Vehicle Electrification and Automation

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

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Outline

About myself (Brij)

John Deere company

Environmental impact of farming operations

Climate smart farming practices

Unlocking economic headroom for farmers

Off-road vehicles' electrification examples

SiC inverter technology development in Deere

Summary

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Brij N. Singh

Geographical Path:
Born (Fatehpur, UP), brought-up and educated in India
Immigrated to North America in 1996

Technical Education:
BE (89), ME (91) and Ph.D. (96)
MMMUT Gorakhpur, IIT Roorkee and IIT Delhi

Professional Experience:
ÉTS, Montreal (1996-1998) - Post Doctoral Fellow
Concordia University, Montreal (1999) - Research Fellow
Tulane University, New Orleans (2000-2007) - Assistant Professor
John Deere Inc., USA, Fargo
- (2007-2011) - Staff Power Electronics Engineer
- (2011-2020) - Senior Staff Engineer - Advanced Power Electronics
- (2020- present) - Region 4 Manager External Relationships

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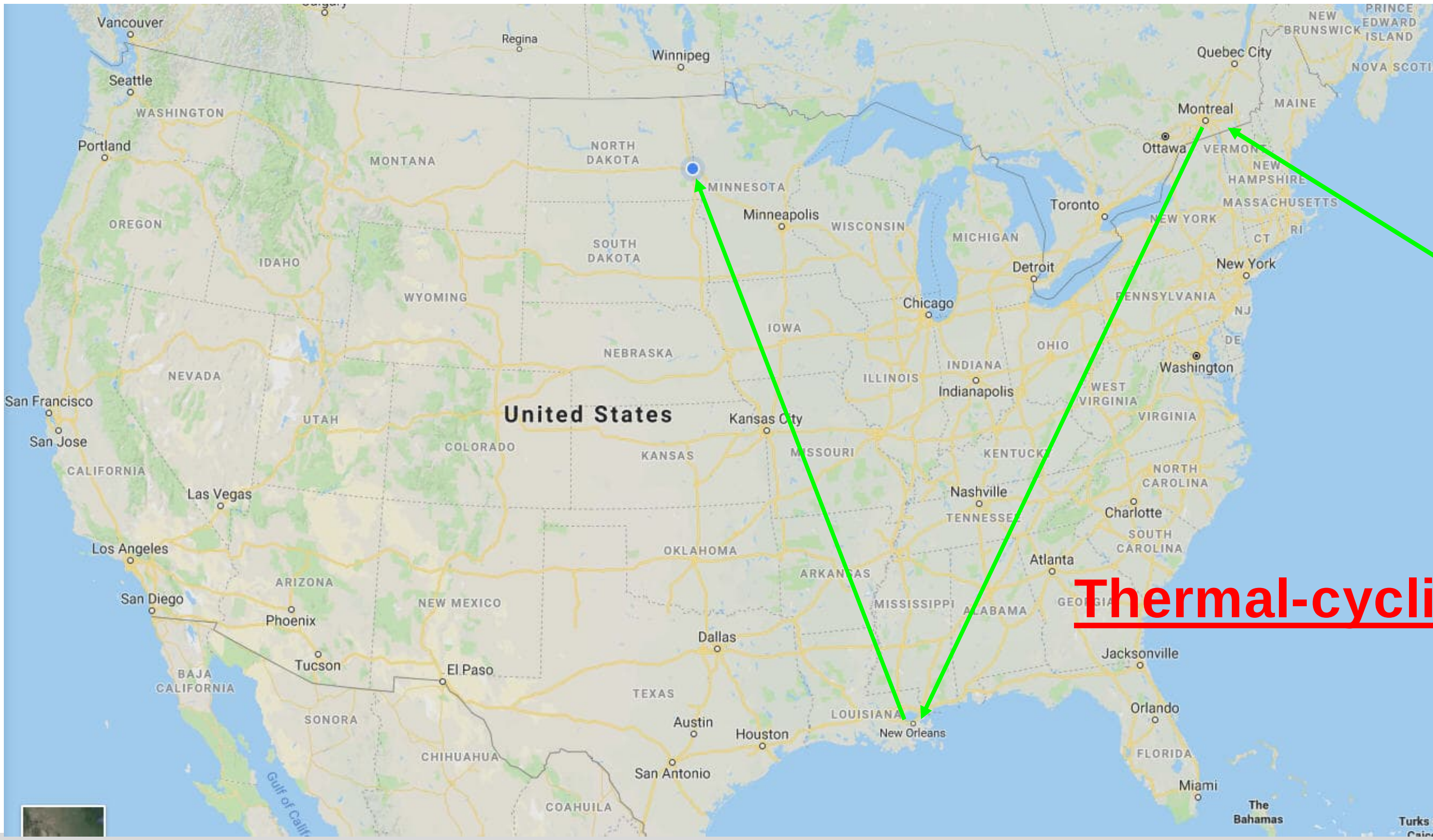
About Brij N. Singh

My ancestors and family members lived in this village for thousand years, record is available as early as year 1360. I am very proud of my roots in village in India and farming

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



Thermal-cycling of Brij

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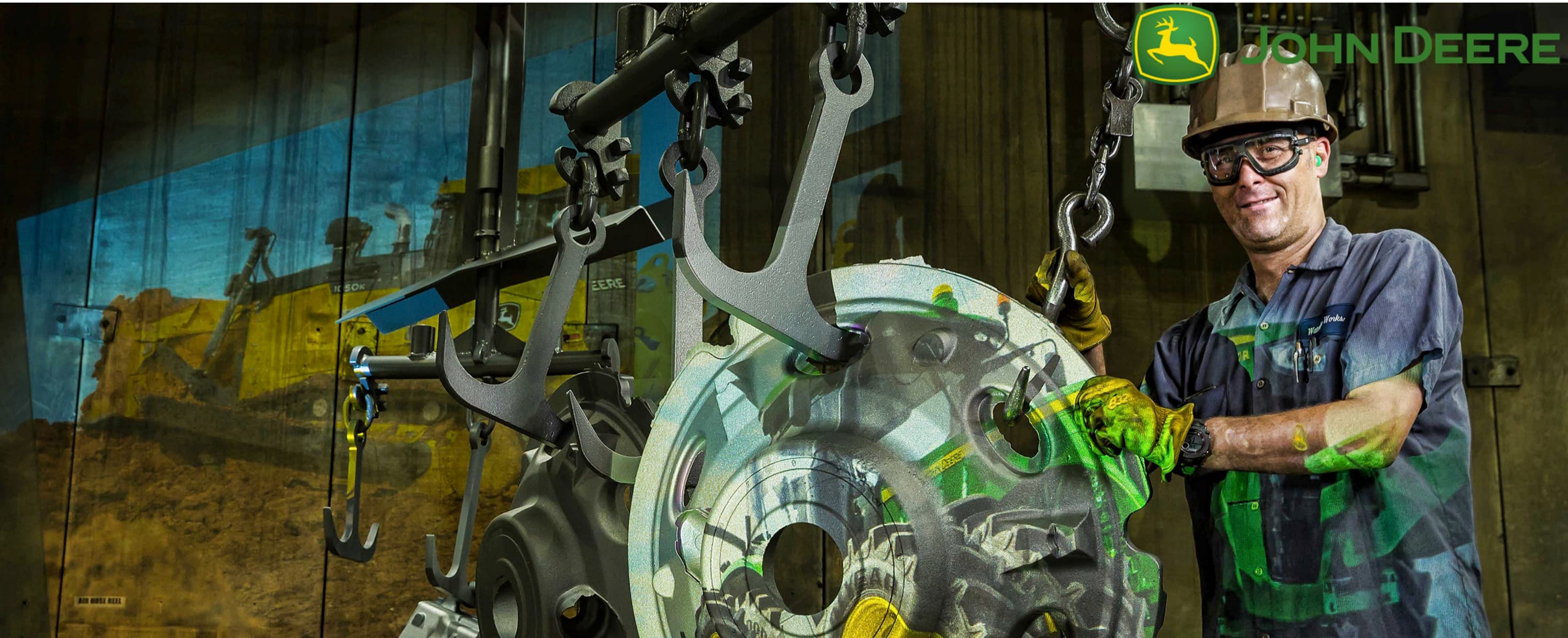

WHO WE ARE

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

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185 History and fast forward 2022

Deere and Company didn't get this far easy way, challenges were overcome with tough decisions since 1837

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INTEGRITY | QUALITY | COMMITMENT | INNOVATION

A Proud Past

Product line in 1900

- – Plows
- – Cultivators
- – Harrows
- – Drill & Planters
- – Wagons & Buggies

John Deere Today

Global Growth Operations

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John Deere Today
Complementary Operations

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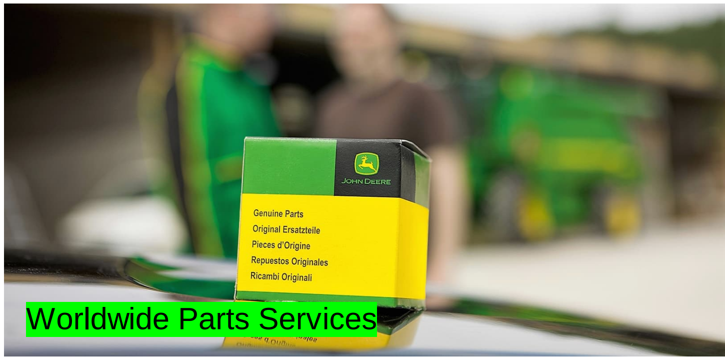
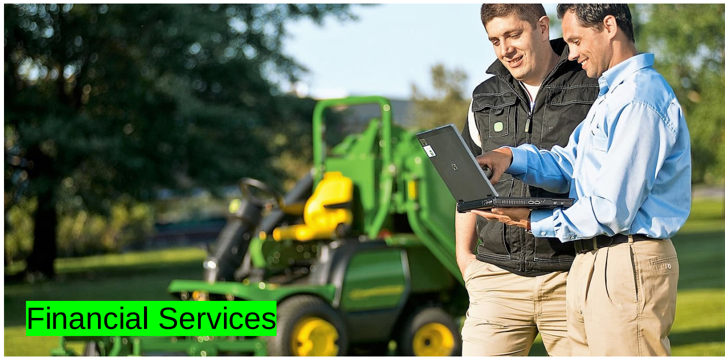
John Deere Today
Supporting Operations

Intelligent Solutions Group (ISG)



