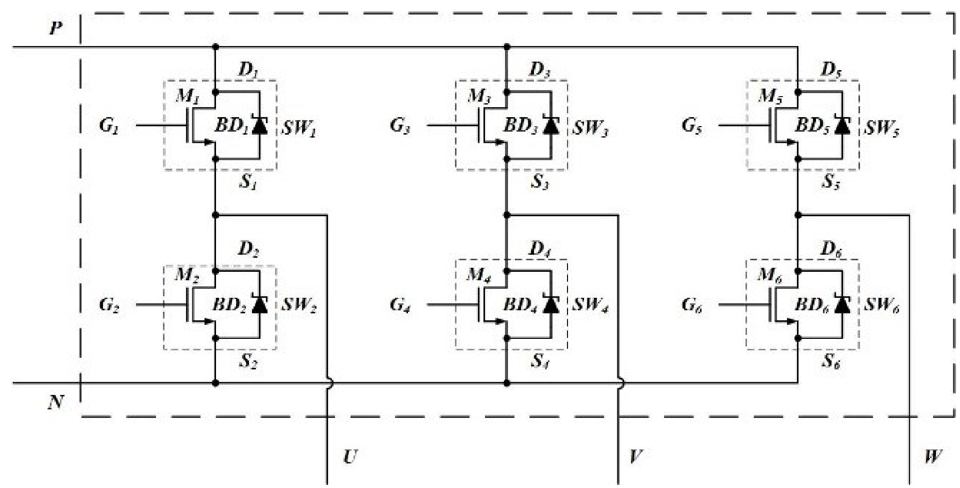


Wolfspeed SiC die
900V 10mΩ &
1200V 13mΩ

System benefits

- Reduced size and weight
- Compact design and inverter packaging
- High efficiency inverter
- Increased power density
- Improved thermal performance and packaging

Functional Circuit

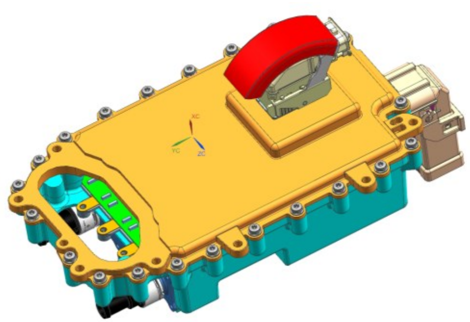


Potential applications

- High efficiency converters
  Such as dc/dc boost converter
- Traction power inverters

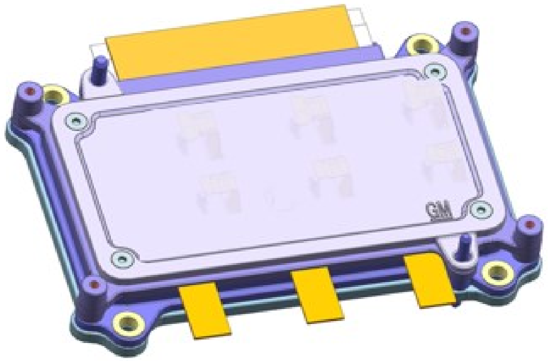
Technical Approach

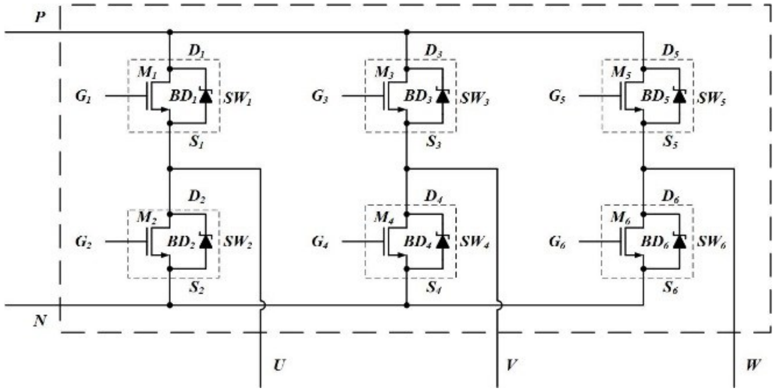
- This program will develop a highly integrated wide band gap automotive power module with smaller package, lower mass and higher efficiency
- Targets higher DC link bus voltage systems (e.g. 600-800Vdc) and maximum phase currents of 300-500Arms
- The high power density module utilizes SiC MOSFET die to enable high efficiency operation
- Higher power density will be further enabled through the removal of the external diode by using the third quadrant operational capability of the SiC MOSFET
- Design a package that has low stray inductance
  - Target below 10nH for the complete power stage
  - Design power module stray inductance below 5 nH
- Develop advanced current sensing and short circuit protection methods



