WBG Converters and Chargers

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Annual Merit Review and Peer Evaluation Meeting

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Project ID: APE054

Overview

Timeline

- Start – FY13
- Finish – FY16
- 38 % complete

Budget

- Total project funding
  - DOE share – 100%
- Funding received in FY13: $750 K
- Funding for FY14: $700 K

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.

Partners

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

Project Objective

- 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 reduced by 50%; weight and volume reduced by a factor of 2; efficiency better than 96%, compared to state-of-the-art)

- FY14 Objective
  - Build and test a 6.6 kW SiC isolation converter
  - Design a 3.3 kW GaN isolation converter

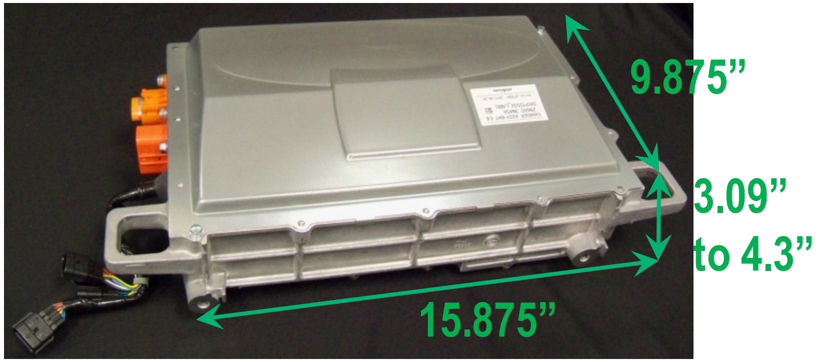
Milestones

Date	Milestones and Go/No-Go Decisions
Jan-2013	Milestone: Completed characterization of a silicon-based integrated charger and converter using an isolation converter architecture.
Sept-2013	Milestone: Completed prototype design for a 6.6 kW SiC isolation converter and validated the design in simulation
Sept-2013	Go/No-Go decision: Prototype design and simulation results indicated the integrated OBC can meet the cost, efficiency, weight, and volume goals
Sept-2014	Milestone: Build and test of a 6.6 kW SiC isolation converter prototype – on track
Sept-2014	Milestone: Functional prototype design for a 3.3 kW GaN isolation converter validated in simulation – on track
Sept-2014	Go/No-Go decision: Determine if prototype design can meet the cost and efficiency goals

State-of-the-Art OBC is Expensive, Bulky, and Inefficient

State of the 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 (85-92%)
  - Limited functionality; incapable of V2G support

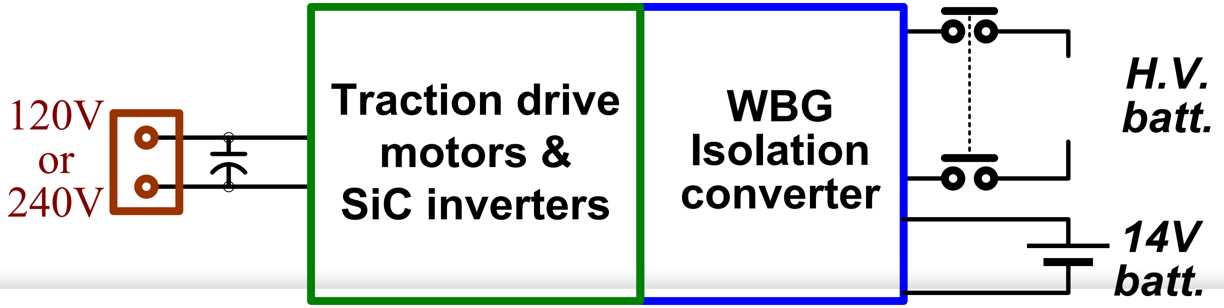


2012 Nissan LEAF 6.6 kW OBC: 0.41 kW/kg, 0.66 kW/L

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

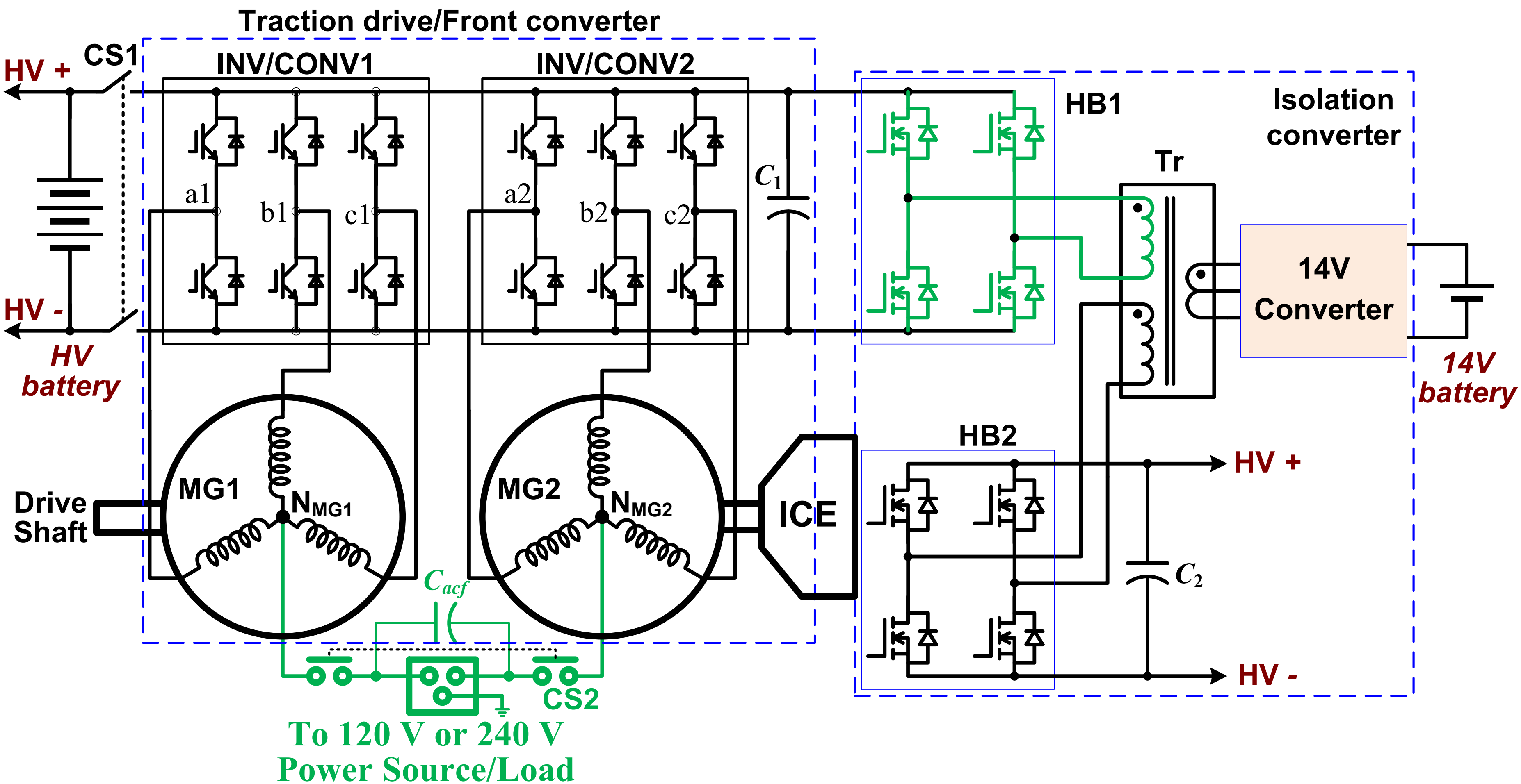
Approach - Integrated OBC using WBG devices significantly reduces cost, weight, and volume

