WBG Converters and Chargers

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Overview

Timeline

- Start – FY13
- Finish – FY15
- 22 % complete

Budget

- Total project funding
  - DOE share – 100%
- Funding for FY13: $750 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

- **ORNL team member:** Lixin Tang, Zhenxian Liang, Puqi Ning, Cliff White
- International Rectifier
- Delphi
- Hitachi/Metglas®
- Univ. of Tennessee
- NREL

Project Objective

- **Overall Objective**
  - Develop low cost, high efficiency, high power density all wide band gap (WBG) dc-dc converter and on-board charger (OBC) (cost reduced by 50%; weight and volume reduced by a factor of 2; efficiency better than 96%, compared to state-of-the-art)

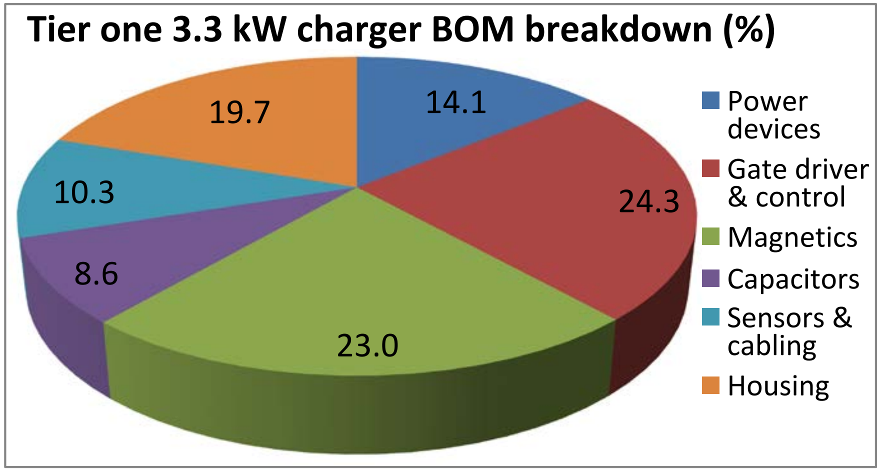
- **FY13 Objective**
  - Research architecture candidates for dc-dc converter and charger best suited for functional integration and target power throughput levels of 2.2 kW for the 14V dc-dc converter and 6.6 kW for OBC. Efficiency of both functions should be greater than 95% at 75% of rated power.

Milestones

Date	**Milestones and Go/No-Go Decisions**	**Status**
Jan-2013	Milestone: Characterization of a silicon-based integrated charger and converter using an isolation converter architecture.	**Completed**
Sept-2013	Milestone: Functional prototype design for a 6.6 kW WBG isolation converter validated in simulation	**On track**
Sept-2013	Go/No-Go decision: Prototype design must meet cost, efficiency, weight, and volume APEEM guidelines	

State-of-the-Art

- SOA onboard chargers (OBCs)
  - Expensive ($273 for a tier one 3.3kW charger)
  - Low power density (2012 Nissan LEAF® 6.6 kW OBC: 0.41kW/kg, 0.66kW/L)
  - Relatively low efficiency (85-92%)
  - Limited functionality; incapable of V2G support
- 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