Accomplishments: Sintering

- Sintering is selected as the attachment method to enable higher temperature operation and long-life reliability
- Both pressure and pressure-less sintering has been evaluated
- Pressure sintering (>10MPa) has been implemented in the power module
- Power module design is more compact as sintered layer conducts heat more effectively
- Results in lower thermal impedance and small cross heating among die, enabling positioning in closer proximity
- High density package of the power module

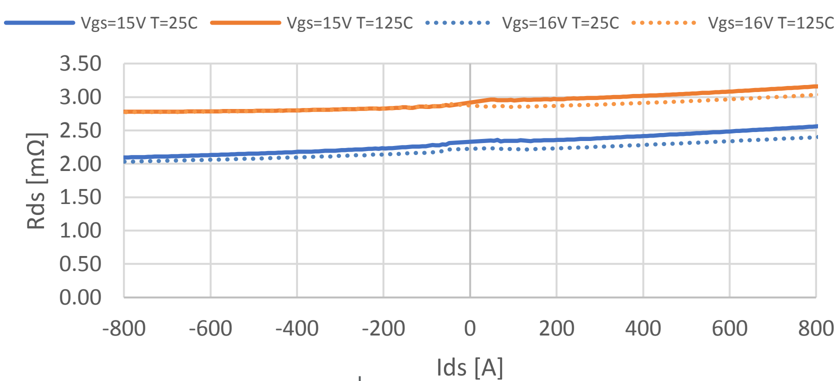




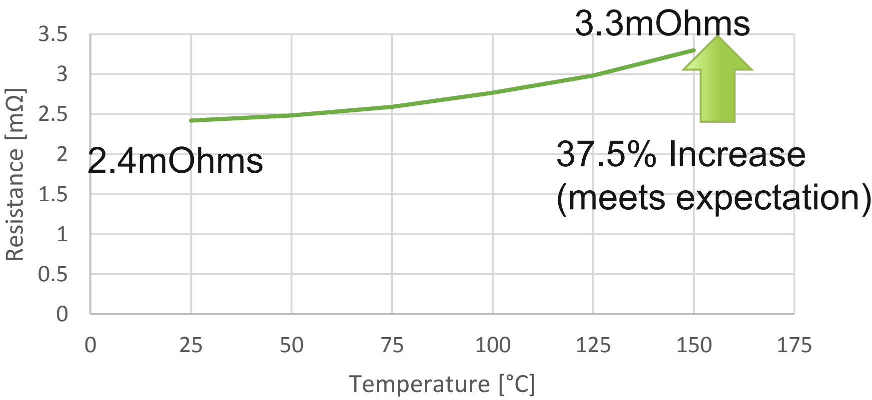
Accomplishments:
Static Characterization

- SiC MOSFETs exhibit low on-state resistance even if biased with low gate source voltages
- Switch resistance reduces when MOSFET conducts in the reverse direction and increases linearly as current is increased
- Switch resistance is close to 2.4mΩ at room temperature and it reaches 3.3mΩ at 150°C

Switch resistance



Switch resistance (Vgs=15V, Ids=300A)



