Wide Bandgap Power Electronics for Heavy-Duty Vehicles

Brij N. Singh, Ph.D., IEEE Fellow and John Deere Technical Fellow

Outline

Background

- Brij
- Deere & Company and JD ISG
- Electrification of non-road vehicles

Electrification examples in Deere & Company

Wide Bandgap (WBG) technology

SiC inverter technology development and in-vehicle testing

Findings and experiences on SiC technology

Summary

Brij has seen extreme weather conditions and has developed appreciation for nature

Thermal-cycling of Brij

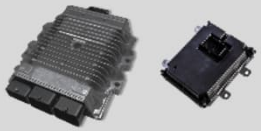
INTEGRITY | QUALITY | COMMITMENT | INNOVATION

WHO WE ARE

John Deere is a world leader in providing advanced products and services and is committed to the success of those linked to the land.

JD ISG Fargo - Product Portfolio

- Founded in 1988 as Phoenix International

	Embedded Controls
	Power Electronics
	Displays and User Interfaces
	Wireless Communication
	Sensing Solutions

Why electrification of off-road equipment is important and carbon footprint story ?

- It is about performance, productivity, precision, reduction of GHG intensive chemicals, and positioning Deere for compliant to govt regulations

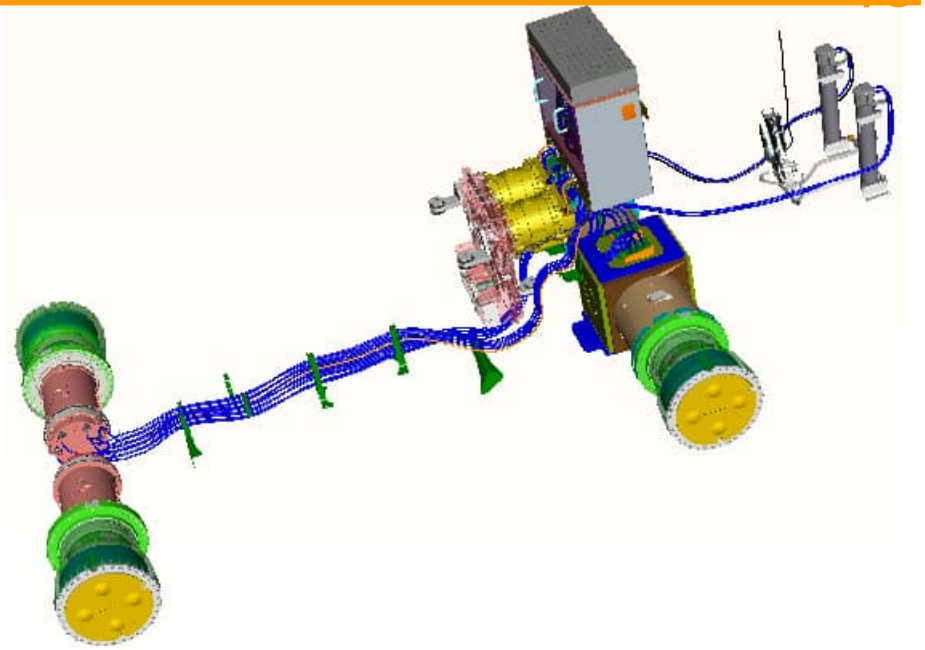
Shortage of skill labor is huge problem for Deere's customers

Some electrification examples of off-road equipment using silicon IGBT and Si MOSFET

944K Hybrid Loader's Powertrain Architecture

- Control system prevents near zero speed tire spin and slicing

https://www.youtube.com/watch?v=zVd6ZNtGmqg



Industry leading reliability goals met by advanced control and pre-power diagnosis

https://www.rermag.com/earthmoving/article/21145781/john-deere-944k-hybrid-wheel-loader-reaches-1-million-field-operating-hours

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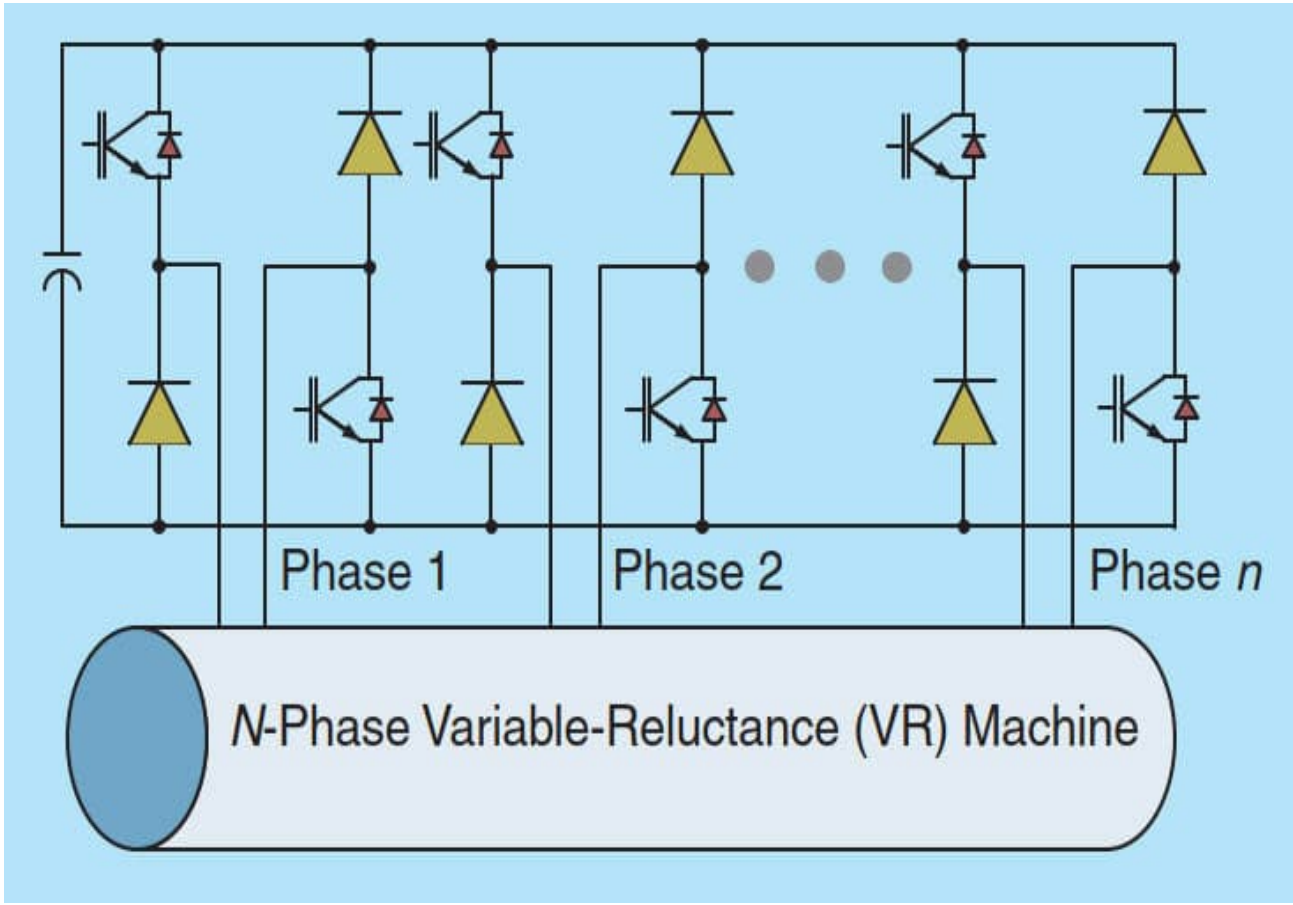
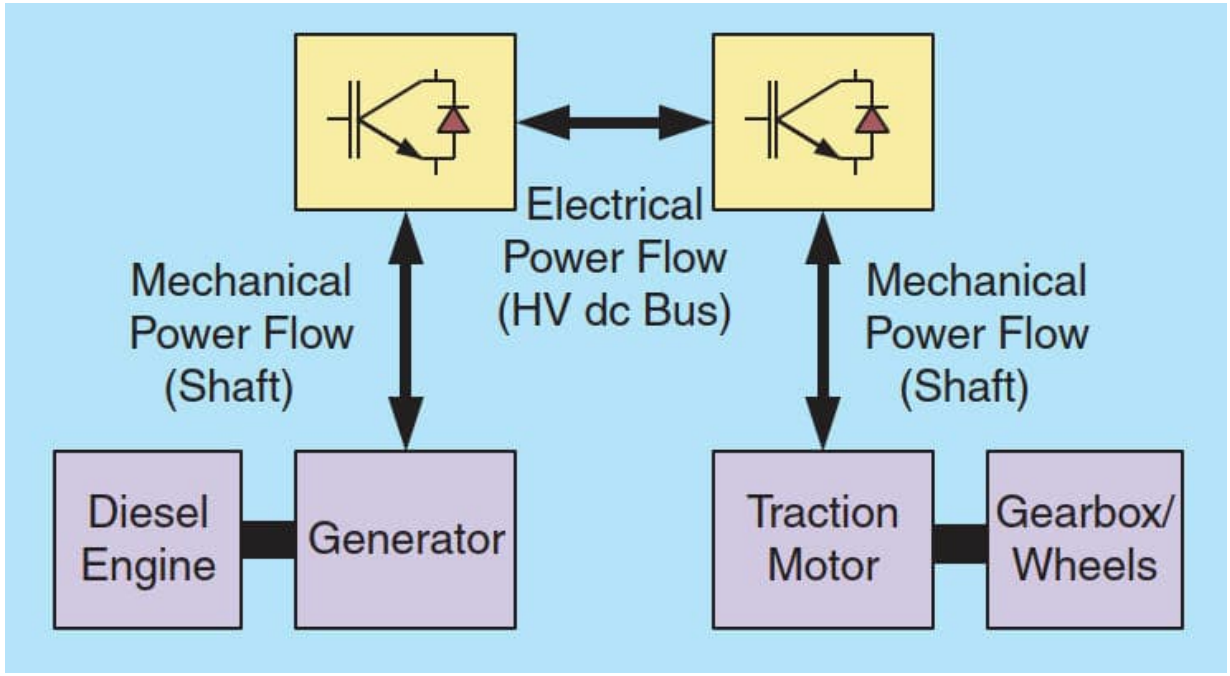