Worldwide Parts Services



Financial Services

Power Systems

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Environmental impacts of farming

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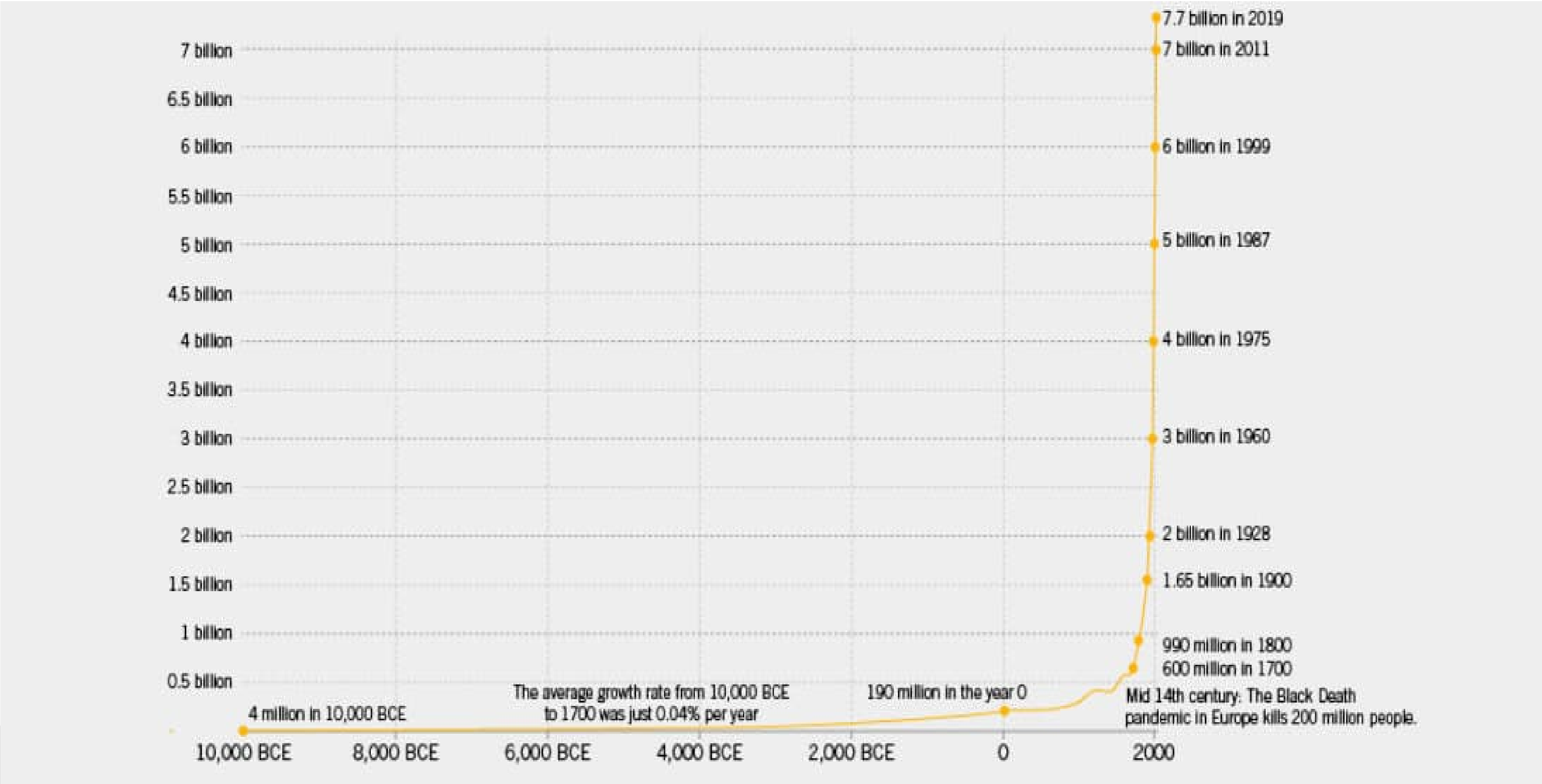
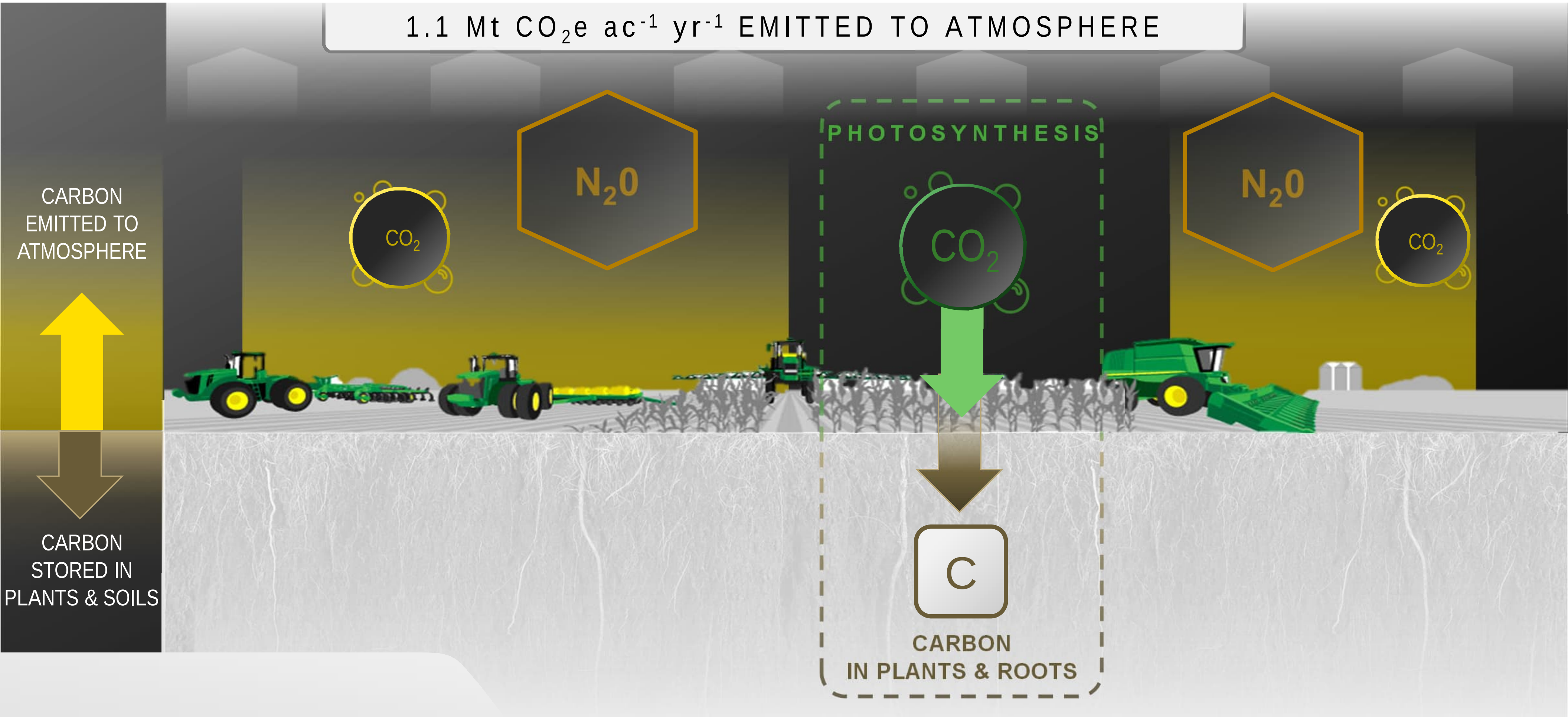
Trend in World Population over last 12,000 years





Typical coarse grain production system

Climate smart farming practices

- Enabled by electrification technologies

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Exact Emerge Planter Video

https://www.youtube.com/watch?v=XebeXoHOI_0

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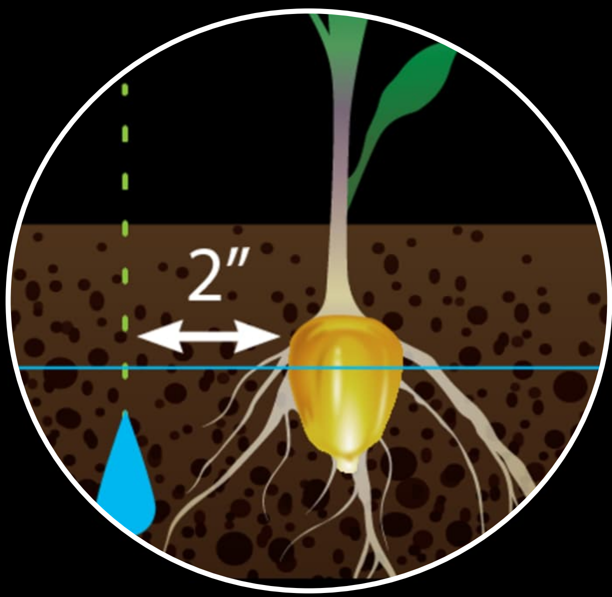
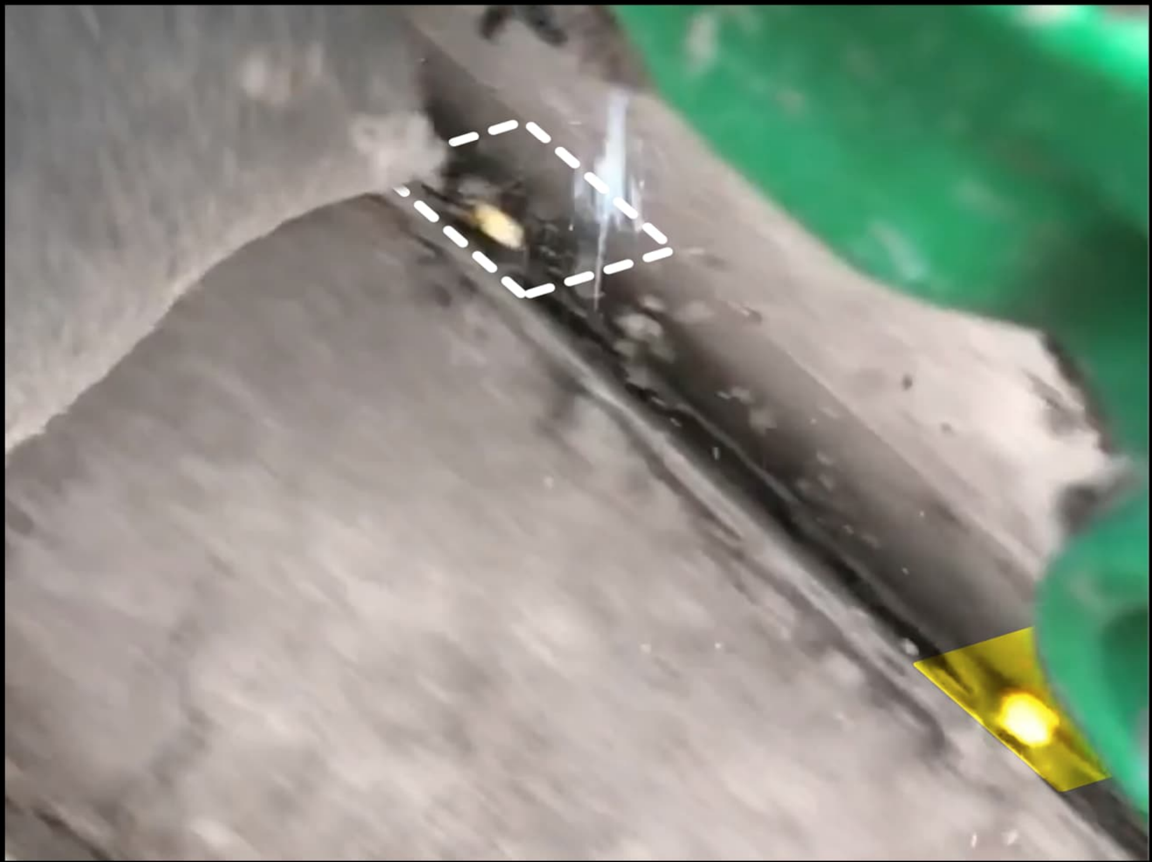
ExactEmerge™ Planter - Video

