VSS103

Wireless Charging

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2014 U.S. DOE Hydrogen Program and Vehicle Technologies Program Annual Merit Review and Peer Evaluation Meeting

June 16-20, 2014

Center for Transportation Analysis

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OAK RIDGE NATIONAL LABORATORY
MANAGED BY UT-BATTELLE FOR THE DEPARTMENT OF ENERGY

OVERVIEW

Timeline	Barriers
• Project start date: Oct. 2012 • Project end date: Scheduled November 2015 • 40% Complete	• Risk Aversion - Partner engagement • Cost - Transfer from laboratory set-up to integration prototype development • Lack of Standardized Test Protocols • Infrastructure – impact of EV charging
Budget (DOE share)	**Partners**
• DOE funding : $8.0M • Partner funding : $3.3M	• Toyota (CRADA) • Evatran (Plugless power) • Clemson University ICAR • Oak Ridge National Laboratory (Project Lead) – Power Electronics & Electric Machines Research Center – Center for Transportation Analysis

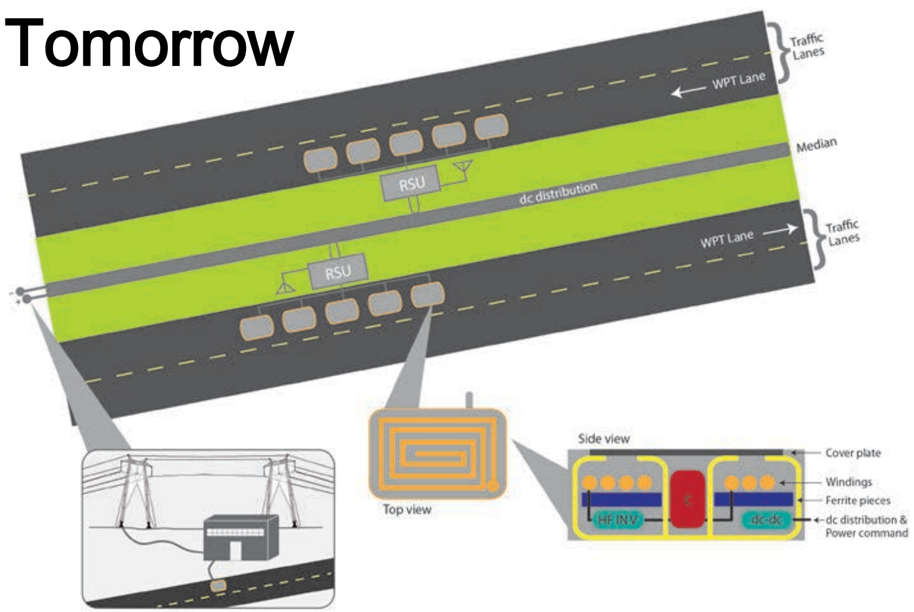
Project Relevance

- Advance technology maturity, identify commercialization, standardization and safety of wireless charging technology

Today

ORNL wireless charging focuses and shields the active zone magnetic field to insure fringe fields are well within international standard limits (ICNIRP)

Tomorrow



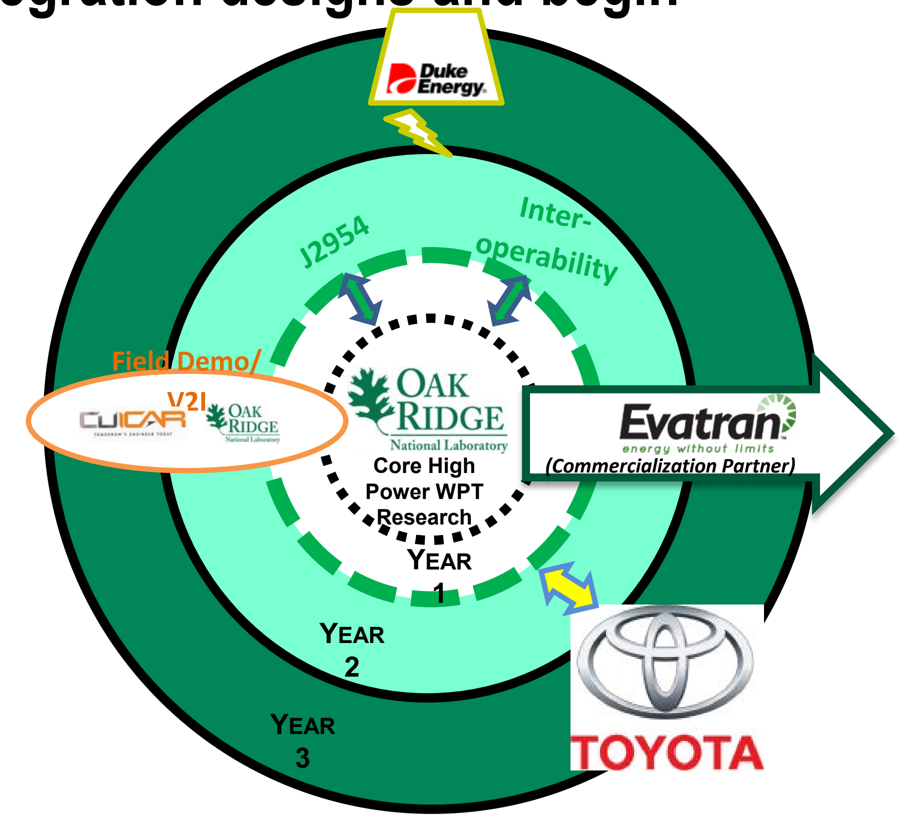
Objective

Objective for FY14

- Coordinate multi-party team activities to validate 6.6 kW capable wireless power transfer (WPT) apparatus @ 85% efficiency, demonstrate on bench, complete integration designs and begin integration into vehicles

Overall program

- Provide unbiased data to promote technology standards
- Work with Evatran, CU-ICAR and Toyota Motor Co. to integrate ORNL developed WPT technology into demonstration vehicles
- Validate system at independent testing laboratory.



ORNL's technology meets international standards on high frequency electromagnetic fields. ORNL interacts with standardization committee -SAE J2954 WPT Task Force for 2015 standard development

OBJECTIVE Phase II: Transfer Laboratory Development of Wireless Power Transfer (WPT) Technologies into Vehicle based test

"WHY"

- Wireless charging is seen as a key enabling technology to increase the adoption of electric vehicles
- Through different applications of WPT there is great potential to displace petroleum currently used in transportation

"HOW"

- Develop and validate safe and methods of wireless power transfer – ongoing standards support
- Integrate technology into OEM supported vehicles to evaluate technology performance
- Research and report on cost savings potential of production run rates of system components.

