Innovative Technologies for Converters and Chargers

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Project ID: EDT054

ORNL is managed by UT-Battelle
for the US Department of Energy

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Overview

Timeline

- **Start – FY14**
- **End – FY16**
- **60% complete**

Budget

- **Total project funding**
  - **DOE share – 100%**
- **Funding received in FY14: $700K**
- **Funding for FY15: $990K**

Barriers

- **Reducing onboard battery charger and dc-dc converter cost, weight, and volume**
- **Achieving high efficiency**
- **Overcoming limitations of present semiconductor and magnetic materials to address charger and converter cost, weight, volume and efficiency targets** (charger technical targets are being developed)

Partners

- **International Rectifier/Infineon**
- **Delphi**
- **Aegis Technology Inc.**
- **Ferroxcube**
- **Hitachi/Metglas®**
- **NREL**
- **ORNL team member:** Cliff White, Larry Seiber, Lixin Tang, Zhenxian Liang, Madhu Chinthavali

Project Objective and Relevance

- **Overall Objective**
  - Develop low cost, high efficiency, high power density all wide band gap (WBG) integrated dc-dc converter and on-board charger (OBC)
  - Goals
    - Cost, weight, and volume reduced by 50%;
    - Efficiency better than 96% (compared to state-of-the-art)

- **FY15 Objective**
  - Incorporating the 6.6 kW SiC isolation converter developed in FY14, design, build, and test a 6.6 kW SiC integrated OBC
  - Design, build, and test a 3.3 kW GaN isolation converter
  - Upscale the GaN isolation converter design to 6.6 kW

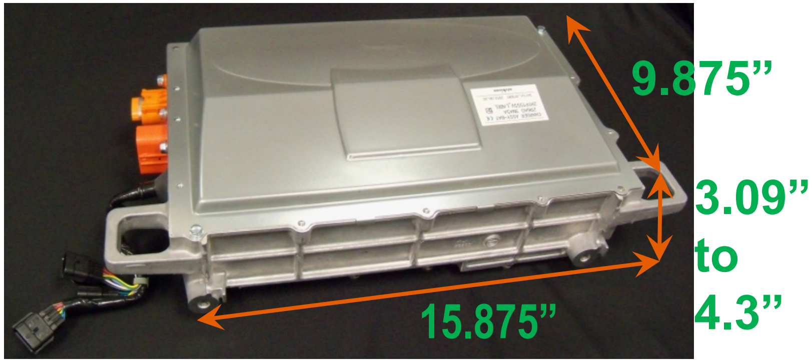
Milestones

Date	Milestones and Go/No-Go Decisions	Status
Sept. 2014	Milestone: Designed, built, and tested a 6.6 kW SiC isolation converter prototype	**Complete**
Sept. 2014	Go/No-Go decision: Prototype design indicated the integrated OBC can meet the cost, efficiency, weight, and volume goals	**Go**
March 2015	Milestone: Designed, built, and tested a 6.6 kW SiC integrated onboard charger	**Complete**
Sept. 2015	Go/No-Go decision: If 6.6 kW all-GaN isolation converter design meets efficiency >98%, proceed to build a prototype and integrate into all-GaN based OBC	

Problem to be Addressed

State of Art

- **Onboard chargers (OBCs)**
  - Expensive ($273 for a tier one 3.3 kW charger, with 1/3 of cost for passive components)
  - Low power density (2012 Nissan LEAF 6.6 kW OBC: 0.41 kW/kg, 0.66 kW/L)
  - Relatively low efficiency (85-93%)
  - Limited functionality; incapable of V2G support



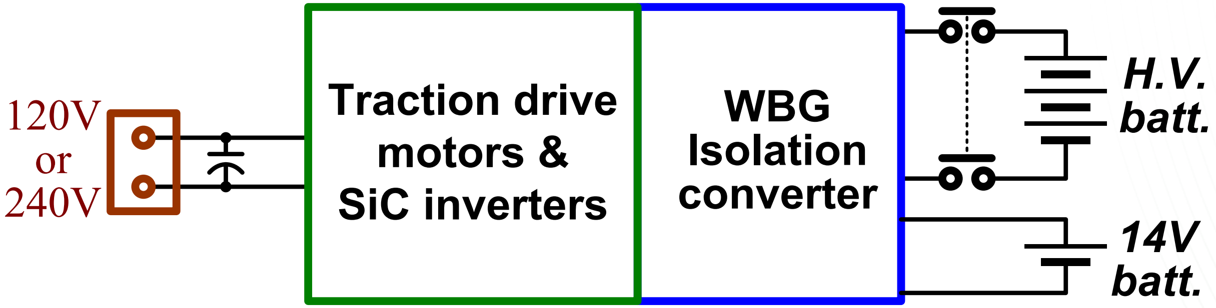
2012 Nissan LEAF 6.6 kW OBC: 0.41 kW/kg, 0.66 kW/L

- **A plateau in charger and converter performance exists because**
  - Si switches constrain switching frequencies to less than 100 kHz
  - Soft ferrite magnetic materials based inductors and transformers further limit power density and efficiency

Doubling Power Density at Half the Cost with Integrated WBG Onboard Charger and dc-dc Converter

Approach
Strategy to Address Limitations of SOA

- **Develop WBG integrated onboard charger**
  - Utilize traction drive inverters and motors as part of the charger converter
  - Provide galvanic isolation
  - Provide high voltage (H.V.) to 14V battery dc-dc conversion
  - Use soft switching for electromagnetic interference (EMI) reduction and efficiency improvement
  - Develop a control strategy to reduce the bulky dc link capacitor, needed to filter out the large voltage ripple of twice the fundamental frequency
- **Aggressive pursuit of power density and specific power without compromising efficiency**
  - All WBG converter (SiC and/or GaN)
  - Advanced soft magnetic materials (Nano-composite)