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

Approach/Strategy

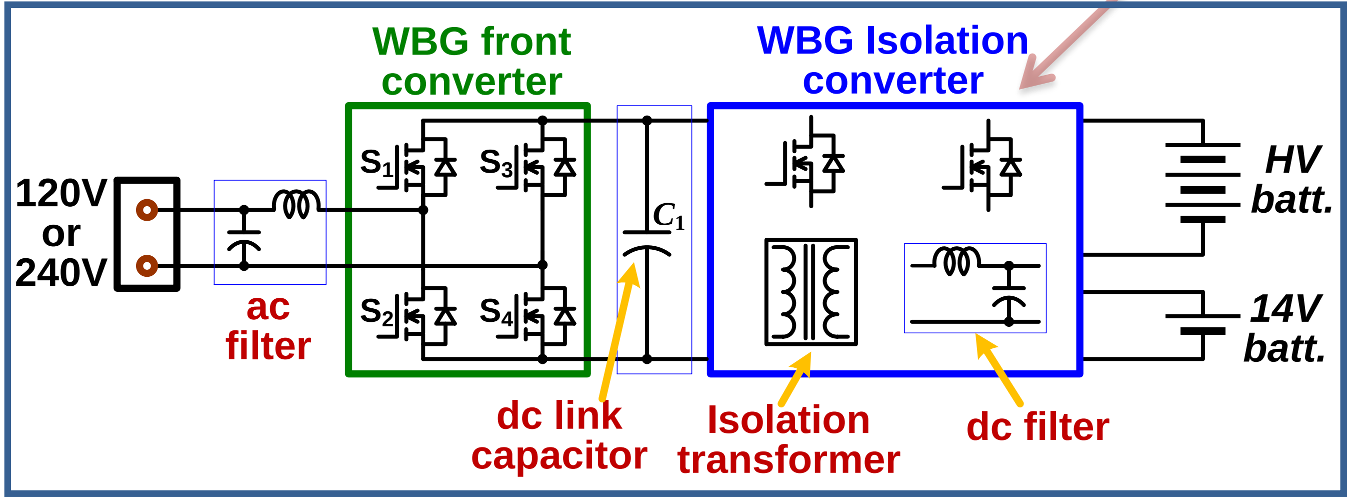
- Technical Approach
  - Develop bidirectional WBG onboard chargers that
    - Provide galvanic isolation
    - Provide high voltage (HV) to 14V battery dc-dc conversion
    - Use soft switching in dc-dc stage for electromagnetic interference (EMI) reduction and efficiency improvement
  - Aggressively pursue power density and specific power without sacrificing efficiency
    - All WBG converter (GaN)
    - Advanced soft magnetic materials (Nano-composite)

- Strategy
  - Drive functional integration of the traction drive, 14V dc-dc converter and OBC.
  - Employ WBG, specifically GaN based power devices to reduce cost, weight and volume of passive components, and improve efficiency.
  - Develop inductor and transformer designs using advanced soft magnetic materials.

Approach/Strategy

- Integrated dc-dc and charger architecture
  - Active front end converter for
    - Bidirectional power flow control
    - Power factor correction
  - Soft-switching, isolated multiport dc-dc converter for
    - Control of power flow between the dc link, high voltage and 14 V batteries
    - Reduction of electromagnetic interference (EMI) and switching loss