Accomplishments:
Representative Switching Waveforms

Turn-on waveforms 600V, 500A

E_{on}=13.37mJ

Turn-off waveforms 600V, 500A

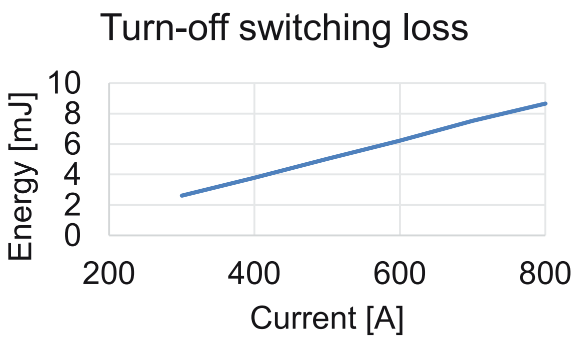
E_{off}=10.08mJ

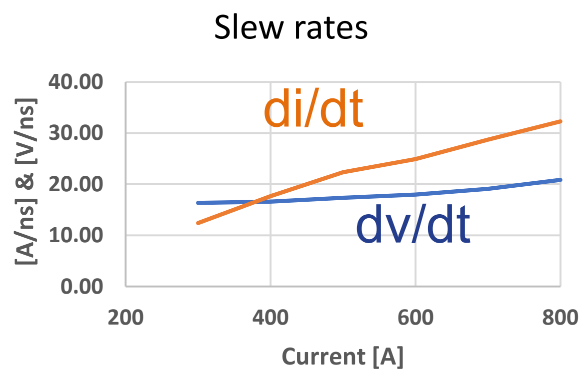
Time scale: 50 ns

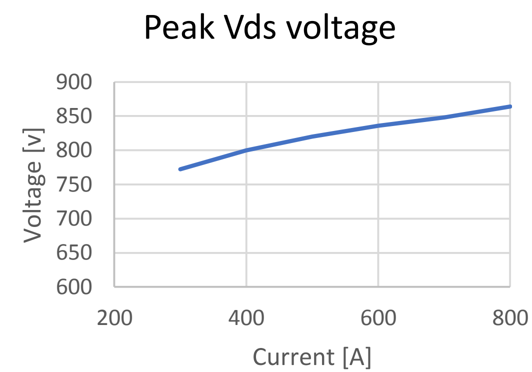
Gate drive +16V, -4V, distributed R_g to reduce oscillations, fast slew rates achieved

Accomplishments:
Detailed Turn-Off Performance Characterization

- Low switching losses are measured
- High slew rates values are observed and measured
- Peak voltage overshoot on drain source voltage is kept below the power device limit







Isw [A]	Vpeak [V]	trise (volt) [ns]	dv/dt [V/ns]	di/dt [A/ns]	Eoff [mJ]
300	748	31.38	15.30	11.00	2.62
400	784	29.17	16.46	16.80	3.8
500	804	29.5	16.27	20.00	5.02
600	824	27.75	17.30	23.00	6.23
700	832	27.25	17.61	26.40	7.53
800	848	26.9	17.84	37.12	8.66