Conceptual diagram of an integrated onboard charger

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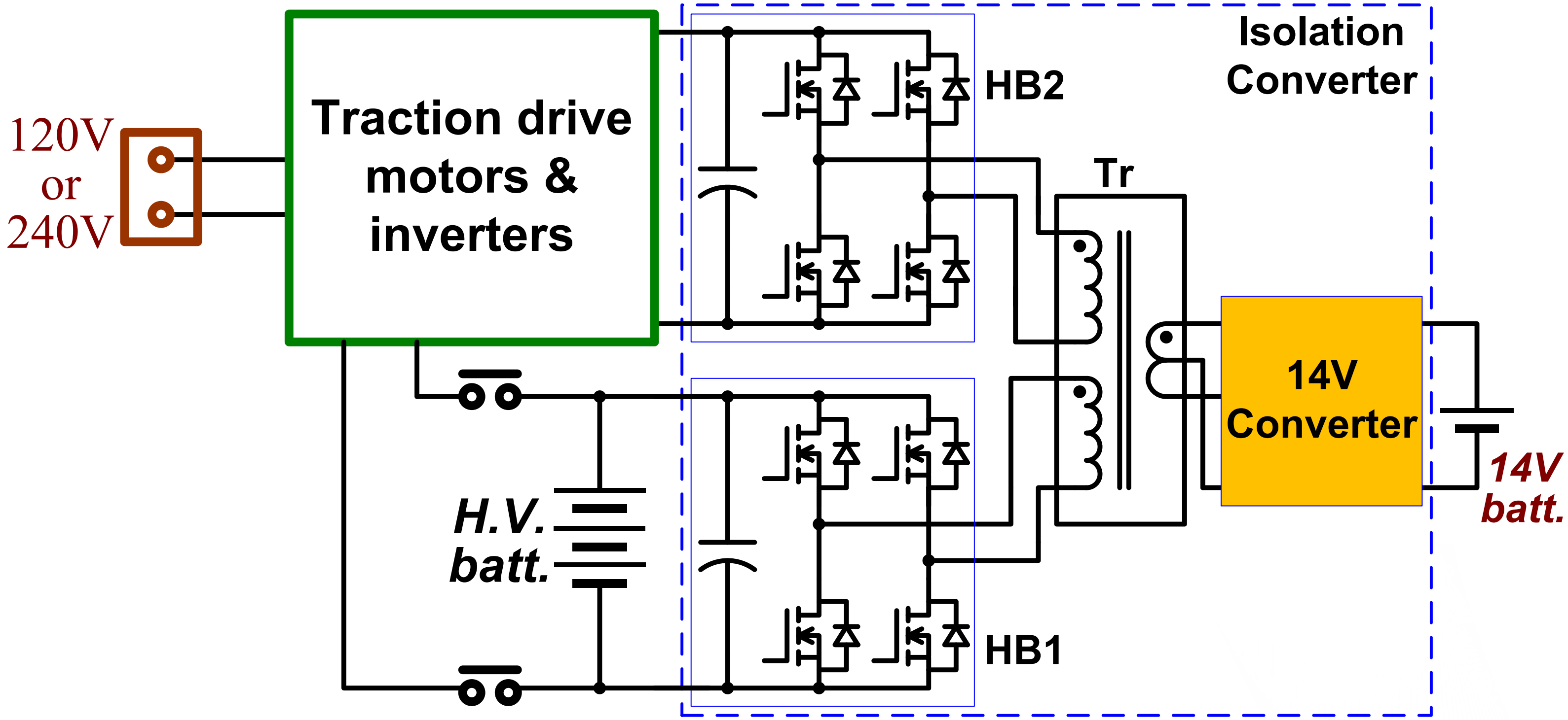
Approach
Strategy to Address Limitations of SOA

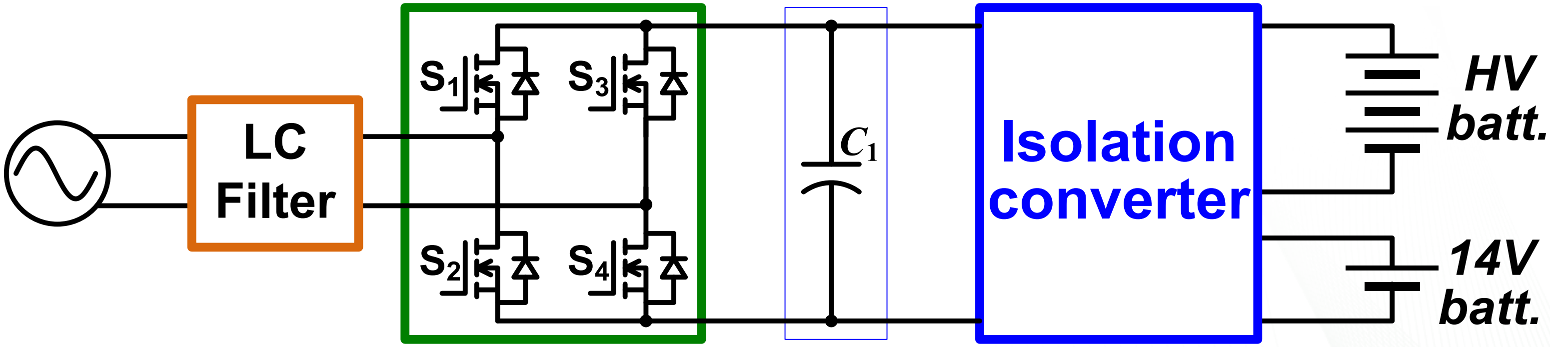


- **Using the traction drive as the OBC AC-DC front end converter**
- **3-port isolation converter**
  - Dual active H-bridge converter (soft switching, synchronous rectification)
  - Sharing converter (HB1) and transformer with the 14V battery charger
- **Bidirectional power flow**

Approach
Strategy to Address Limitations of SOA

- **Can be applied to most traction drive systems**
  - Dual inverter and motor (does not need to have same ratings)
  - Single inverter and motor with a boost converter
  - Segmented inverter traction drive (single inverter and motor)
  - Single inverter and motor without a boost converter-need to add a pair of switches or diodes

- **The isolation converter can also be applied to standalone OBCs**

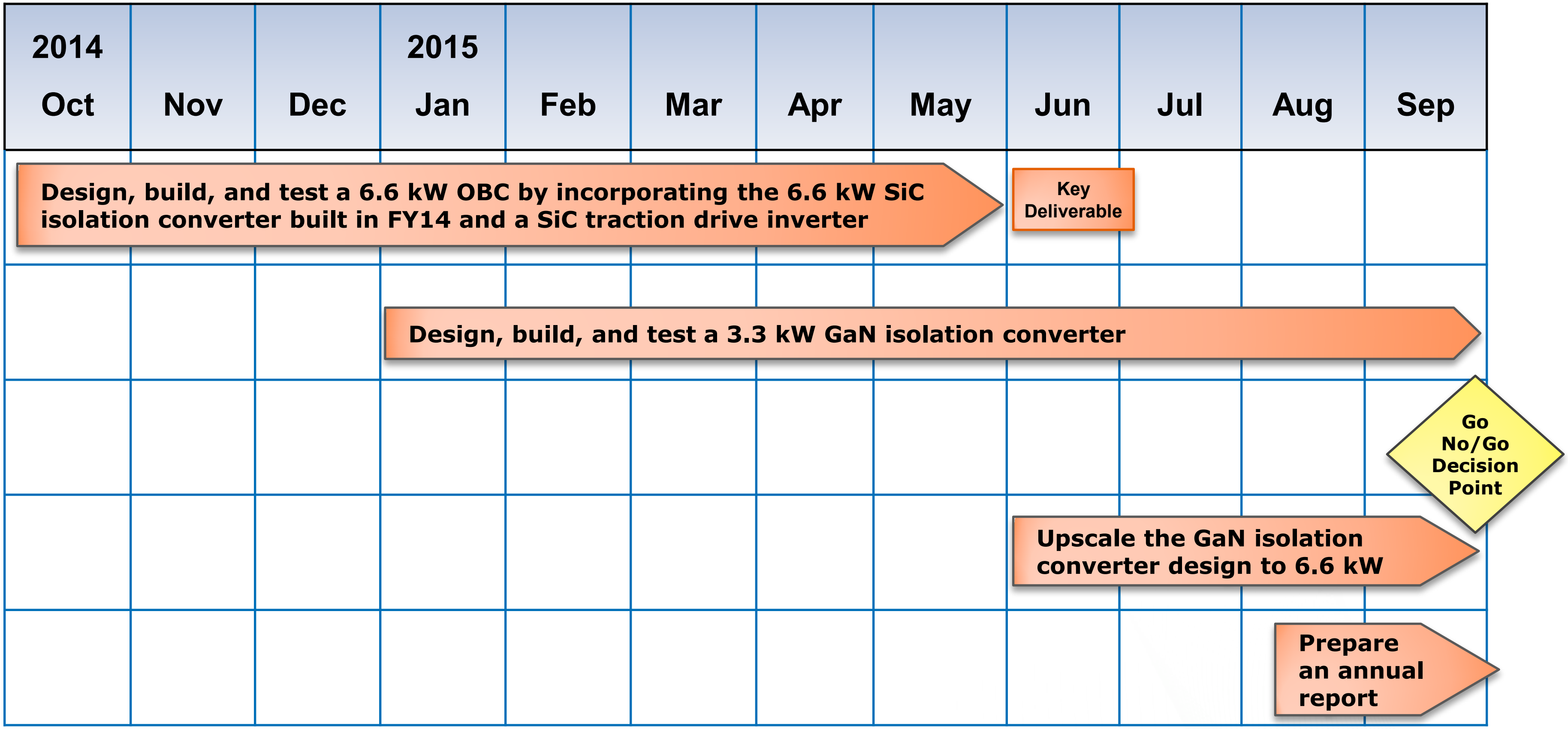


Approach is flexible and applicable to various traction drive system architectures

