Silicon Carbide Inverter Technology Development - A Success Story

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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/dm³) Gen-2 SiC dual inverter in JD 644K Hybrid Loader

**Significant Equipment Acquisition:** None

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

**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
5. Current Technology Readiness Level: TRL 3/4
6. 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
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
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
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
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
Questions?

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