Trench View
ExactRate™





Company Use

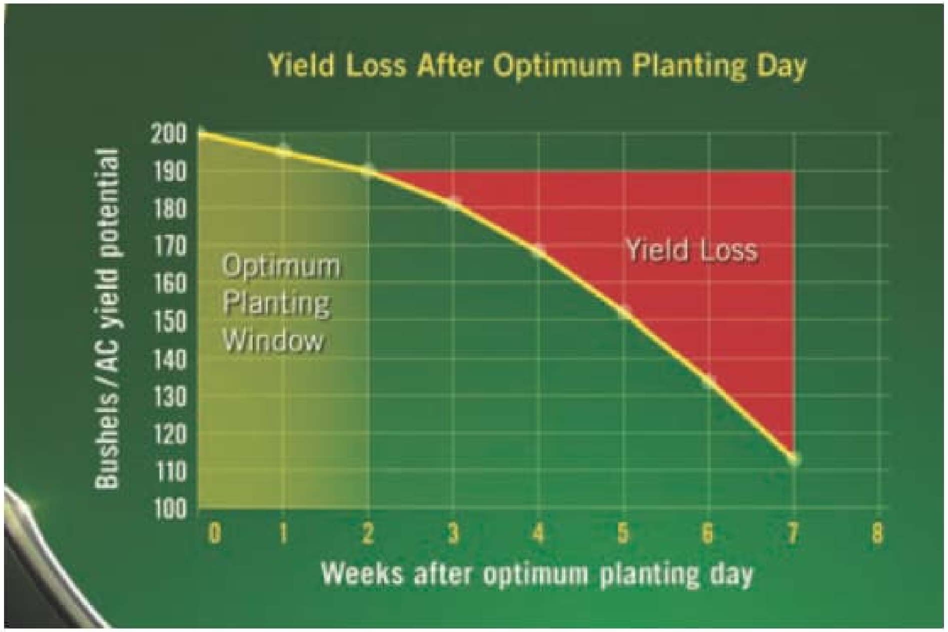
ExactEmerge™ Planter

Criticality of planting window

– Yield potential is highly affected by when the seeds are planted

We can't control the weather…

– What can we do to help farmers stay within or close to optimum planting window?



Lost Productivity by Missing Planting Window

Corn is $3.5/bushel, missed planting by 2 weeks, loss is 10 bushels

For 5,000 acres field, total loss = $3.5*10*5000 = $175,000

Missed planting by 8 weeks loss would be ~$2M

Job Quality by Automation and Control

Job optimization

System optimization


BLUE RIVER
TECHNOLOGY

See & Spray video

https://www.youtube.com/watch?v=-YCa8RntsRE

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[redacted]


See & Spray™ Select

Economic Headroom for Famers

- **Automation and autonomy**
- **Smart equipment making decisions**
    - Improved job quality
- **Mitigation of skilled workers shortage**

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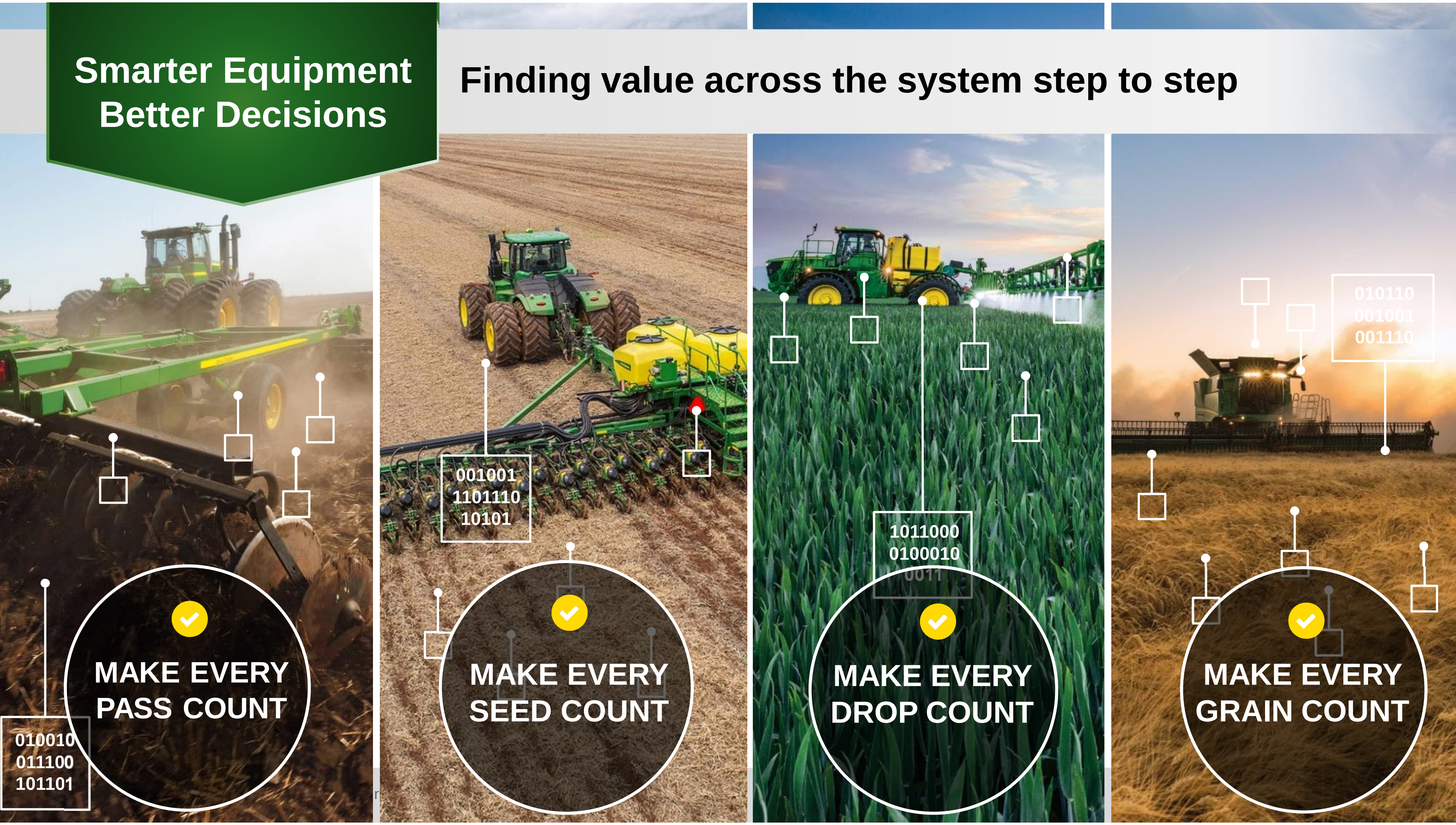
Farming

Our customers need intelligent solutions


Smarter Equipment
Better Decisions
Finding value across the system step to step
001001
1101110
10101
1011000
0100010
010110
001001
001110
010010
011100
101101
MAKE EVERY
PASS COUNT
MAKE EVERY
SEED COUNT
MAKE EVERY
DROP COUNT
MAKE EVERY
GRAIN COUNT

Data is the fuel, not the exhaust

3,000,000,000

15,000,000

104

Building large, diverse, real data sets

Computer Vision, Machine Learning and Automation

Changing the landscape of agriculture

Field level decisions

Plant level decisions

Production system decisions

Made in real-time

John Deere thinks rural 5G could help feed the world

https://www.fiercewireless.com/5g/john-deere-thinks-rural-5g-could-help-feed-world

- ❑ Machine to machine connectivity
- ❑ Machine to cloud server connectivity
- ❑ Machine to John Deere operation center connectivity

Electrification programs in Deere

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Why electrification of off-road Ag vehicle 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

