Innovative Chargers and Converters

Veda Galigekere
Email: galigekerevn@ornl.gov
Phone: 865-946-1291

Oak Ridge National Laboratory

2018 U.S. DOE Vehicle Technologies Office Annual Merit Review

June 19, 2018 **Project ID:ELT077**

This presentation does not contain any proprietary, confidential, or otherwise restricted information

Overview

Timeline

- Start – FY17
- End – FY19
- 50% complete

Barriers

- Meeting DOE ELT 2025 efficiency (98%) and power density targets (4.6 kW/L) while reducing cost
- Achieving DOE ELT 2025 power density target without active cooling solution
- Reliability of the high voltage power electronics due to increased usage

Budget

- Total project funding
  - DOE share – 100%
- Funding received in FY17: $650K
- Funding for FY18: $500K

Partners

- NREL
- Lear Corporation
- ORNL team members: Veda Galigekere, Omer Onar, Jason Pries, Madhu Sudhan Chinthavali, Saeed Anwar, and Zhiqiang Wang

Any proposed future work is subject to change based on funding levels

Project Objective and Relevance

- **Overall Objective**
  - To develop an optimized integrated wireless electric vehicle (EV) charging system which utilizes the high voltage power electronics of the electric drive to target DOE ELT 2025 power density, efficiency, and cost targets. The integrated wireless charger will have
    - Increased system level power density
    - Low profile or planar vehicle assembly
    - Scalability for power levels up to 50 kW
- **FY18 Objective**
  - Validate operation of optimized 11 kW wireless power transfer (WPT) coils which can enable WPT for vehicles with different ground clearances
  - Evaluate sensitivity and stability of 11 kW integrated wireless charging system to variation in load power and coupling coefficient
  - Validate operation of 11 kW integrated wireless charger

Any proposed future work is subject to change based on funding levels

Milestones

Date	Milestones and Go/No-Go Decisions	Status
Dec 2017	Go/No-Go Decision: If laboratory characterization of optimized DD coils indicate feasibility of 11 kW operation over 100 mm – 210 mm, go ahead with power electronics hardware development	Go
Mar 2018	Milestone: Complete sensitivity analysis of the 11 kW WPT system to variation on load power and coupling coefficient	Completed
Jun 2018	Milestone: Complete hardware assembly of integrated wireless charging system	On-track
Sep 2018	Milestone: Validate operation of 11 kW integrated wireless EV charging system	On-track