RELEVANCE

- **Supports major LD VSST powertrain electrification goals:**
  - Demonstrate market readiness of grid-connected vehicles by 2015
  - Develop methods to reduce impact on infrastructure due to EV charging.
  - Address codes and standards needed to enable wide-spread adoption of electric-drive transportation technologies.
- **Directly supports VSST component and systems evaluation.**
  - Supporting J2954 standards
  - Component efficiencies highlighting system efficiencies and project deliverables
- **Directly supports VSST laboratory and field vehicle evaluations.**
  - Phase III is deployment and evaluation test phase
- **Addresses the following VSST Barriers:**
  - **Risk aversion**: Industry aversion for investment where market does not yet exist
  - **Cost**: Utilizes ORNL's manufacturing partner to identify large scale cost reduction opportunities.

***Reference: Vehicle Technologies Multi-Year Program Plan 2011-2015:**
http://www1.eere.energy.gov/vehiclesandfuels/pdfs/program/vt_mypp_2011-2015.pdf

Milestones

Date	Milestones and Go/No-Go Decisions	Status
Nov-2013	Milestone: WPT efficiency >85% wall to battery (or equivalent) at 6.6 kW power Go /No-Go Decision: Achieves 6.6 kW continuous power at >85% efficiency	DOE and NETL were in attendance at ORNL for bench top demonstration of technology at > 85% @6.6kW, and 10kW non-PFC 89% Efficiency
March - 2015	Milestone: Integrate WPT System into commercial PEV's. Demonstrate 85% efficiency is retained Go/No-Go Decision: Vehicle battery charging power regulation performed using dedicated radio communications and message set	Toyota is now the only OEM partner. Initial Integration designs complete, CRADA completed – vehicles will have modified ESS prior to integration of technology
March - 2015	Milestone: Deploy and demonstrate 6.6 kW WPT charging facilities as required to meet Test and Evaluation plans	

Note: FY14 milestone: 6.6 kW successful demonstration at ORNL with DOE and NETL representatives present and observing the 85% system efficiency.

Approach and Strategy

Stationary Wireless Charging

Opportunistic/Quasi Dynamic Wireless Charging

In motion/Dynamic Wireless Charging

Managed by UT-Battelle
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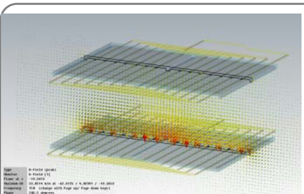
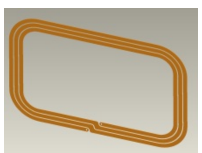
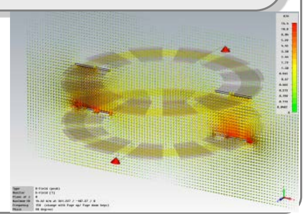
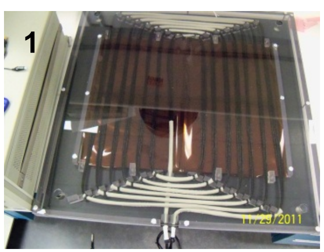
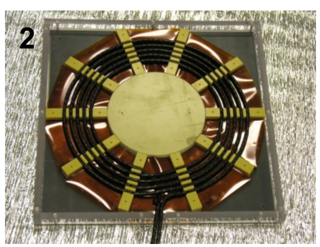
ORNL's Technology Development in WPT