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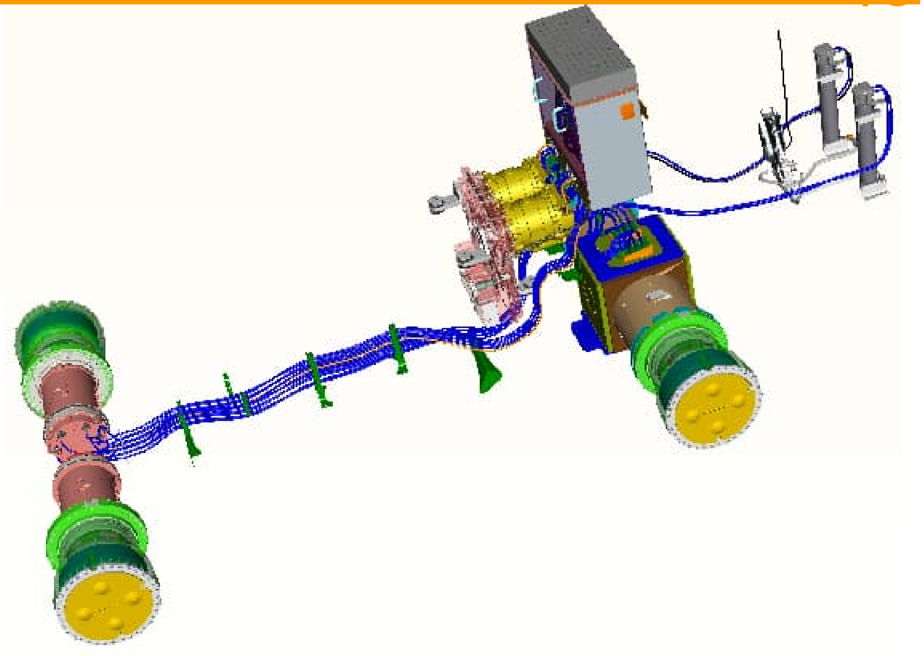
944K Hybrid Loader's Powertrain Architecture

- 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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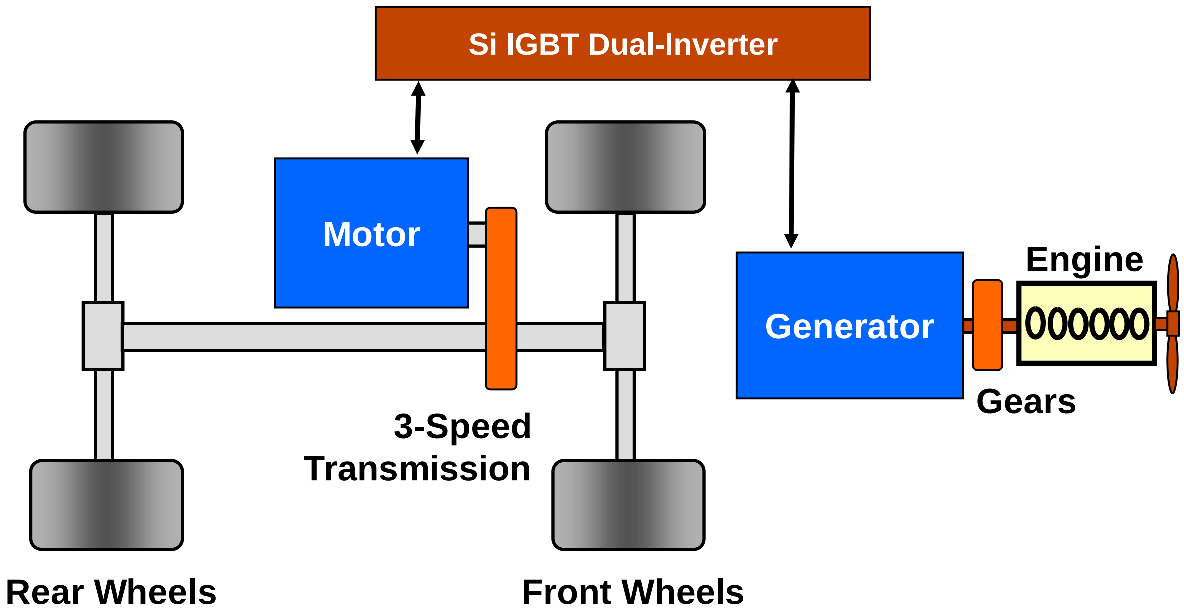
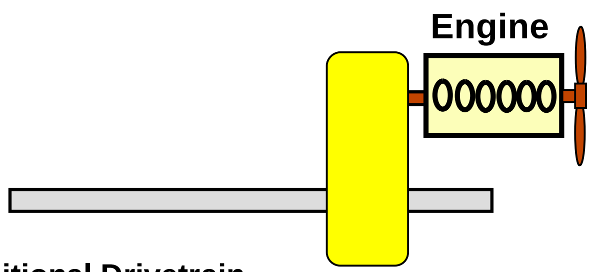
644K Hybrid Loader's Powertrain Architecture

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





Traditional Drivetrain
Torque Converter Drop Box

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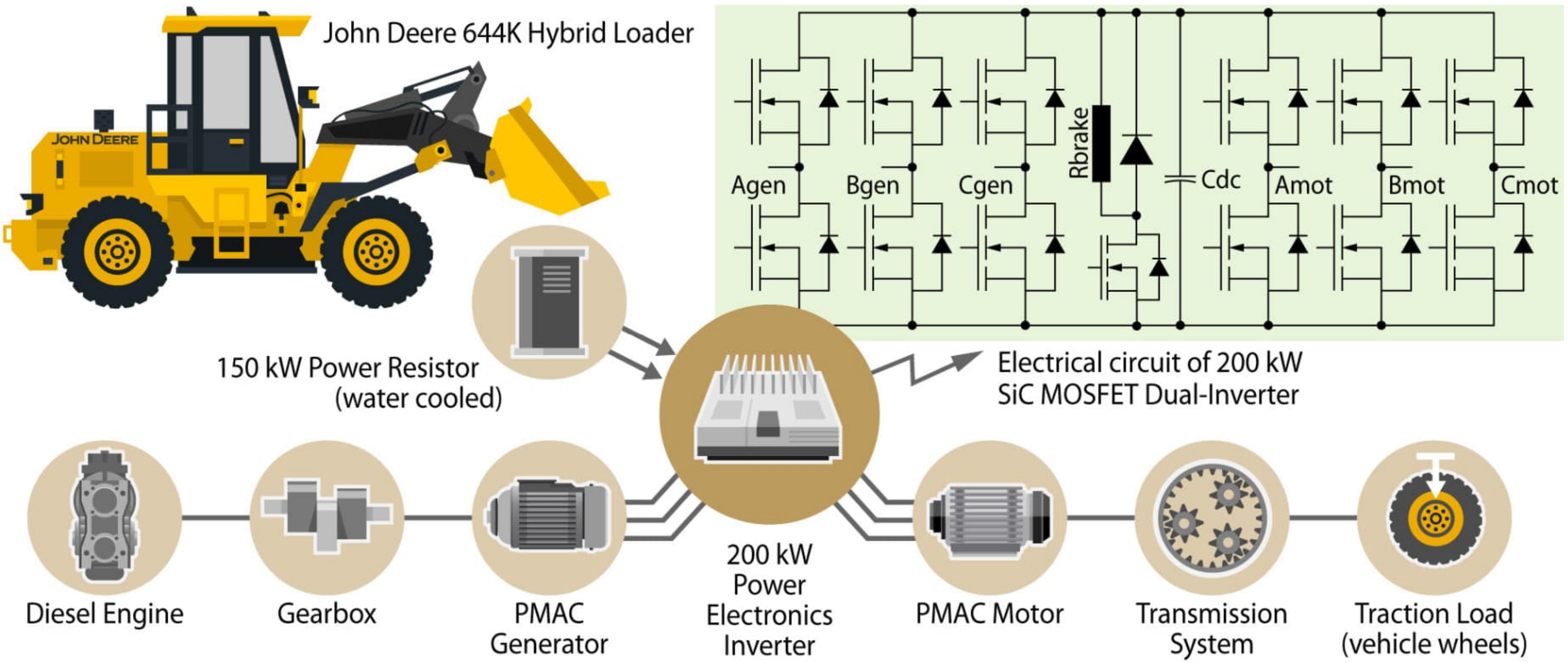
Power Electronics Applications

Power Electronics Applications

JD 644K Hybrid Loader - Powertrain Architecture
- Vehicle power management (VPM) enabled by advanced control system



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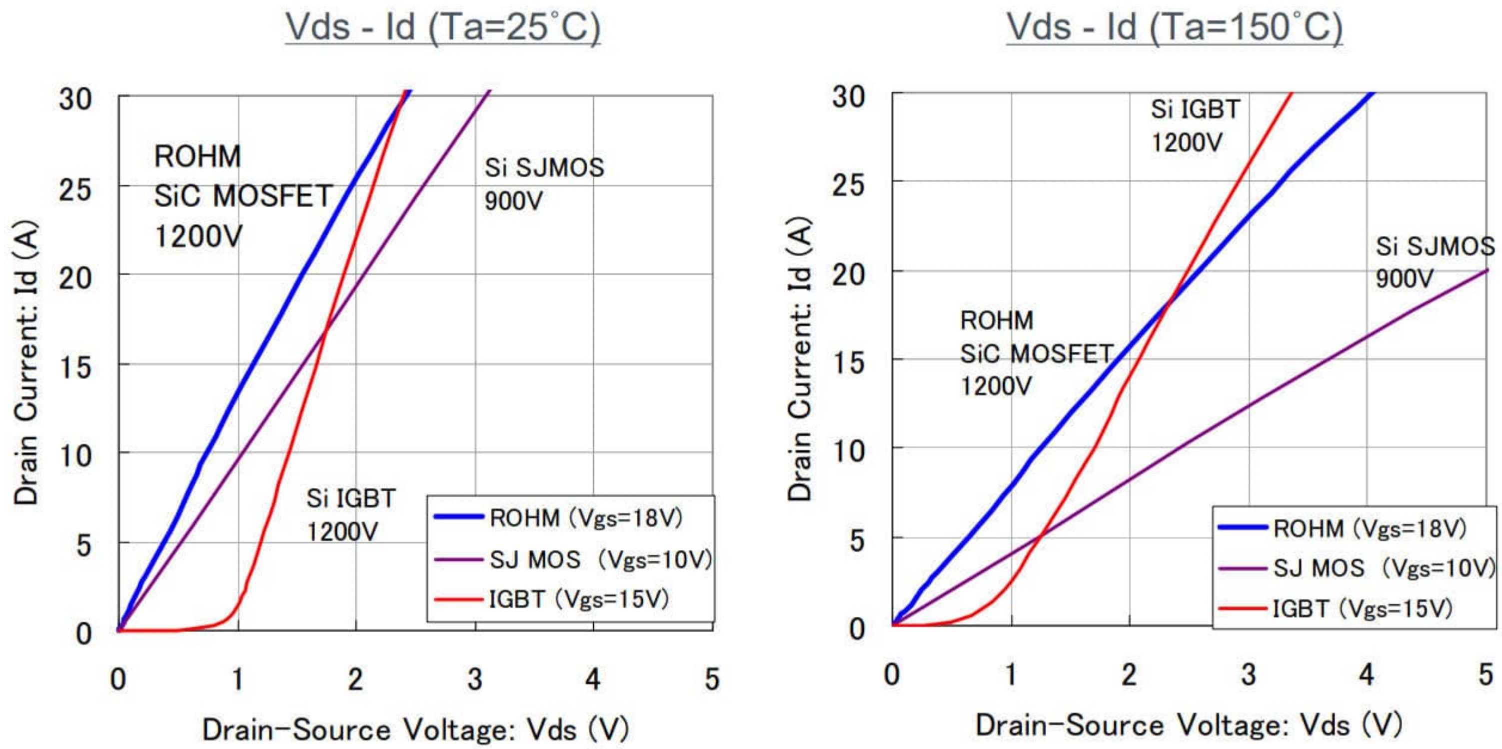
Wide Bandgap (WBG) Technology

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

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SiC inverter technology

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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

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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 compared to Si IGBT inverter

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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 vehicle system
- Improved performance and high temperature: system benefits

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Why off-road vehicles are different ?