Approach
Strategy to Address Limitations of SOA

- **The goal of this research is to**
  - Minimize components through utilization of onboard power electronics and significantly increasing switching frequency
  - Reduce weight and volume of the dc-dc converter and charger by a factor of two
  - Increase efficiency to better than 96%, (> 40 % loss reduction compared to that of the SOA)
- **Potential to impact industry**
  - Introduction of all-WBG devices enables higher power density and higher efficiency chargers and converters
- **Uniqueness**
  - A unique charger topology that
    - minimizes the number of components through functional integration
    - is applicable to various traction drive system architectures
  - Fully utilizing the capabilities of WBG semiconductor and novel magnetic materials

Approach FY15 Timeline

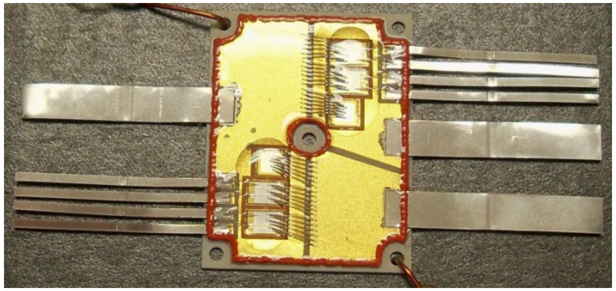


Go No/Go Decision Point: If design meets cost and efficiency goals, proceed to build a 6.6 kW all-GaN isolation converter prototype.

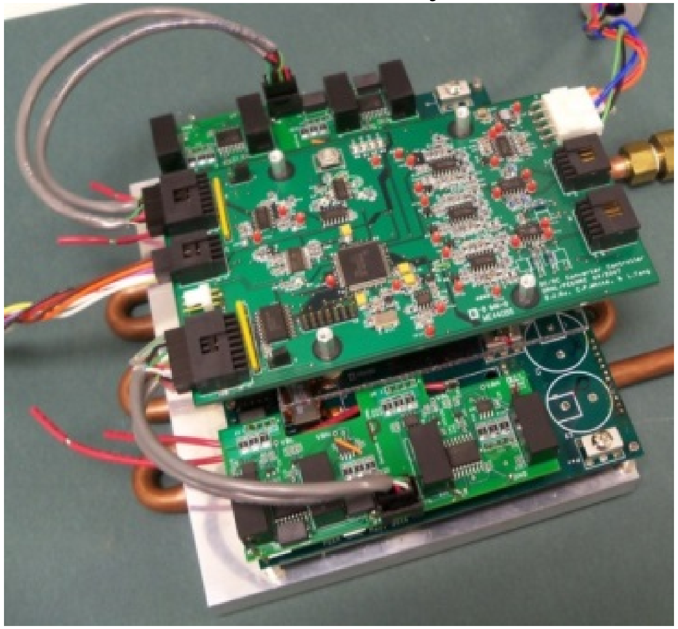
Key Deliverable: 6.6 kW SiC OBC prototype

Technical Accomplishments – FY14

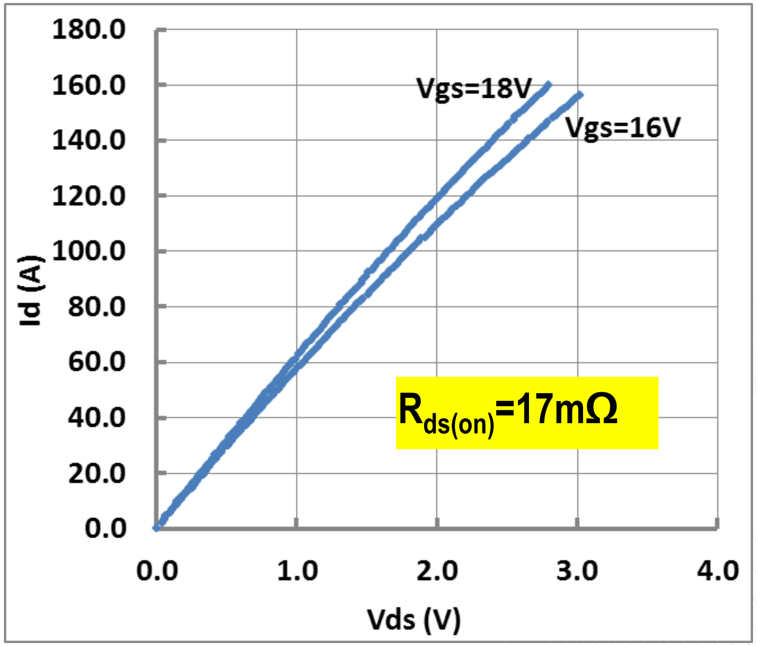
- Designed, built, and tested a 6.6 kW SiC isolation converter that have be used for building a 6.6 kW SiC-based Integrated OBC
  - Built-in 2 kW 14V converter
  - ORNL designed DBC and SiC switch phase-leg module using Cree SiC MOSFETs
  - Planar transformer
  - Heavy copper PCBs
  - High resolution pulse width/phase shift based control (180ps vs. 10ns)
  - Peak efficiency: 99% at 100 kHz, 97.5% at 200 kHz



SiC MOSFET phase-leg modules (36x46mm): 1200V/100A



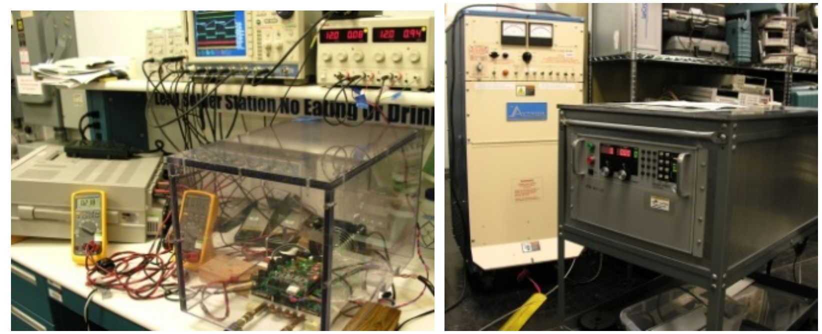
3-port 6.6 kW SiC bidirectional isolation converter



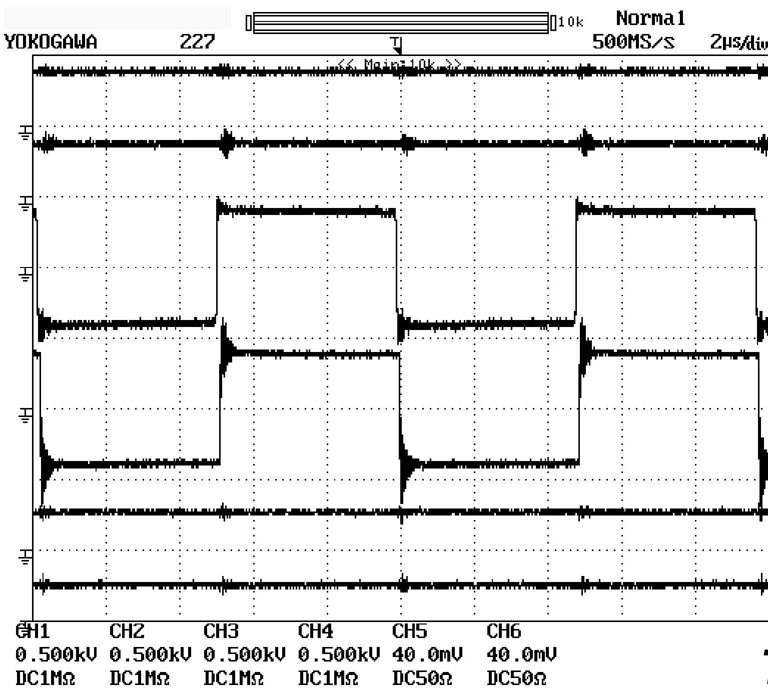
SiC MOSFET phase-leg modules static characteristics