644K Hybrid Loader's Powertrain Architecture

- Control system allows application of maximum power where it is needed the most



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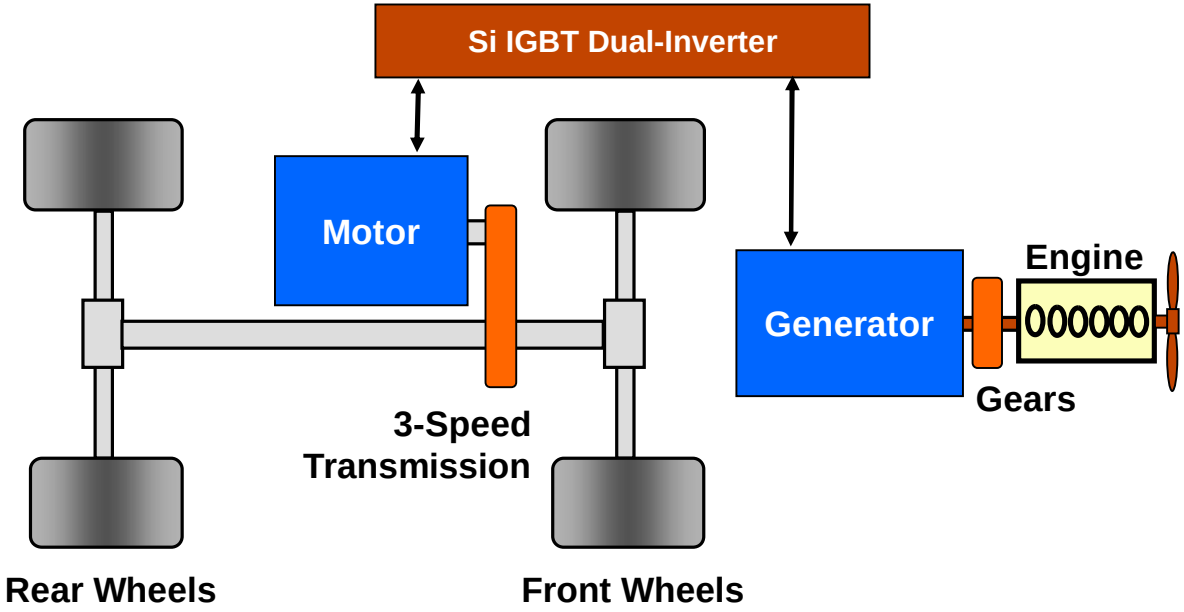
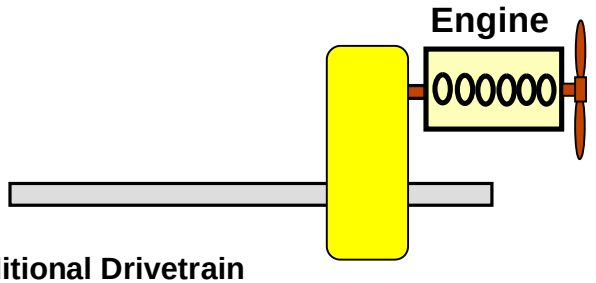
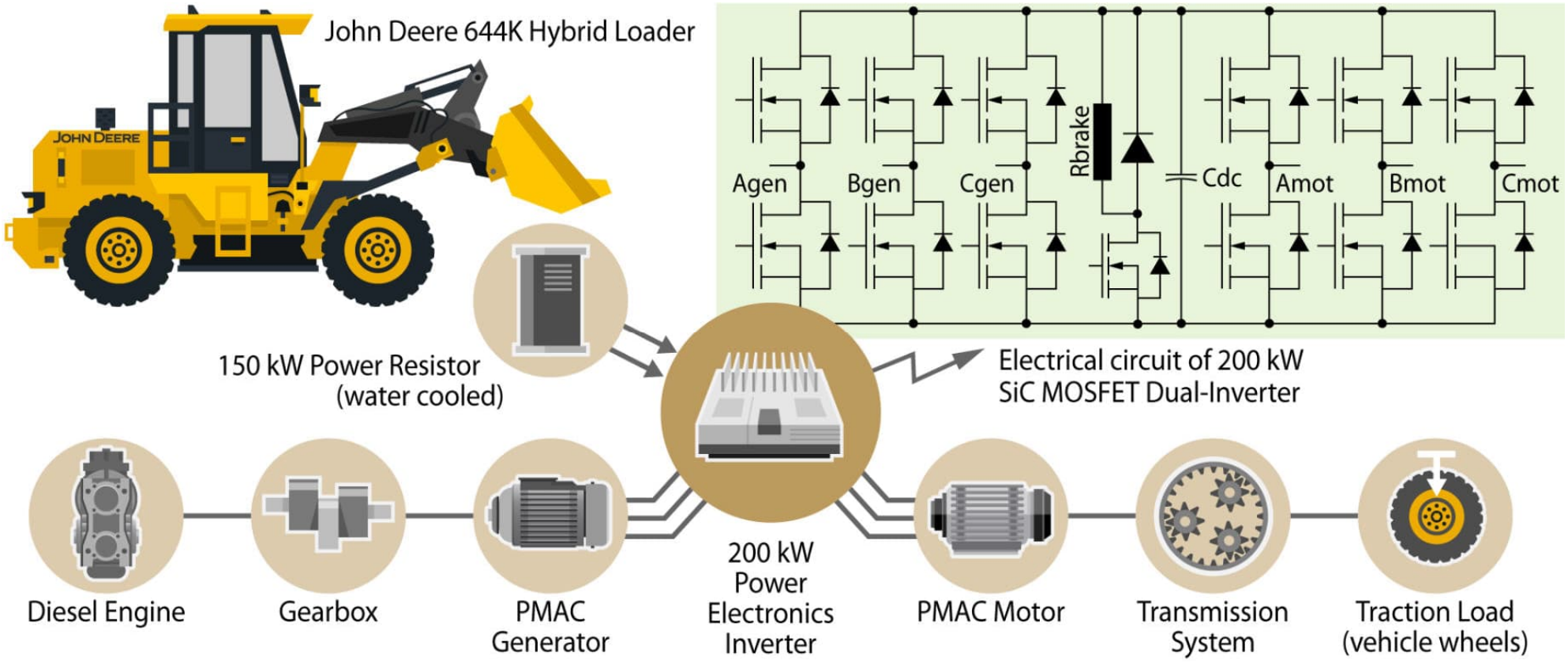