- Requirement of stall-torque

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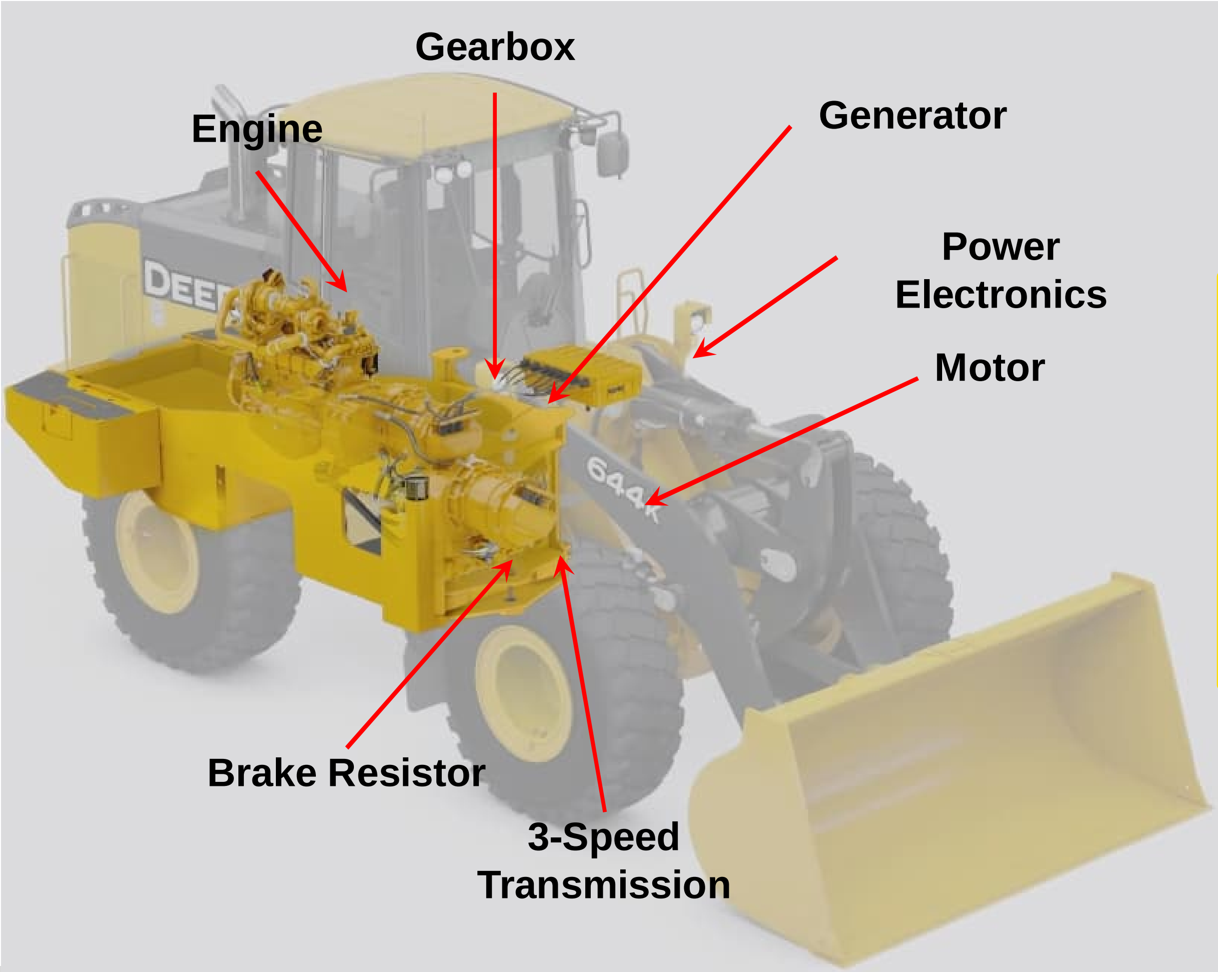
John Deere 644K Hybrid Loader



Engine-coolant capable power-dense SiC inverter could significantly simplify vehicle architecture of the 644 Hybrid Loader

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Three generations of SiC inverter

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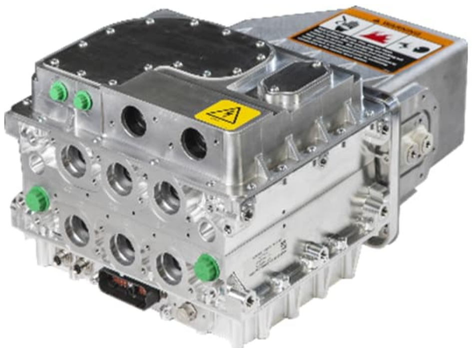
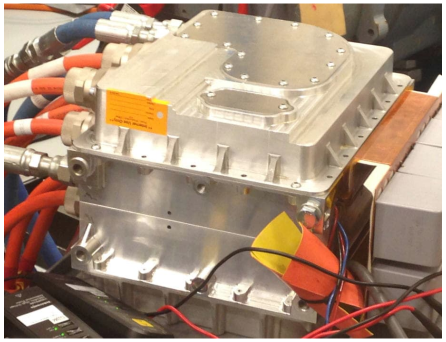
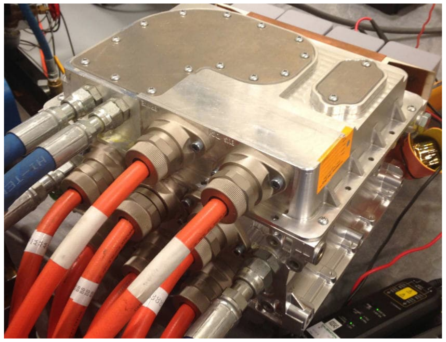
Gen-0 SiC Inverter Development

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

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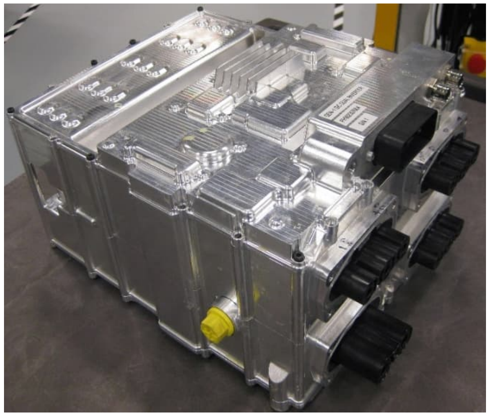
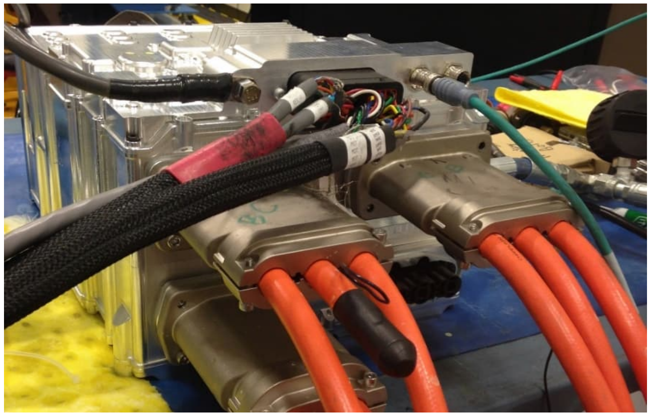
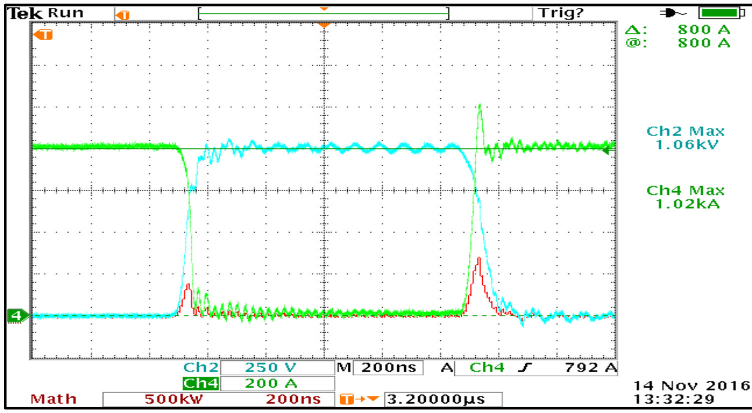
Gen-1 SiC Inverter Development

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



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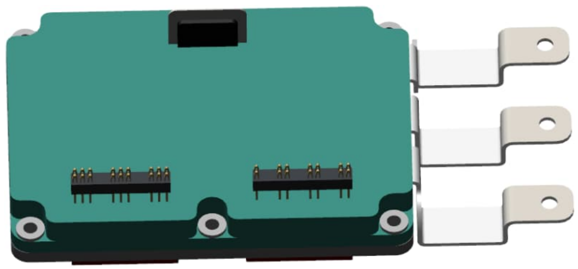
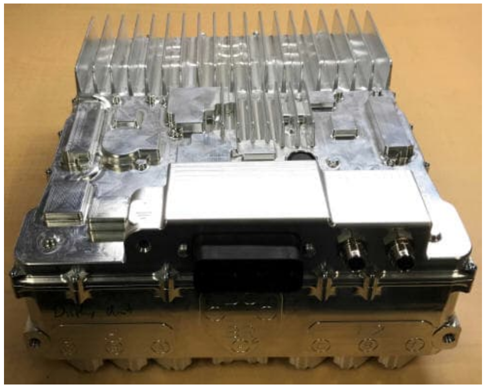
Gen-2 SiC Inverter Development


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)