Any proposed future work is subject to change based on funding levels

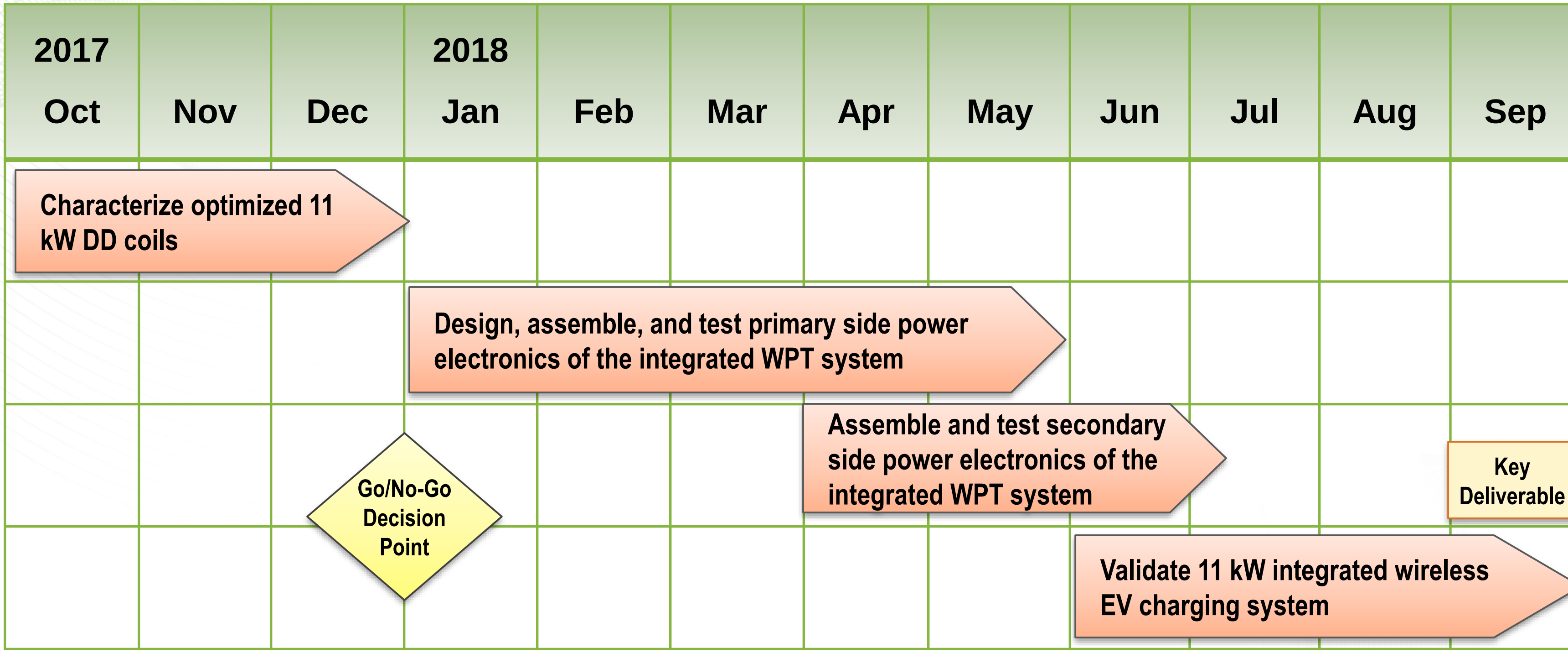
OAK RIDGE National Laboratory

Approach/Strategy

- To increase the power density and specific power and to reduce the cost of the wireless charging system by integrating the power electronics of the electric drive train in to the wireless EV charging system
- On-board components of the integrated wireless charging system include
  - Receiver coil and resonant capacitor
  - Inverter and dc-dc converter of the electric drive train
- Receiver WPT coil will be optimized for power density and specific power by
  - Selecting WPT coil geometry which will enable a smaller receiver coil
  - Optimal placement of ferrites
- Sensitivity and stability analysis will be performed to ensure safe and robust operation for a range of load variation and coil-to-coil misalignment
- The integrated wireless EV charging system has the additional benefit of having the ability to exercise secondary side control of power in addition to control from the primary side

Any proposed future work is subject to change based on funding levels

Approach FY18 Timeline



Go/No-Go Decision Point: If laboratory characterization of optimized DD coils indicate feasibility of 11 kW operation over 100 mm – 210 mm, go ahead with power electronics hardware development

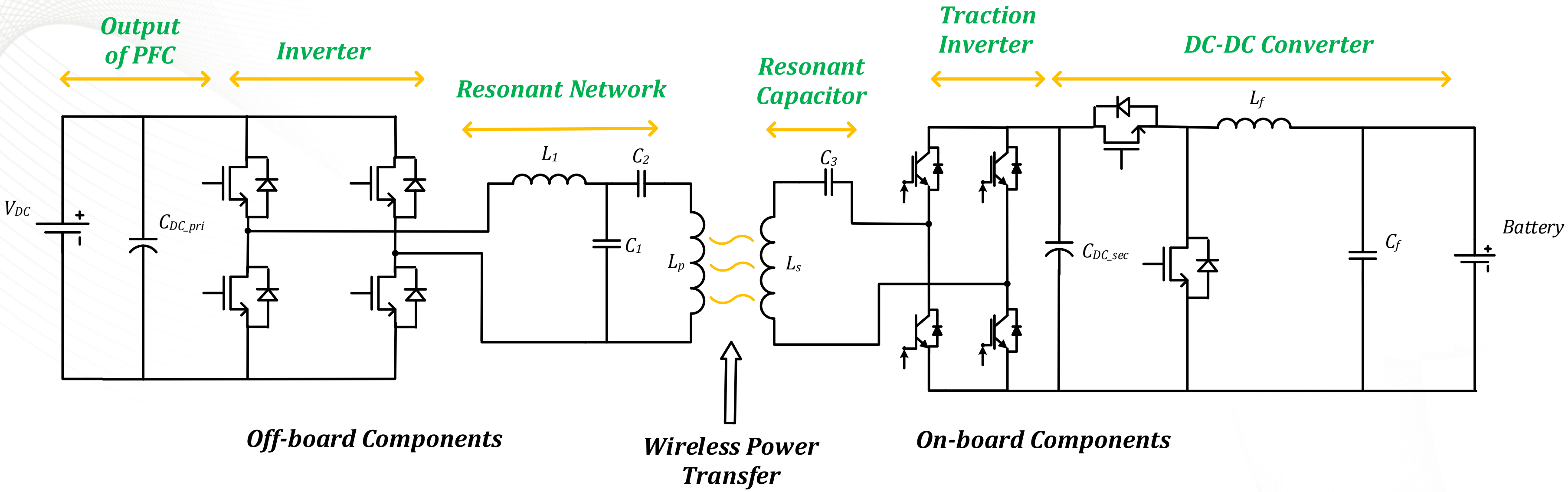
Key Deliverable: Project report detailing the design process and discussion on hardware validation results including a comparison to the DOE ELT 2025 targets

