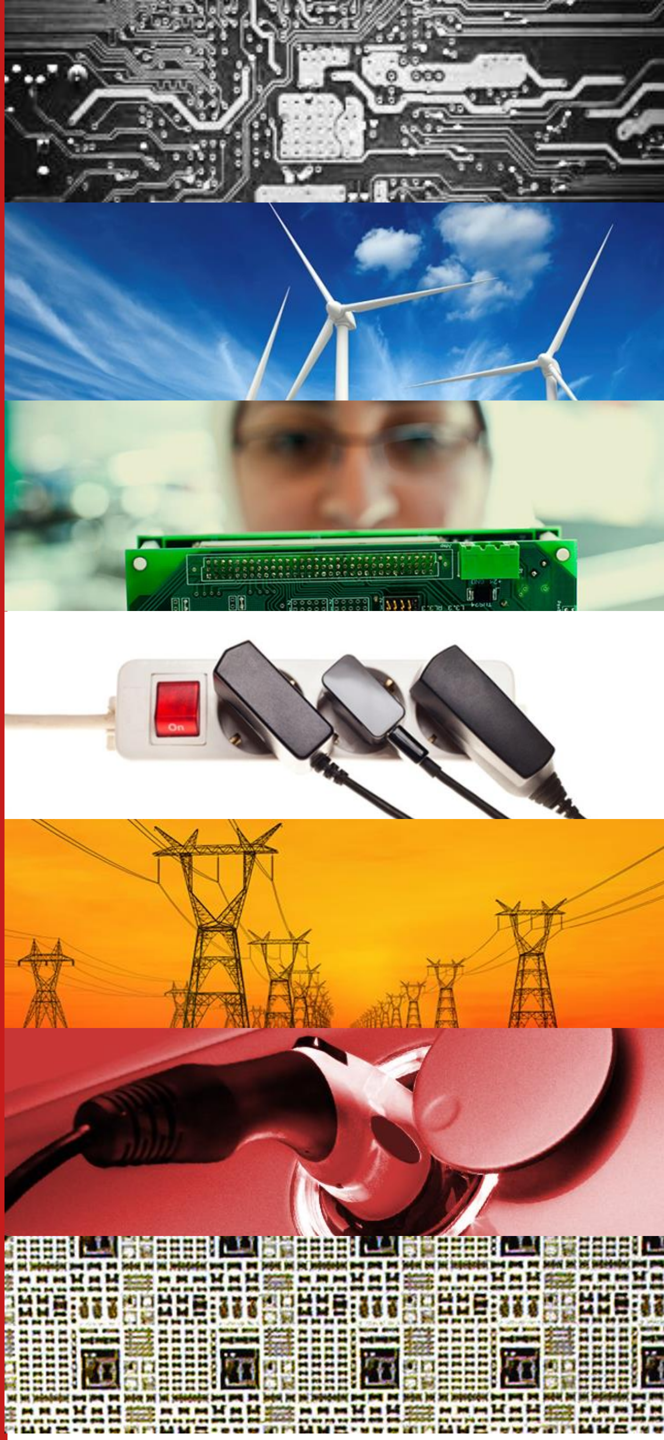
DOE-PowerAmerica

Silicon Carbide Inverter Technology Development - A Success Story

Brij N. Singh
John Deere Electronic Solutions (JDES), Inc.
Fargo, North Dakota

Partner: DOE-NREL



Project Title: Development, Testing, and Deployment of SiC Inverter for Heavy-Duty Vehicles

Objectives: 200kW 1050V DC bus SiC dual manufacturing and commercialization

Major Milestones: Deployment of engine coolant (95°C - 115°C) high power density (> 20 kW/dm^3) Gen-2 SiC dual inverter in JD 644K Hybrid Loader (upper right picture)

Significant Equipment Acquisition: None

Deliverables: Dedicated cooling system for inverter eliminated in 644K Hybrid Loader

TPOC: Dr. Brij N. Singh
Email: SinghBrijN@JohnDeere.com
Phone: (701) 552-8516

WBG Technology Impact

1. Higher DC bus voltage, higher switching frequency, higher junction temp and heat flux, higher kW/L and kW/kg, smaller passives and system level advantages.
2. Heavy-duty off-highway and on-highway vehicles.
3. Technology development completion by Jun 2020
4. Switching frequency (> 15 kHz with SiC versus 8 kHz with Si). DC bus cap (300 µF - 400 µF with SiC versus 1500µF with silicon). Inverter power density (> 25 kW/L with SiC versus 17 kW/L with silicon)