Multiple candidates under simulation study in FY13

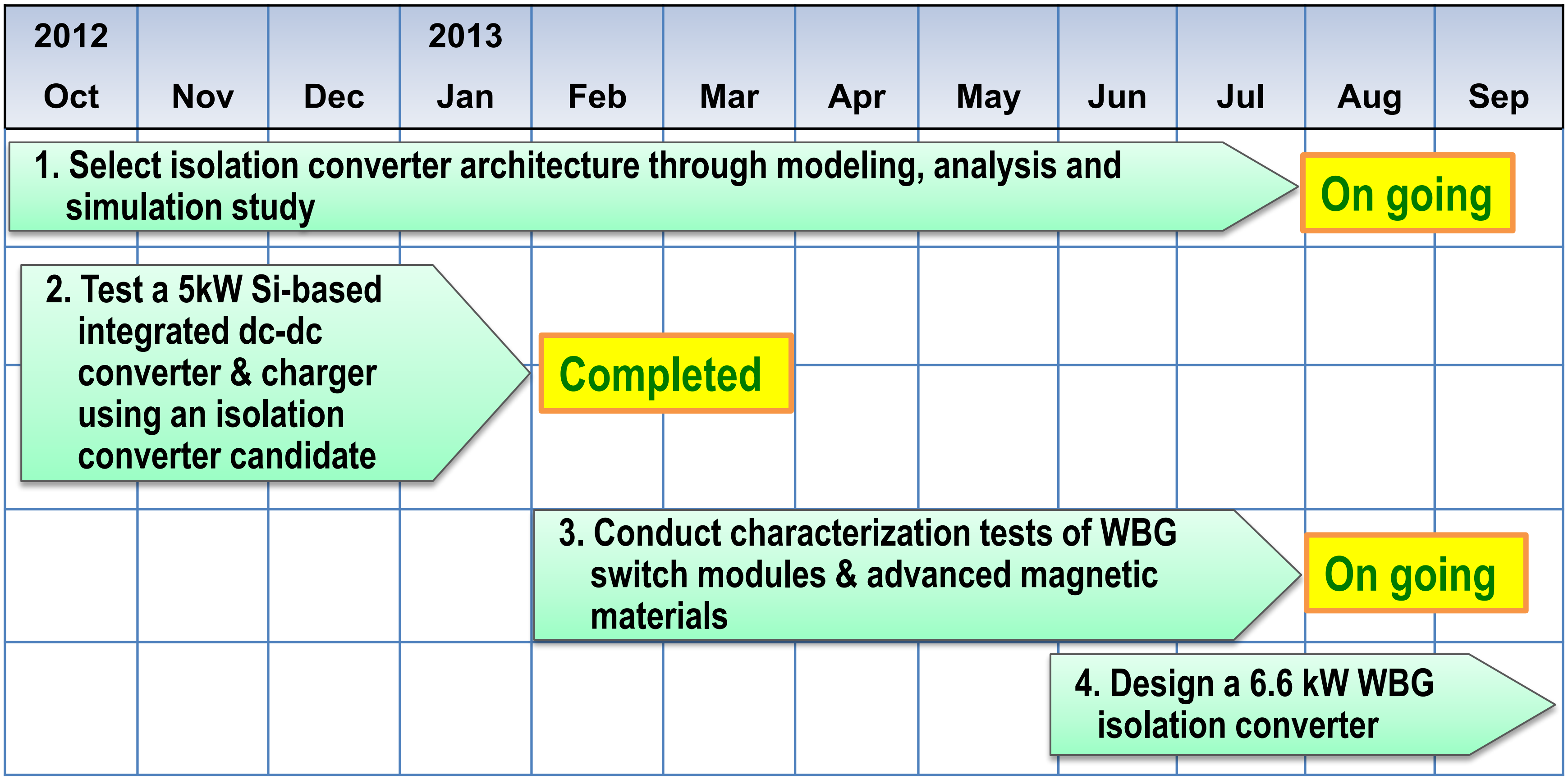


Integrated dc-dc converter and charger architecture

- *Exploit high switching frequency with WBG devices to drastically reduce the cost, weight and volume of ac filter, isolation transformer and dc filters*
- *Develop a control strategy for the isolation converter to reduce the bulky dc link capacitor, needed to filter out the large voltage ripple of twice the fundamental frequency*