- 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 sacrificing efficiency
  - All WBG converter (SiC and GaN)
  - Advanced soft magnetic materials (Nano-composite)



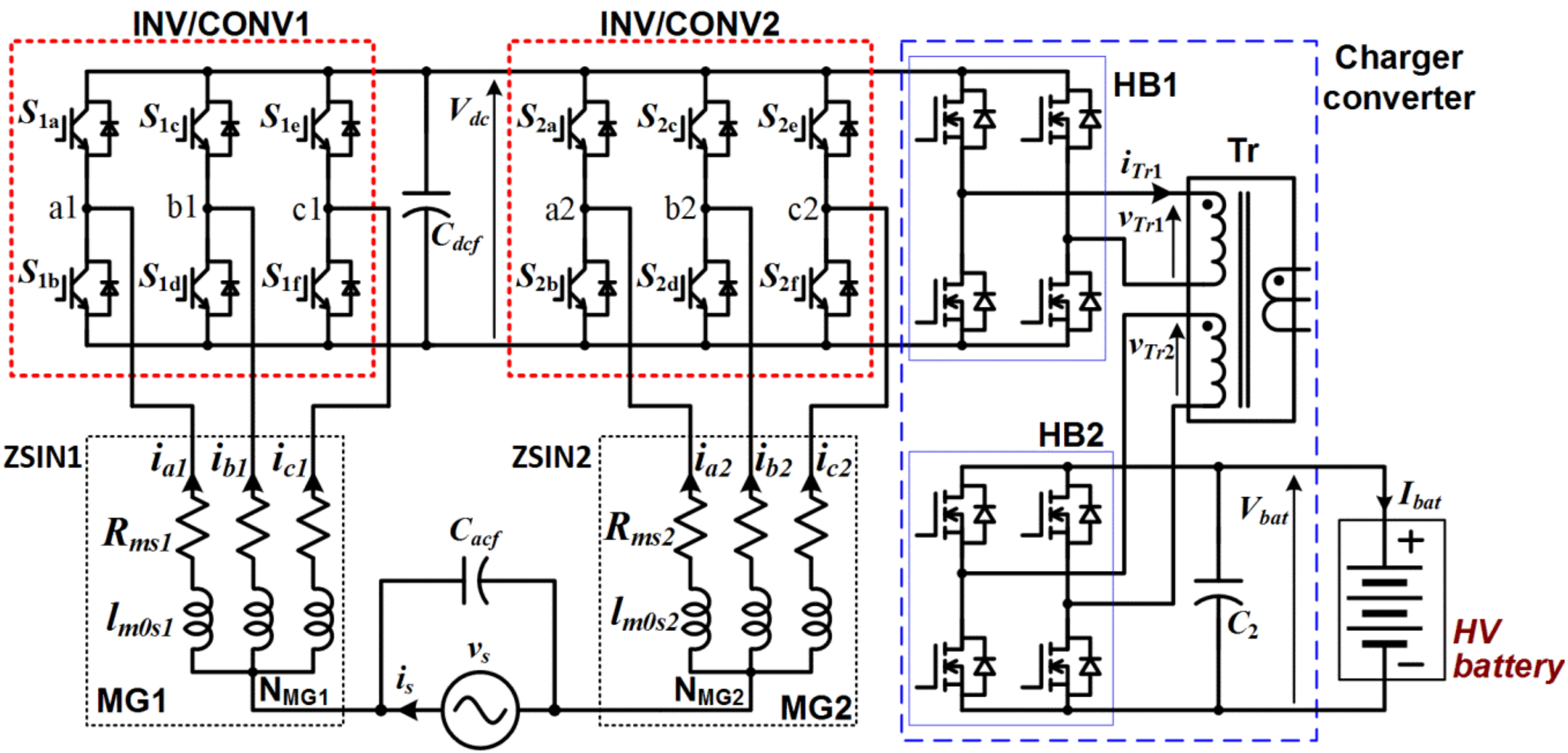
Conceptual diagram of an integrated onboard charger

Approach - Integrated OBC (1)



- Using the three phase inverters as the OBC front converter with the motor zero sequence impedance network (ZSIN) as ac filter inductor
- Sharing the converter (HB2) and transformer with the 14V battery charger