I_{sw}=800A

V_{dc}=600V

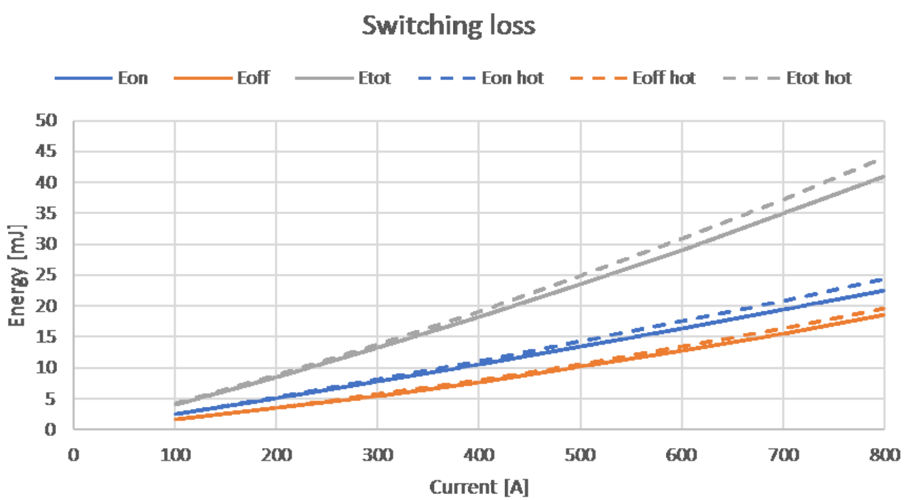
V_{peak}=848V

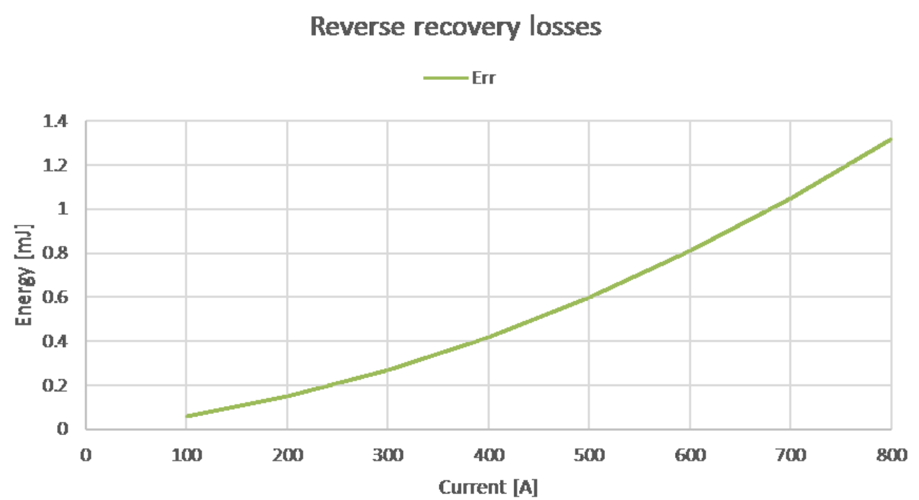
di/dt=37.12A/ns

E_{off}=8.66mJ

Accomplishments:
Complete Dynamic Characterization

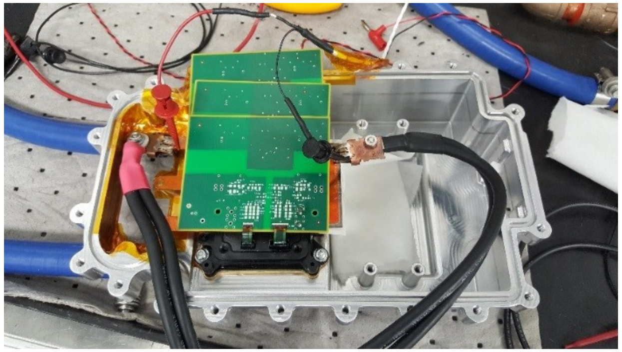
- In addition, temperature of the baseplate is controlled to provide module characterization at increased temperatures
- Energy curves at hot temperature are shown in dashed line
- As expected the hot temperature losses increase by several percent, in the range from 5% to 7% depending on the device current
- Ultra low reverse recovery losses, due to the fast body diode