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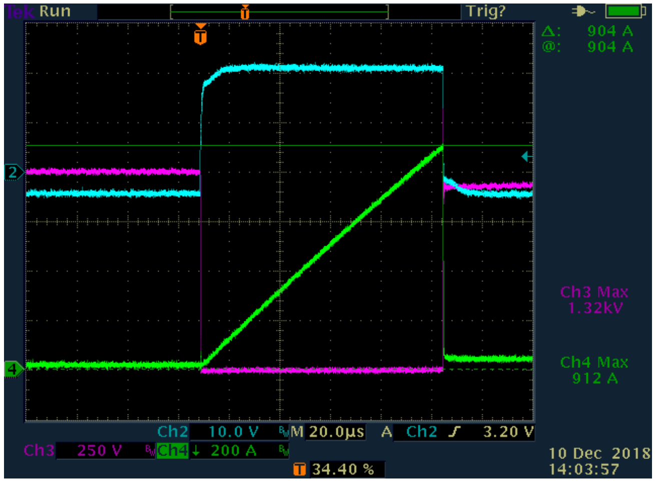
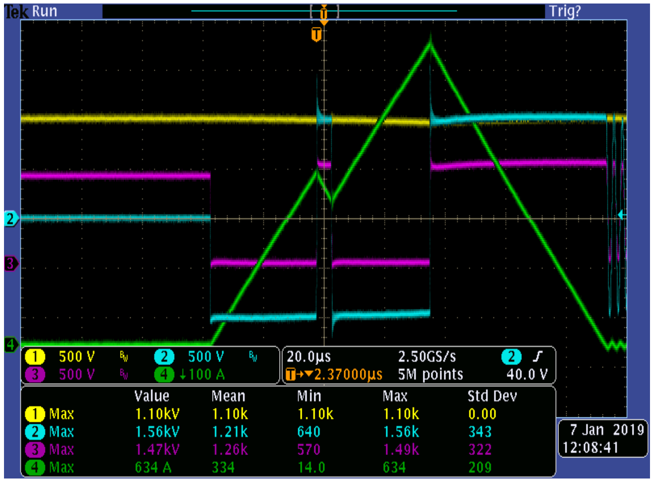
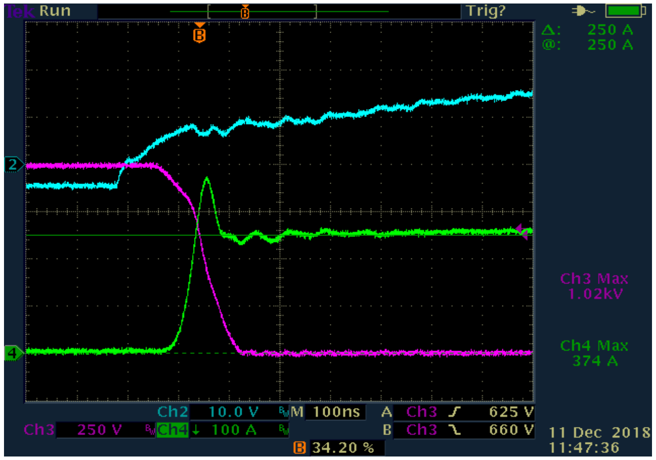
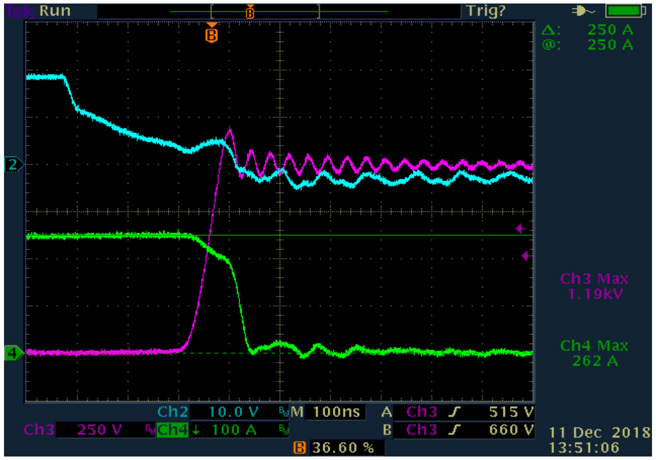
Gen-2 SiC Inverter Test Waveforms for Six-Pack Power Module

1700 V 400 A DC
GEAS SiC module









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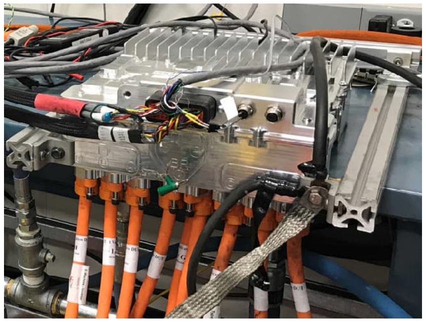
Gen-0 to Gen-2 SiC Inverters' Comparison

Gen-0 SiC inverter

Gen-1 SiC inverter



Gen-2 SiC inverter

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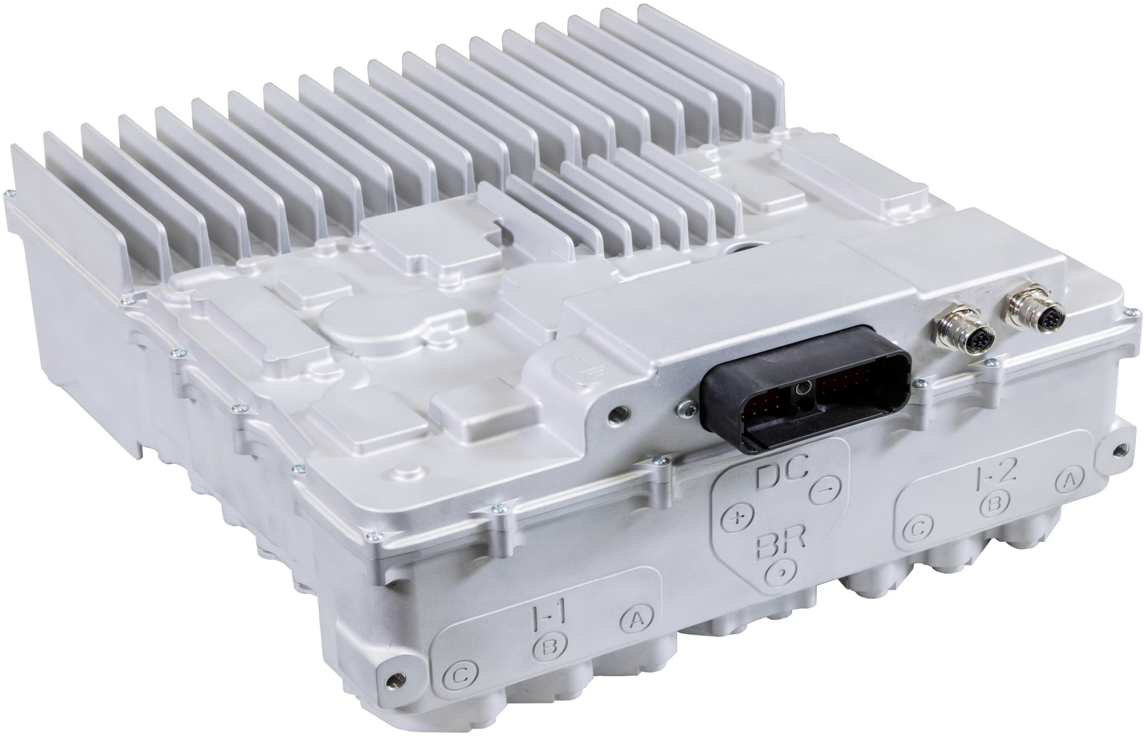
Innovative EXPECT SiC Technology

<u>EX</u>tremely **<u>P</u>**ower-Dense **<u>E</u>**ngine-**<u>C</u>**oolan**<u>T</u>**-Capable



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

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Key Lessons

- Packaging
- Thermal management
- Technology proliferation to peripherals
    - Batteries
    - Electric motors
    - Power interconnects

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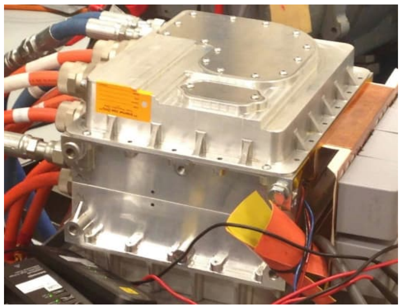
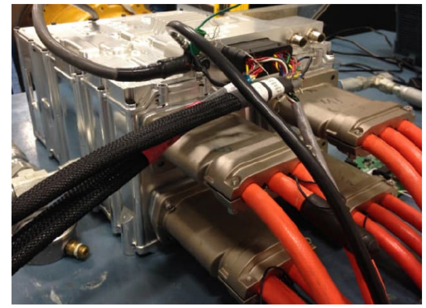
Lessons - Si IGBT Mind-Set Doesn't Work

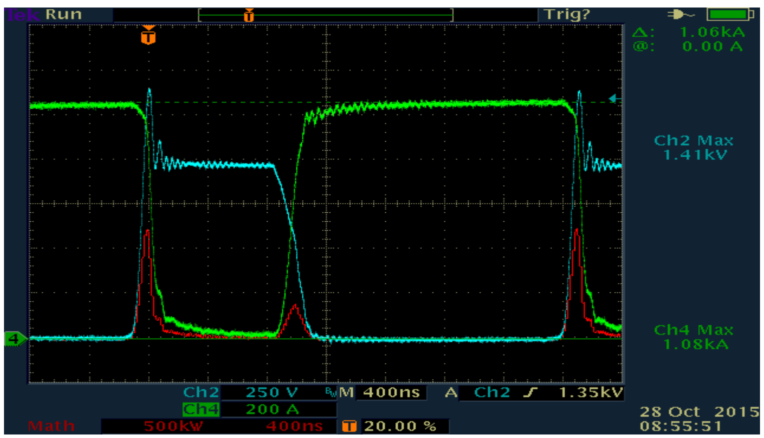
Gen-0 Inverter
(11 kW/L)