Additional Impacts of WBG Technology

1. Engine coolant power electronics
2. **WBG tech suitable for innovations by 9C solutions:** copper, capacitor, cable, connector, coolant, case, (CCS) coreless current sensor control, and cost
3. WBG product manufacturing jobs in Fargo
4. WBG power electronics workforce development
   - Summer internship opportunities at JDES

4. Current Technology Readiness Level: TRL 3/4

5. Projected TRL at end of project: TRL 6/7

Public Release

John Deere Electronic Solutions (JDES) greatly appreciates the Department of Energy (DOE) funding through PowerAmerica Institute at North Carolina State University, Raleigh. This DOE funding has enabled JDES to carry out research and development work for the next generation of power electronics, evaluating the potential use of wide bandgap (WBG) power devices such as silicon carbide (SiC) power modules. JDES anticipates a SiC-based inverter can provide overall system benefits in off-road applications, including vehicle efficiency and fuel savings, comparable to data published in SAE Off-Highway Engineering magazine issues dated February 2016 **[Ref 1]** and February 2013 **[Ref 2]**. For example, the John Deere 644K Hybrid Loader is a construction machine that currently uses an IGBT- (insulated gate bipolar transistor) based inverter in its hybrid drivetrain. This loader offers up to 25% fuel saving as compared to a conventional 644K loader. The proposed SiC inverter under development through PowerAmerica funding could potentially outperform IGBT-based inverters that are currently commercially available for certain construction and other off-road machines. Additional information including benefits of the SiC technology for off-highway vehicles is also published in IEEE Electrification magazine, issue June 2014 **[Ref 3]**.

References

[1] Bruce Morey, “Off-Highway Hybrids: Opportunities and challenges,” SAE Off-Highway Engineering, magazine.sae.org/ofh, pp. 16 – 18, February 2016

[2] Jean L. Broge, “Deere’s first hybrid construction machine,” SAE Off-Highway Engineering, magazine.sae.org/ofh, February 11, 2013

[3] Brij N. Singh, Kent D. Wanner, and Zimin Vilar, “Novel and ruggedized power electronics for off-highway vehicles,” IEEE Electrification Magazine, pp. 31-41, June 2014

JDES Inverter Power-Density/Capability

Si IGBT PD550 Inverter
9 kW/L, 700 VDC,
70°C Coolant
2013 Production

Si IGBT PD400 Inverter
11.4 kW/L, 700 VDC
70°C Coolant
2017 Production

Gen-1 SiC Inverter
18 kW/L, 1050 VDC
105°C Coolant
2017 TRL3/4

Gen-2 SiC Inverter
43 kW/L, 1050 VDC
115°C Coolant
2020 TRL5/6
440 μF DC bus cap
Six-Pack SiC modules

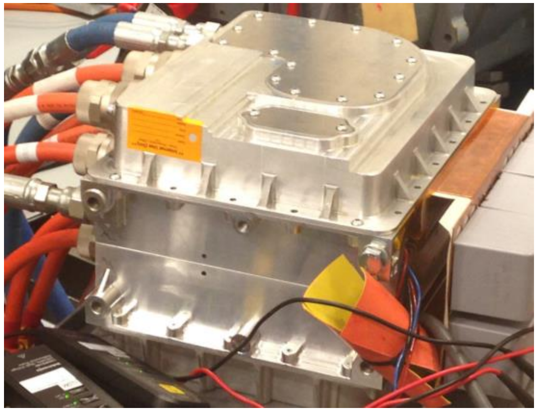
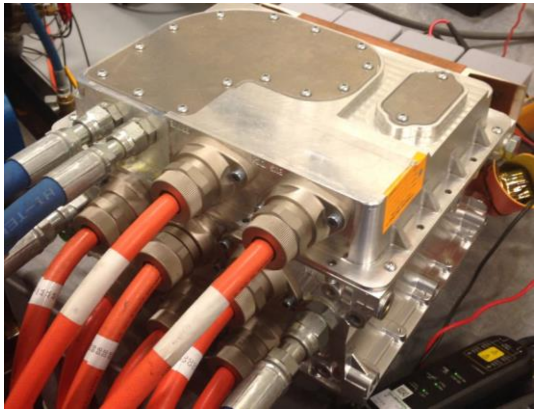
JDES's 200 kW dual-inverters with electric braking

- Increasing power density
- Decreasing weight, size, and farm-factor
- Increasing coolant temperature
- Improved performance

Vehicle Platform for Field Testing

JD 644K Hybrid Loader Manufactured using IGBT Inverter [1-3]