WPT Technology Evolution

Electromagnetics & Coil Design

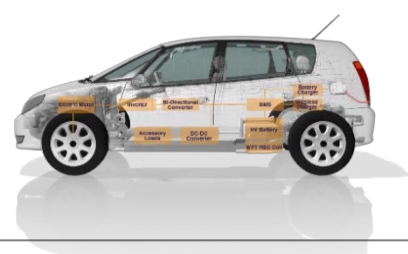




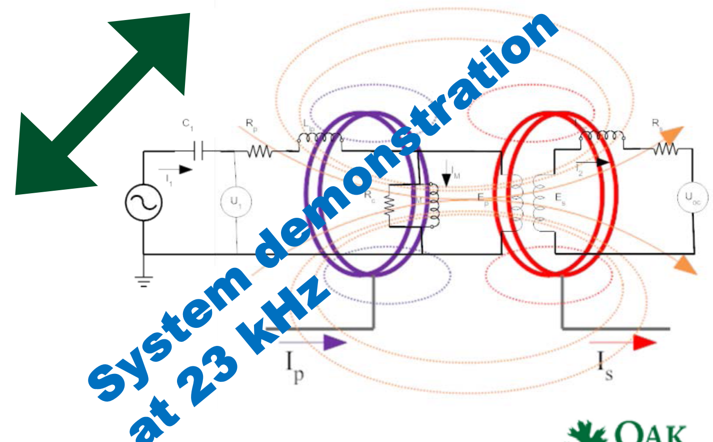




WPT Grid Side Regulation & Front End Power Electronics

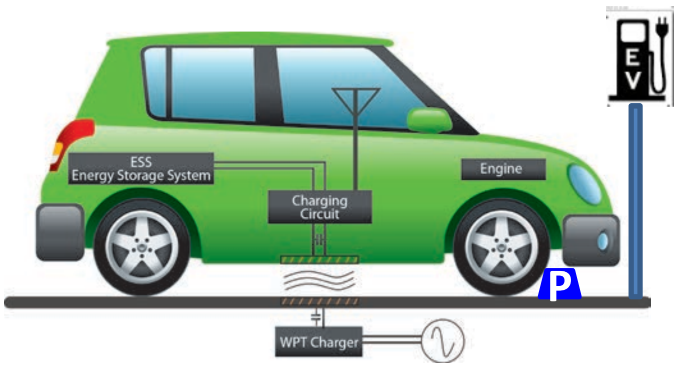

Vehicle Integration and Communication

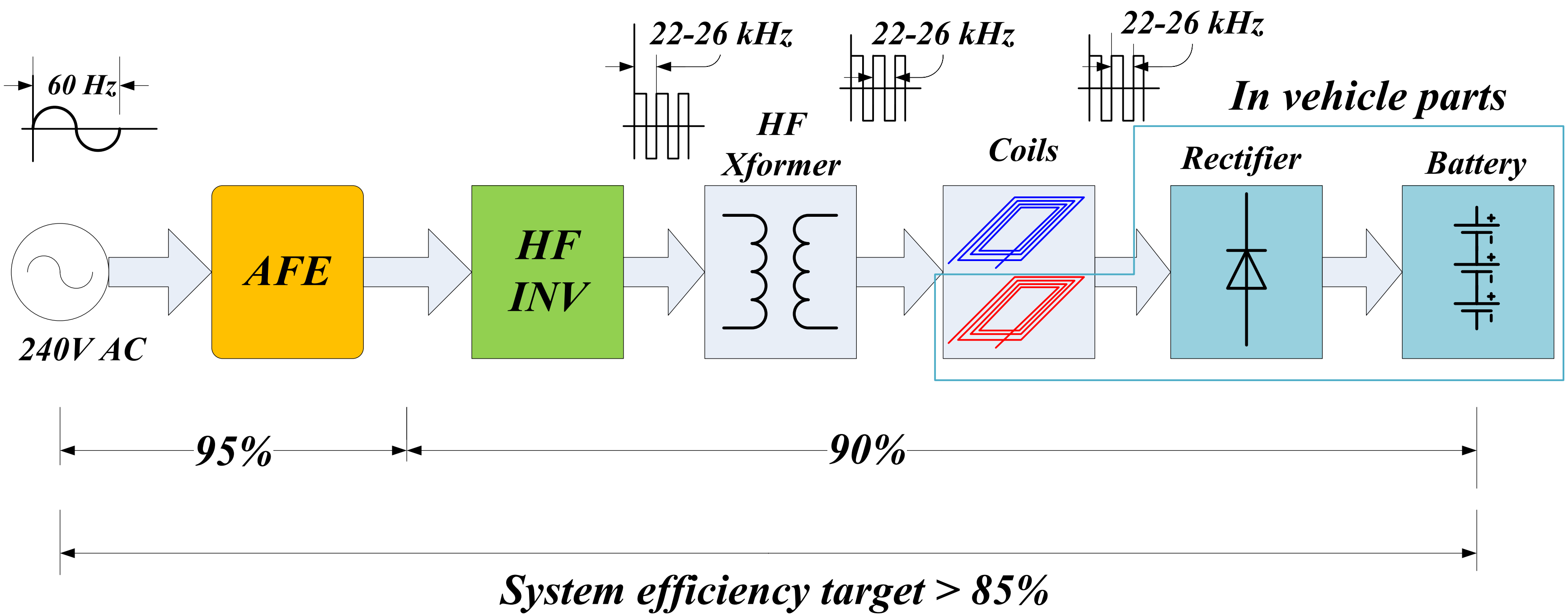




Approach and Strategy

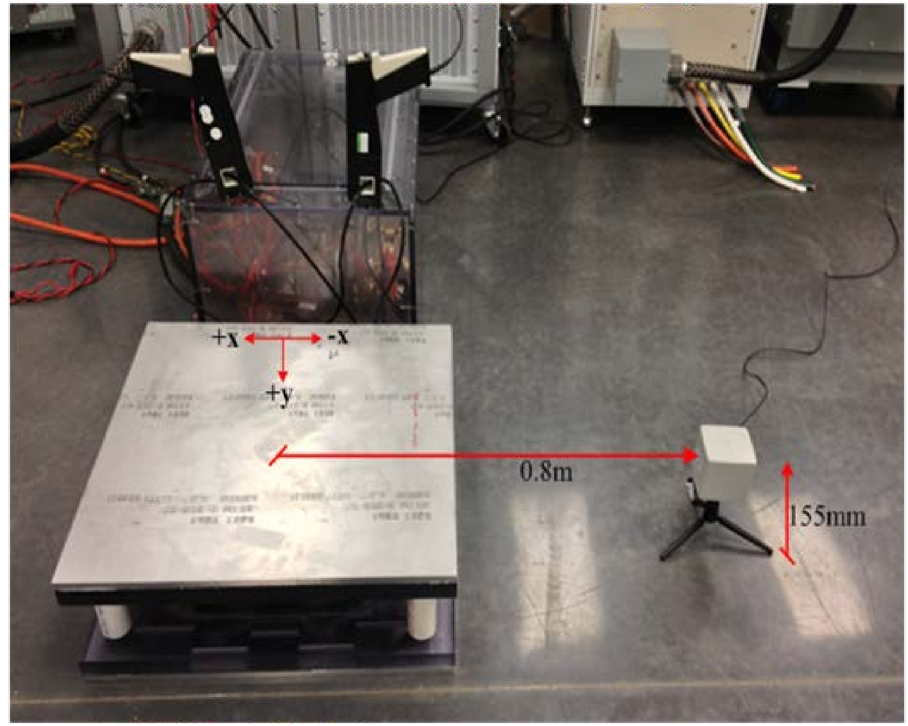
- **National Laboratory Role in Wireless Charging Technology R&D**
  - Inter-lab coordination on WPT R&D
  - Support standards creation thru R&D
  - Assessment of leakage fields
  - Consensus on system efficiency measurement, where measured, and what vehicle functions are to be included in the measurements.





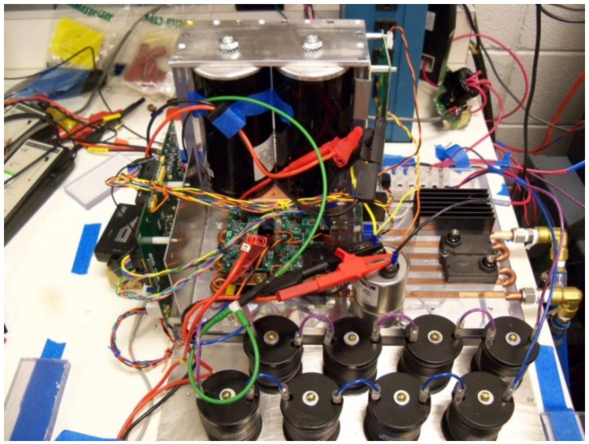
FOA #667 Project Goals

- Develop and bench demonstrate a WPT system capable of 6.6kW continuous charging power into a 370V nominal load (battery emulator) at >90% dc to dc efficiency (>85% from 240Vac line to battery)
- Validate coupling coil fringe field emissions <6.25 uT and <87V/m at 0.8 m from primary coil center
- Implement bidirectional radio communications that closes the loop on battery charge power regulation
- Implement control strategy that tracks variations in coil gap and load variation due to battery SOC level
- Integrate WPT technology into demonstration vehicles and evaluate in field testing