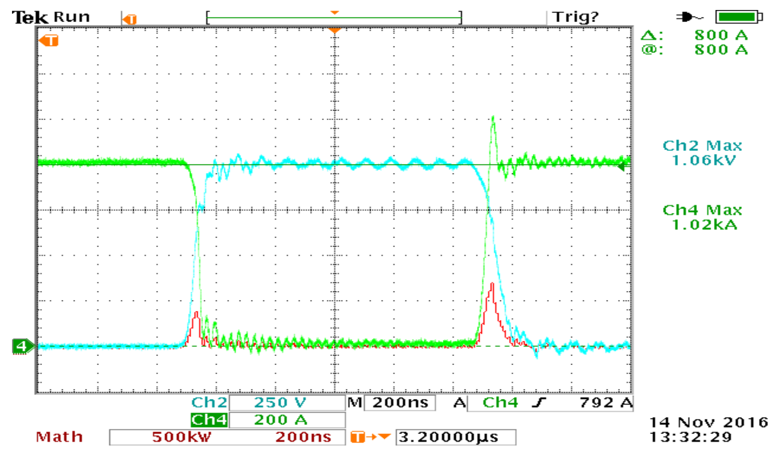
- Over-voltage issue with connectors, cables, and electric machine
- Improvement in common mode voltage and bearing current
- EMI and EMC improvements



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

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In-lab inverter characterization

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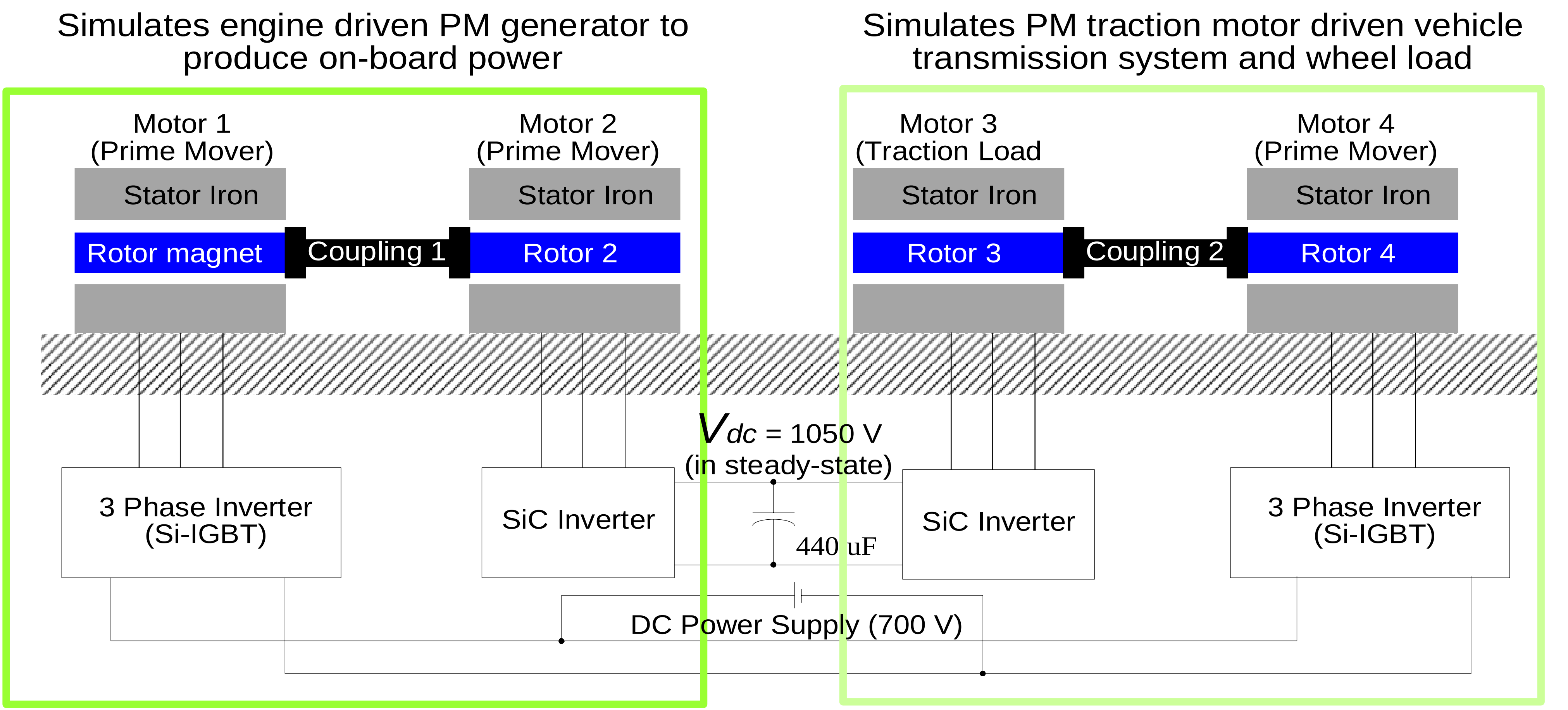
Dynamic Testing of Inverter (4 inverters and 4 electric machines set-up)



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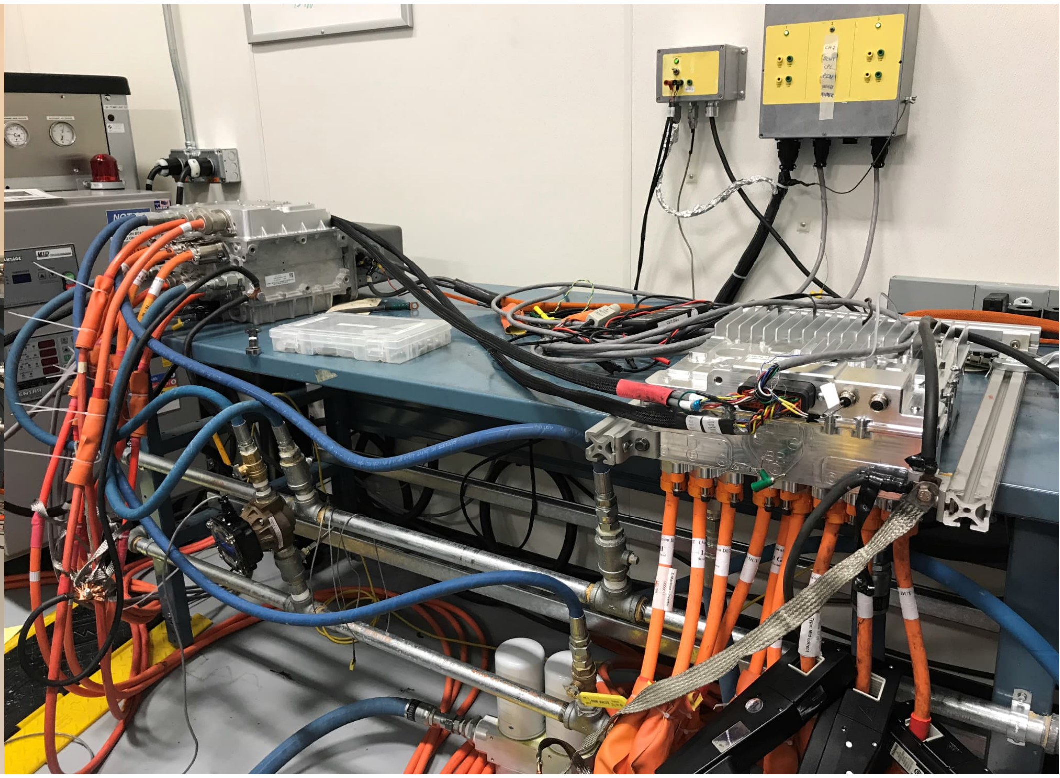
Dynamic Testing of Inverter (4 inverters and 4 electric machines set-up)



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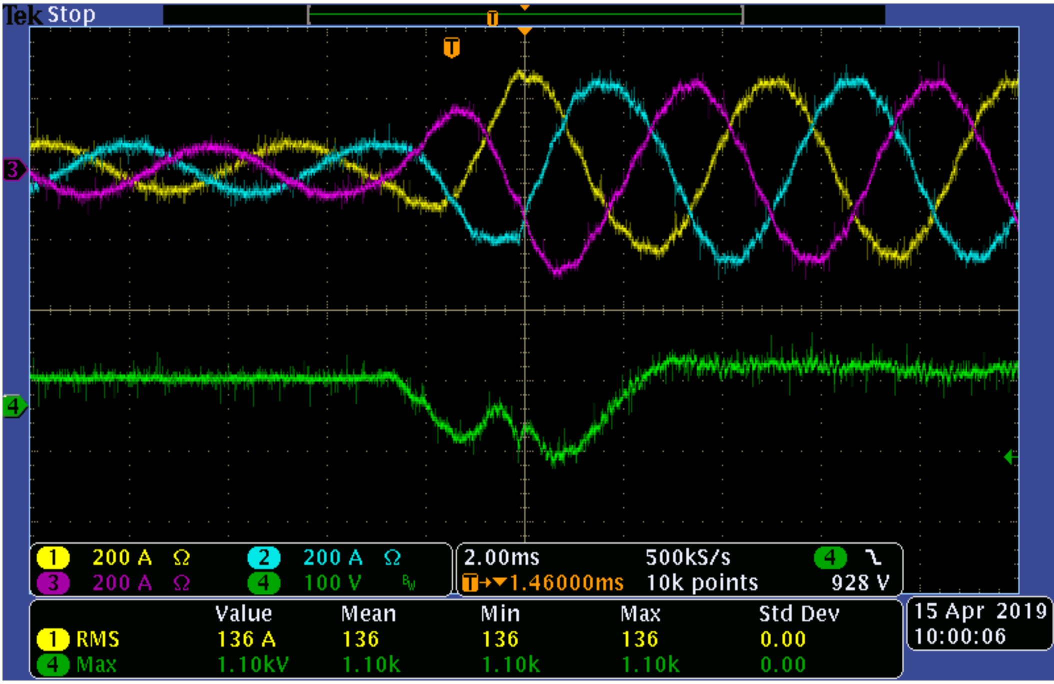
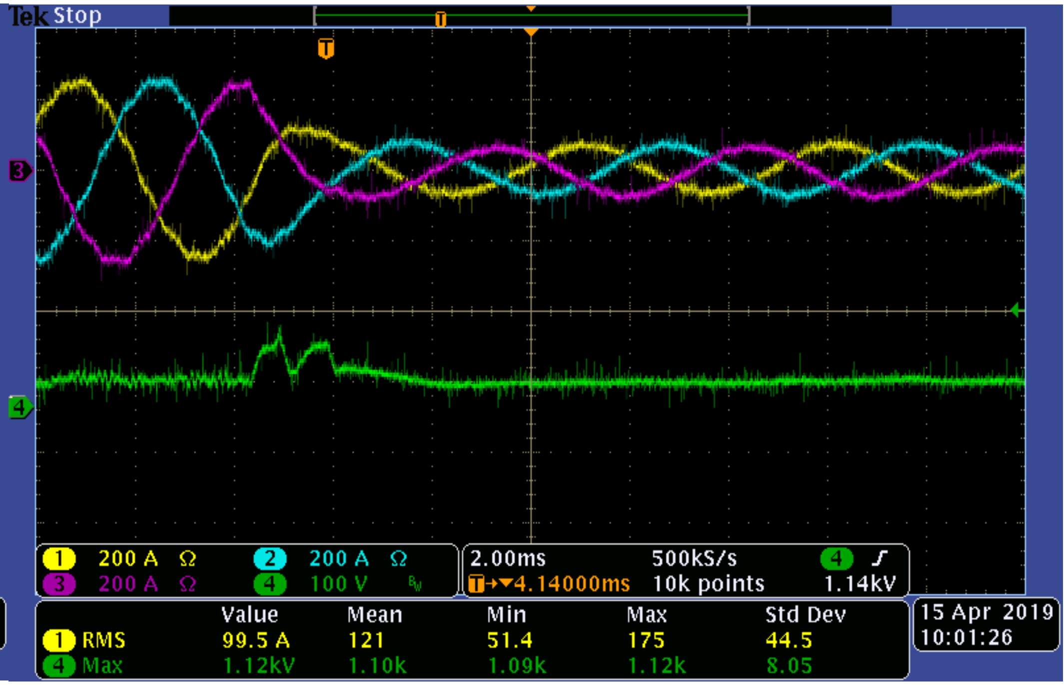
Dynamic Testing of Gen-2 SiC Inverter