Gen-0 SiC Inverter Development

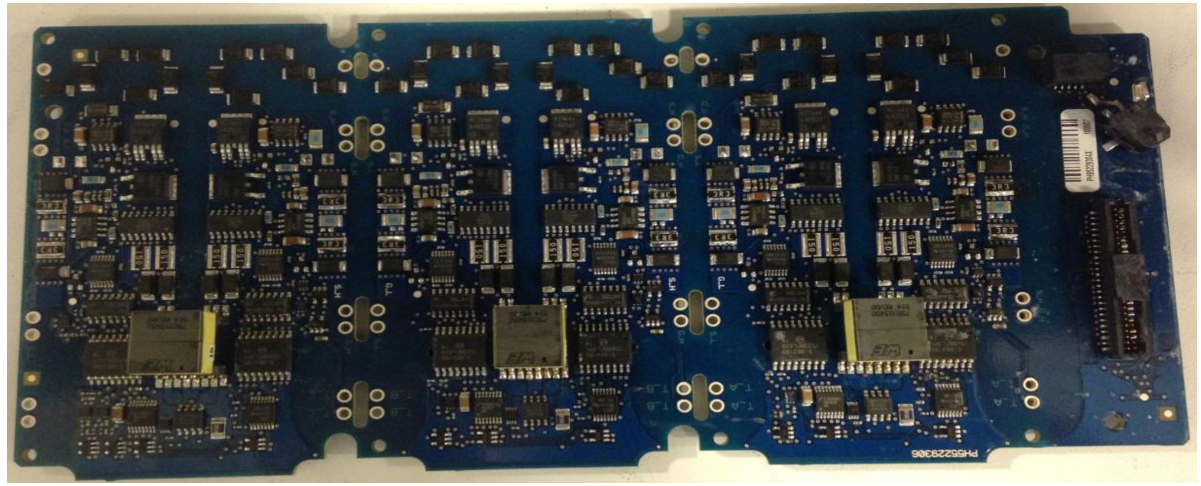
 

JDES's PD400 IGBT Inverter Retrofitted with SiC Power Modules

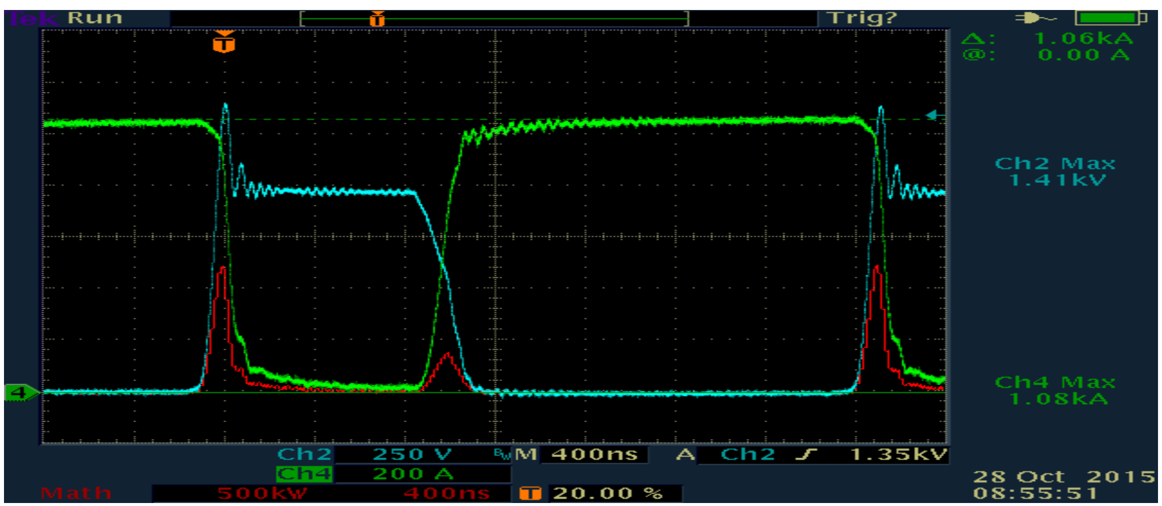
- SiC gate driver development
- 1100 V rated DC bus capacitor development
- 690 V permanent magnet AC motor development
- dv/dt filter
- Bench-top and back-to-back motor dyno testing
  - ➢ Spinning of PMAC motor within 10 months start of project