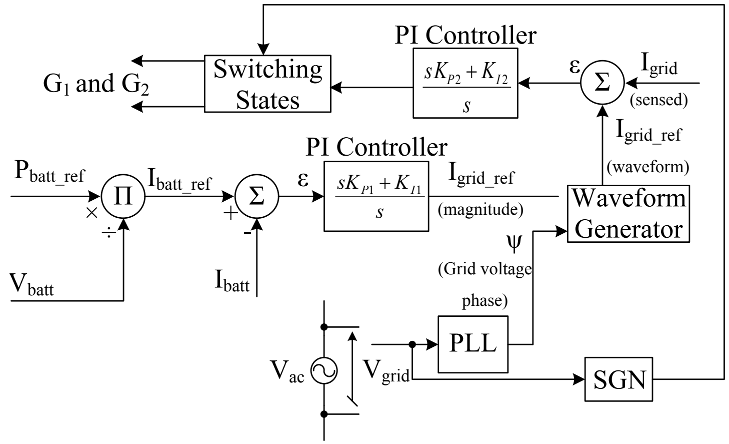


Technical Accomplishments: Complete System Integration for Test Bench Demo- FY13/14 Milestone

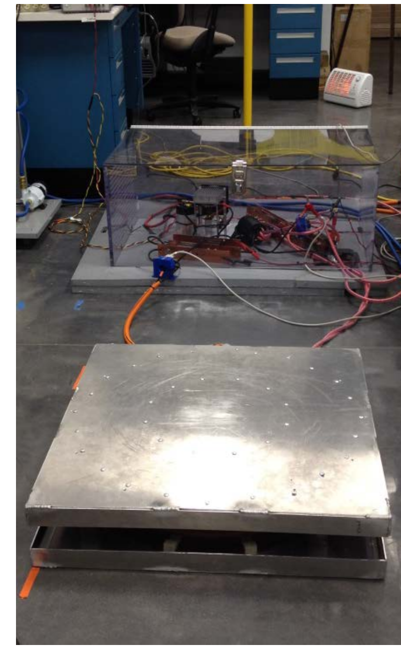
- SiC Active Front-end Rectifier (AFER) with power factor correction (PFC)