Load change

30 kW to 150 kW

150 kW to 30 kW

Power-Shift dynamics of 644K WBG Loader

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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

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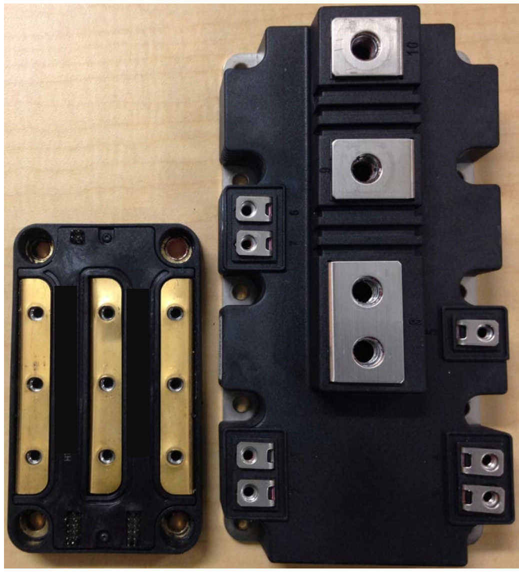
Competing Technology Trade-Offs

SiC MOSFET Inverter	Silicon IGBT Inverter
200 kW, 1050 VDC	200 KW, 1050 VDC
Performance	Performance
Capability	Capability
High temp coolant	High temp coolant
High frequency	High frequency
300 A 1700 V MOSFET	900 A 1700 V IGBT
Capability cost (A$): Expected	Capability cost (A$) : Market value



110 x 65 x 17
140 g

172 x 89 x 37
825 g

Gen-1 SiC Inverter

PD550 IGBT Inverter

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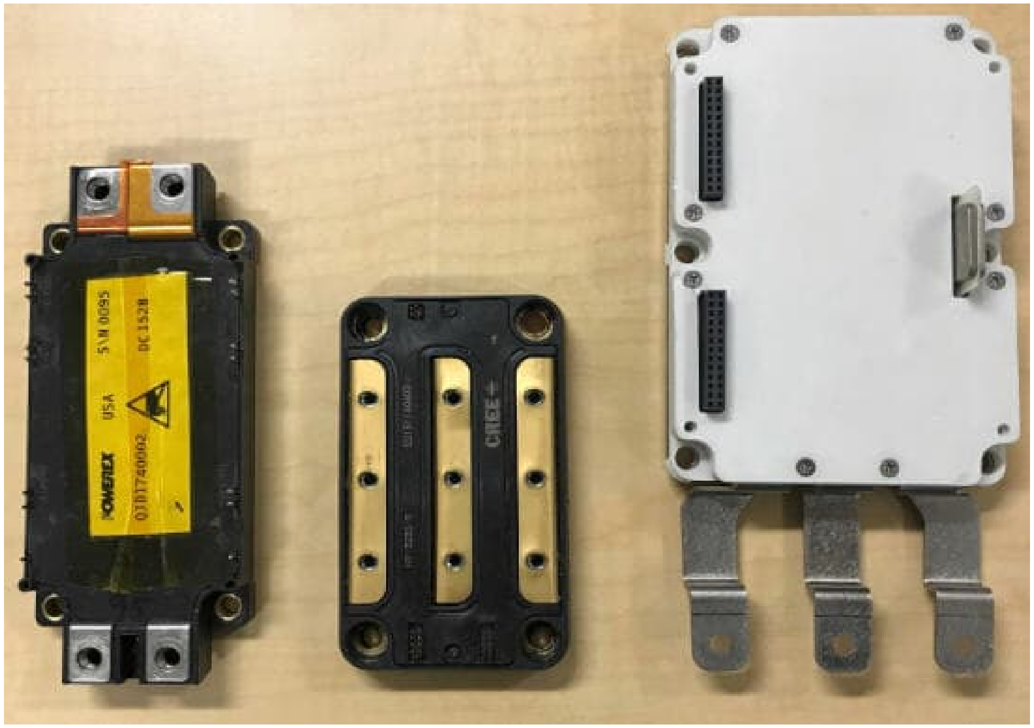
Experience with Variety of SiC Power Modules



Supply-chain issues understood/addressed

- Variant of six-pack SiC module
- Dual-sourcing of six-pack SiC modules
- Working experience with many suppliers

Power Modules for 200 kW Gen-0, Gen-1 and Gen-2 SiC Inverters

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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

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Summary

- Power electronics can enable climate smart farming
  - Per acre higher grain production with increased protein content
  - Result in low carbon intensity foodgrains
  - Support feeding the world in environmentally responsible manner

- 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

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Acknowledgement

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

NREL
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PowerAmerica

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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.

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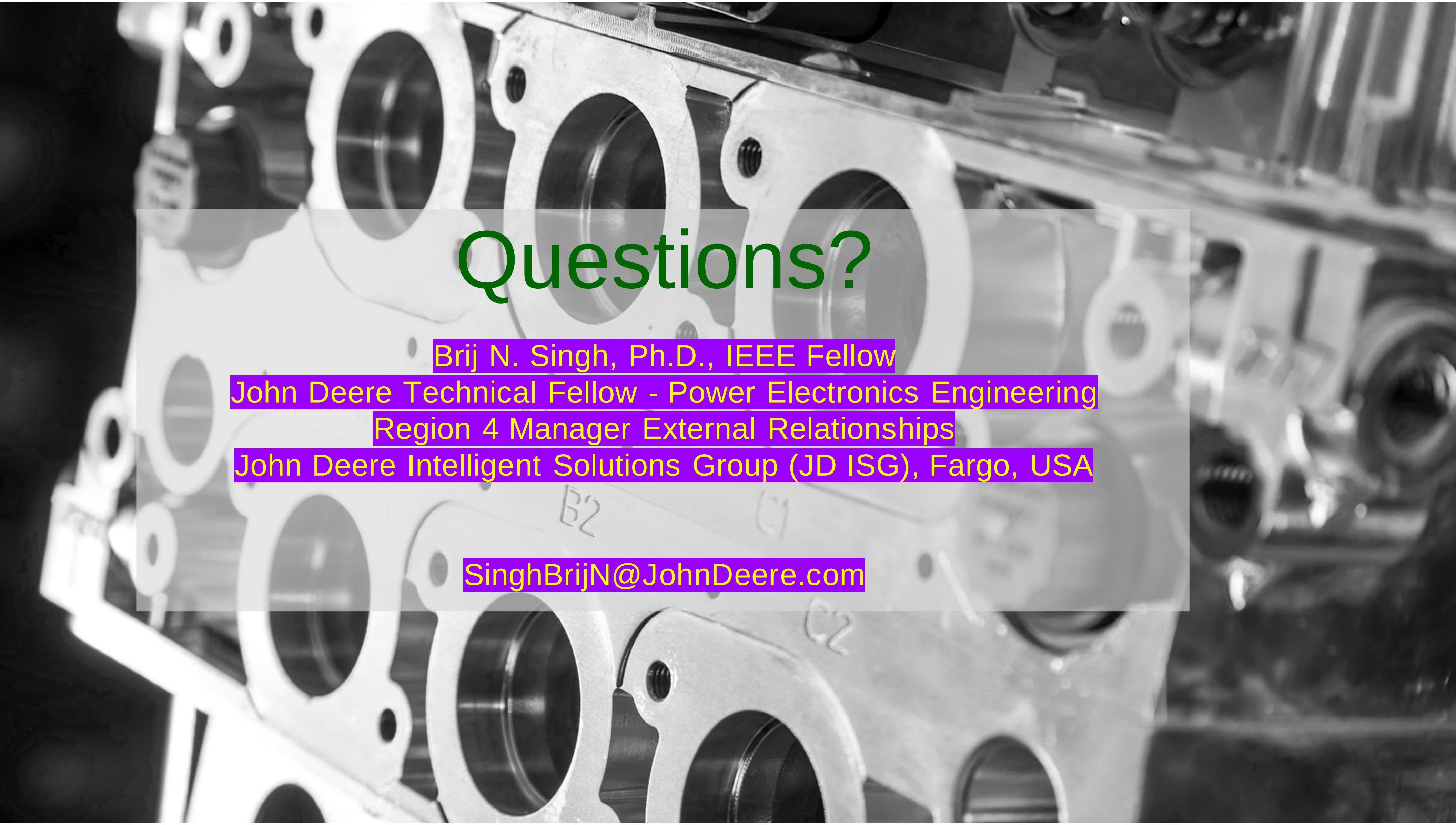

Questions?

Brij N. Singh, Ph.D., IEEE Fellow
John Deere Technical Fellow - Power Electronics Engineering
Region 4 Manager External Relationships
John Deere Intelligent Solutions Group (JD ISG), Fargo, USA

SinghBrijN@JohnDeere.com

John Deere