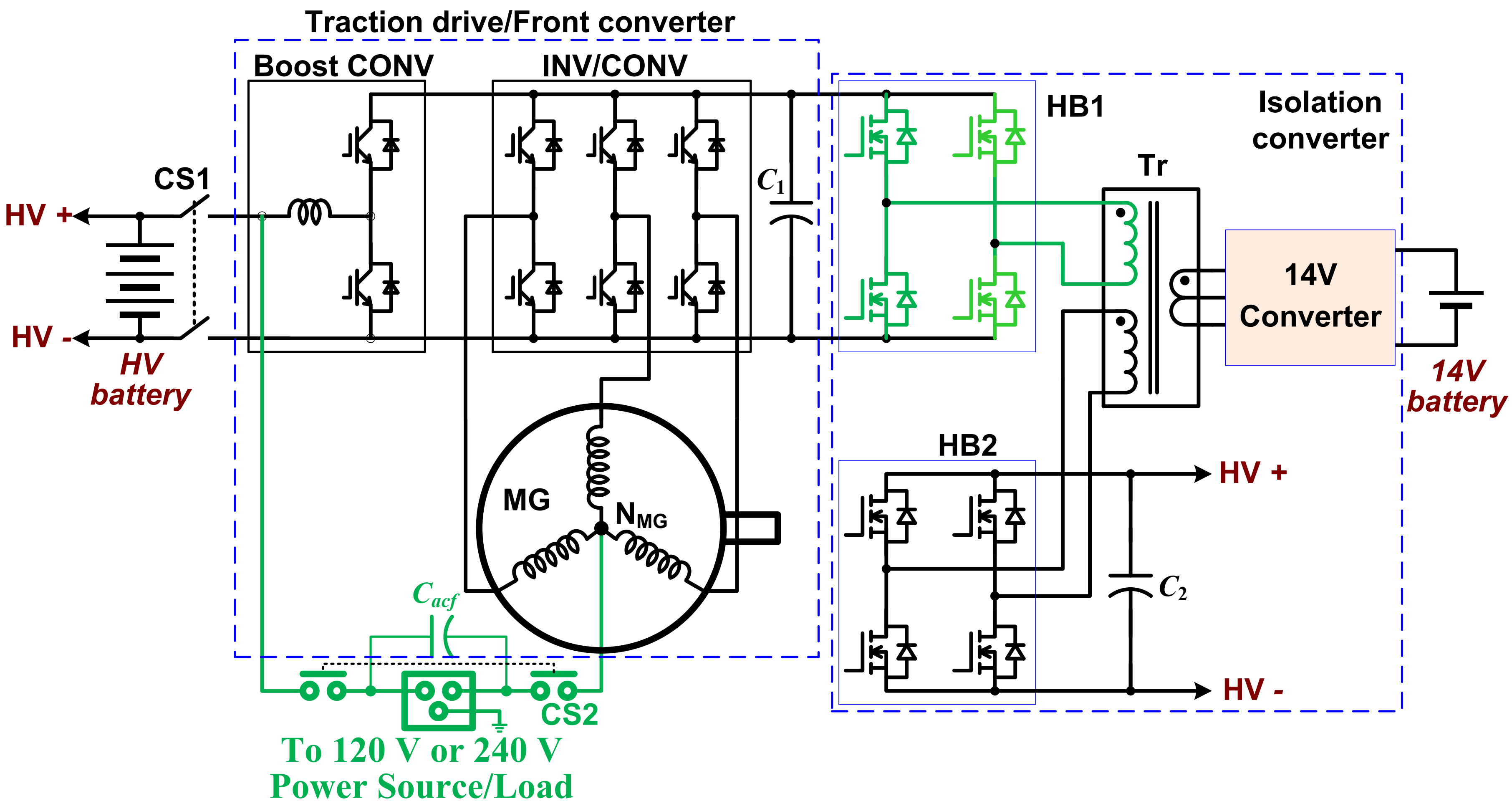
Approach - Integrated OBC (1)
- Equivalent Circuit for Charging the HV Battery



- Three phase inverters as a single phase converter with interleaved switching
- Motor zero sequence impedance network (ZSIN) as ac filter inductor

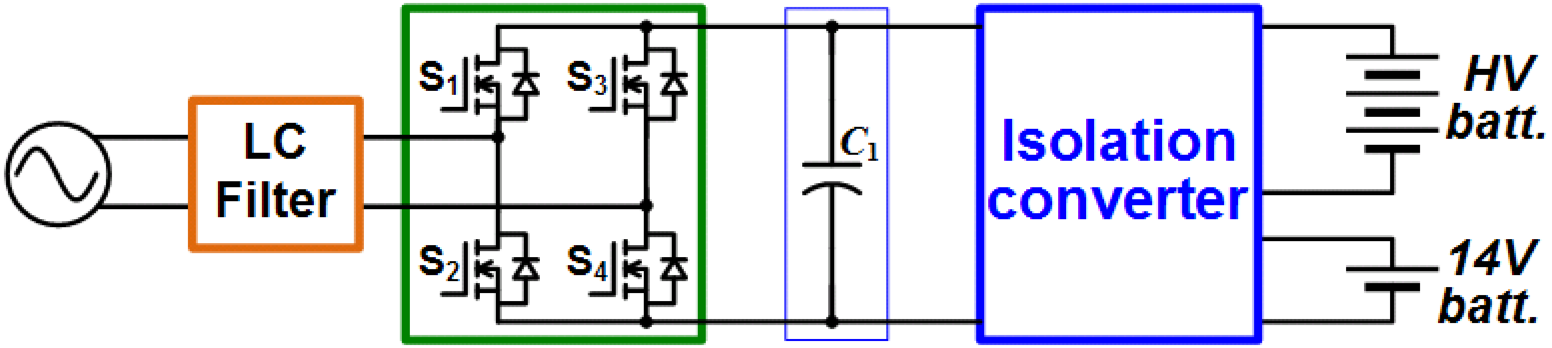
Approach - Integrated OBC (2)

- Integrated OBC for traction drive systems with a boost converter



Approach - Integrated OBC (3)

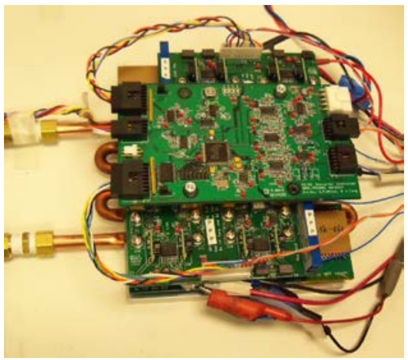
- Other configurations
  - Integration with the segmented inverter traction drive
  - Integration with multiphase boost converter
- The isolation converter can also be applied to standalone OBCs