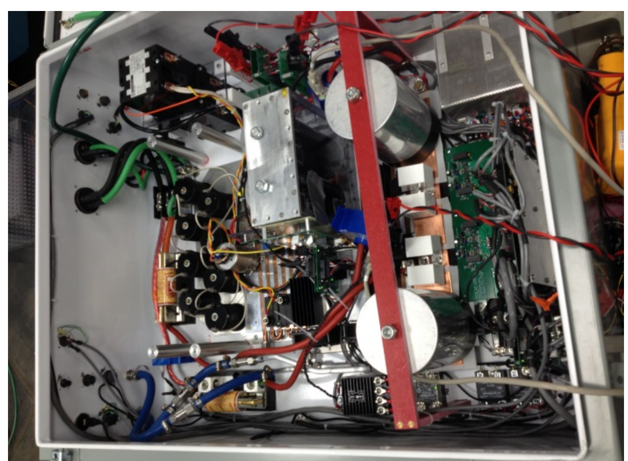
- PFC converter control system



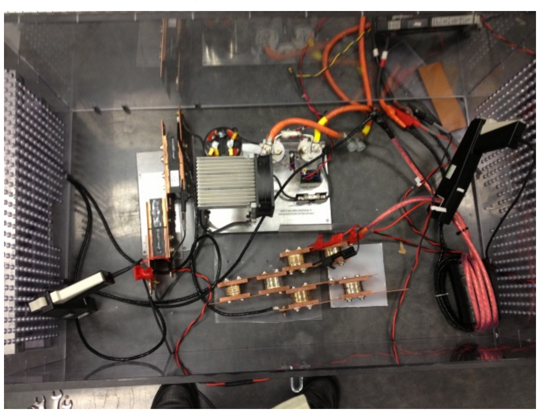
- Primary and secondary coils



- Integrated PFC and HF power inverter

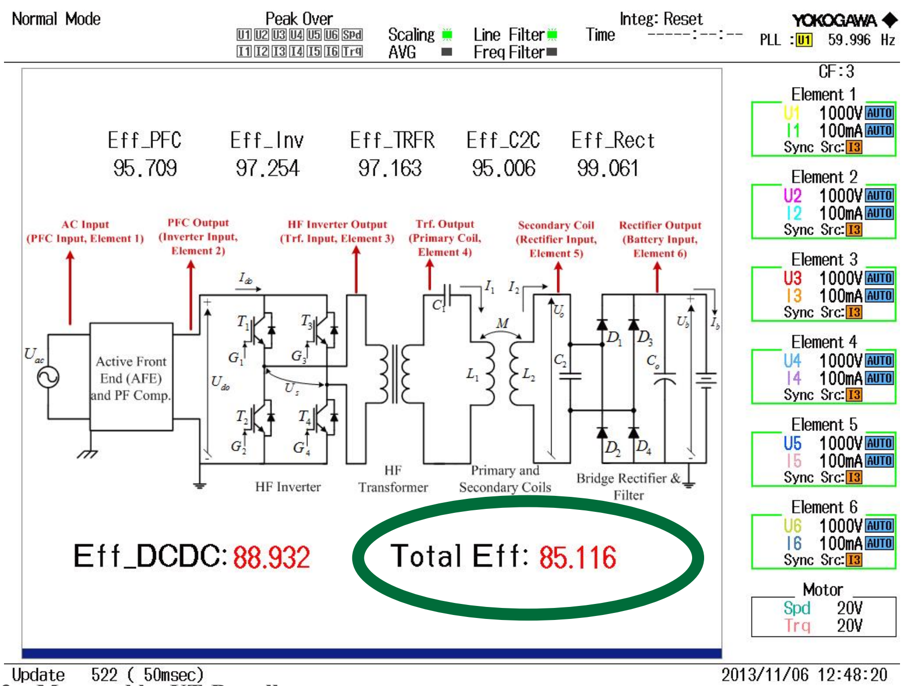


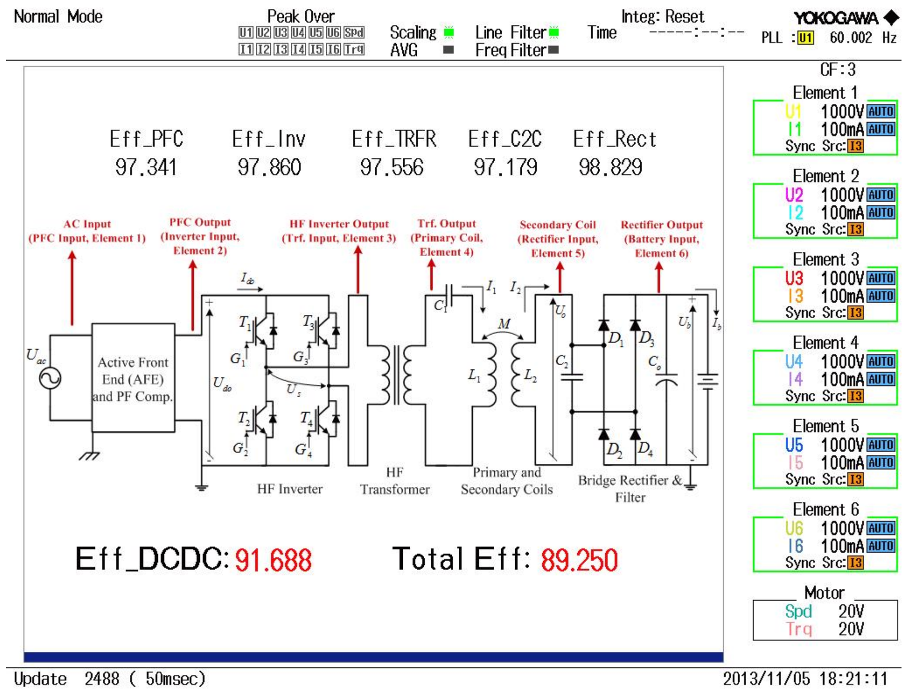
- Tuning capacitors and HF transformer



Technical Accomplishments: Complete System Integration for Test Bench Results

- Test results @137mm airgap at 6.6kW

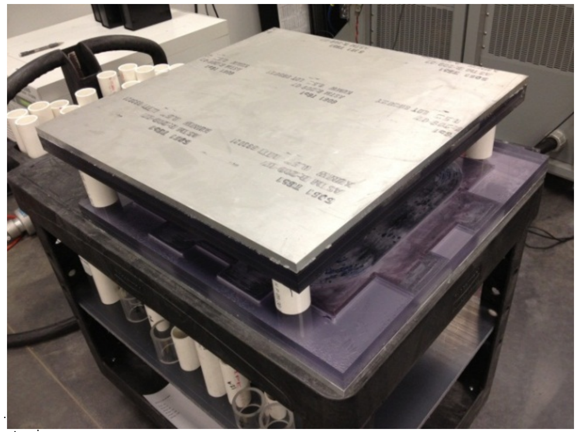


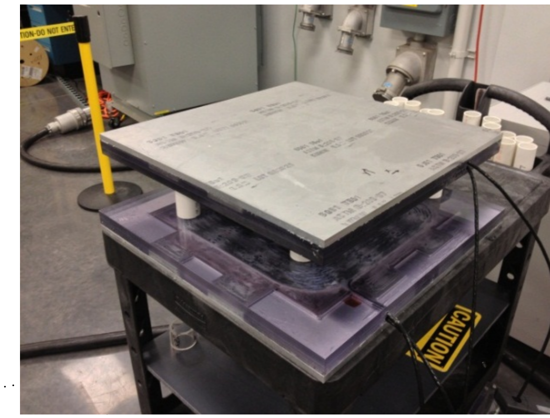


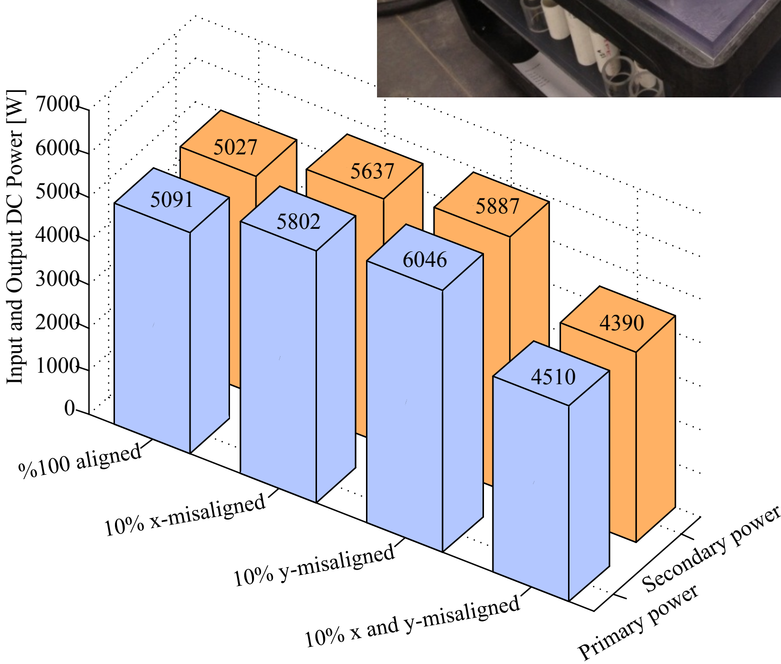
- Test results @160mm airgap at 6.6kW

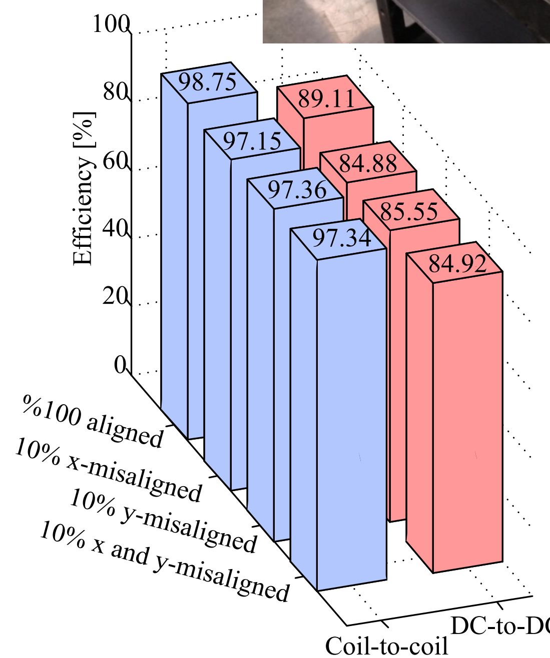
Technical Accomplishments and Progress – FY13 (contd.)