Technical Accomplishments – FY14

- **6.6 kW SiC Isolation Converter Test Results**
  - Voltage and current waveforms showing successful operation at 100 kHz and 200 kHz



Test setup



fsw=100 kHz

V_{in}: 500V/div

V_{out}: 500V/div

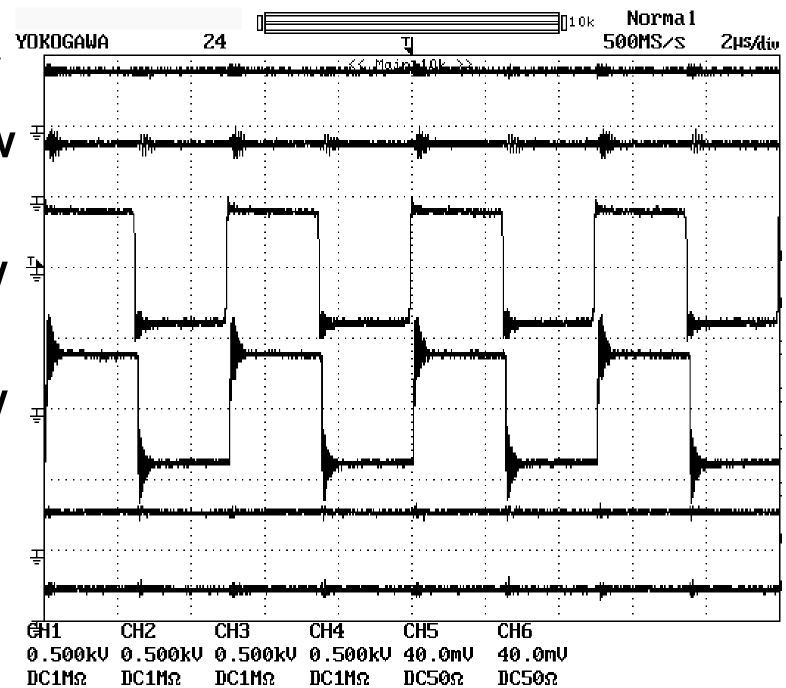
v_{Tr1}: 500V/div

v_{Tr2}: 500V/div

I_{in}: 40A/div

I_{out}: 40A/div

Time: 2μs/div



fsw=200 kHz

Operating waveforms

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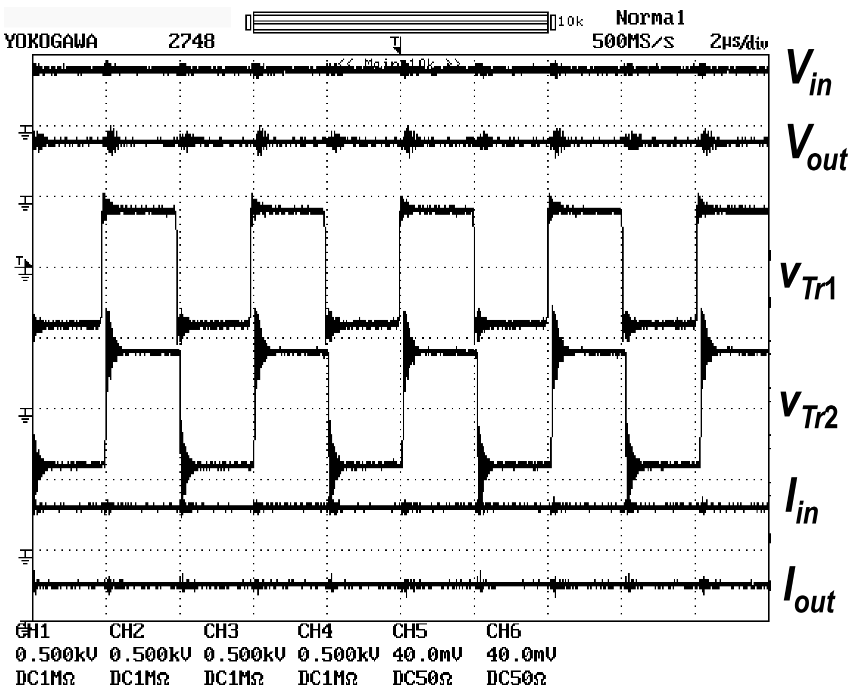
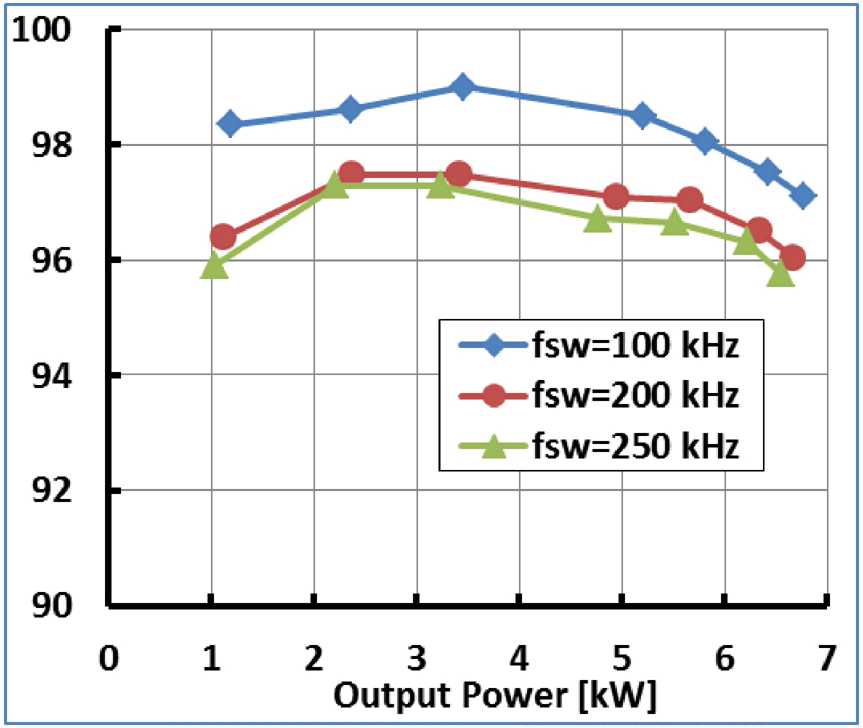
Technical Accomplishments – FY14

- **6.6 kW SiC Isolation Converter Test Results**
  - Voltage and current waveforms showing successful operation at 250 kHz
  - Maximum efficiency: 99.0 % at 100 kHz, 97.5 % at 200 kHz, and 97.3 % at 250 kHz