Traditional Drivetrain
Torque Converter Drop Box

JD 644K Hybrid Loader - Powertrain Architecture

- Vehicle power management (VPM) enabled by advanced control system

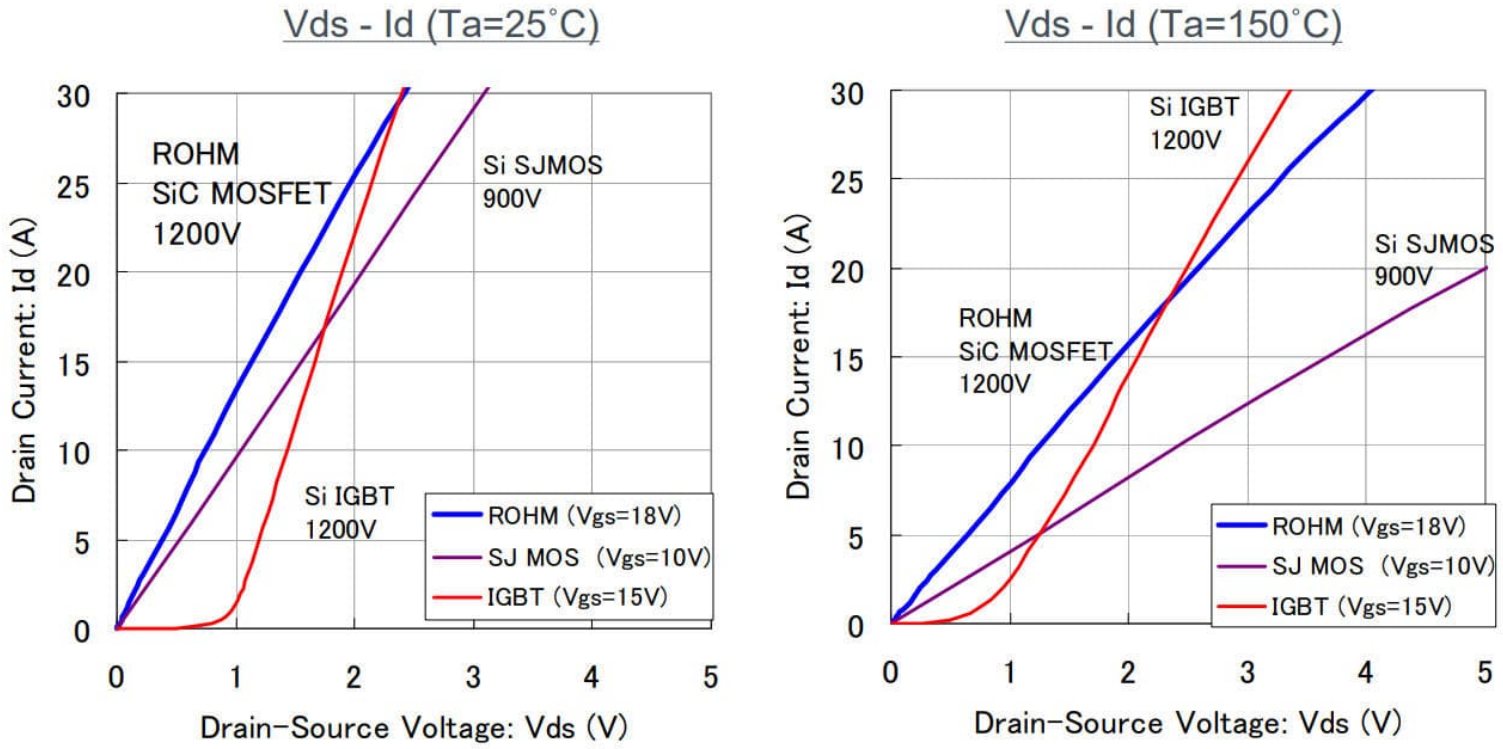


Wide Bandgap (WBG) Technology

Silicon Carbide Inverter Technology Development

- A project co-funded by DOE-PowerAmerica

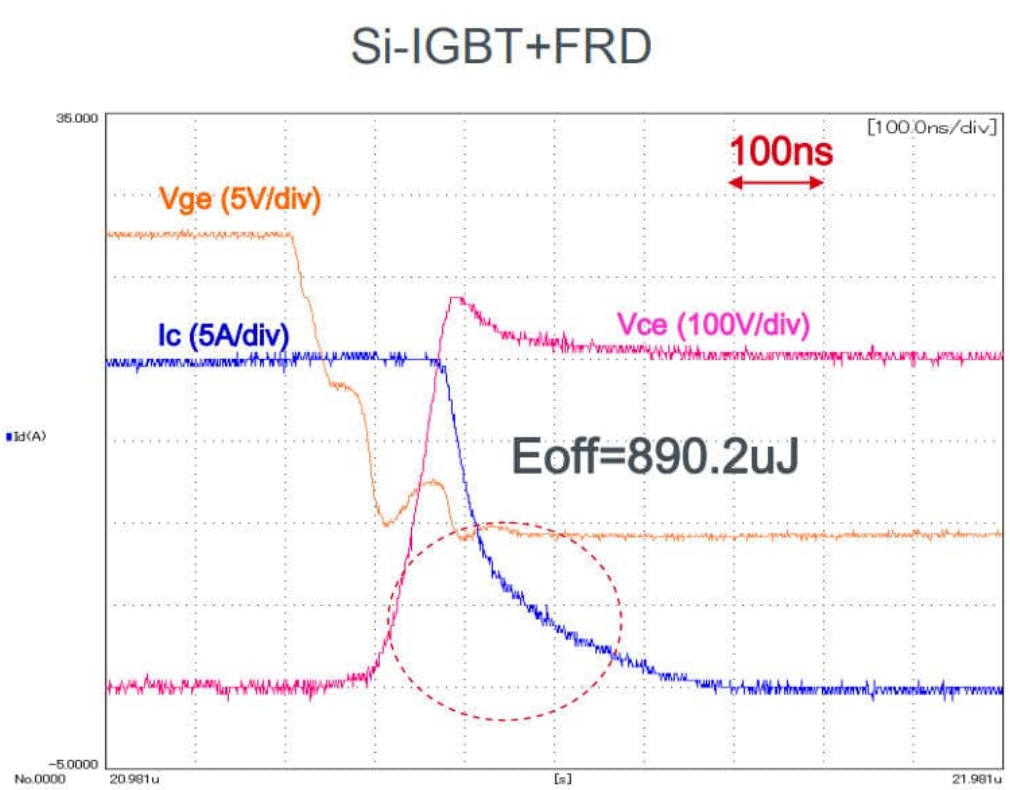
Si IGBT vs SiC MOSFET - Partial Load Advantage