- Misalignment tests at Po=5 kW, +/-10% Δx, +/-10% Δy









Technical Accomplishments and Progress – FY14

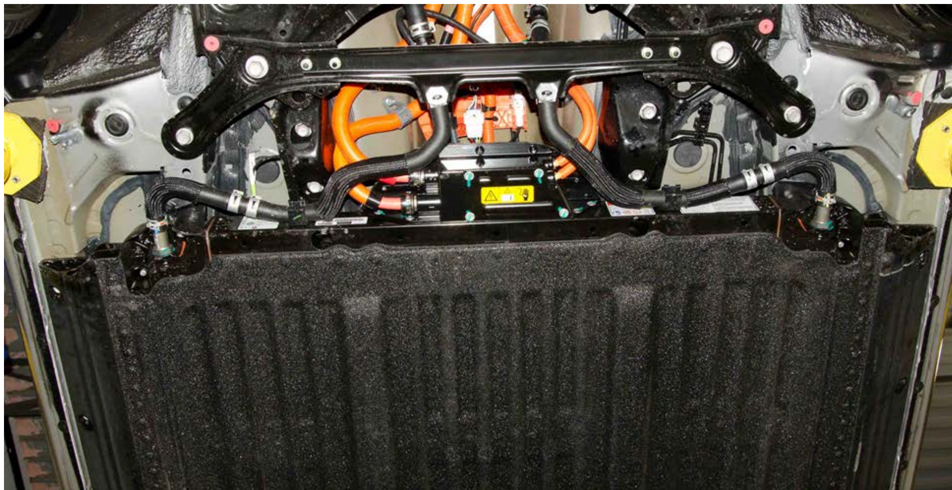
- **SAE J2954 standards development support**

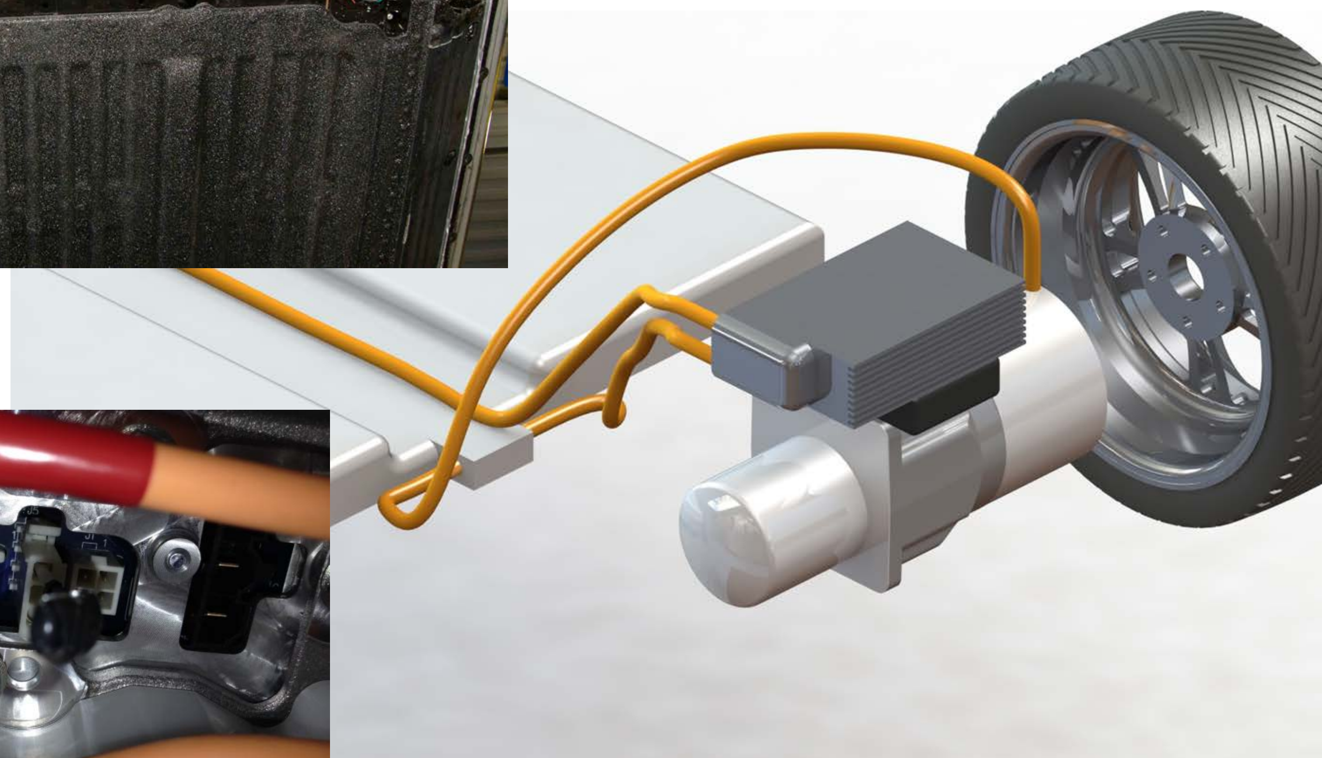
Efficiency	Aligned				10% misaligned			
Frequency (kHz)	22	48	80	142	22	48	80	142
Inverter (%)	98.2	98.8	96.9	98.1	94.7	98.4	98.4	-
Coupler (%)	95.8	96.2	97	85.9	95.5	94.1	89	-
Rectifier (%)	96.9	94.1	94.2	90.5	97	93.5	92.7	-
Overall (%)	91.2	89.4	88.5	76.2	90.5	86.5	81.1	-

Resulting paper: "COMPARISON TESTING OF WIRELESS POWER TRANSFER (WPT) OVER FOUR FREQUENCY BANDS FOR EFFICIENCY AND LEAKAGE FIELDS " Omer C. Onar, et al.