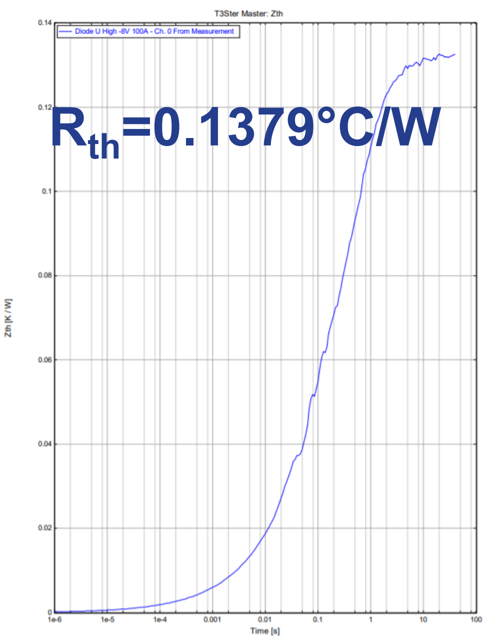


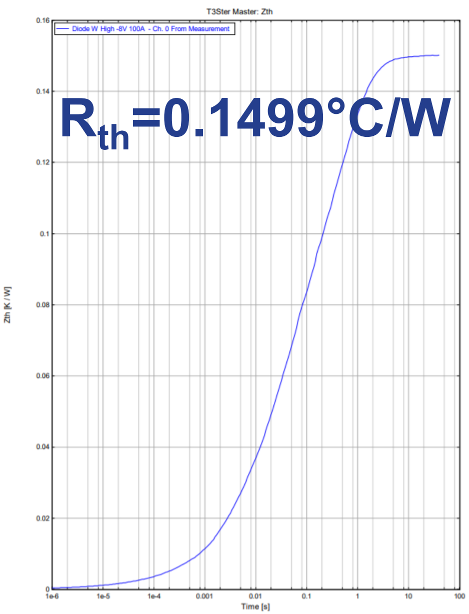


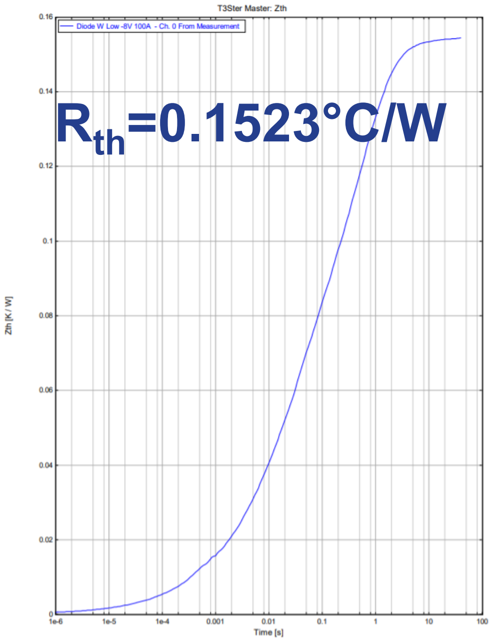
Accomplishments:
Thermal Impedance Characterization

- Power module has been installed inside the inverter housing
- Thermal impedance measurements performed and Z_{th} values are estimated
- Different measurement methods explored
- Most precise results obtained when biasing device through body diode (V_{gs} voltage set lower than -5V)
- Experimental measurements correlated to FEA results









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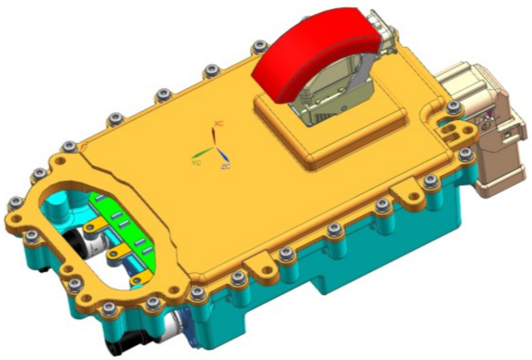
Accomplishments:
Inverter Loss Estimation

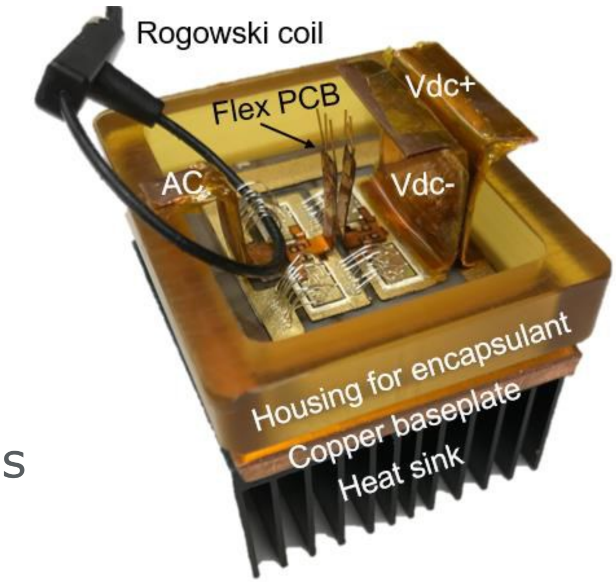
- Static and dynamic characterization results are used to evaluate power module losses
- Thermal impedance value is estimated from the material stack-up and with tri-tester measurement
- Analytical equations are derived and used to calculate inverter losses and temperature rise