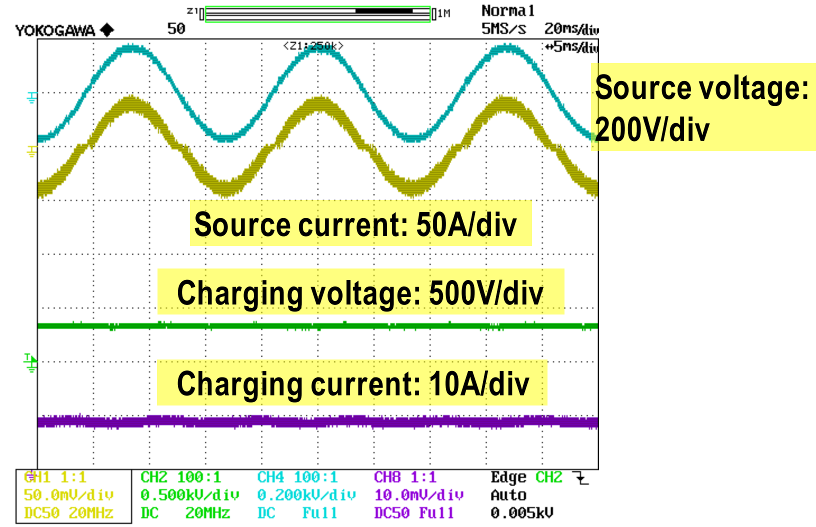
Approach is flexible and applicable to various traction drive system architectures

Technical Accomplishments and Progress

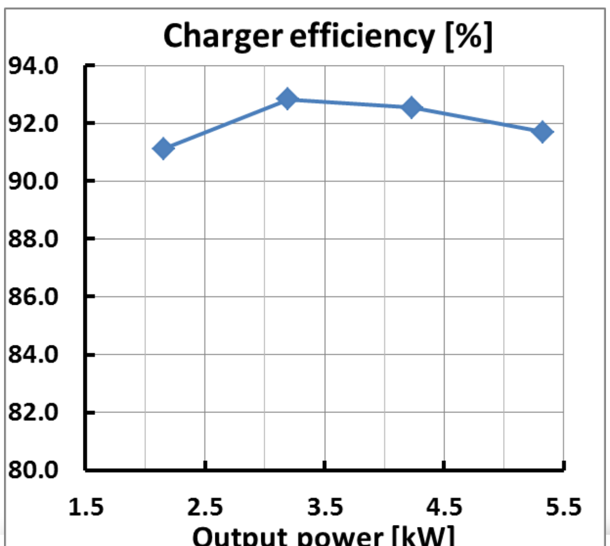
- **Tested a 5kW Si-based integrated dc-dc converter & charger using an isolation converter candidate**
  - Demonstrated the architecture



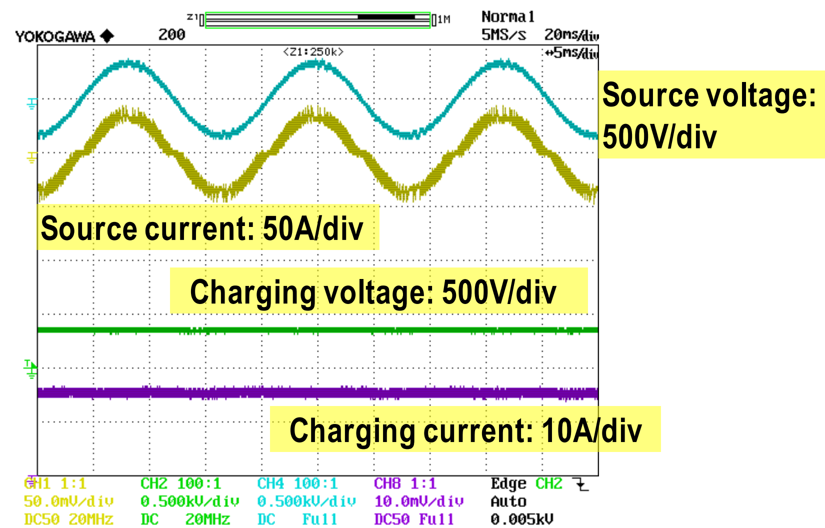
5 kW Si-based isolation converter (6”x7”x3.5”)



Charging at 3 kW from a 120V source



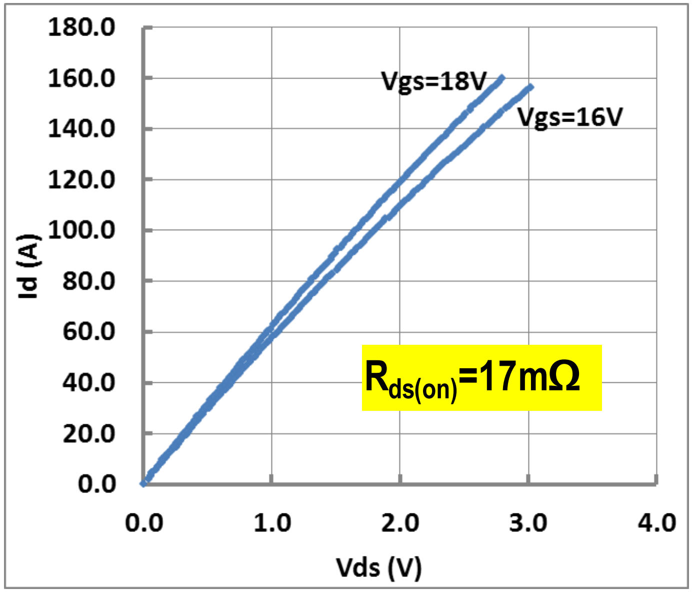
Measured efficiency of the Si-based 5kW charger



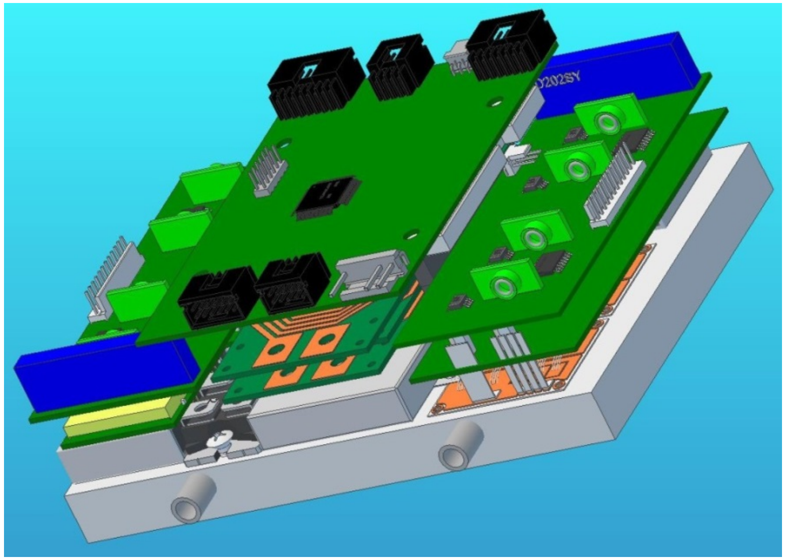
Charging at 5 kW from a 240V source

Technical Accomplishments and Progress

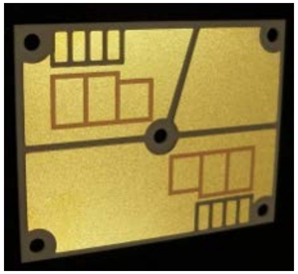
- Designed 6.6 kW SiC isolation converter that will be used for building a 6.6 kW SiC-Based Integrated OBC
  - Built-in 14V converter of 2 kW
  - ORNL designed DBC and SiC switch phase-leg module using Cree SiC MOSFETs
  - Planar transformer
  - Heavy copper PCBs
  - Max. efficiency >98%