Any proposed future work is subject to change based on funding levels

OAK RIDGE National Laboratory

Technical Accomplishments – FY18

Proposed Novel Topology



Advantages of proposed integrated wireless charger architecture

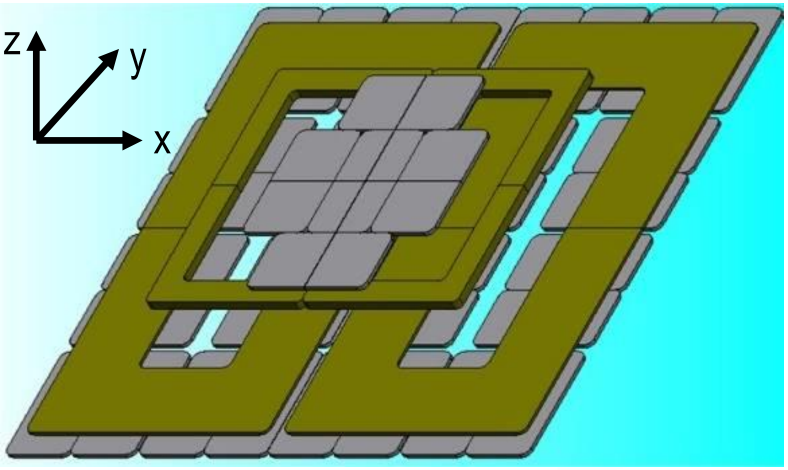
- Utilizes the existing power electronics of the electric drive train
- Requires only the vehicle side receiver coil and tuning capacitor to be added
- Secondary side control of power is also possible
- Will work with or without the boost converter in the electric drive train

Any proposed future work is subject to change based on funding levels

OAK RIDGE National Laboratory

Technical Accomplishments – FY18
Completed Design and Optimization of DD Coils

- Optimized vehicle coil 480 mm x 368 mm x 32 mm
- 11 kW power transfer capability in Z axis 100 mm – 210 mm
- Tolerance to horizontal misalignment along x and y axes ± 150 mm
- Simulated coupling coefficient values are close to the measured values



Model of the 11-kW optimized coil simulated in JMAG.

FEA simulation and measurement results of optimized 11 kW coils

	Simulated Values			Measured Values
Z Distance (mm)	Primary coil inductance (μH)	Secondary coil inductance (μH)	Coupling coefficient k	Coupling coefficient k
100	82.86	84.21	0.302	0.251
125	81.20	81.62	0.239	0.210
150	80.14	79.88	0.190	0.170
175	79.56	78.88	0.151	0.138
210	79.35	79.22	0.121	0.107

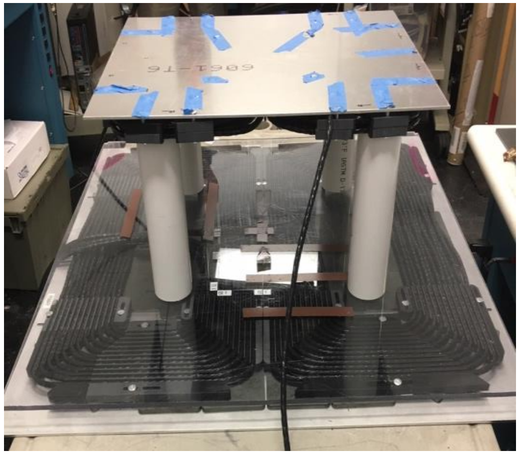
Effect of aluminum shield and Litz wire not considered