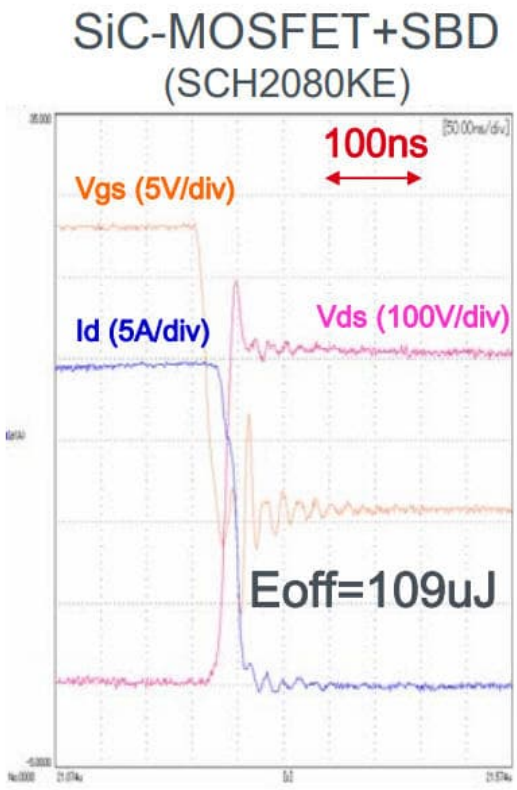


V-I characteristics of Si IGBT and SiC MOSFET

Observations: SiC MOSFET is far more efficient – good for extended range in EVs

Si IGBT vs SiC MOSFET - Switching Behavior





Observations: Tail current in IGBT is due to minority charge carriers and tail current hurts IGBT switching behaviors, MOSFET is unipolar device

John Deere Project in PowerAmerica

Deere & Company is Founding Member of Power America

SiC Technology Development (US DOE funding $6M)

- Technology objectives

Design Goals for SiC Dual Inverter

- 200 kW, 1050 VDC SiC dual inverter
- 97% efficiency, < 25 L, < 25 kg
- Power density > 25 kW/L
- > 25% gain in fuel economy as compared to conventional drivetrain
- 115°C coolant operation in off-highway vehicles

- SiC advanced and emerging technology for off-road vehicle applications
  - Risks: being new and first in the field of use
  - Supply chain issues must be addressed
  - Competitive advantages should be put for greater use
- Innovations could mitigate risks

WBG Technology Objectives - Current Status

SiC inverter power density > 25 kW/L

- Gen-2 SiC inverter power density > 43 kW/L

Full-load efficiency of SiC inverter: 97%

- Gen-1 SiC inverter > 98% over coolant temperature

Engine coolant (maximum 115°C WEG) SiC inverter

- Gen-1 SiC inverter tested with 105°C WEG coolant
  - At 150 kW maximum junction temperature ~165°C (extrapolated data)
- Gen-2 SiC inverter test verified with 115°C WEG coolant
  - At 150 kW maximum junction temperature ~145°C (in-lab testing data)

Achieve system-level cost parity with the silicon IGBT inverter

- Costs for SiC inverter is many folds of the Silicon inverter's cost

JDES Inverter Power-Density and Capability Progression

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

John Deere 200 kW dual-inverters (400 kW) with electric braking

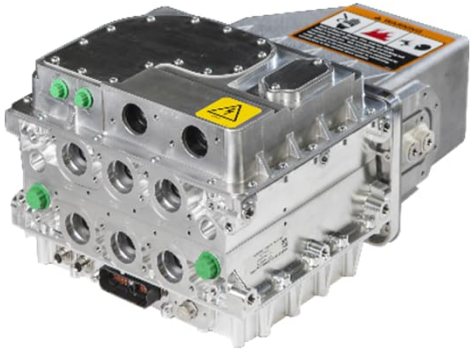
Three generations of SiC inverter developed and tested in lab and vehicle

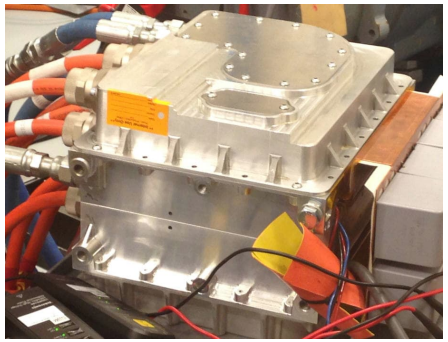
- Modularity: useful for many applications
- Increasing power density: competitive advantage
- Decreasing weight, size, and form-factor: easier integration in vehicles
- Improved performance and high temperature: system benefits

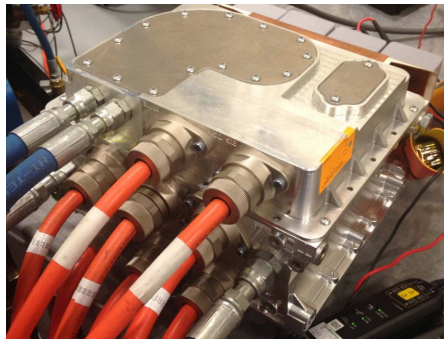
Why heavy-duty off-road vehicles are different ?

- Requirement of near zero-speed and stall-torque

Gen-0 SiC Inverter Development

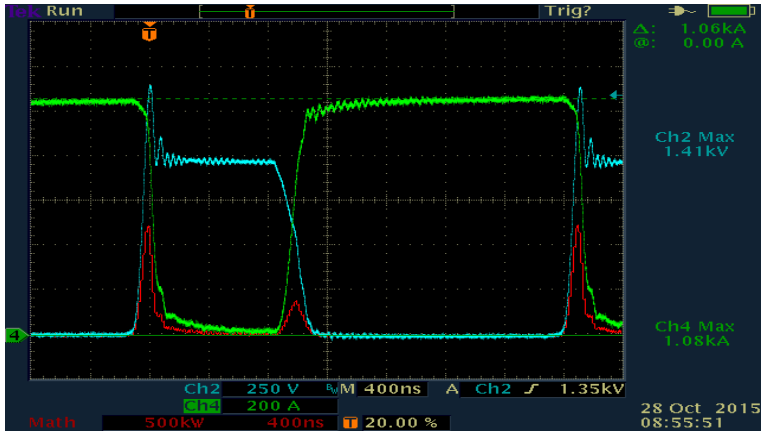




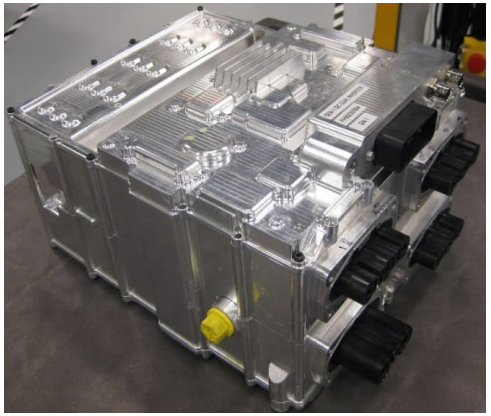


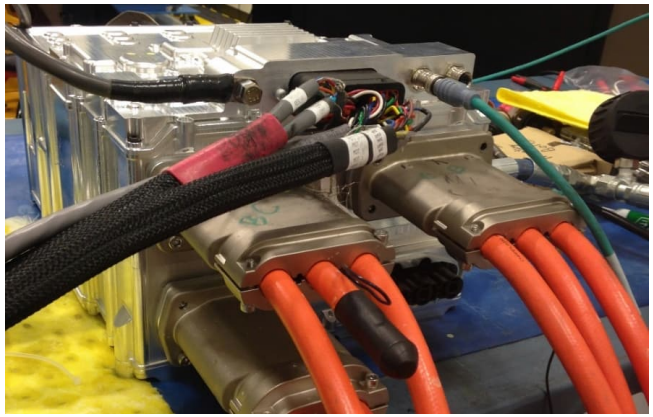
JD ISG's PD400 IGBT Inverter Retrofitted with SiC Power Modules

- 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
  - ➢ PMAC motor drives by SiC inverter within 10 months from start of project