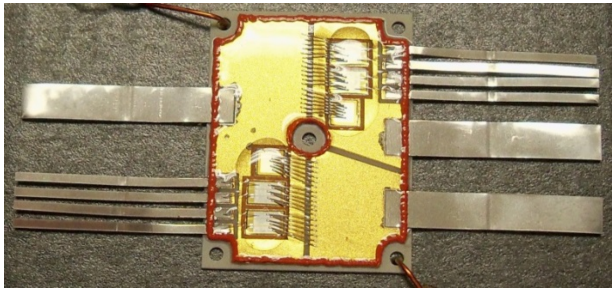
SiC MOSFET phase-leg modules static characteristics



6.6 kW SiC isolation converter design (7”x5”x2.7”, 1.55 L)



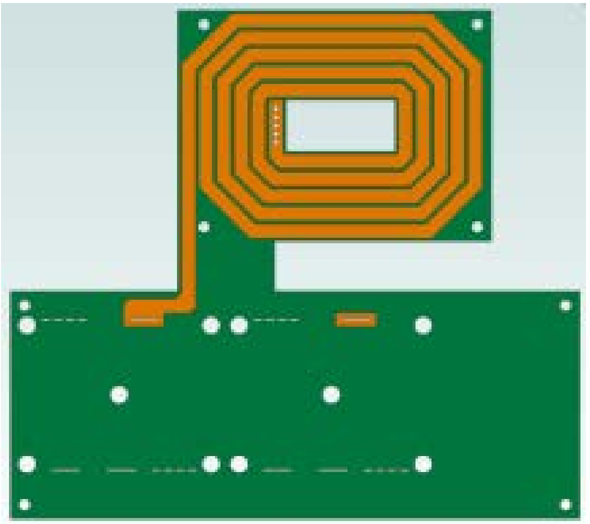
DBC design for SiC MOSFET phase-leg modules (36x46mm)



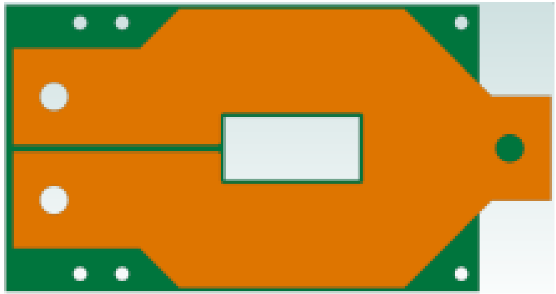
SiC MOSFET phase-leg modules (36x46mm): 1200V/100A

Technical Accomplishments and Progress

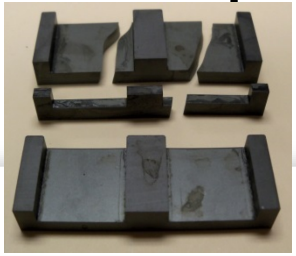
- Completed primary PCB winding design and 14V PCB winding design for a 6.6 kW SiC isolation converter that will be used to build a 6.6. kW SiC on-board-charger
  - Heavy copper PCBs transformer windings
  - Two primary PCBs for high voltage windings
  - Double side copper traces in parallel in 14V PCB winding for high current
- Off-the-shelf ferrite planar cores were resized for use in the 6.6 kW SiC isolation converter prototype
- Working with Aegis Technology, generated a transformer core design using their light-weight, low loss nano-magnetic material; sample cores will be produced at the end of their SBIR project



Primary PCB winding design for 6.6 kW SiC isolation converter



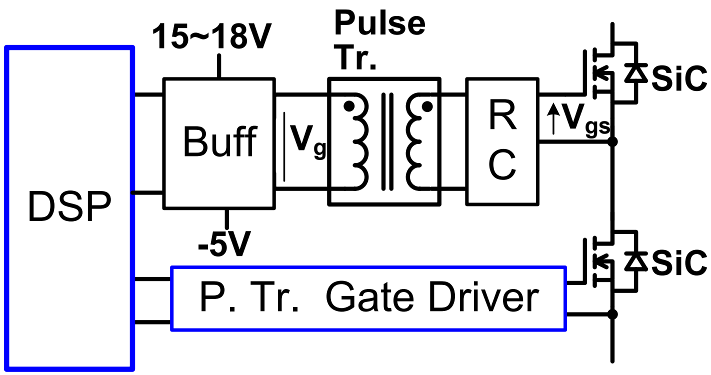
14V PCB winding design for 6.6 kW SiC isolation converter



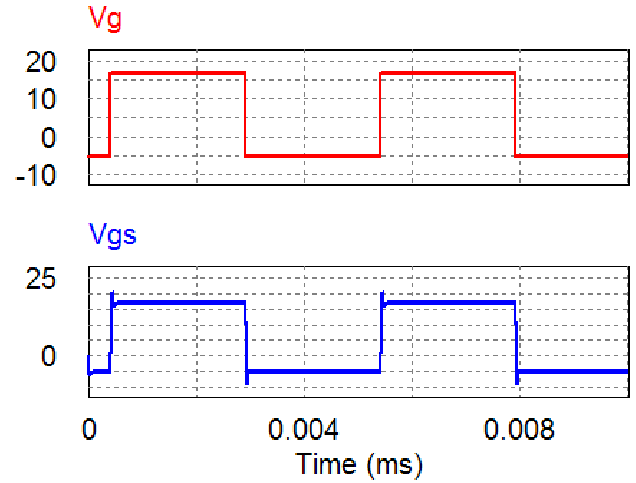
Core pieces cut with a diamond saw (width: 64mm, height: 10mm)