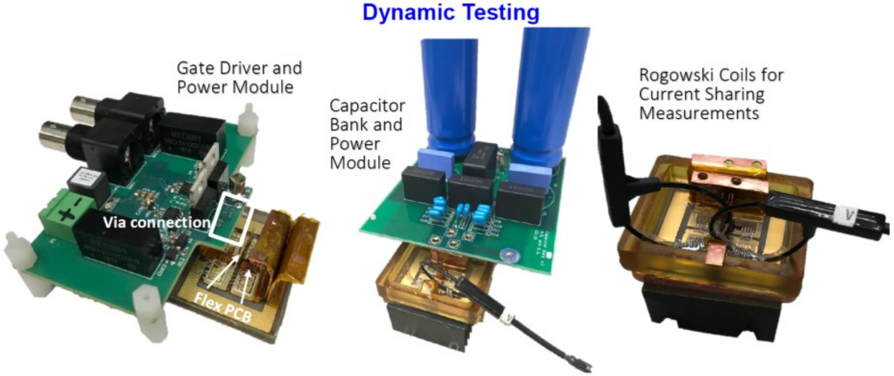
	Operating point 1	Operating point 2	Operating point 3	Operating point 4
Bus voltage	600V	600V	600V	600V
Phase current	300Arms	350Arms	400Arms	500Arms
Conduction loss	135W	184W	241W	380W
Switching loss (f_{sw}=10kHz)	63W	75W	87.5W	114W
Thermal impedance	0.15°C/W	0.15°C/W	0.15°C/W	0.15°C/W
Total inverter loss	**1.14kW**	**1.37kW**	**1.75kW**	**2.67kW**
Inverter power	**168kW**	**196kW**	**225kW**	**281kW**
Efficiency	**99.32%**	**99.30%**	**99.22%**	**99.05%**
Temperature rise	**29.7°C**	**38.9°C**	**49.3°C**	**74.1°C**

Accomplishments:
Power Module Development

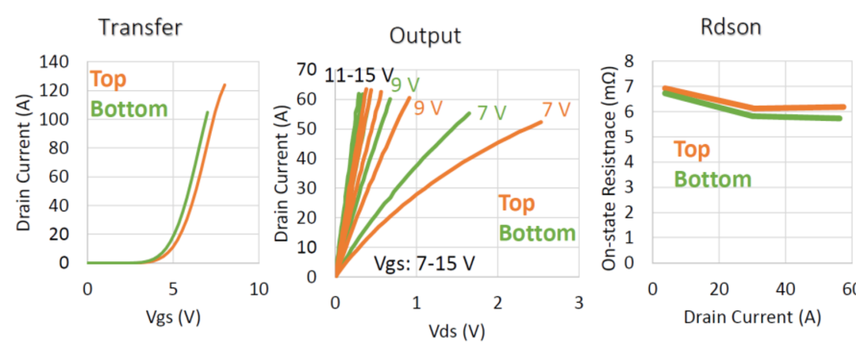
- Design optimization and fabrication of half bridge power module with symmetrical layout
- Cree 1200V-13mOhm die sintered on AlN DBC Substrate
- Flex circuit directly connected to the power module substrate and die
- Low inductance design
- Full static characterization of the power module is performed
- Dynamic characterization in progress



Dynamic Testing



Static Results

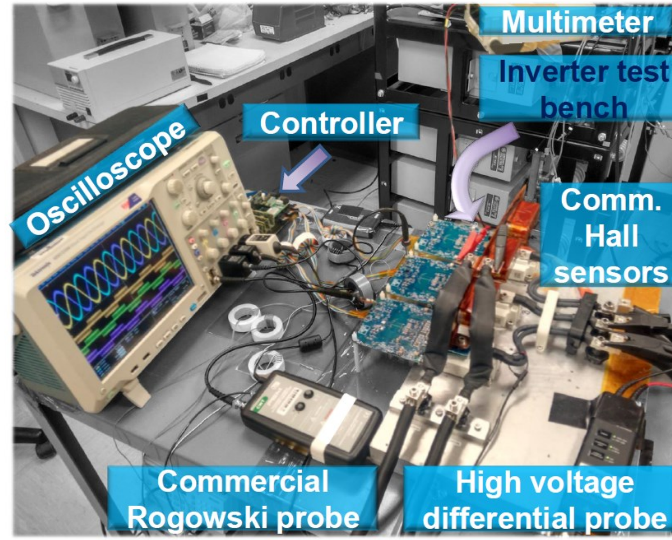


Performed by subrecipient: Virginia Polytechnic Institute and State University

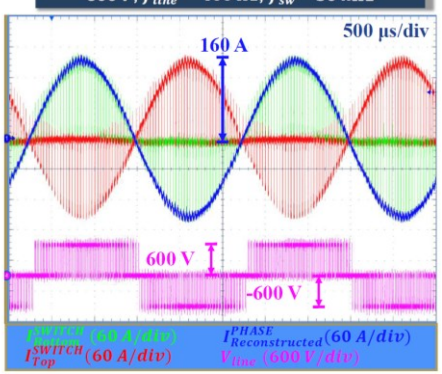
Accomplishments: Gate Drive Phase Current Reconstruction