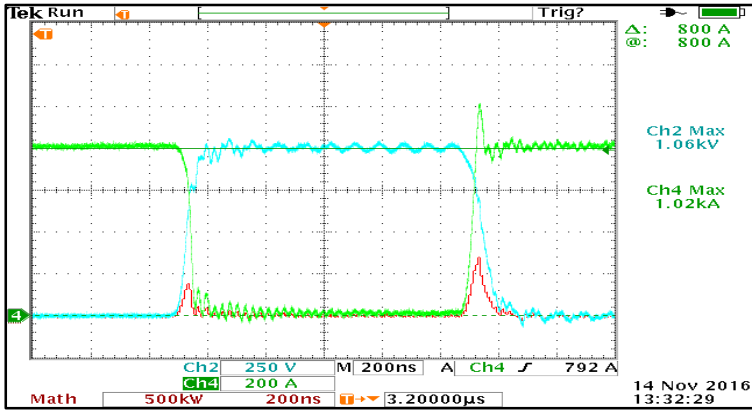
Gen-1 SiC Inverter Development



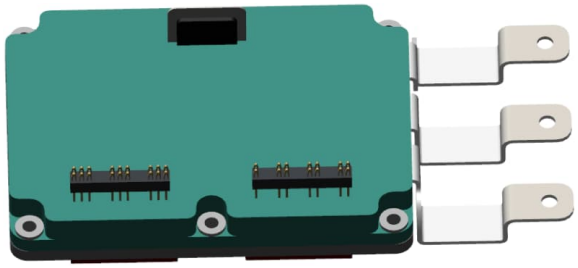


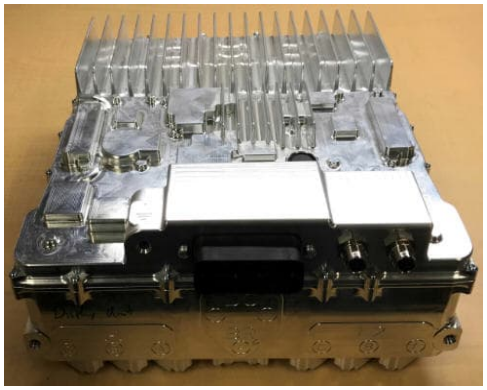
Improved electrical and thermal systems for inverter

- Super low-inductance DC bus bar < 1 nH
- Super low-inductance power module < 4 nH
  - Only 10 V over-shoot at 800 A turn-off
- Power density improvements: 11 kW/L to 18 kW/L
- 105ºC WEG coolant operation at 150 kW power



Gen-2 SiC Inverter Development



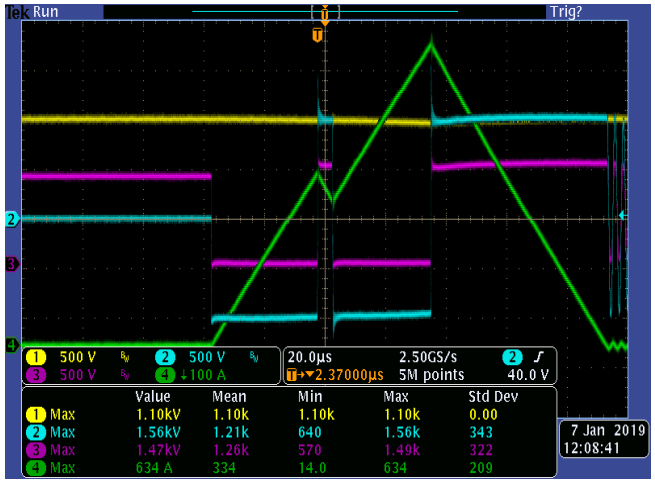


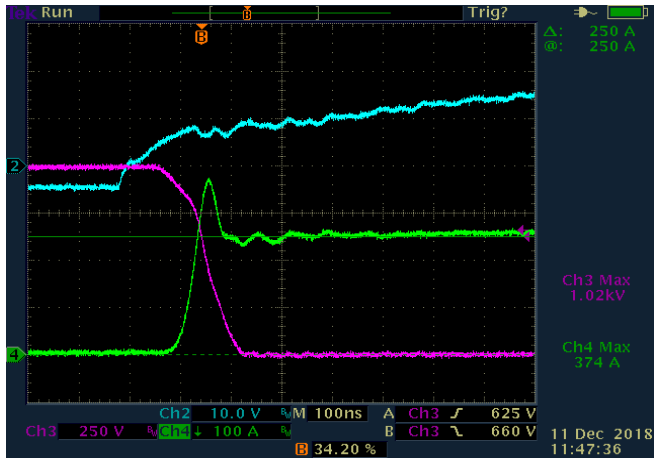
Power-Density Improvements by SiC module's miniaturization

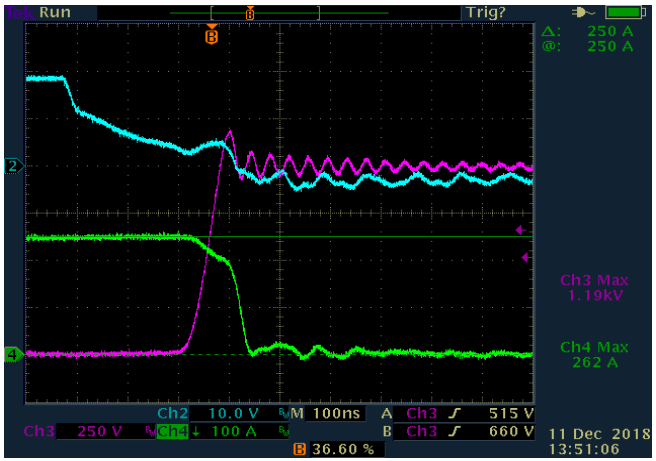
- Significant miniaturization of SiC power module
  - 1700 V and 250 A rated six-pack SiC power module developed
- Both inverters on same side
  - Low inductance between both inverters
  - Easier manufacturing of inverter including in-vehicle deployment
- Power density improvements: 18 kW/L (Gen-1) to 43 kW/L (Gen-2)