Any proposed future work is subject to change based on funding levels

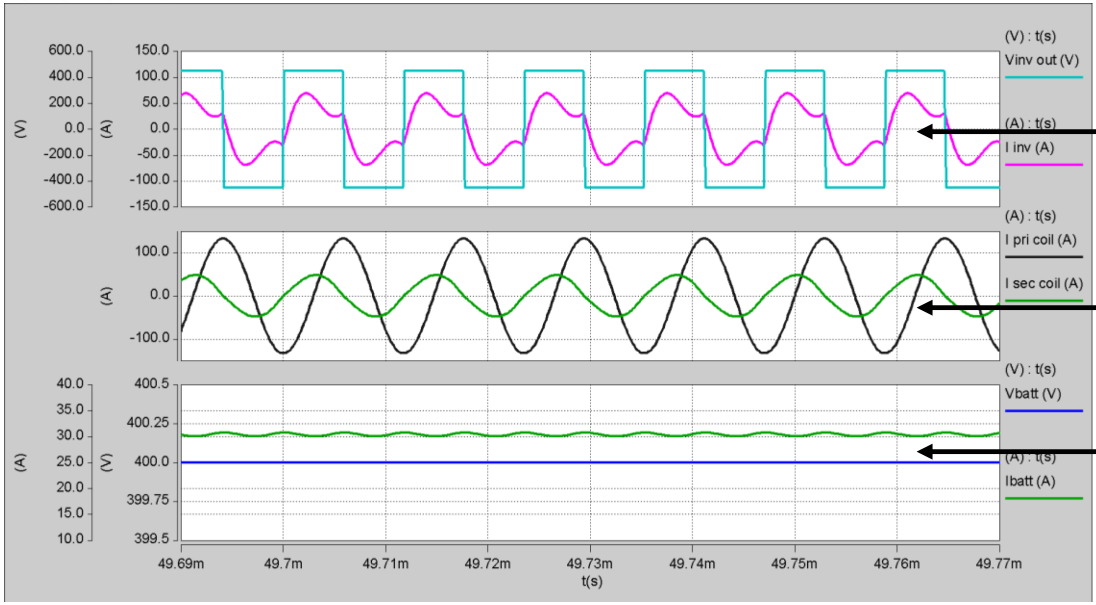
Technical Accomplishments – FY18
Characterized DD Coil Prototype

Completed laboratory characterization of optimized DD coil and circuit simulation

- Benchtop characterization results matched the FEA simulation and design methodology
- Circuit simulation based on coil characterization validated the feasibility of 11 kW wireless power transfer
- Component stresses and circuit behavior are evaluated by detailed circuit simulations



Prototype DD coils of the 11 kW integrated wireless EV charger



Minimal phase difference between inverter output voltage and current indicates optimal operation

Coil current is less than current capability of the primary coil winding

11 kW output power for coil-to-coil gap of 200 mm

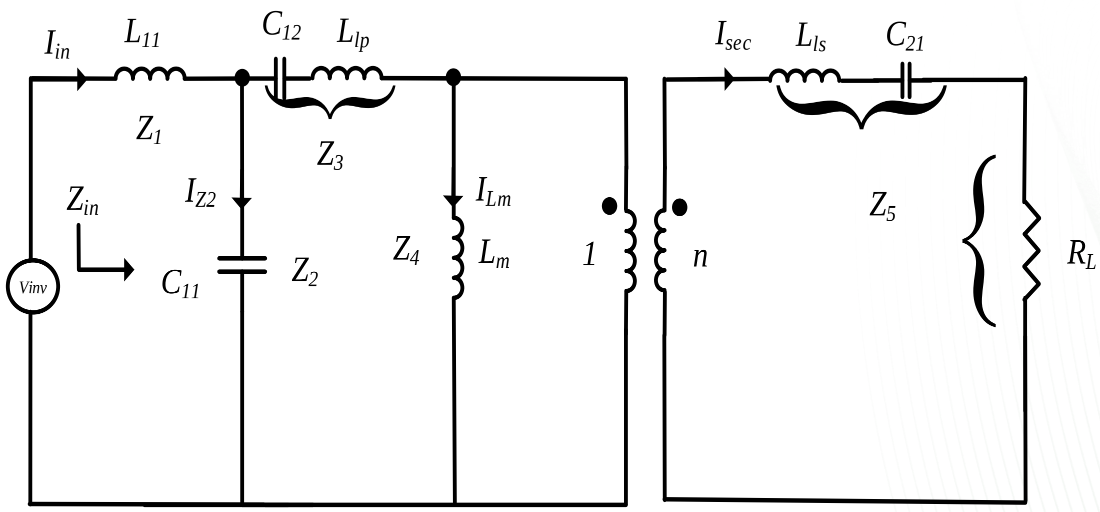
Circuit simulation results for worst-case coil-to-coil gap of 210 mm