Technical Accomplishments and Progress

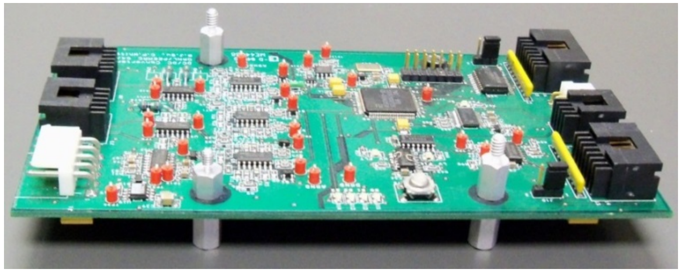
- Developed a SiC MOSFET gate driver circuit that uses a pulse transformer to substantially simplify the gate drive circuit
  - Sharing gate drive power supplies
  - Pulse transformers can be built onto the main PCB boards
- Circuit simulation results confirmed the pulse transformer based gate drive circuit can generate adequate gate voltage and current to the SiC MOSFET and produce satisfactory switching behaviors
- Completed a DSP control board design



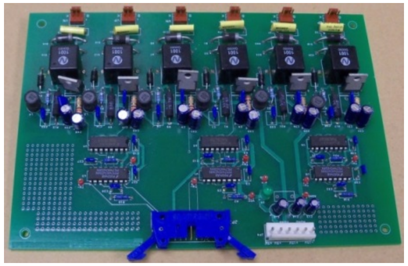
SiC MOSFET gate driver circuit using a pulse transformer



Simulation results



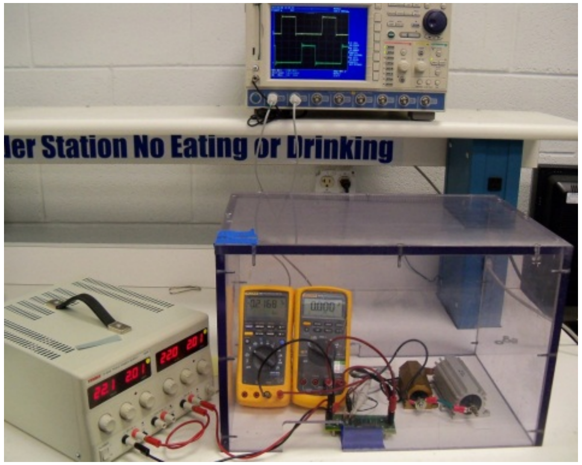
DSP control board



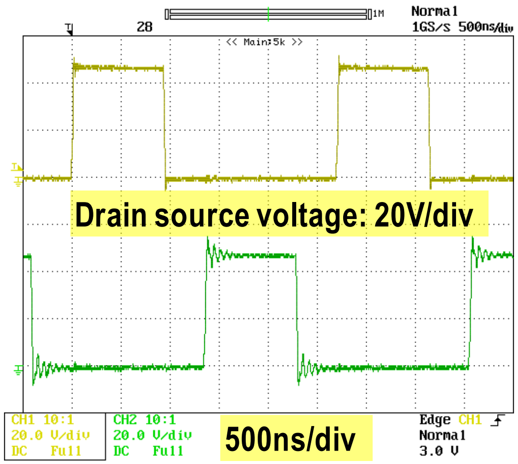
Pulse transformer based gate driver board

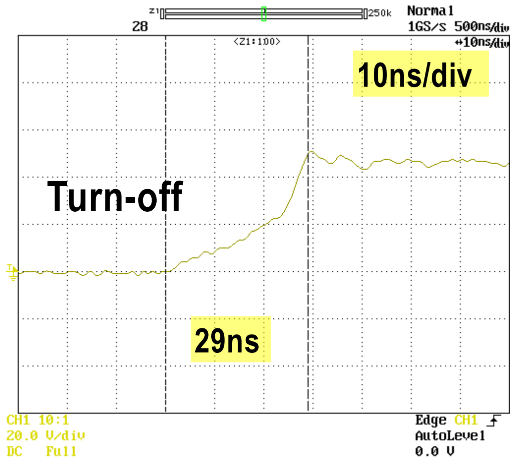
Technical Accomplishments and Progress

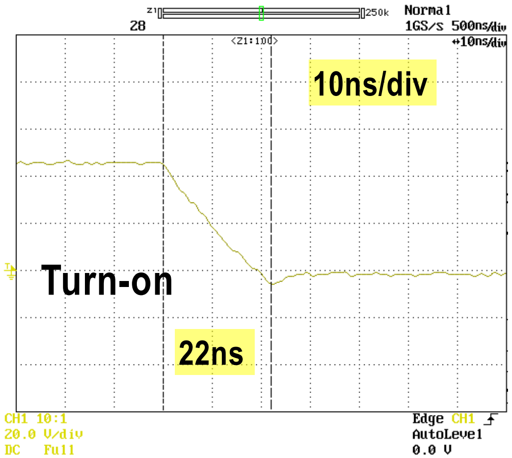
- Performed characterization tests on GaN switches
  - Tested EPC eGaN switches (<200V) for use in the 14V dc-dc converter
  - Tested IR/Delphi GaN small and medium size switches (600V) for use in the OBC converters



EPC eGaN test setup



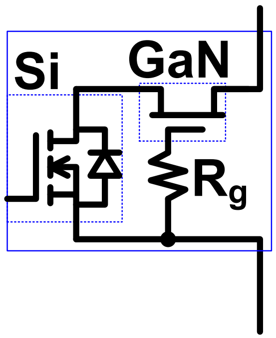




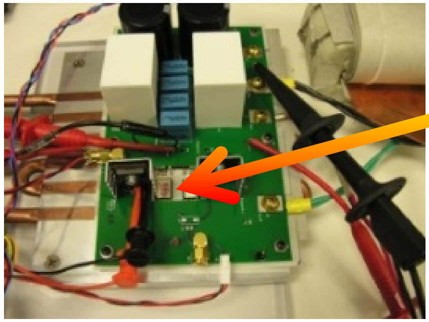
EPC eGaN switching waveforms

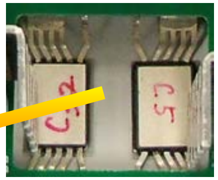
Technical Accomplishments and Progress

- Tested and characterized IR/Delphi 600V small-size GaN switches
  - Double pulse
  - Half-bridge converter