Gen-2 SiC Inverter Test Waveforms for Six-Pack Power Module

1700 V 400 A DC
GEAS SiC module



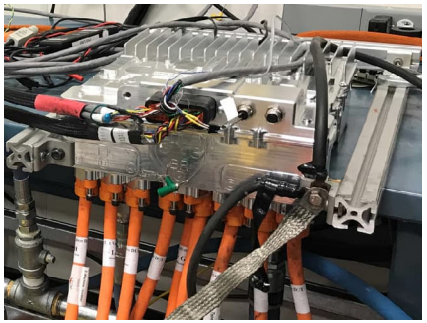




Gen-0 to Gen-2 SiC Inverters' Comparison

Gen-0 SiC inverter

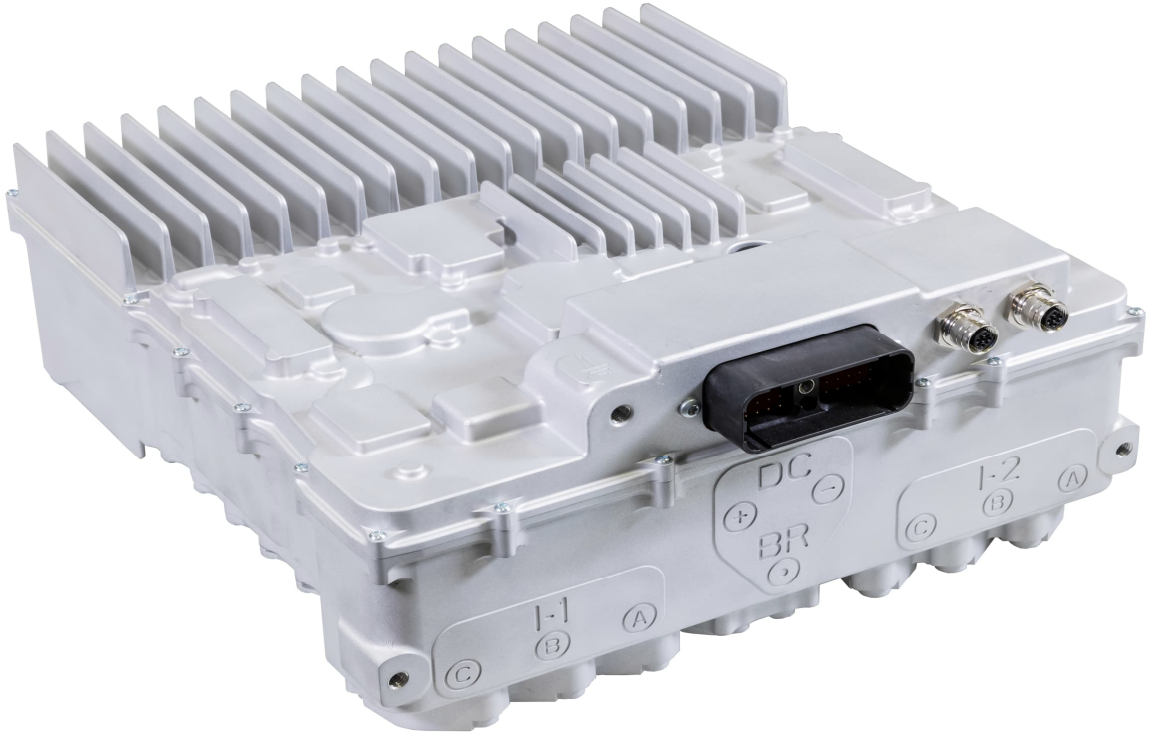
Gen-1 SiC inverter



Gen-2 SiC inverter

Innovative EXPECT SiC Technology

EXtremely **P**ower-Dense **E**ngine-**C**oolan**T**-Capable



https://vimeo.com/437142186/4b026a218f

Gen-1 SiC Inverter in Comparison to PD550 Si IGBT Inverter

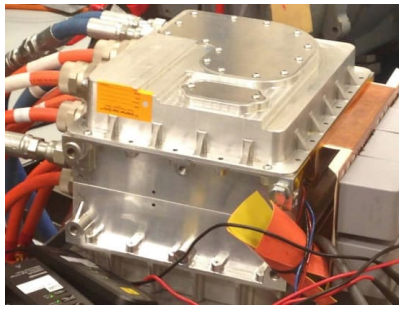
PD550 Si IGBT Inverter
- 9 kW/L, 70ºC Coolant
- Used dedicated cooling-pack

Gen-1 SiC Inverter
- 18 kW/L
- Requires 1/3 the space
- Eliminates dedicated cooling-pack

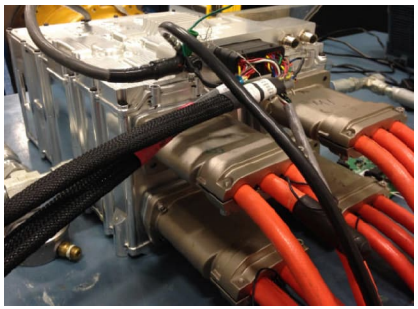
Key lessons

Lessons - Si IGBT Mind-Set Doesn't Work

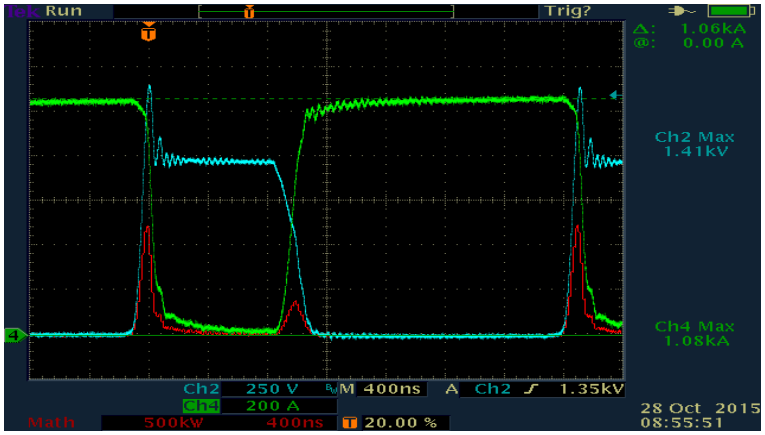
Gen-0 Inverter (11 kW/L)



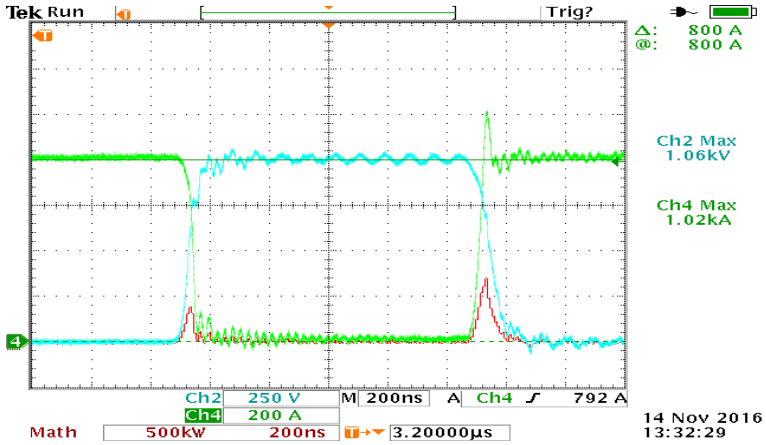
- Over-voltage issue with connectors, cables, and electric machine
- Improvement in common mode voltage and bearing current
- EMI and EMC improvements



Gen-1 Inverter (18 kW/L)



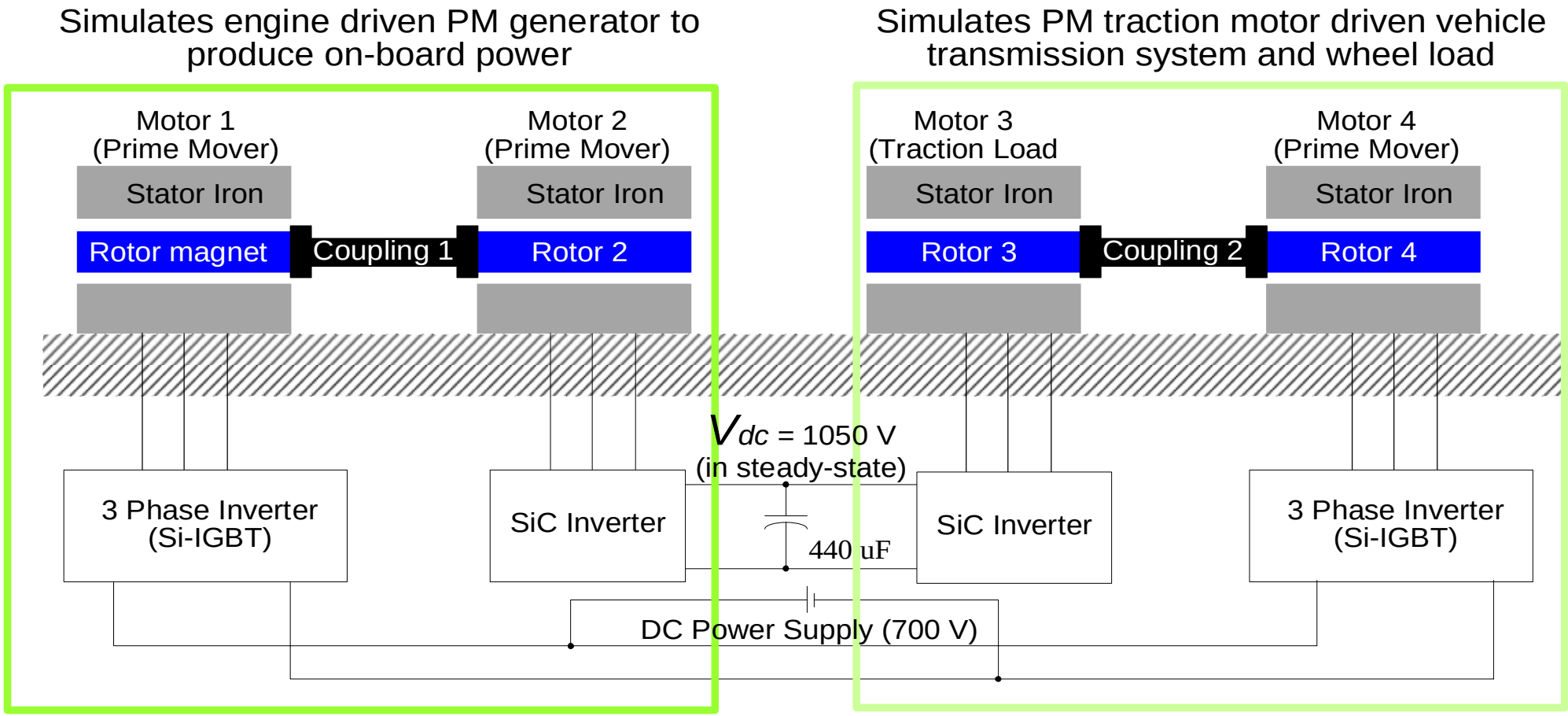
1000 A turn-off with 360 V overshoot energy