Any proposed future work is subject to change based on funding levels

Technical Accomplishments – FY18
Performed Sensitivity Analysis

Completed sensitivity analysis of 11 kW integrated wireless charging system

- Derived linear models for primary side LCC and secondary side series tuned architecture based on
  - Replacing WPT coils by loosely coupled model of the transformer
  - Approximating the output of the inverter by the fundamental frequency component
- Analyzed sensitivity of the system to
  - Misalignment of coils along the x and y axis
  - Variation of coil-to-coil distance
  - Variation of load power



Linear model derived to perform sensitivity analysis

Any proposed future work is subject to change based on funding levels

OAK RIDGE National Laboratory

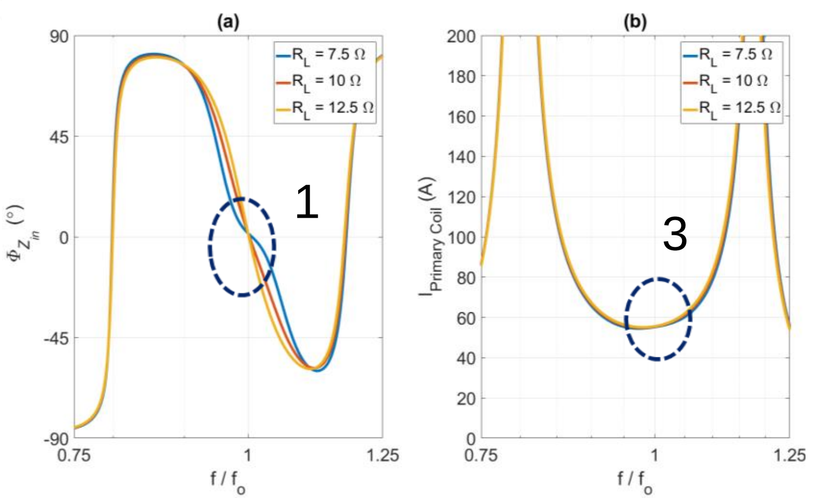
Technical Accomplishments – FY18
Performed Sensitivity Analysis

1. Inverter current has near zero phase angle independent of load resistance
2. Inverter current has near zero phase angle independent of the coupling between the WPT coils

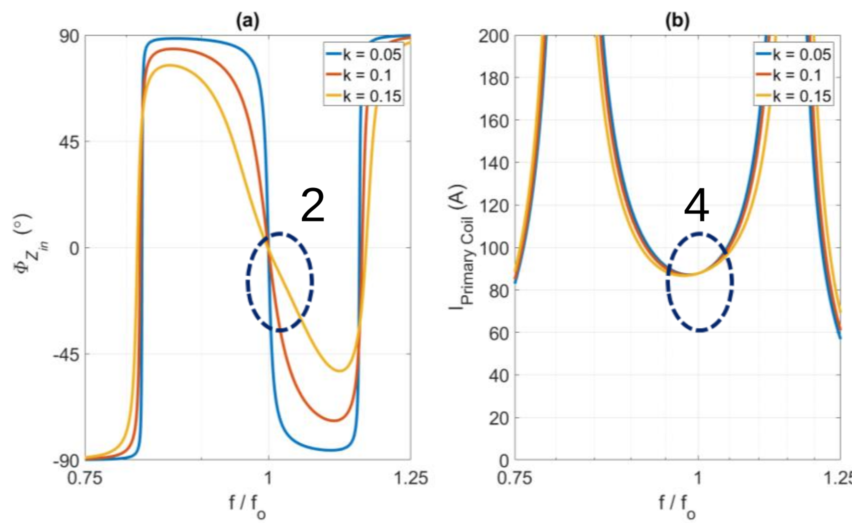
Leads to high efficiency operation and the inverter does not need to be oversized

3. Primary coil current is constant independent of load resistance
4. Primary coil current is constant independent of coupling between the coils

Primary side is decoupled from the secondary side disturbances



(a) Inverter voltage and current phase angle as a function of load resistance
(b) Primary coil current as a function of load resistance