Power Module Testing for Gen-0 SiC Inverter

Low-inductance SiC module

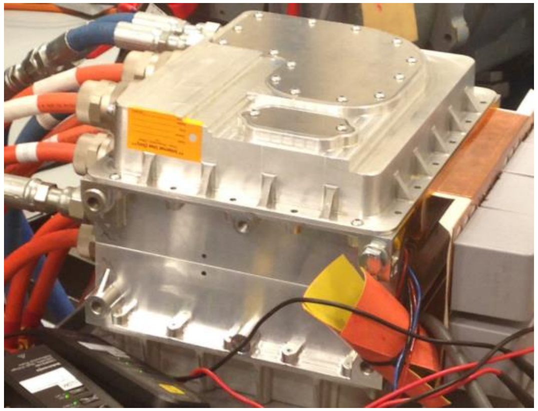


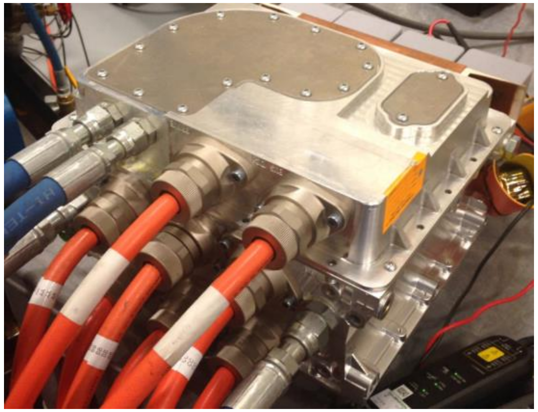
SiC gate-driver



High-current turn-on and turn-off events

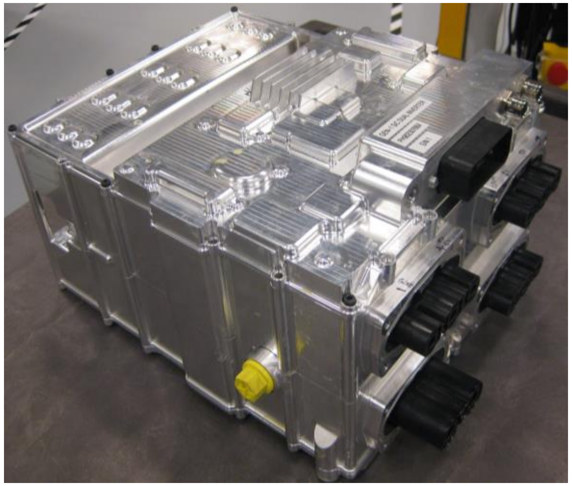
Gen-0 SiC Inverter's in-Vehicle Deployment

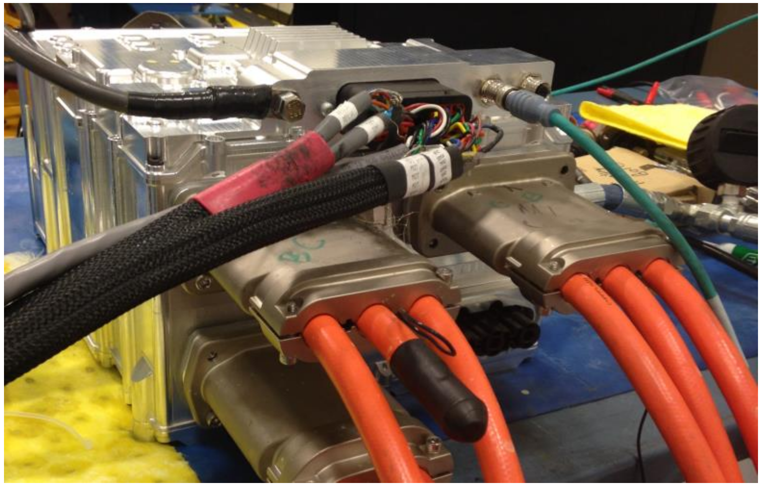




JDES's Experience in IGBT Inverter Technology and Readily Available Vehicle Platform Expedited Development Work - Big Contributor to PowerAmerica Early Wins

Gen-1 SiC Inverter Development





SiC inverter in its own housing

- Super low-inductance DC bus bar
- Super low-inductance power module
  - Only 10 V over-shoot at 800 A turn-off
- Power density improvements: 11 kW/L to 18 kW/L
- Coolant temperature upgrade: 70°C to 105°C