Scales: voltage, 500V/div; current, 40A/div; time, 2μs/div

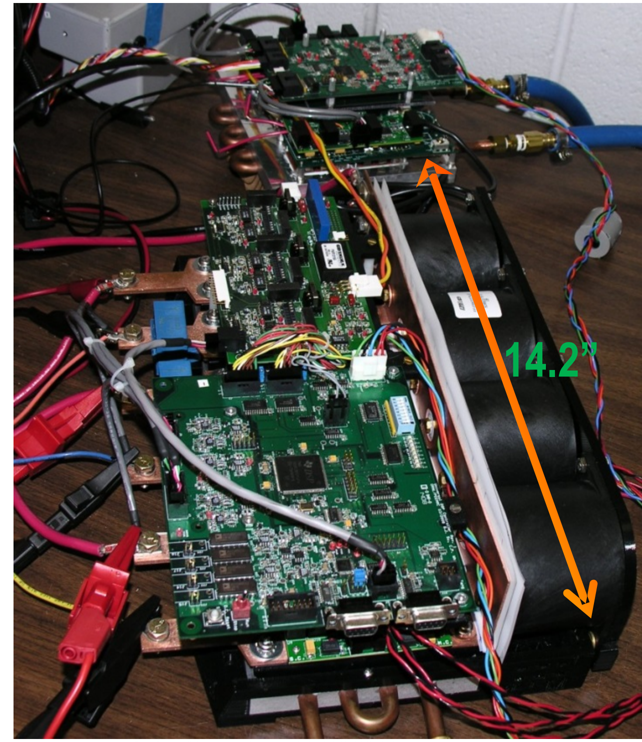
Operating waveforms at fsw=250 kHz.



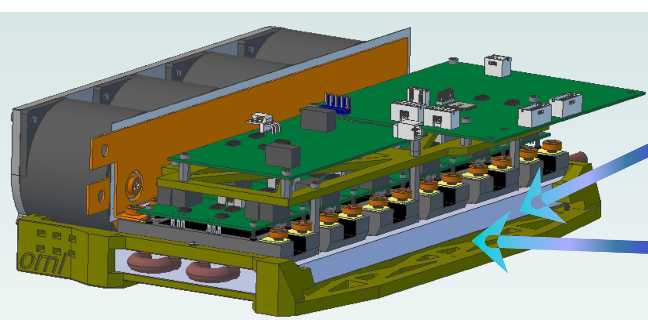
Efficiency v.s. output power

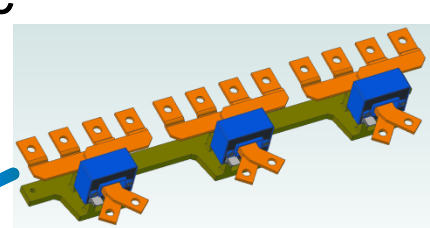
Technical Accomplishments – FY15

- Designed, built, and tested a 6.6 kW SiC-based integrated OBC
  - Designed and built a SiC traction drive inverter using commercial SiC MOSFET phase-leg modules rated at 1200V/120A
    - 3D printed frame
    - Can operate as dual 3-phase inverters or segmented 3-phase inverter to reduce dc bus capacitor ripple current
  - Incorporated the 6.6 kW SiC isolation converter developed in FY14
  - Peak charger system efficiency: 96.5 % at 240V ac source voltage

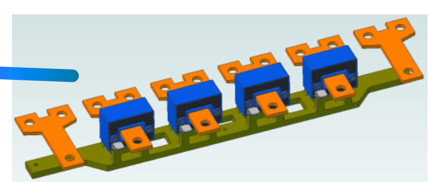


SiC traction drive inverter with an integrated 6.6 kW OBC





Segmented 3-phase inverter for single motor systems



Dual 3-phase inverter for two motor systems

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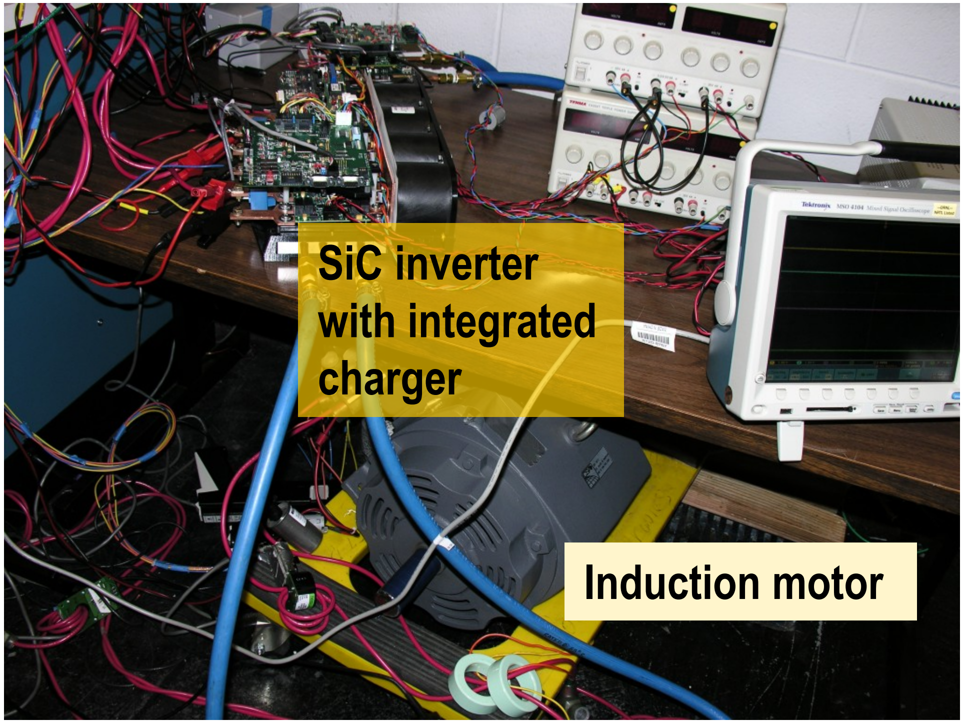
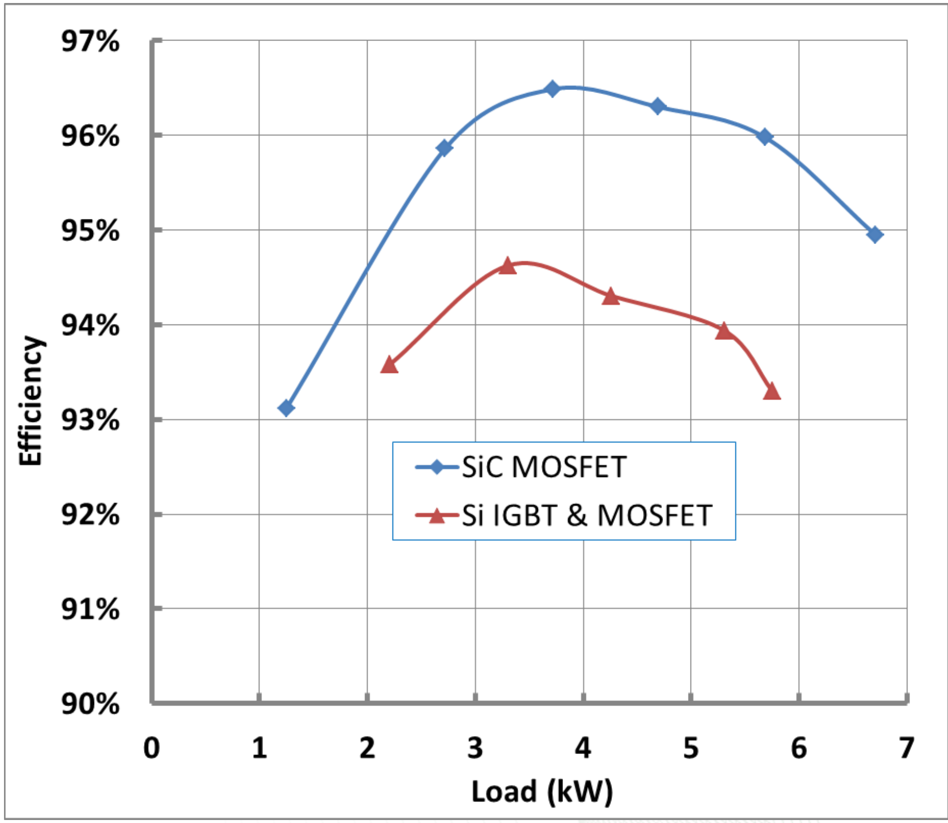
Technical Accomplishments – FY15