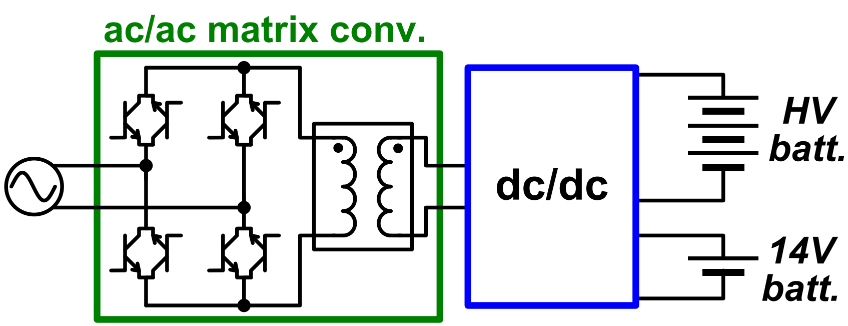
Technical Accomplishments and Progress

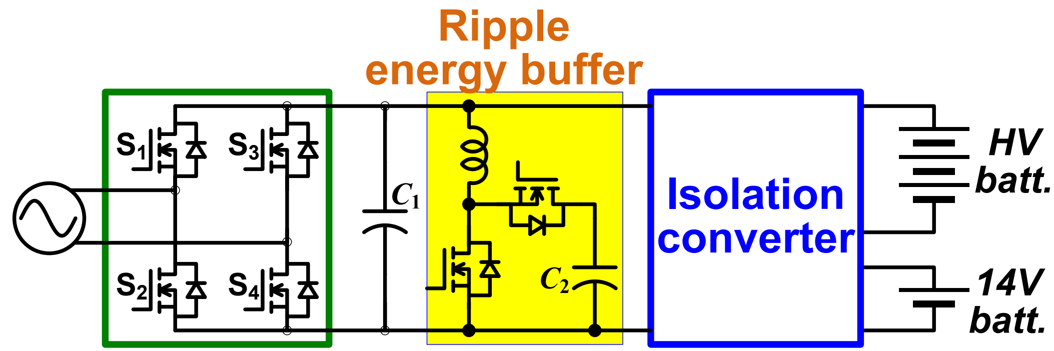
- FY13 Tasks and Status



Technical Accomplishments and Progress

- **Performed isolation converter architecture selection through modeling, analysis and simulation study**
  - Need to reduce battery ripple current caused by the low frequency (twice the fundamental) voltage ripple in single phase ac-dc converters without using a bulky dc link capacitor.





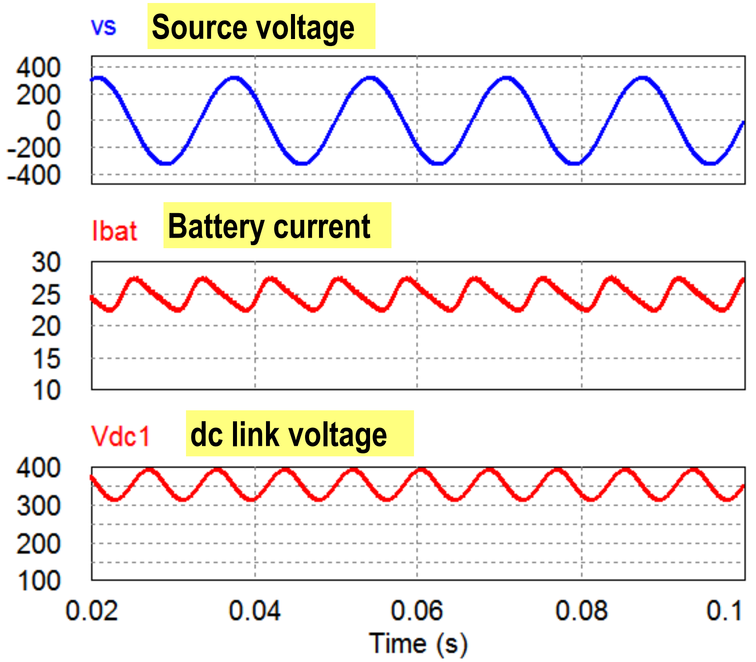
- **Simulated the ac/ac matrix converter to eliminate the dc bus capacitor**
  - **Require reverse blocking switches; not available**
  - **Series connection of switch & diode; high conduction loss**

- **Simulated the use of a ripple energy buffer to eliminate the ripple voltage**
  - **Shifting cost of the bulky dc bus capacitor to the additional switches and passive components; higher system cost**

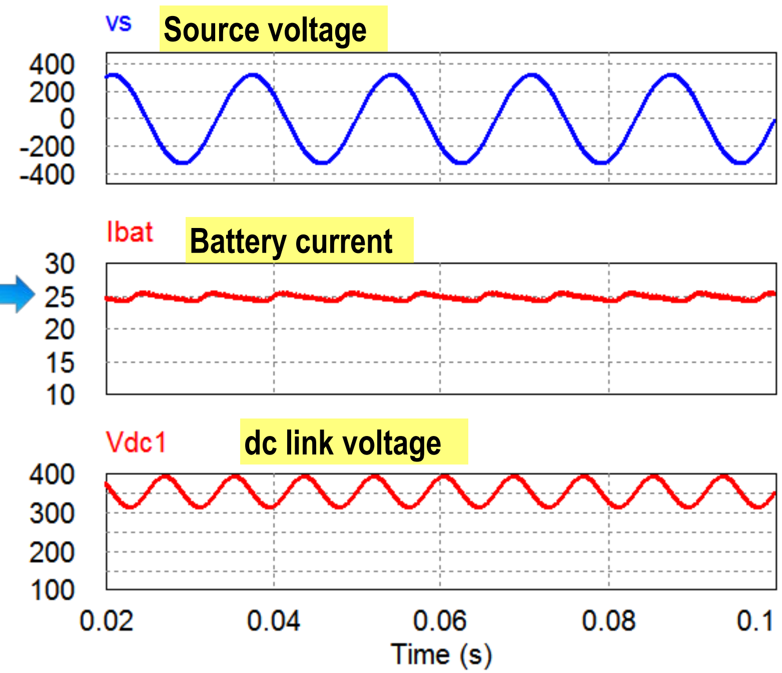
➢ ***Developed a battery ripple current reduction control strategy for the isolation converter to reduce the bulky dc link capacitor***