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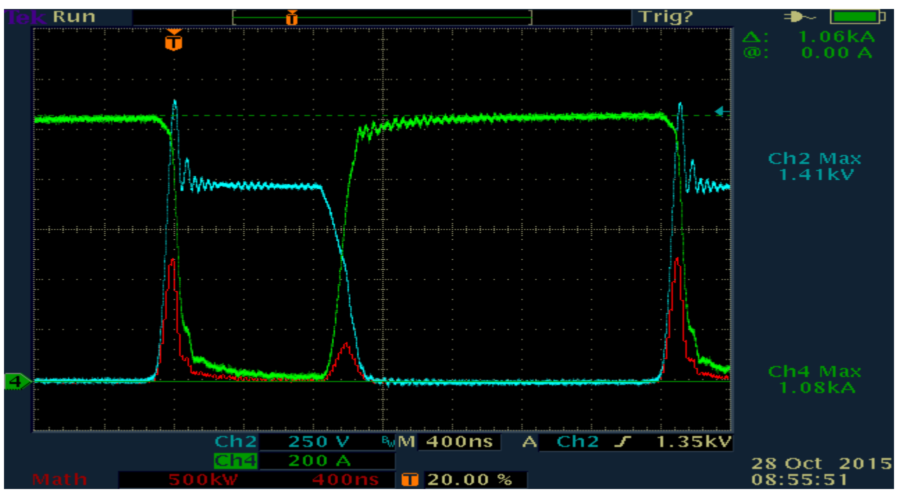
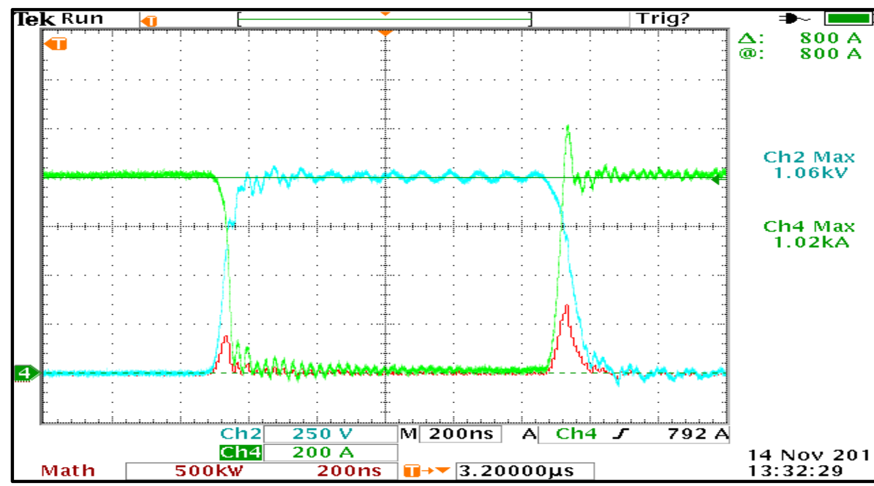
Gen-1 SiC Inverter Test Waveforms

1700 V 400 DC PowerEx module

1700 V 400 DC Cree module



1000 A and 1000 V



800 A and 1000 V

High-current turn-on and turn-off events

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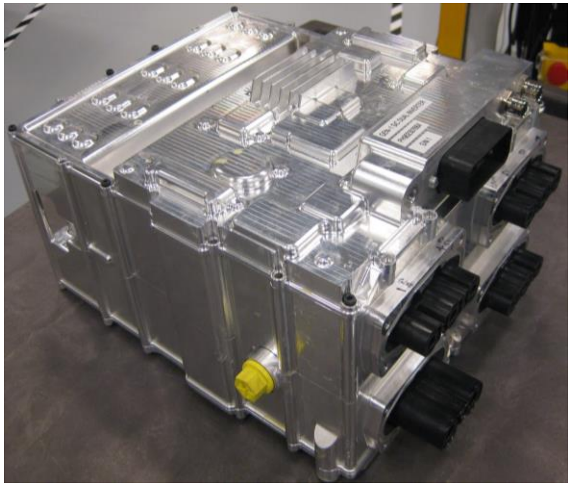
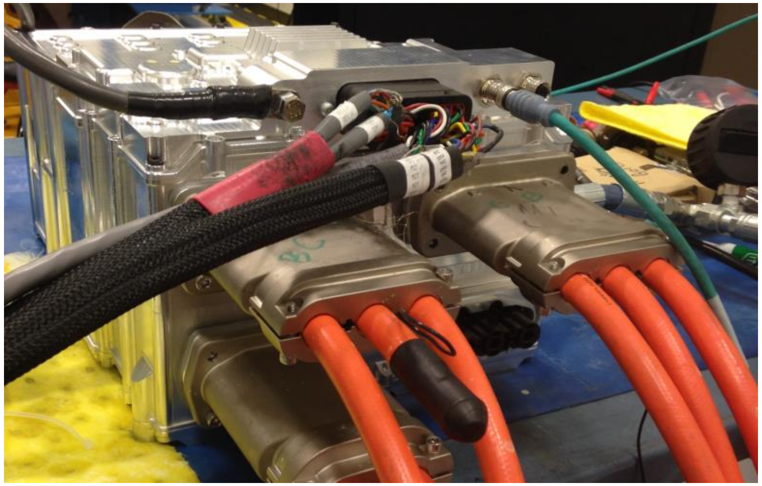
Gen-1 SiC Inverter Testing