800 A turn-off with 10 V overshoot energy, reverse recovery, easy for electric motor

SiC Inverter – In-Lab Testing Prior to Vehicular Deployment

Dynamic Testing of Inverter (4 inverters and 4 electric machines set-up)



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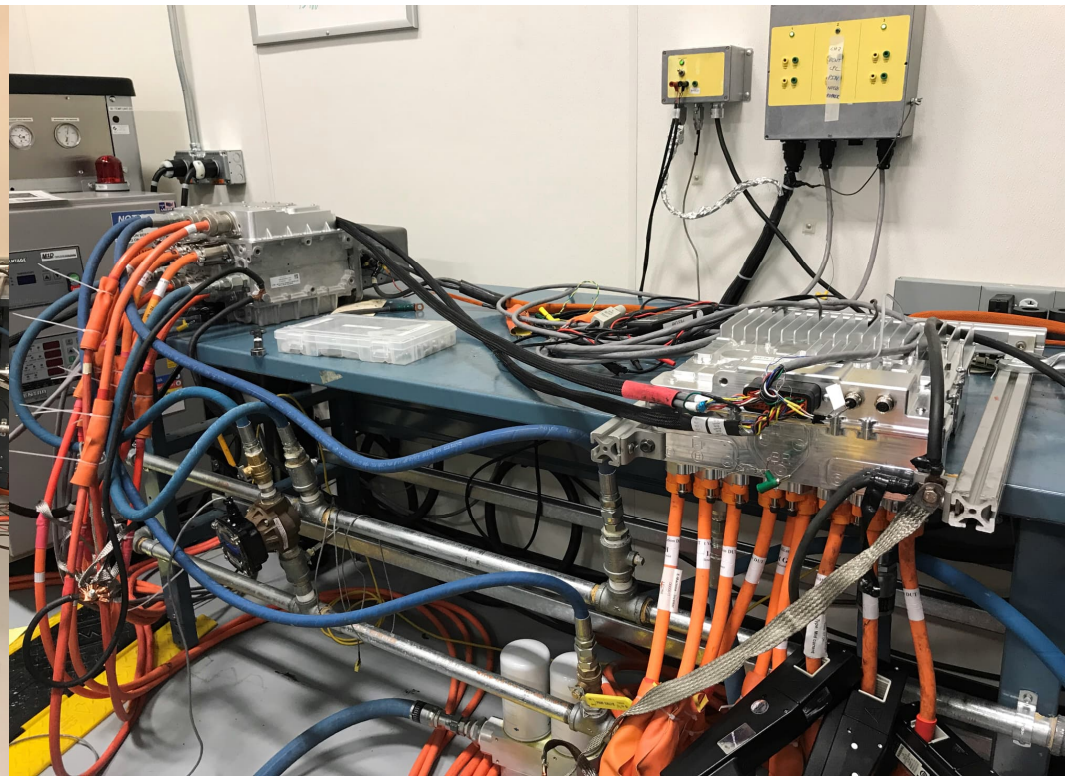
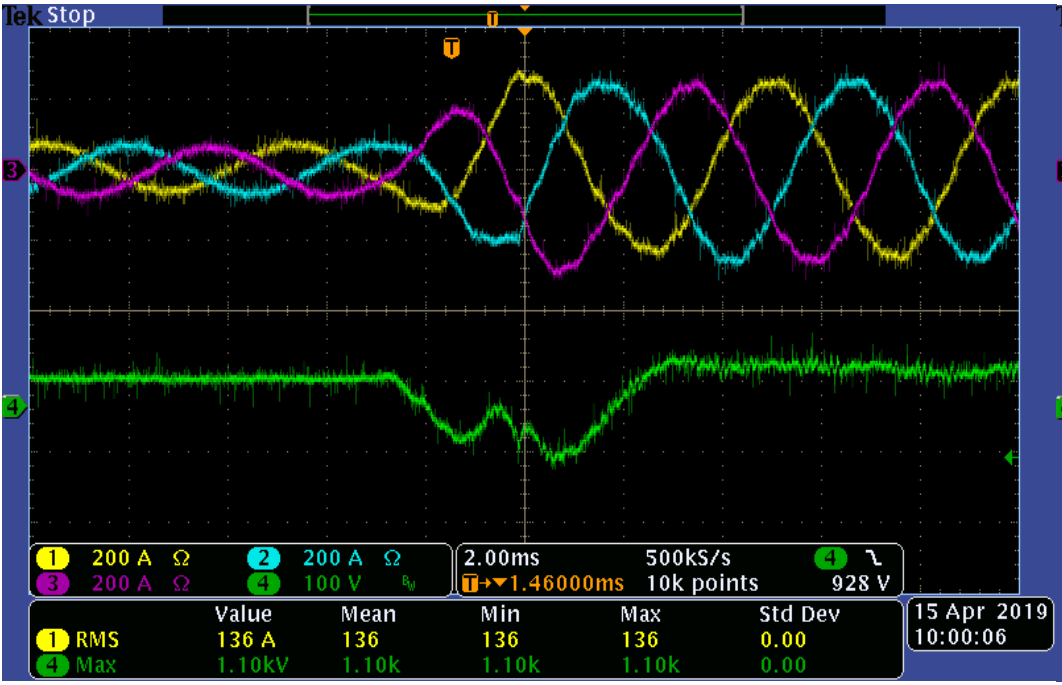
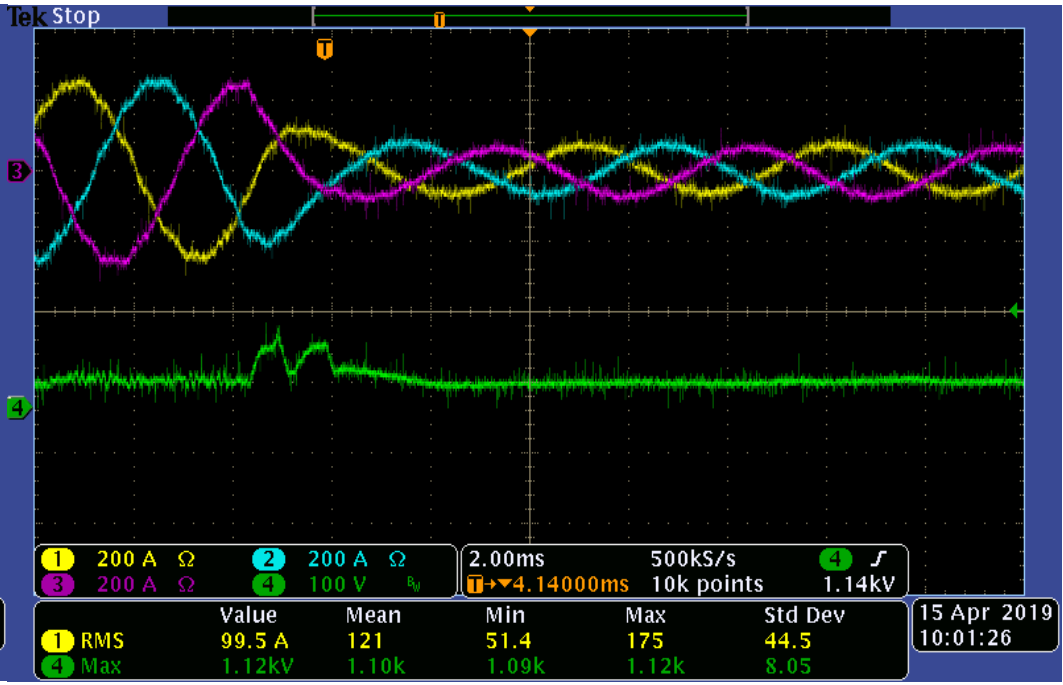