Technical Accomplishments and Progress

- **Performed isolation converter architecture selection through modeling, analysis and simulation study**
  - Demonstrated the ripple current reduction control strategy for the isolation converter to reduce the bulky dc link capacitor



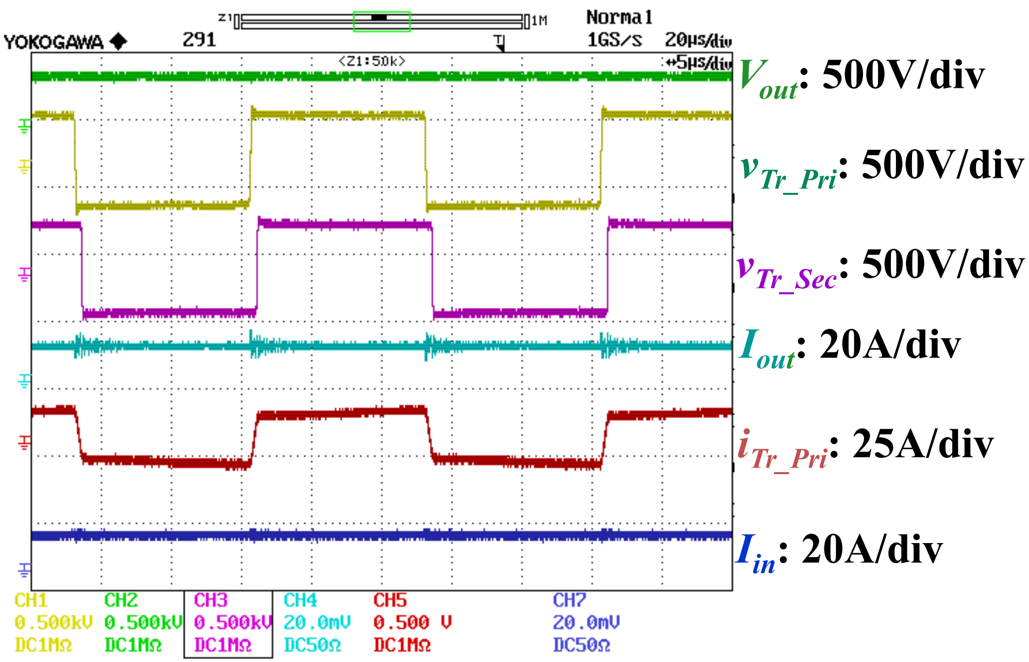
Waveforms showing large ripple in battery current without the ripple reduction control



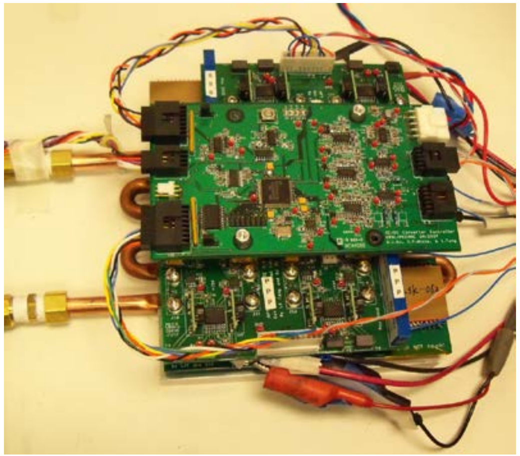
Waveforms showing significant reduction of battery ripple current with the ripple reduction control