SiC inverter in its own housing

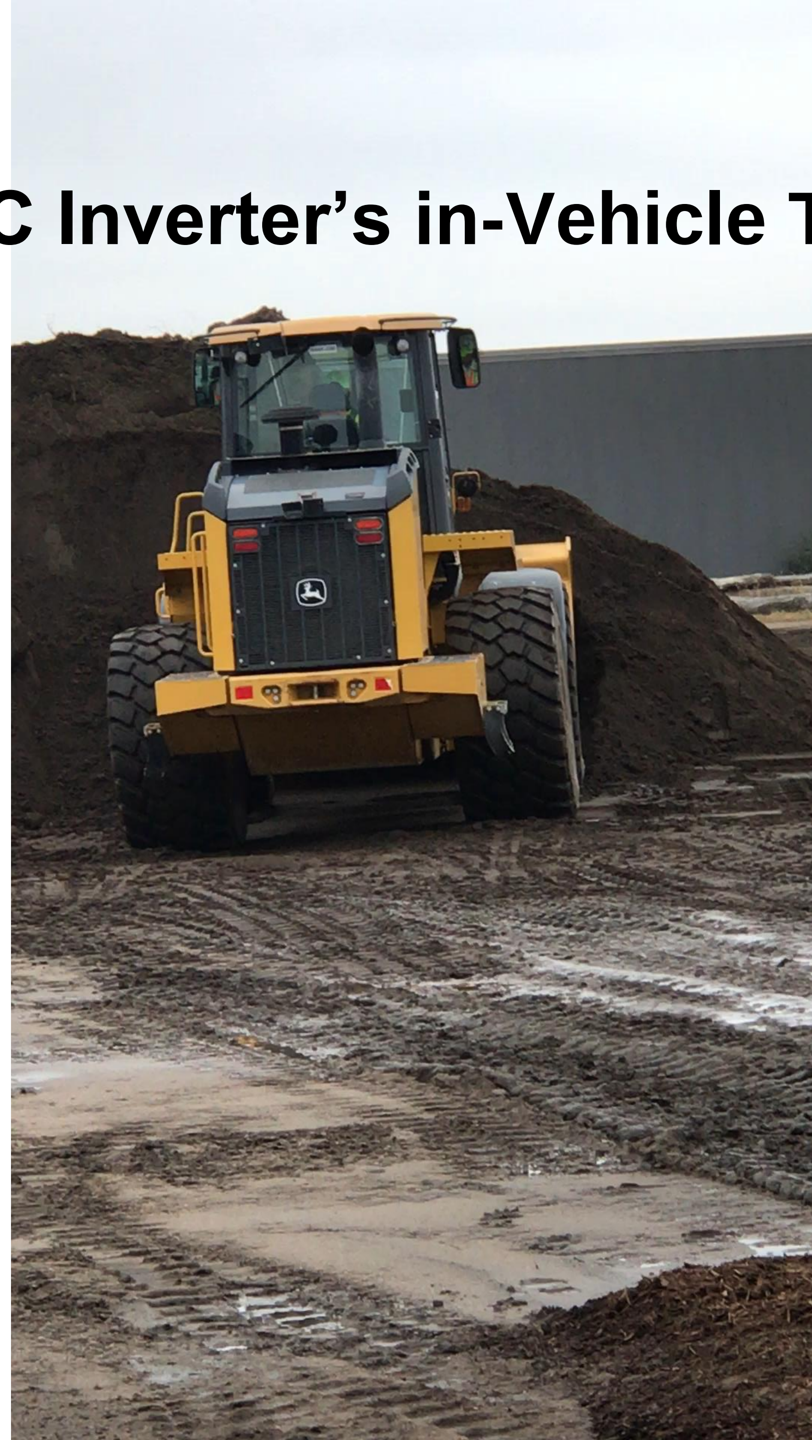
- Characterization of 690 V PMAC motor and generator
- Back-to-back dynamometer testing up to 90°C coolant
  - Extrapolation of data for 105°C coolant
  - Dual-inverter efficiency over coolant > 98.5%
  - Full-load maximum junction temperature ~165°C at 105°C coolant

Gen-1 SiC Inverter's in-Vehicle Deployment

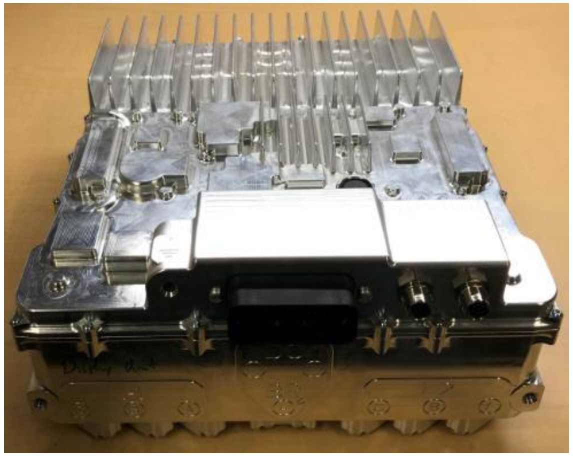
- Inverter cooled with engine coolant
- Continuous operation for hours and hours with no issue
  - Maximum coolant temperature remained below 105°C