Dynamic Testing of Gen-2 SiC Inverter





Load change

30 kW to 150 kW

150 kW to 30 kW

Power-Shift dynamics of 644K WBG Loader

High Temperature Testing in John Deere Lab

Data obtained so far with Gen-2 SiC inverter

25°C - 115°C coolant and up to 75°C ambient for 90 minutes operation

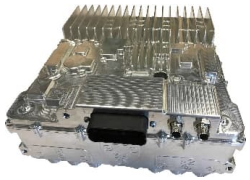
- Beyond 90°C coolant inverter needs to de-rate from 150 kW
  - At 55°C ambient and 115°C, power rating is 60 kW

John Deere may need 105°C ambient and 115°C coolant SiC inverter with no flexibility to de-rate

- Inverter with thermal treatment has achieved capability
  - At 55°C ambient and 115°C, power rating is 150 kW

Enlarged view of six-pack SiC power module

Technology Innovations by 9C Solutions



Capacitor: 5x size reduction and 10x cost reduction

Coolant: 70°C WEG to 115°C WEG

Connector: Simpler, cost-effective, and easier for shielding

Case: Power density ~11 kW/L to 43 kW/L

Control: Advanced control due to higher switching frequency

CCS: Magnetic core based current sensor replaced with coreless current sensor: cost reduction and simplified design

Cable: Smaller diameter cables

Copper: Lower overall copper content

Cost: Competitive with silicon IGBT technology at system level

Summary

- SiC power electronics is real
  - Early adopter likely to be a niche application
  - By 2025 SiC MOSFET technology may compete out silicon IGBT technology
  - John Deere has ~3,500 hours operating experience
- Cost reduction for SiC power devices needs to happen
  - $x for IGBTs versus $3x for SiC MOSFETs
- System approach is required for successful commercialization
  - WBG technology innovations by 9C solutions
    - Capacitor, Coolant, Connector, Case, Control, CCS (coreless current sensor), Copper, Cable, and Cost

Acknowledgement

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy
ADVANCED MANUFACTURING OFFICE

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

PowerAmerica

JOHN DEERE

More Government Funding

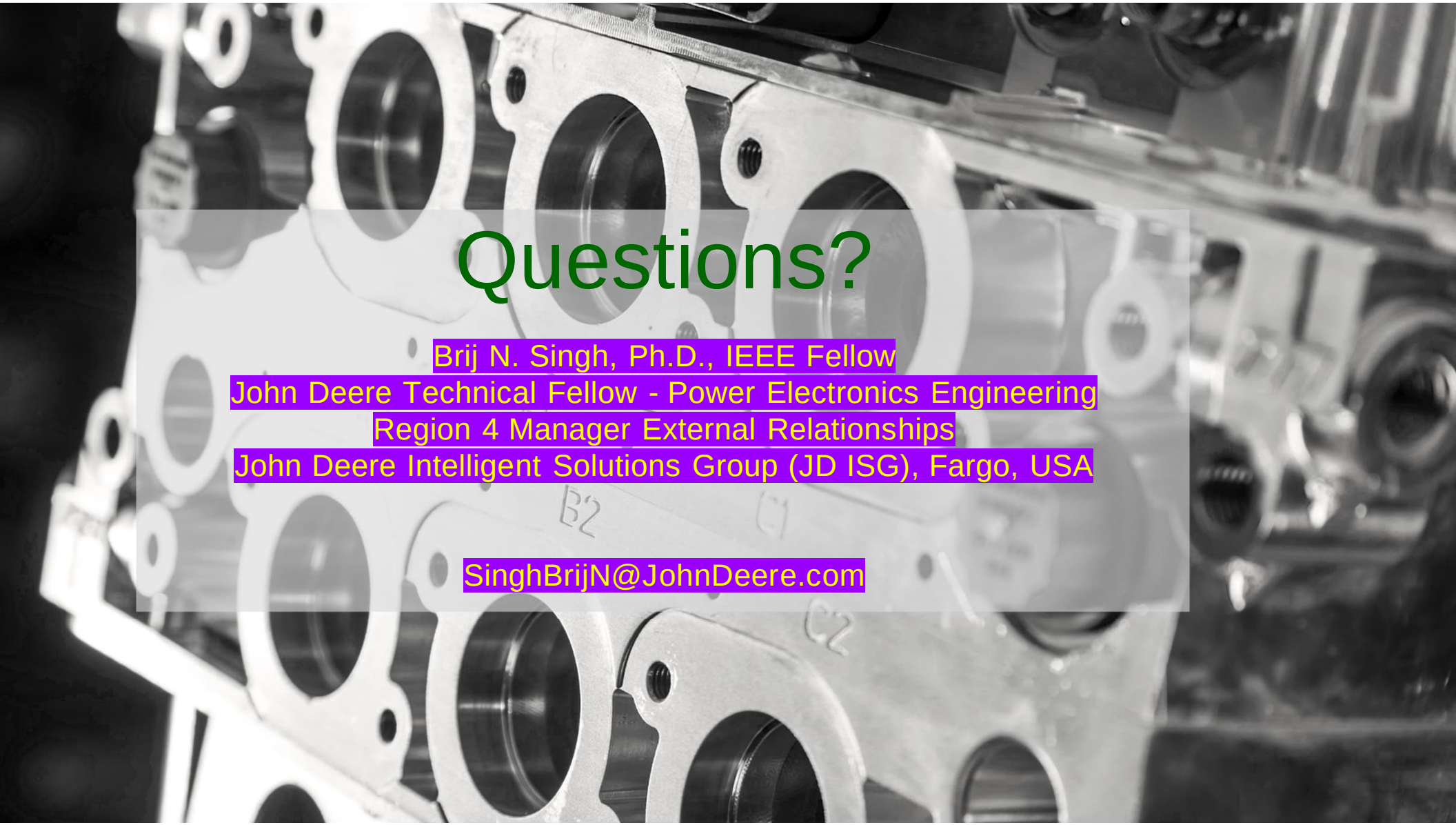
Fiscal Year 2021 Low Greenhouse Gas (GHG) Vehicle Technologies Research, Development, Demonstration and Deployment

FOA # DE-FOA-0002475

AOI 4b - Electrified Construction Vehicle Research, Development, and Validation			
John Deere	Moline, IL	Articulated Dump Truck (ADT) Electrification - GHG Reductions and Commercialization of New Technology in Construction Vehicles Fleet	$2,756,732

With in-kind cost share, this project cost is ~$4M plus abundance of resources for in-vehicle testing of the diesel-electric-hybrid powertrain testing in the electrified Articulated Dump Truck (eADT).

Societal impacts of innovative diesel-electric-hybrid powertrain technology will be multi-million metric tons of GHG reductions in a fleet of eADTs.



Questions?

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