Technical Accomplishments and Progress

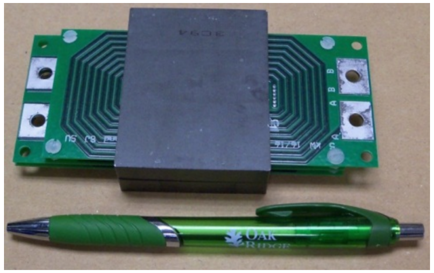
- Tested a 5kW Si-based integrated dc-dc converter & charger; Si-based isolation converter design:
  - Si power MOSFETs
  - Planar transformer
  - TI TMS320F1208 DSP controller
  - 6”x7” cold plate



Waveforms showing transformer voltages with smooth transitions due to soft switching



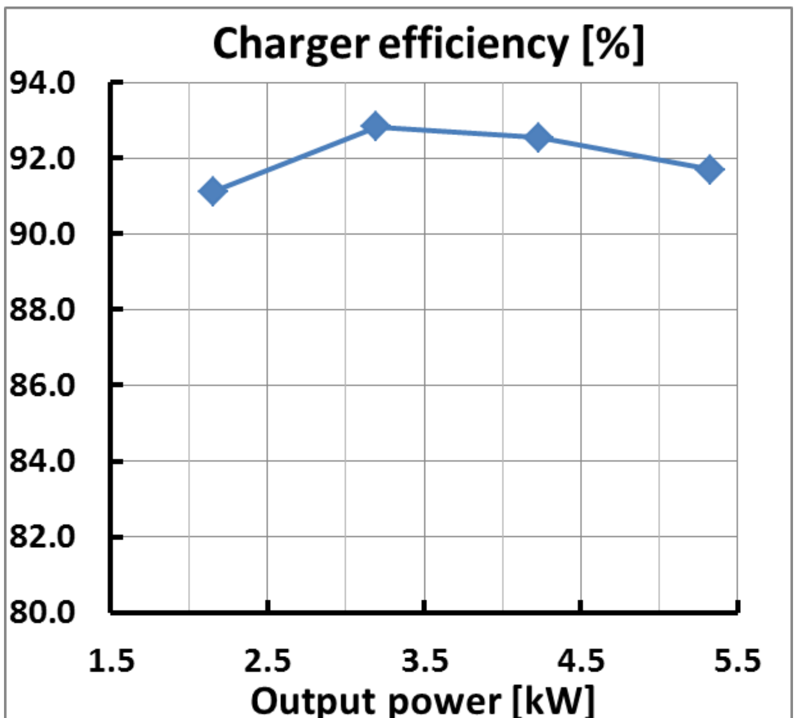
5 kW Si-based isolation converter



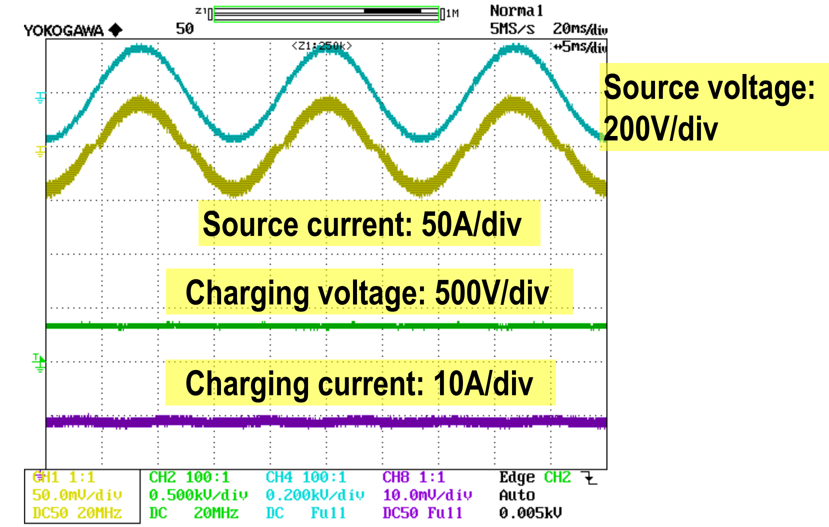
Ferrite planar isolation transformer (5”x2.5”x0.78”)