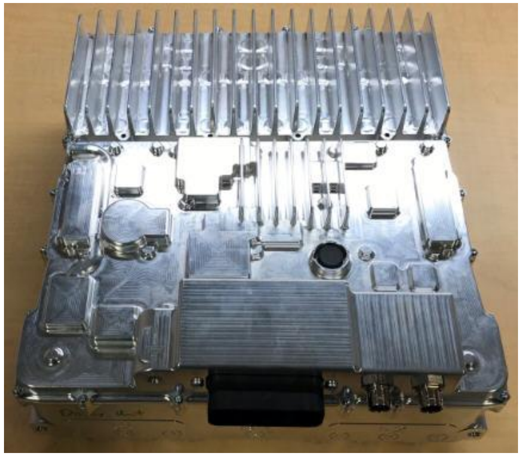
Gen-1 SiC Inverter’s in-Vehicle Testing

In-vehicle test video



Gen-2 SiC Inverter Development

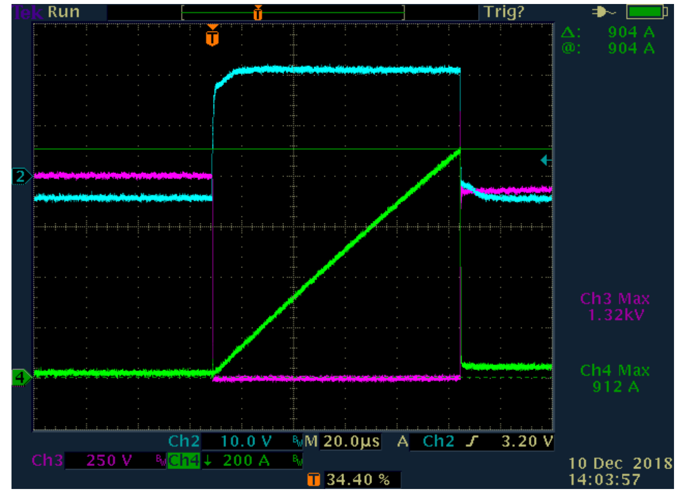


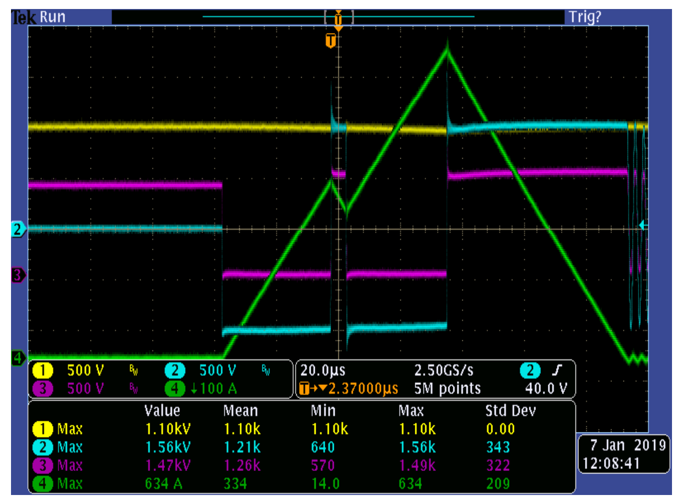


- Significant miniaturization of SiC power module
  - 1700 V and 250 A rated six-pack SiC power module developed
- Both inverters on same side
  - Low inductance between both inverters
- Power density improvements: 18 kW/L to 43 kW/L
- Coolant temperature upgrade: 105°C to 115°C
- Significant modularity
  - With minimal changes single and dual inverters with and without electric braking can be realized