- 6.6 kW SiC Charger Efficiency
  - Isolation converter switching at 100kHz
  - Max. efficiency: 96.5 %
  - 2 % point improvement over the Si-based integrated charger built in FY12 over a wide load range



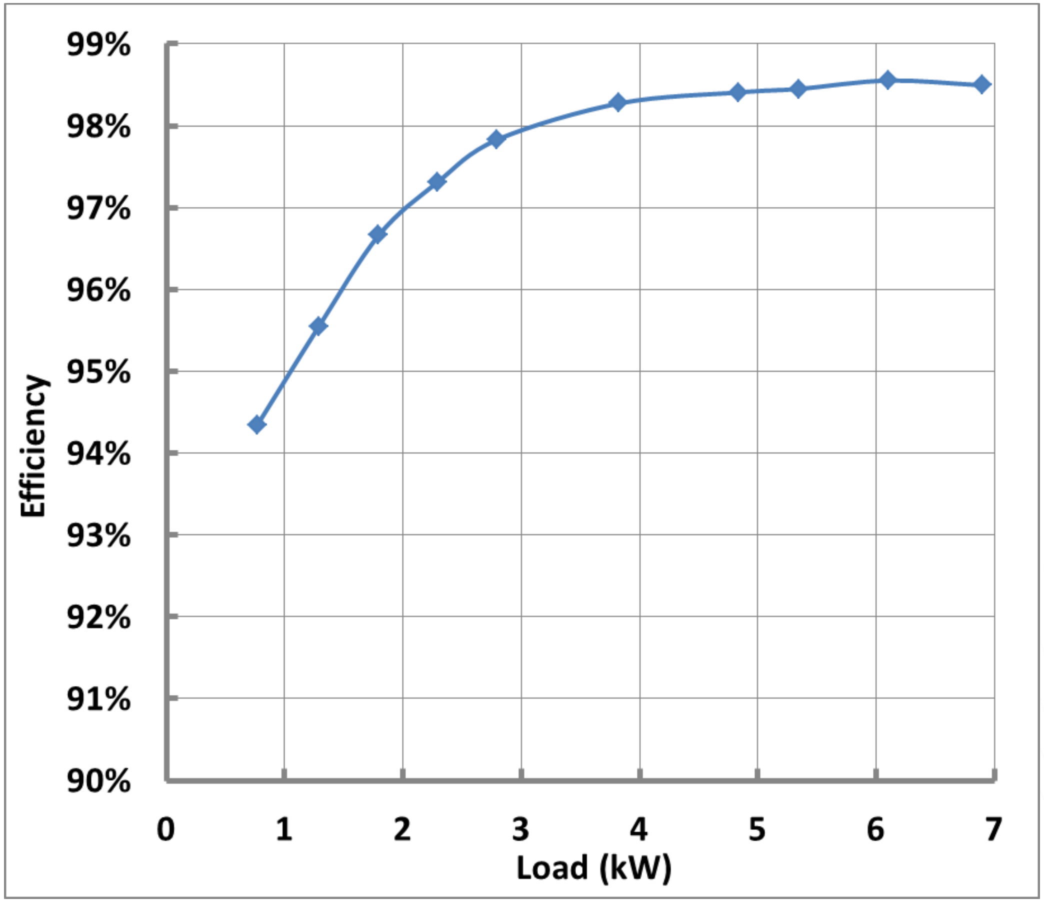
Test setup



Charger efficiency v.s. output power

Technical Accomplishments – FY15

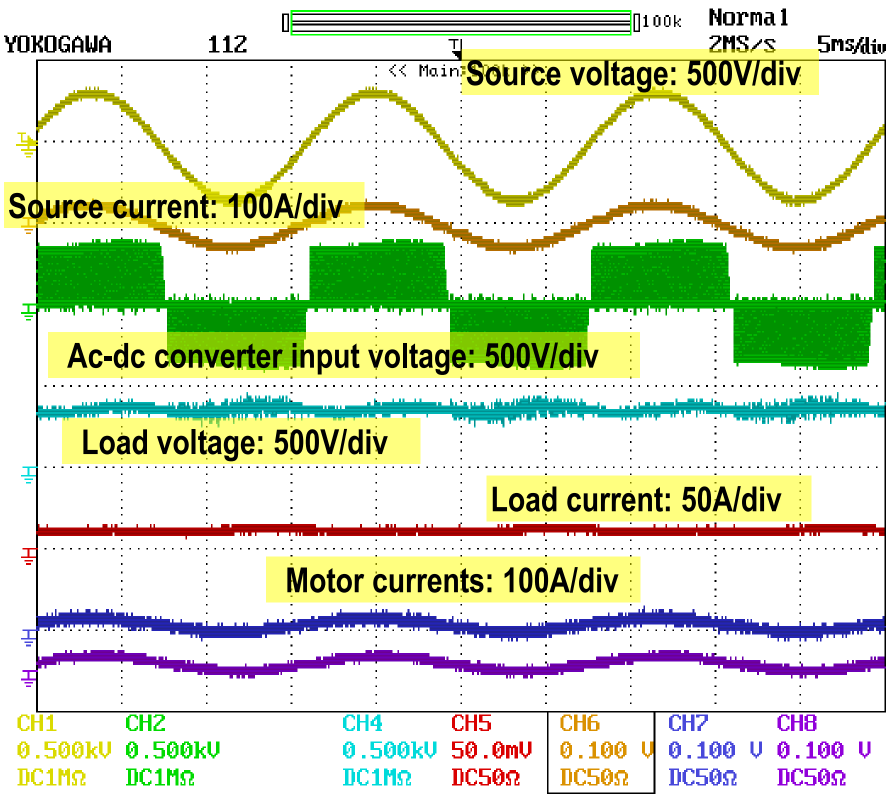
- **6.6 kW SiC Charger AC-DC Front End Converter Efficiency**
  - Interleaved switching at an equivalent frequency of 150 kHz
  - Max. efficiency: 98.5 %



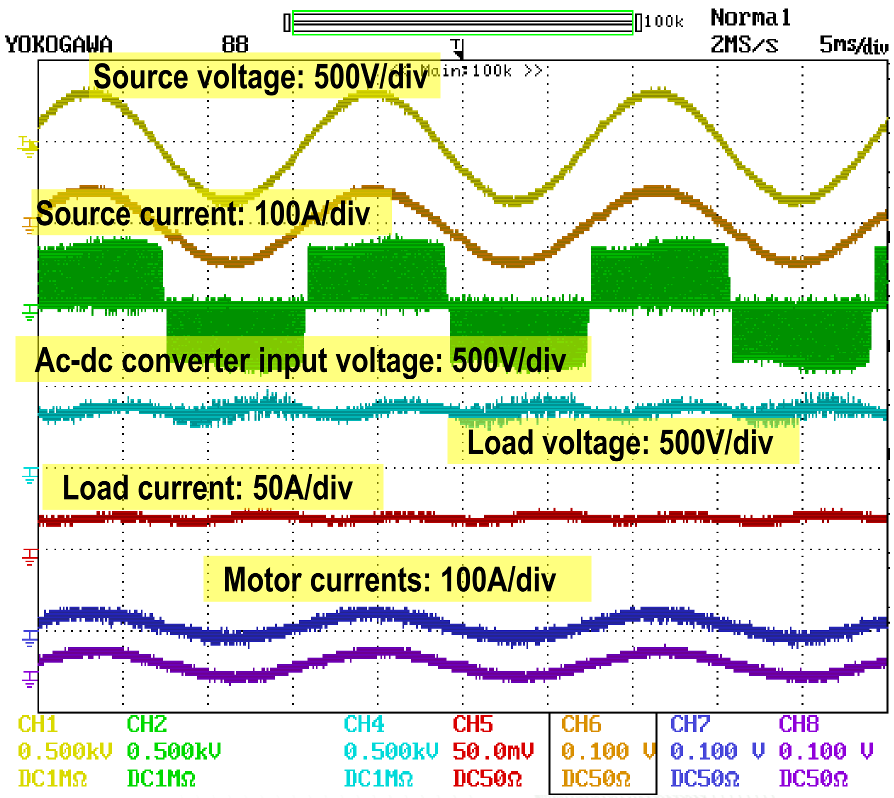
Charger front end converter efficiency v.s. output power