- Integrated Rogowski coil sensors are developed to provide fast short circuit protection
- Performed successful phase current reconstruction with digital implementation
- Applicable for both Si IGBT and SiC MOSFETs based power modules
- Current sensing performance is comparable to existing hall effect sensors

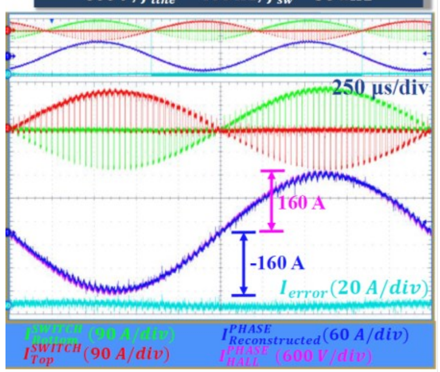
Inverter Experimental Setup

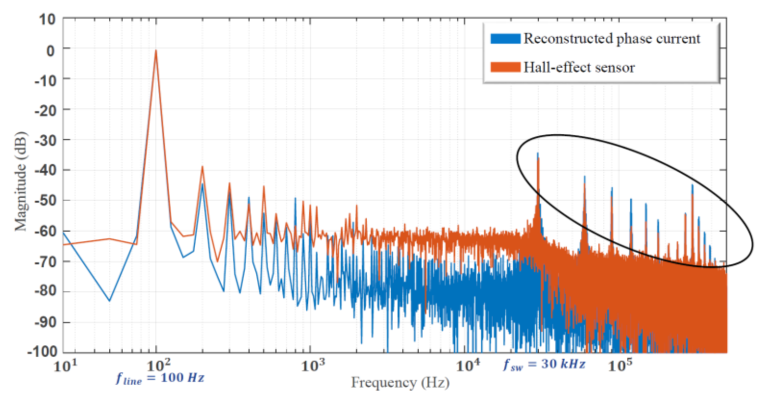


Phase Current Reconstruction Verification
600 V, f_{line} = 400 Hz, f_{sw} = 30 kHz



Phase Current Reconstruction Comparison
600 V, f_{line} = 400 Hz, f_{sw} = 30 kHz





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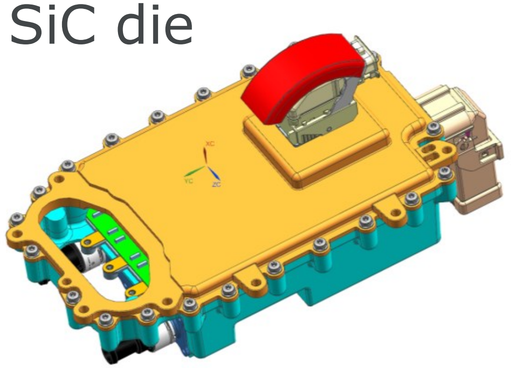
Remaining Challenges, Barriers & Future Plans

Challenges & Potential Barriers

- Power module reliability and yield during prototype phases
- Development of high bandwidth low cost current sensing
- Gate drive improvements: design reliable and fast short circuit protection that is integrated and faster than standard "de-sat" protection
- EMI noise generation due to the high dv/dt switching
- Electric motor insulation (increased dv/dt)
- Inverter cost is increased due to the high cost of SiC die

Future Plans (FY2019)

- Development of power module with 1200V SiC die
- Finalize SiC inverter packaging concept
- Test electric drive solution on dyno
- Perform power cycling tests



Proposed future work is subject to change based on funding levels and Go/No-Go gate review

Summary

- Power module successfully built and completely characterized (SiC MOSFETs 900V, 2.5mOhm)
- Very low conduction and switching losses measured
- Gate drive solutions tested and fully developed
- Complete power stage package is about 60% of the standard Si power stage
- Package inductance, and thermal performance have been modeled & are below targets
- Prototype manufacturing process defined and verified
- High efficiency power stage built and designed that can deliver up to 280kW
- Project is progressing to phase three – fabrication & inverter level testing on dyno (build new samples with 1200V, 13mOhm die)