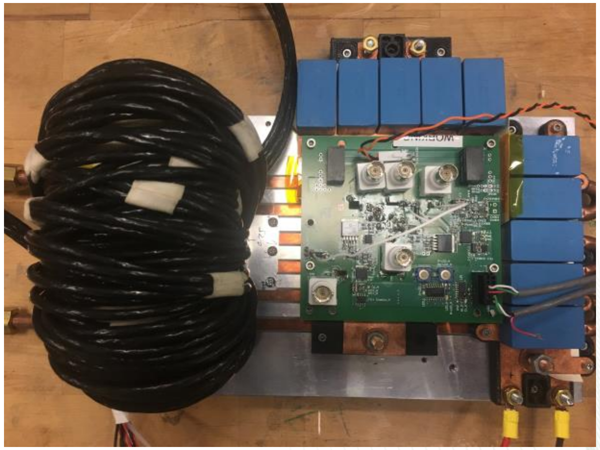


(a) Inverter voltage and current phase angle as a function of coupling coefficient
(b) Primary coil current as a function of coupling coefficient

Technical Accomplishments – FY18
Completed Power Electronics Hardware Design

- Primary side power electronics
  - Completed assembly of primary side 85 kHz inverter using 1200 V SiC BSM120D12P2C005 ROHM phase-leg module
  - Verified operation of digital control platform using TI DSP TMS320F28335PGFA
- Secondary side power electronics
  - Completed prototyping of SiC based boost converter using ORNL packaged 1200 V SiC phase leg module
  - Hardware design of secondary side rectifier is completed using 1200 V SiC Schottky diode C4D40120D

Primary side SiC inverter assembled for 85 kHz operation



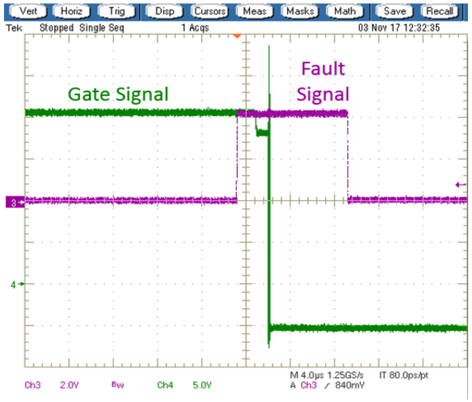
Secondary side dc-dc converter assembled using ORNL packaged WBG phase leg module

Any proposed future work is subject to change based on funding levels

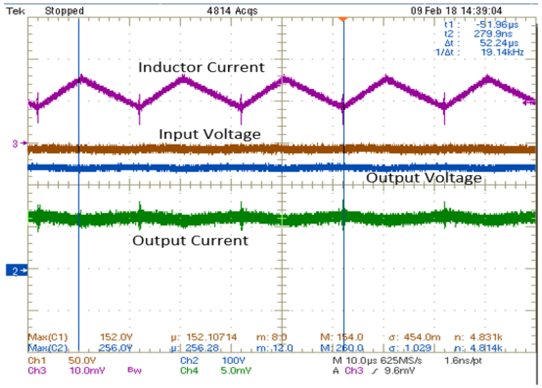
Technical Accomplishments – FY18

Verified Functionality of Secondary Side SiC DC-DC Converter

- Completed over current protection evaluation and preliminary functionality of secondary side SiC dc-dc converter
- Preliminary validation of functionality of SiC dc-dc converter is completed (2 kW operation)