Technical Accomplishments – FY15

- 6.6 kW SiC Charger Test Results
  - Operating waveforms showing charging at 3.7 kW and 6.7 kW
  - High power factor, 99 %



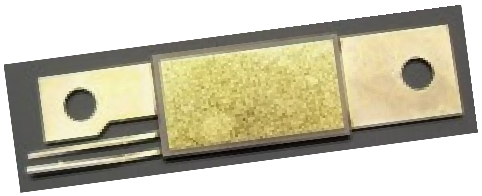
Charging at 3.7 kW



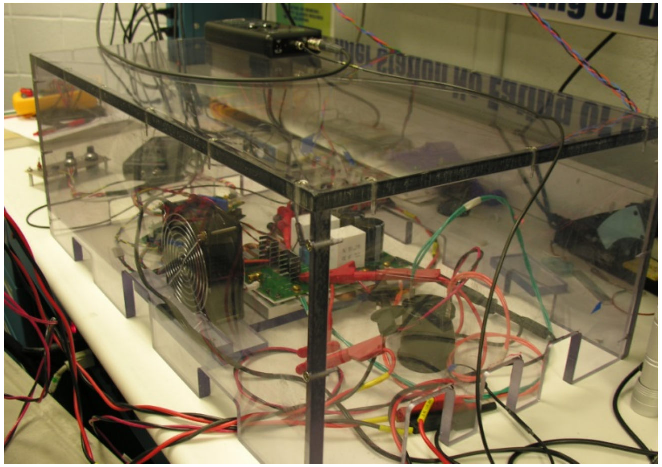
Charging at 6.7 kW

Technical Accomplishments – FY15

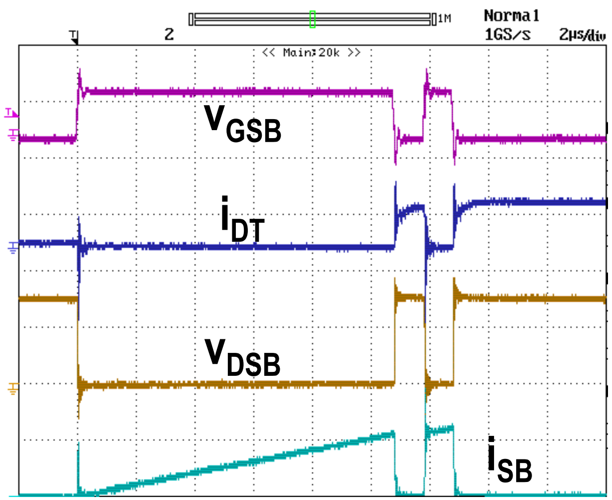
- 3.3 kW GaN isolation converter design
  - Performed switching characterization tests of IR/Delphi 600 V medium size GaN switches
    - Double pulse
    - Half-bridge converter
  - Collected data for GaN converter design



IR/Delphi 600 V medium-size GaN FET
Package Size: 1.7cmx3.1cm

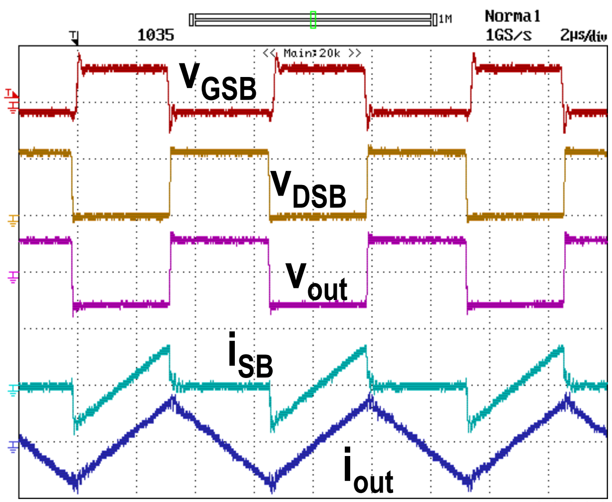


Test setup



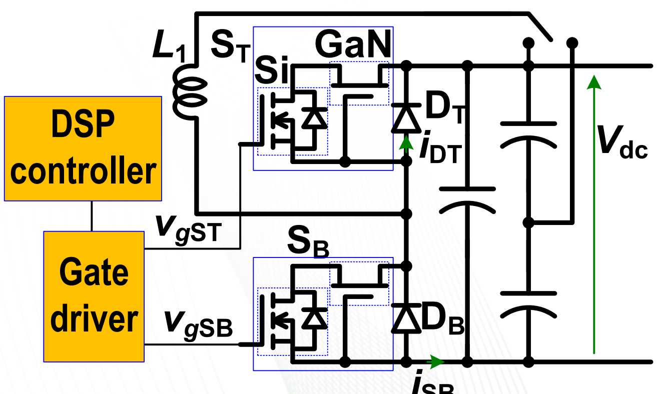
v_{gSB}, 10V/div; i_{DT}, i_{SB}, 50A/div; v_{DSB}, 200V/div; time, 2μs/div

Double pulse test



v_{gSB}, 20V/div; v_{DSB}, v_{out}, 300V/div; i_{SB}, i_{out}, 100A/div; time, 2μs/div