Technical Accomplishments and Progress

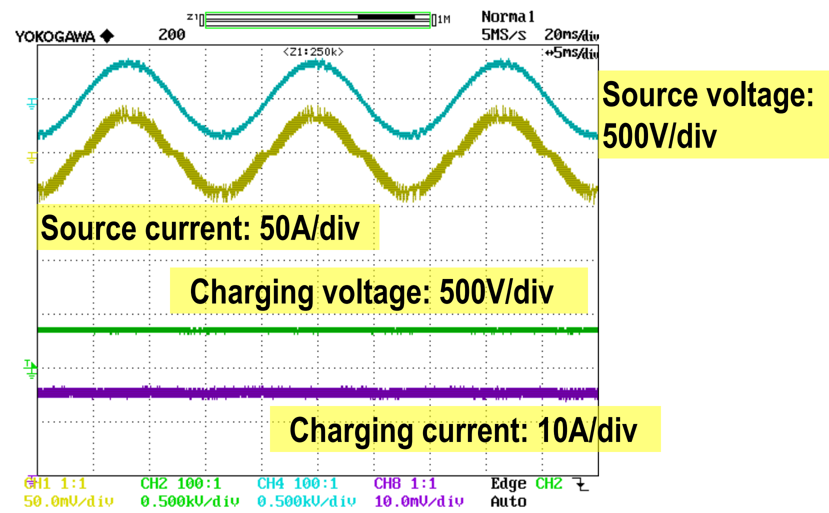
- **Tested a 5kW Si-based integrated dc-dc converter & charger using an isolation converter candidate**
  - Demonstrated the architecture



Measured efficiency of the Si-based 5kW charger



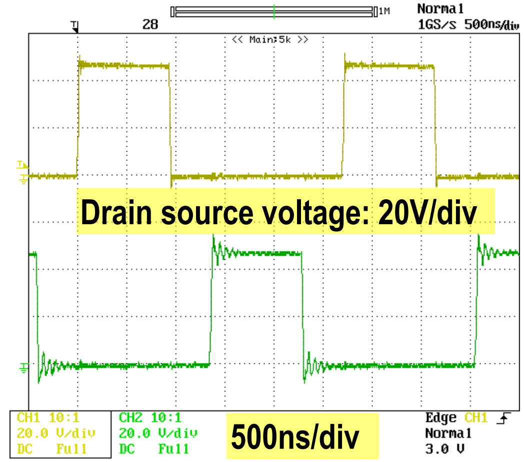
Charging at 3 kW from a 120V source



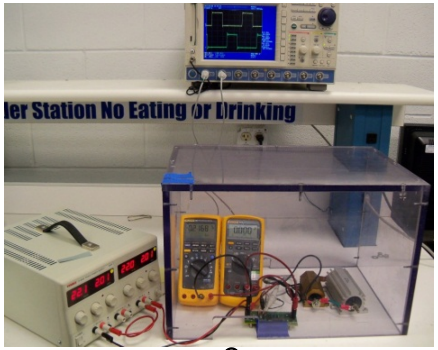
Charging at 5 kW from a 240V source

Technical Accomplishments and Progress

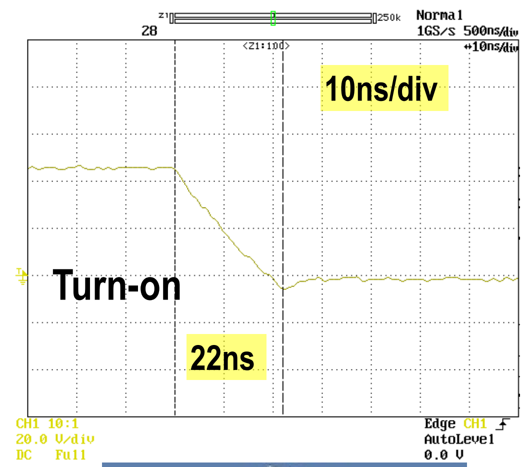
- **Performed characterization tests of WBG switch modules**
  - Completed DBC design for WBG switch phase-leg modules for CREE SiC MOSFETs
  - Conducted tests of EPC eGaN® switches for possible use in the 14V dc-dc converter. Tests were performed in buck, boost, and full bridge converter configurations.
  - Test results were applied in the EPC eGaN® switch model for the 14V dc-dc converter simulation study