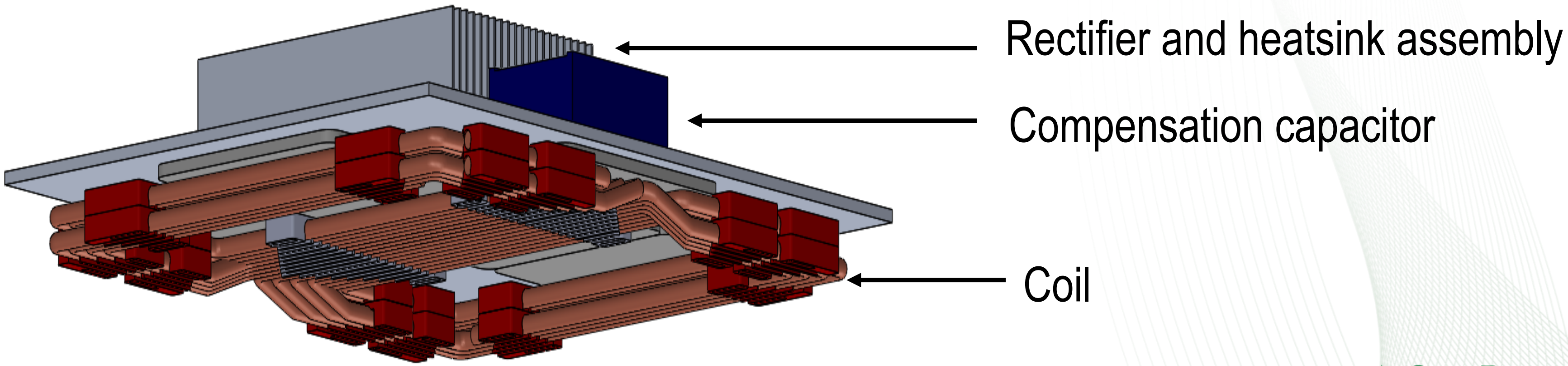


Over current protection test of WBG dc-dc converter



WBG dc-dc converter test results at 2 kW power level

- Completed hardware design of on-board system of integrated wireless EV charger



Any proposed future work is subject to change based on funding levels

Responses to Previous Year Reviewers' Comments

Reviewer comment: It was not clear why the increased use of boost converter is a technical barrier.

Response/Action: The DOE ELT 2025 target specifies a lifetime of 300,000 miles. Since the charging and the discharging of the EV battery both take place via the boost converter, the boost converter has to have a lifetime of 600,000 miles. However, the proposed architecture will function with or without the boost converter.

Reviewer comment: The project is utilizing NREL to help with power management, but it lacks co-ordination with other institutions and vehicle OEMs.

Response/Action: Lear Corporation a Tier-1 automotive supplier who is engaged with several OEMs for the design, development, and production of wireless EV chargers has been engaged as a partner. Lear Corporation will provide feedback and identify technology gaps that need to be addressed by research and development.

Reviewer comment: The boost converter is shared by an existing power inverter module, the focus should be on the 11 kW charger side.

Response/Action: Majority of the research effort is focused on the 11 kW integrated charger mode.

Any proposed future work is subject to change based on funding levels

Collaboration and Coordination with Other Institutions

NREL NATIONAL RENEWABLE ENERGY LABORATORY	National Renewable Energy Laboratory – Thermal management
LEAR CORPORATION	Lear Corporation, Tier – 1 Automotive manufacturer of EV charging systems – Project feedback and discussion on identifying technology gaps and constraints on WPT based EV charging systems

Any proposed future work is subject to change based on funding levels

Remaining Challenges and Barriers for FY18

- Achieving transfer of rated 11 kW with 90% efficiency over wide range of coil-to-coil horizontal misalignment
- Ensuring magnetic fields are within the 27 μT at worst-case coil-to-coil misalignment (x = 150 mm and y = 150 mm)

Any proposed future work is subject to change based on funding levels

Proposed Future Work

- **Remainder of FY18**
  - Validate 11 kW power transfer capability of the prototype DD coils for coil-to-coil gap of 4 inches to 8 inches at 85 kHz
  - Integrate wireless 85 kHz optimized wireless power transfer system with the inverter/SiC bi-directional dc-dc converter
  - Validate by hardware 11 kW operation of integrated wireless EV charging system

- **FY19**
  - Evaluate scalability to 50 kW
  - Build a high power integrated wireless EV charger on track for wireless fast charging

Any proposed future work is subject to change based on funding levels

Summary

- **Relevance:** Increasing the power density and specific power of the wireless EV charging system to achieve the DOE ELT 2025 targets

- **Approach:** Proposed an integrated charger architecture wherein the inverter and the boost converter of the electric drive train is absorbed into wireless EV charging

- **Collaborations:** NREL and LEAR Corporation

- **Technical Accomplishments:**
  - Completed hardware design and prototyping of optimized 11 kW DD coils assembled
  - Designed primary and secondary power electronics of 11 kW integrated wireless EV charger
  - Derived models necessary to evaluate sensitivity of the 11 kW integrated charger to variation in coil-to-coil misalignment and distance

- **Future Work:**
  - Validate the operation of 11 kW integrated wireless charger by hardware implementation in the laboratory
  - Evaluate scalability for 50 kW integrated wireless EV charger

Any proposed future work is subject to change based on funding levels