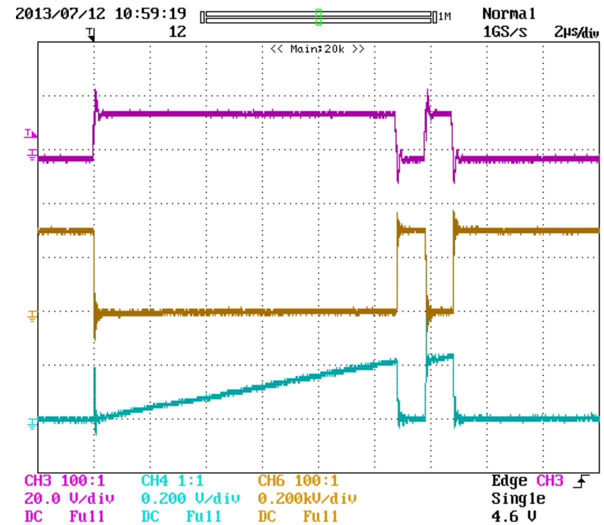


IR GaN switch

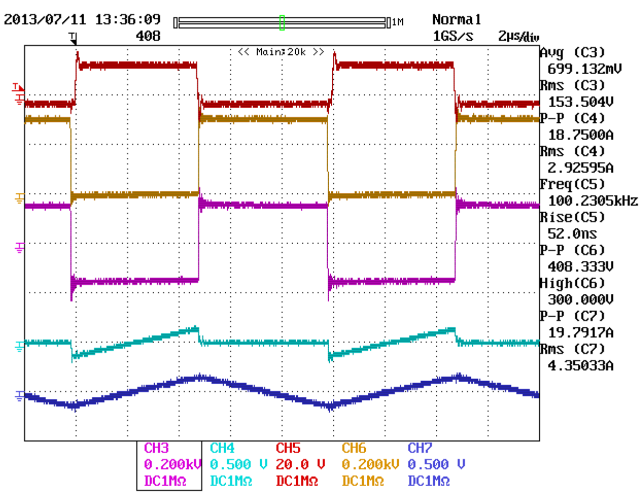




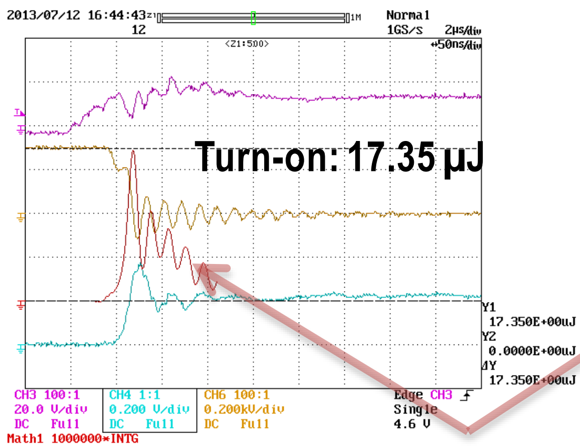
IR 600V GaN switch & test board

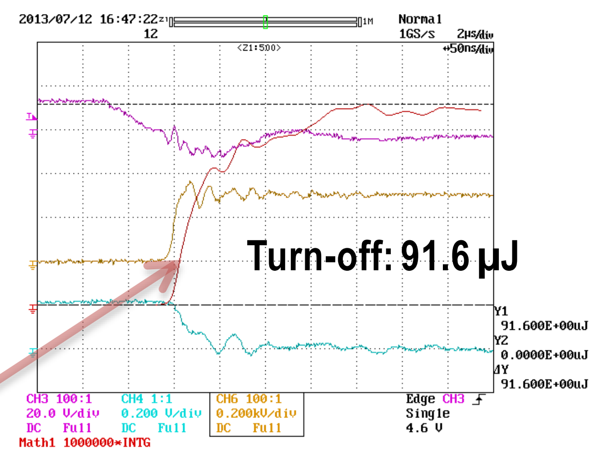


CH3: v_{GSB}, 10V/div; CH4: i_{SB}, 10A/div; CH6: v_{DSB}, 200V/div; 2us/div



CH3: v_{out}, 200V/div; CH4: i_{SB}, 25A/div; CH5: v_{GSB}, 20V/div; CH6: v_{DSB}, 200V/div; CH7: i_{out}, 25A/div; 2us/div

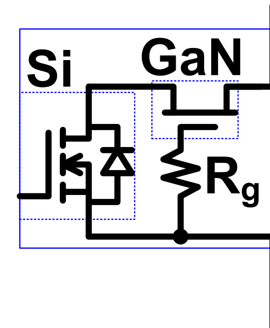


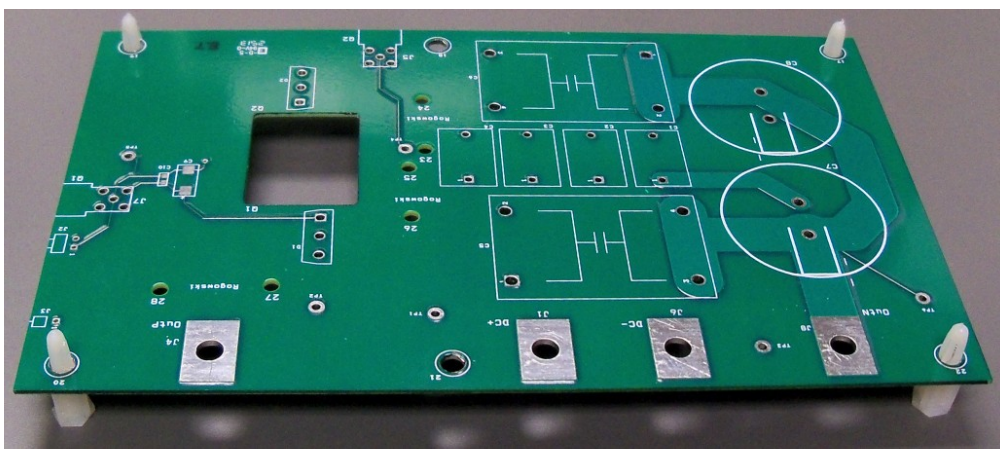


Math1: 1000*(v_{ds}*i_s), uJ

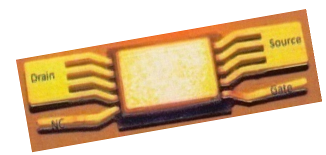
Technical Accomplishments and Progress

- Completed a test board design for new IR 600 V medium-size GaN switches packaged by Delphi
  - The design is reconfigurable for conducting various tests of double pulse and half bridge dc-dc converter
  - Heavy copper PCBs
  - Switches have different embedded gate resistance values
  - Will choose an optimal gate resistance value for 6.6 kW OBC design