Technical Accomplishments and Progress – FY14

- **OEM agreement and support for technology integration connection points and mounting**





Collaboration and Coordination

Organization		Type of Collaboration/Coordination
Evatran energy without limits	Evatran - Plugless Power	WPT packaging, vehicle integration, vehicle testing
CU-ICAR TOMORROW'S ENGINEER TODAY	Clemson University ICAR	Communications technology, demonstration site
TOYOTA	Toyota Motor Corp	Demonstration vehicles (RAV4) and integration guidance, CAN
Duke Energy	Duke Energy	Grid readiness and interaction
CISCO	CISCO Systems	DSRC Communications

Collaborations

- **SAE J2954 Wireless PEV Charging Task Force**
  - ORNL is a voting member of SAE J2954
    - Support committee with data
    - Center frequency comparison study of 4 considered frequency bands

PROPOSED FUTURE WORK

- **FY2014 (remainder)**
  - Optimize Grid-side unit design for deployment builds
  - Begin integration of WPT technology into OEM supplied vehicles
  - Finalize T&E plan and identify procedures of industry interest and program maximum impact

- **FY2015**
  - Complete facility improvements for Test and Evaluation
  - Demonstration of technology integrated test vehicle and demonstration level grid-side power electronics unit meetings Phase II deliverables
  - Complete technology integration into vehicle fleet
  - Deploy for test and evaluation phase

SUMMARY: Completed Phase I Deliverables and Integration Progress

- WPT of 6.6kW at full system efficiency of 85% made during benchtop demonstration in November 2013
- Toyota CRADA signed, integration design approved, vehicles being prepared for shipment to Integration partners
- Loss of other OEM vehicle partner placed additional stress on program timing and strategy
- Continuing to support standards development with R&D

ACKOWLEDGEMENTS

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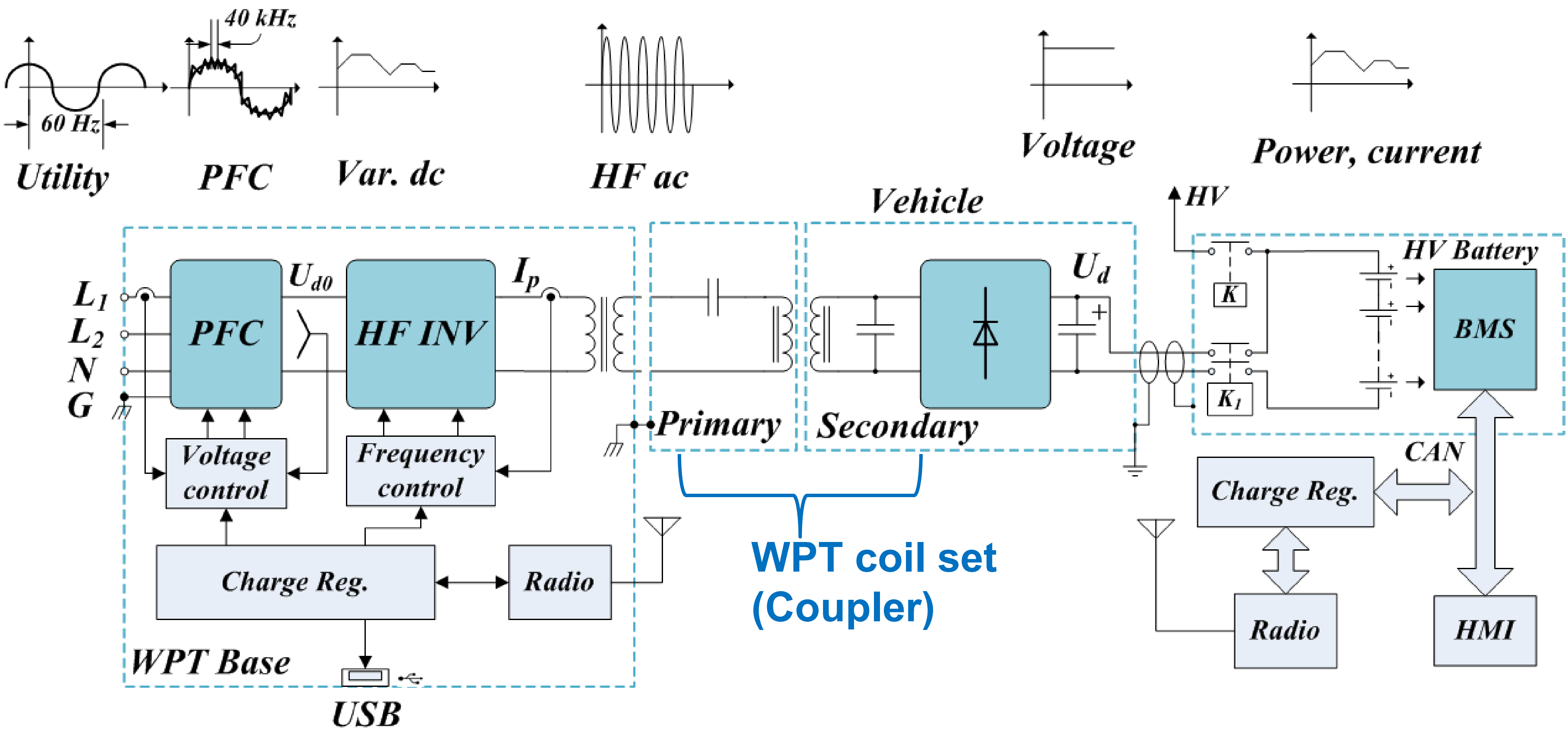
Technical Back-Up Slides

(Note: please include this "separator" slide if you are including back-up technical slides (maximum of five technical back-up slides). These back-up technical slides will be available for your presentation and will be included in the DVD and Web PDF files released to the public.)