Gen-2 SiC Inverter Test Waveforms

1700 V 400 DC
GEAS module





High-current turn-on and turn-off events

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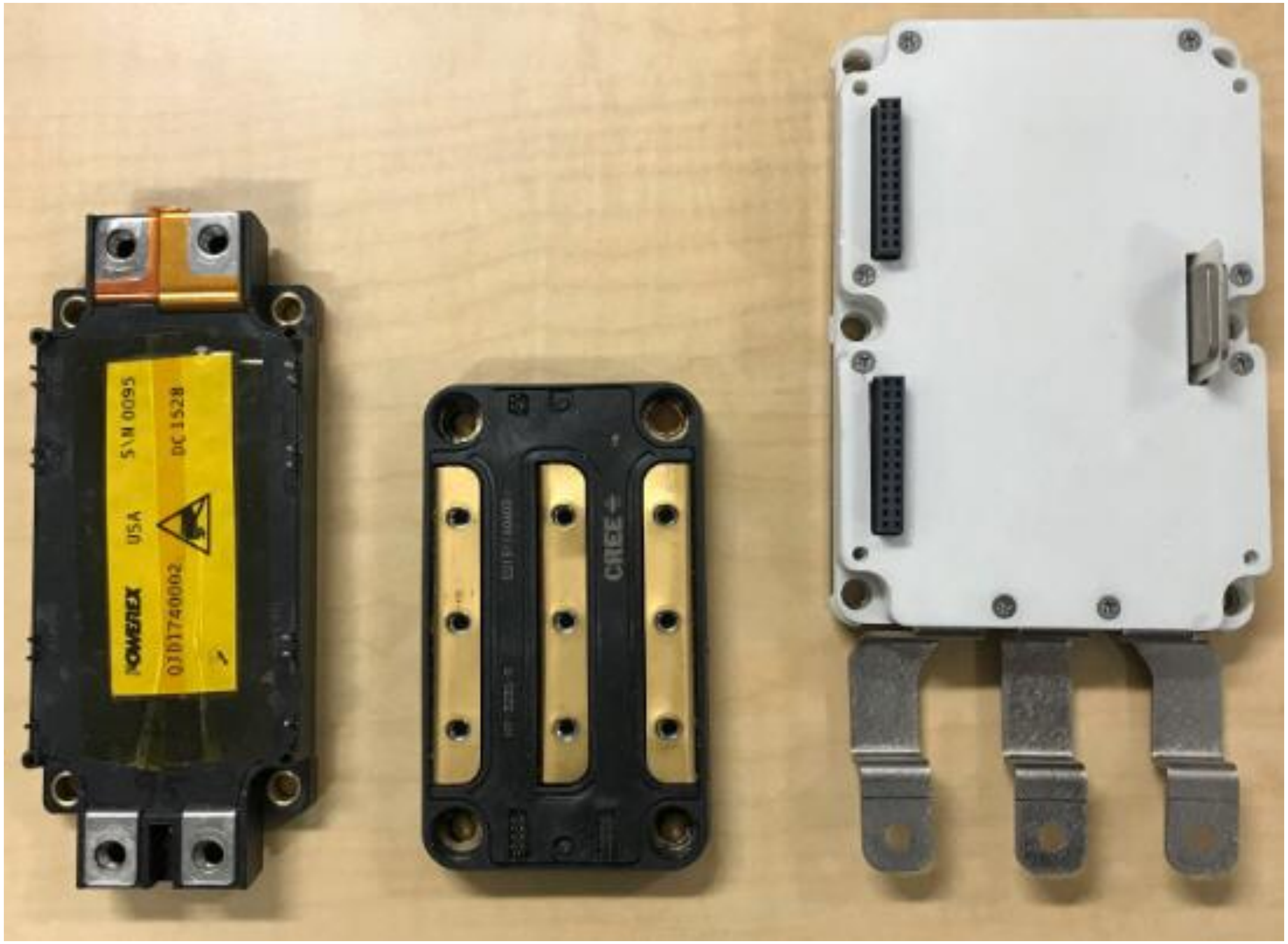
SiC Power Module Development



Power Modules for 200 kW Gen-0, Gen-1 and Gen-2 Inverters (Supply-chain issues can be addressed)

WBG Technology Advantages

SiC MOSFET offers unique advantages

- Higher voltage - increased power density
- Higher frequency - improved bandwidth
- Higher temperature - simpler cooling systems
- Higher thermal conductivity - higher thermal loading
- Lower risk of thermal runaway
- Engine coolant (115°C) power electronics - simpler architecture

Summary

- SiC power electronics for niche applications is real
- Cost reduction for SiC power devices needs to happen
  - $x for IGBTs versus $ 3x for SiC MOSFETs
- System approach is required
- Technology innovations by C solutions is needed:
  - Copper, Capacitor, Cable, Connector, Coolant, CCS (coreless current sensor), Case, Control, and Cost

Acknowledgement

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NATIONAL RENEWABLE ENERGY LABORATORY

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Questions ?

Dr. Brij N. Singh
Sr. Staff Engineer - Advanced Technology
John Deere Electronic Solutions (JDES), Inc., USA

SinghBrijN@JohnDeere.com