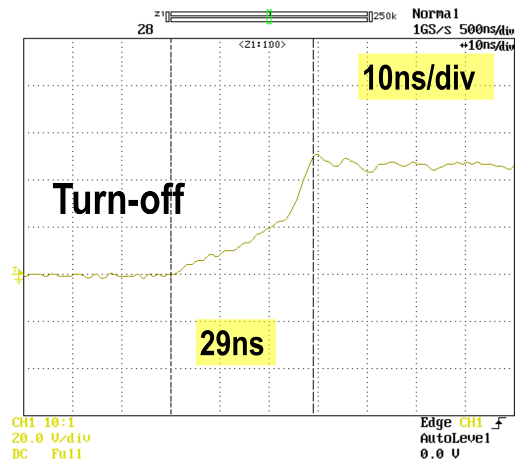


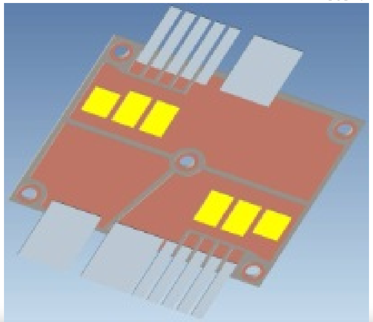
EPC eGaN® switching waveforms



EPC eGaN® test setup







DBC design for WBG switch phase-leg modules (36x46mm)

Collaboration and Coordination

Organization	Type of Collaboration/Coordination
International Rectifier	High voltage (600 V) EPC eGaN® devices and modules, requirements for gate drivers
Delphi	High voltage EPC eGaN® power modules
Efficient Power Conversion Corporation	Guidance on design of 14 V converter using the low voltage EPC eGaN® devices and modules
Hitachi/Metglas	Inputs on design and fabrication of high frequency inductors and transformers using FINEMET®
University of Tennessee	EPC eGaN® gate drive circuit design
NREL	Thermal modeling and guidance on design of an interacting cooling system with traction drive inverter (FY14 & FY15)

- **Opportunity for collaboration with academia/industry on WBG power devices and emerging nano-composite magnetic materials.**

Proposed Future Work

- **Remainder of FY13**
  - Complete isolation converter selection through modeling, analysis and simulation of candidate converters
  - Complete characterization tests of WBG switch modules & procure advanced magnetic materials
  - Design a 6.6 kW SiC isolation converter
- **FY14**
  - Build and test a 6.6 kW SiC isolation converter based on the FY13 design.
  - Design and build a 6.6 kW all WBG isolation, introducing GaN into the dc-dc stage.
  - Design the dc-dc converter that can be integrated with traction drive inverter (thermal management collaboration with NREL).
  - Design of all WBG isolation converter stage must show efficiency >98%.
- **FY15**
  - Test and refine the 6.6 kW all WBG isolation converter built in FY14.
  - Integrate the refined isolation converter with an all WBG on-board charger. (thermal management collaboration with NREL).

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, advanced magnetic materials and novel control strategies to significantly increase power density, specific power and efficiency at lower cost.
- **Collaborations:** Collaborations with several industry stakeholders, universities, and other national labs are being used to maximize the impact of this work.
- **Technical Accomplishments:**
  - Simulated several converter architectures and developed a battery ripple current reduction control strategy for the isolation converter to reduce the bulky dc link capacitor.
  - Identified one isolation converter candidate and completed test of a 5kW Si-based integrated dc-dc & charger using the candidate.
  - Completed DBC design for WBG switch phase-leg modules for CREE SiC MOSFETs.
  - Conducted tests of EPC eGaN switches for possible use in the 14V dc-dc converter.
- **Future Work:** Plans are in place; charger technical targets are being developed by DOE in collaboration with industry.