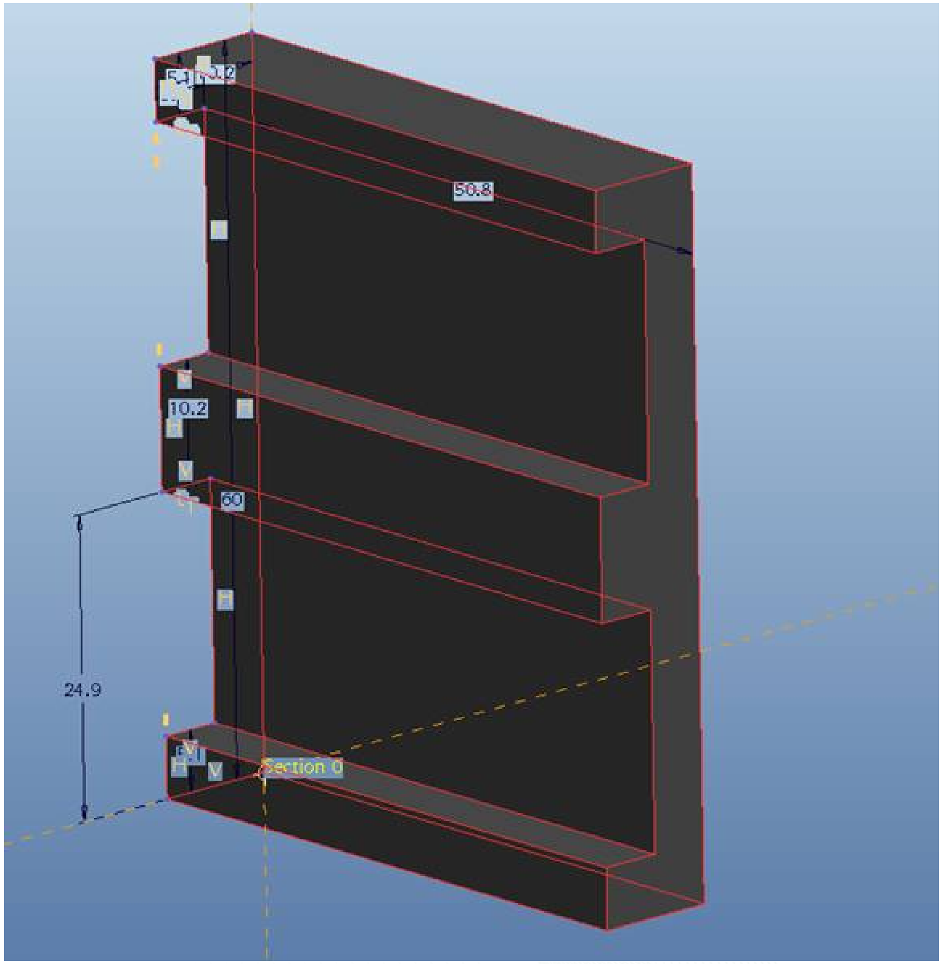
Half-bridge converter test



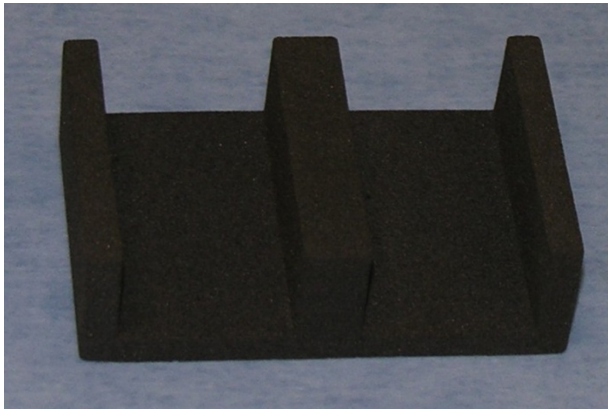
GaN switch test circuit

Technical Accomplishments – FY15

- Working with Aegis Technology, generated a transformer core design using their light-weight, low loss nano-magnetic powder material and printed an E-core at ORNL's manufacturing demonstration facility.
- Characterization tests will be conducted to evaluate its feasibility for use in GaN based charger converter designs.



Core design



Printed E core

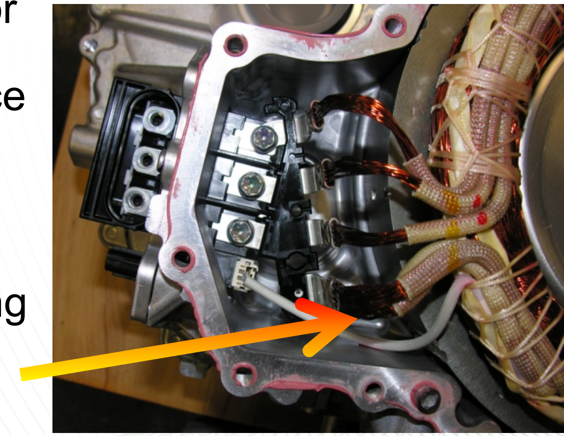
Responses to Previous Year Reviewers' Comments

- <u>One reviewer commented</u>: "The identified designs assumed either a dual motor system or a single-motor boosted system which may not cover all implementations. There are single-motor non-boosted systems that still require a charger."
  <u>Response</u>: The proposed integrated approach can be applied to single-motor non-boosted systems by adding a phase-leg of two switches for bidirectional chargers or a pair of diodes for unidirectional chargers. In addition, if the segmented drive is employed, none of the additional switches or diodes are needed.

- <u>One reviewer asked</u>: "What the impact was to the function in a dual-motor system that uses motors of different sizes, and thus different inductances."
  <u>Response</u>: In general, there is no impact to the function in such systems as long as the combined three-phase motor current ratings of each motor is large enough for the required charging current because the sum of the zero-sequence impedances of the two motors are used as the ac input filter inductor.

- <u>One reviewer asked</u>: "Whether the required DC-inductor value and the machine winding inductance compatible with each other."
  <u>Response</u>: The machine is used as the ac input filter inductor. For machines of very low inductance, an additional inductor may be needed for Si-IGBT based traction drive inverters due to their low switching frequency. This should not be an issue for SiC or GaN based traction drive inverters. In addition, interleaved switching among the three phase legs can be used to further reduce the requirement of machine inductance.

- <u>One reviewer noted</u>: "There was a cost associated with bringing the neutral point of the motor(s) out of an oil-cooled drive unit."
  <u>Response</u>: We agree. However it should be a minor cost by bringing one additional wire over the 3 phase leads. Some motors such as the 2010 Toyota Prius motor have already brought out the neutral.



Partners/Collaborators

- International Rectifier/Infineon — GaN devices and modules, requirements for gate drivers
- Delphi — GaN power modules
- ROHM — SiC power modules and gate drive chips
- Aegis Technology Inc. — light-weight, low loss nano-magnetic materials
- Hitachi/Metglas — input on design and fabrication of high frequency inductors and transformers using FINEMET
- Ferroxcube USA — input on design and fabrication of high frequency inductors and transformers using soft ferrites
- NREL — input on thermal management design

DELPHI
International IOR Rectifier
AEGIS TECHNOLOGY, INC.
ROHM SEMICONDUCTOR
NREL NATIONAL RENEWABLE ENERGY LABORATORY
FERROXCUBE A YAGEO COMPANY
Metglas®
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Remaining Challenges and Barriers

- Further increase charger efficiency and reduce cost
  - There is a trend pushing for higher efficiency
  - Si-substrate based GaN devices have potential to provide lower cost solutions over SiC devices

Proposed Future Work

- **Remainder of FY15**
  - Complete build and test of a 3.3 kW GaN isolation converter
  - Complete a design for 6.6 kW all-GaN isolation converter
- **FY16**
  - Build and test a 6.6 kW all-GaN isolation converter
  - Integrate the 6.6 kW all-GaN isolation converter with a WBG traction drive for an all-WBG OBC and test and characterize the integrated OBC

Summary

- **Relevance:** This project is targeted toward leapfrogging the present Si based charger technology to address charger and converter cost, weight, volume, and efficiency targets.
- **Approach:** The approach being pursued is to overcome the limitations of present semiconductor and magnetic materials with WBG devices and advanced magnetic materials to significantly increase power density, specific power and efficiency at lower cost, and to further reduce cost by using novel integrated topologies and control strategies.
- **Collaborations:** Collaboration with several industry stakeholders are being used to maximize the impact of this work.
- **Technical Accomplishments:**
  - Completed design, build, and test of a 6.8 kW SiC isolation converter using in-house developed SiC switch phase-leg modules rated at 100 A/1200 V.
  - Designed, built, and tested a 6.8 kW SiC-based integrated charger by incorporating the 6.8 kW SiC isolation converter into a segmented SiC traction drive inverter.
  - Conducted tests of IR/Delphi 600 V medium GaN switches and collected data for use in a design for 3.3 kW GaN isolation converter.
- **Future Work:** Build and test 6.6 KW GaN based integrated chargers; topologies developed in this research have been licensed to Arcimoto, Inc.