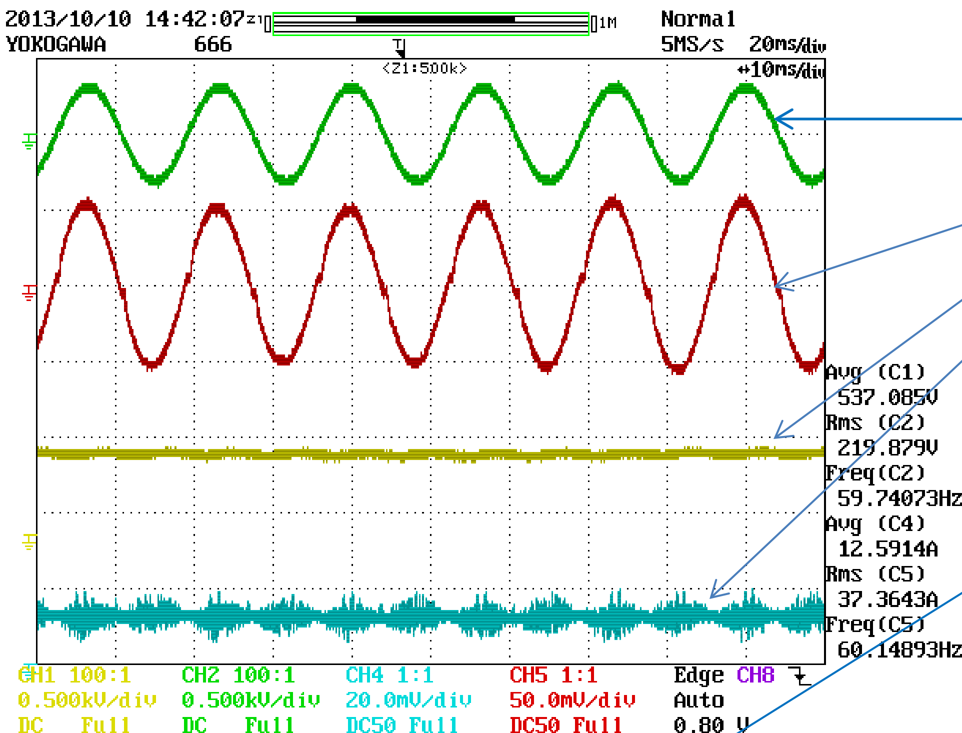
ORNL Grid-side Regulated WPT

- Wireless charging with grid side regulation moves the vehicle OBC function to the grid connection, much the same as DCFC with the addition of a coupler

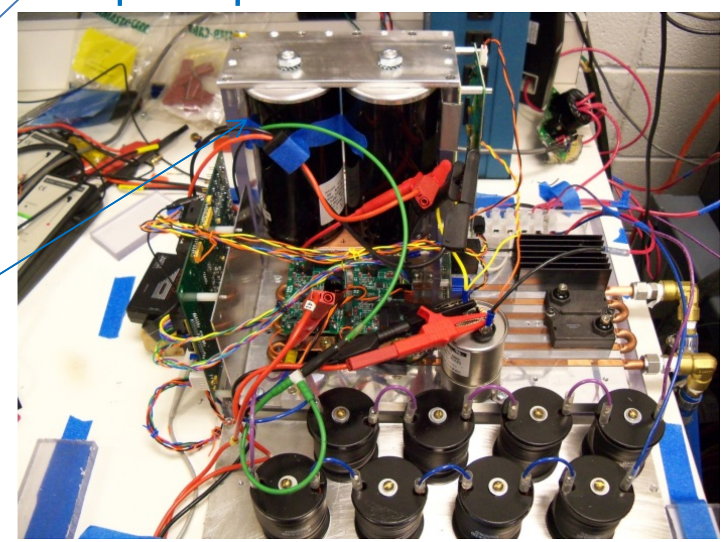


Active Front-End Rectifier with Power Factor Correction

- **2-switch boost type PFC experimental results at 7.7 kW**
  - Input 220Vac; Output: 590 Vdc at 4.65 kW; included in Demo #1
  - Input line current 36 Arms (7.92 kVA); PF~0.99, eff: 96.5% to 97.4%, THD<5%



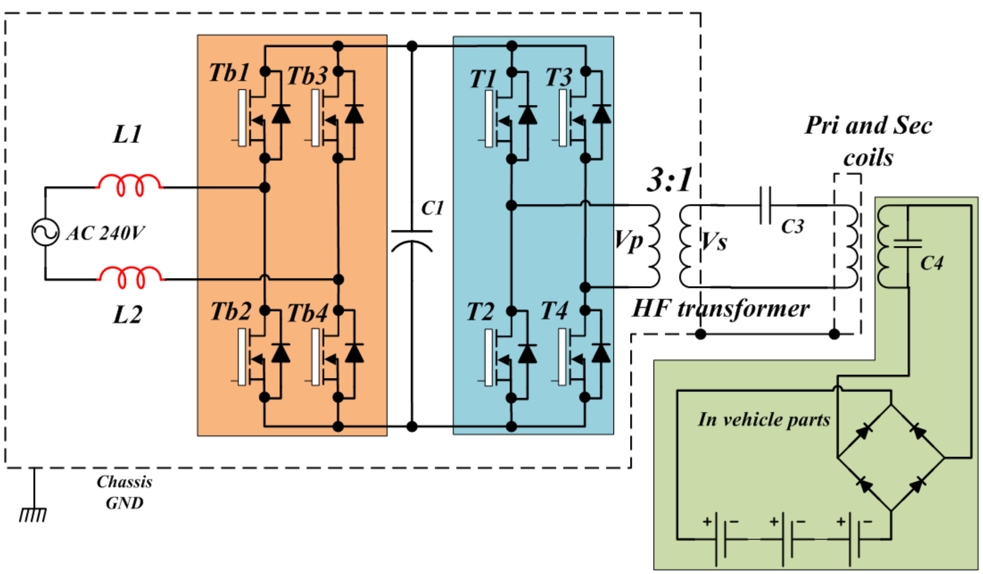
Line Volts: 500 V/div
Line Amps: 50 A/div
Output Volts: 500 V/div
Output Amps: 20 A/div



Capacitors– AVX 800V film main dc link ripple control
HF power inverter snubbers are Kemet 1,000V film
Issue: Dc link high voltage, high ripple current rated, film capacitor

Active Front-End Rectifier with Power Factor Correction

- Only left leg is utilized, right leg acts as diode phase-leg,
- Boost PFC circuit with more than 10 times boosting capability,
- Ideally run at 2-3 times boost factor,
- Can be interleaved for higher power rating,
- APT100MC120JCU2 SiC MOSFET is utilized for high efficiency, low loss, high switching frequency for reduced current ripples.



Control System – HF Inverter

- **Stationary Wireless Charging**
  - ORNL 10 kW WPT demonstration part of DOE DE-FOA-0000667 Oct. 2012
  - Develop deep knowledge in coupling coil design essentials, power flow regulation, leakage field minimization, misalignment tolerance, plus
  - Work closely with SAE J2954 Wireless Charging Task Force on interoperability

$$U_{do} = \left(\frac{\pi}{2\sqrt{2}}\right)\left[|U_s| + r_p|i_p|\right] + U_{sw}$$

$$U_s(t) = \frac{4U_{do}}{\pi}\sin\left(d\frac{\pi}{2}\right)\cos(\omega t) \quad (V_{rms})$$

$$PF = \cos\left(\arg(U_s) - \arg(i_p)\right)$$