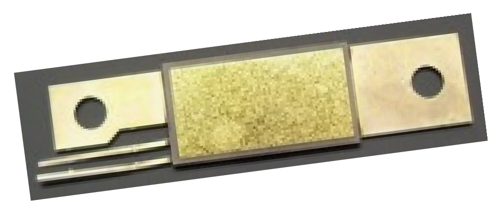




New test board design



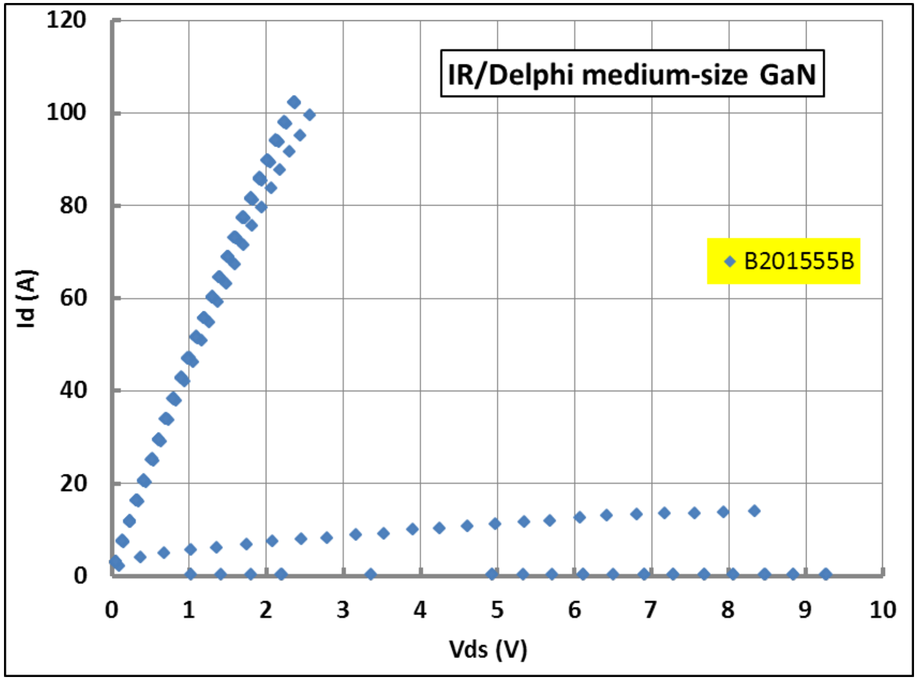
IR/Delphi 600 V small-size GaN switch (10x12mm)



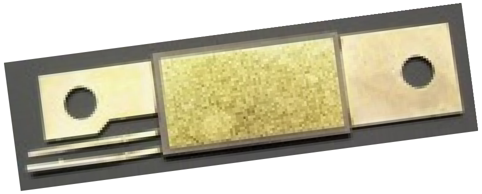
New IR/Delphi 600 V medium-size GaN switch(17x31mm)

Technical Accomplishments and Progress

- Performed static characterization tests of IR/Delphi 600 V medium-size GaN switches
- 35% lower specific on resistance than the best Si MOSFET (CoolMOS)



Typical I-V curve for IR/Delphi 600 V medium-size GaN switch



IR/Delphi 600 V medium-size GaN FET
Package Size: 1.7cmx3.1cm
R_{dson}=17mΩ
Specific on resistance: 89.6mΩcm^2

Infineon CoolMOS IPW60R041C6*

Package Size: 2.1cmx1.6cm
R_{dson}=41mΩ
Specific on resistance: 137.8mΩcm^2

*http://www.infineon.com/cms/en/product/mosfets/power-mosfets/n-channel-mosfets-coolmos-tm-500v-900v/IPW60R041C6/productType.html?productType=db3a304426e7f13b0127f2050dcb45ac

Responses to Previous Year Reviewers' Comments

Overall, the reviewers' comments were very positive.

- One reviewer commented: "Bidirectional charger capability is also good, but roaming grid inverters face grid integration standard and regulatory changes which are being address by the Smart Grid Interoperability Panel (SGIP) Distributed Renewables, Generation & Storage (DRGS) and the Vehicle to Grid (V2G) Domain Expert Working Groups (DEWGS). The reviewer noted that ORNL and NREL are becoming members of SGIP so it might be appropriate for this project to monitor these efforts or to coordinate through National Institute of Standards and Technology (NIST)."

  Response/Action: We agree and will monitor developments in standards and regulations.

- One reviewer commented: "A cost rational of how this lowers cost was needed."

  Response/Action: Passive components contribute more than 30% of the cost of on-board chargers (OBC). Their size and cost can be significantly reduced by using wide bandgap (WBG) semiconductors and advanced soft magnetic materials to operate chargers at higher frequencies (~300kHz) and with lower losses. In addition, this project is developing integrated charger converter topologies that eliminate an additional converter entirely. As the cost of WBG devices (in particular, GaN on Si substrates) drops as technology matures, we believe our approach will lead to low cost, high efficiency, high power density all WBG dc-dc converters and on-board chargers.

Partners/Collaborators

- International Rectifier — GaN devices (engineering samples) and modules, requirements for gate drivers
- Delphi — Packaged GaN power modules
- 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

Proposed Future Work

- **Remainder of FY14**
  - Complete fabrication and test of a 6.6 kW SiC isolation converter prototype
  - Complete characterization tests of GaN switches
  - Design a 3.3 kW GaN isolation converter

- **FY15**
  - Assemble and test a 6.6 kW OBC using the 6.6 kW SiC isolation converter built in FY14 and a SiC traction drive inverter
  - Build and test a 3.3 kW GaN isolation converter
  - Introduce GaN into the 14V dc-dc stage and design a 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:**
  - Identified one isolation converter candidate and completed test of a 5kW Si-based integrated dc-dc & charger using the candidate.
  - Completed a 6.6 kW SiC isolation converter design using the in-house developed SiC switch phase-leg modules rated at 100A/1200V.
  - Completed fabrication of several parts for a 6.6kW SiC isolation converter prototype
  - Conducted tests of EPC eGaN switches for possible use in the 14V dc-dc converter and IR/Delphi 600 V GaN switches for charger converter designs.
- **Future Work:** Build and test 6.6 KW WBG integrated chargers; charger technical targets are being developed by DOE in collaboration with industry.