Wireless Charging of Electric Vehicles

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Oak Ridge National Laboratory

U.S. DOE Vehicle Technologies Office
2015 Annual Merit Review and Peer Evaluation Meeting

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Project ID: VSS103

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Overview

Timeline

- Project start date: Oct. 2012
- Project end date: Scheduled for November-December 2015
- 75% Complete

Barriers

- Risk Aversion - Partner engagement
- Cost - Transfer from laboratory set-up to integration prototype development
- Lack of Standardized Test Protocols
- Infrastructure – impact of EV charging
- Interoperability with different vehicle energy storage system requirements.

Budget (DOE share)

- DOE funding : $8.0M
- Partner funding : $3.3M

Partners

- Oak Ridge National Laboratory (Project Lead)
  - Power Electronics & Electric Machinery Group
  - Center for Transportation Analysis
- Toyota (CRADA)
- Evatran (Plugless power)
- Clemson University – ICAR Center

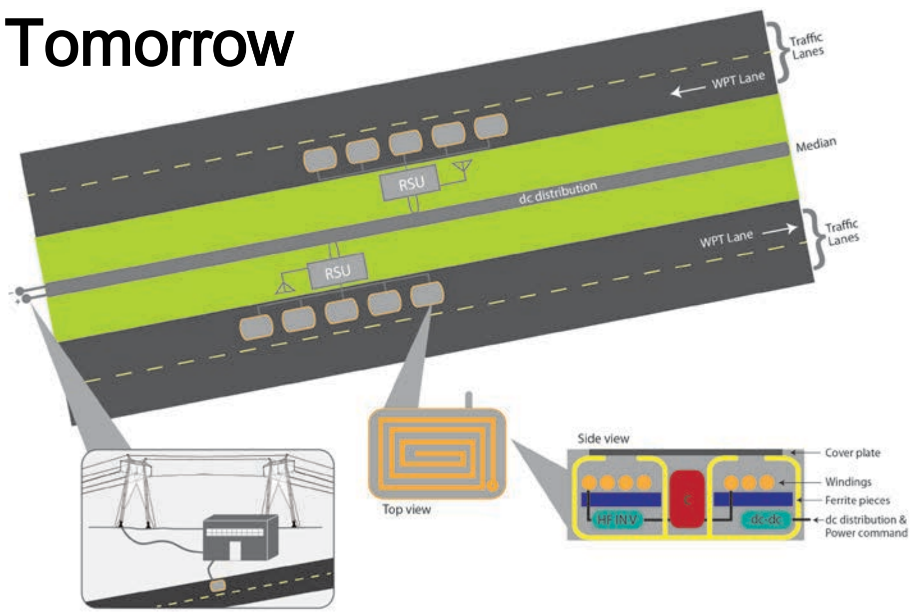
Project Objective and Relevance

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

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

Today

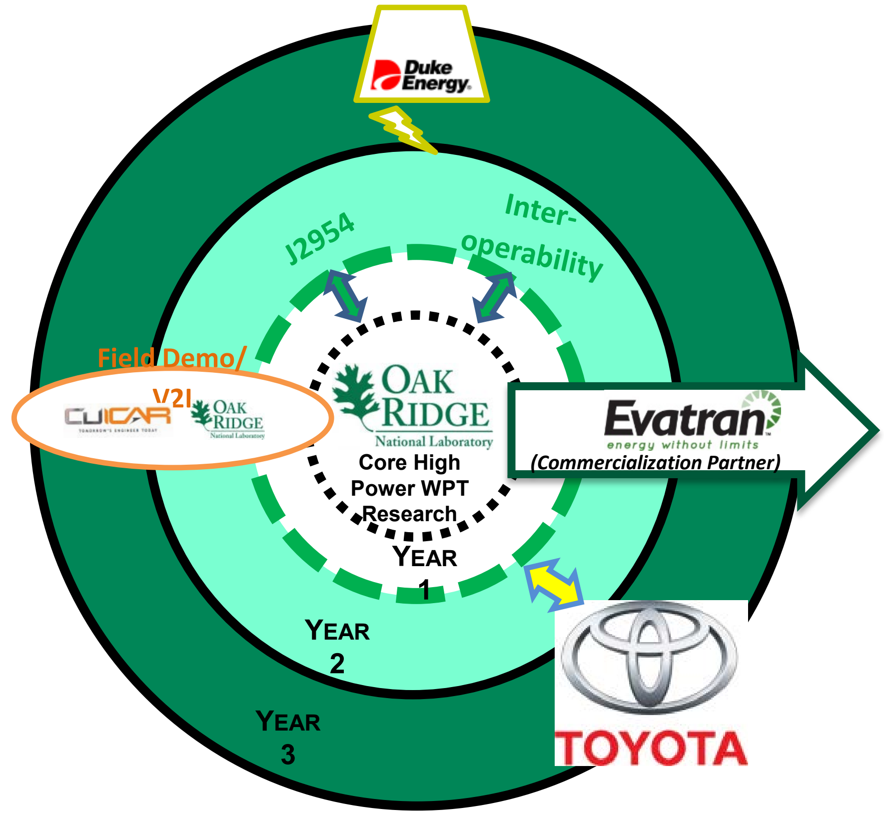
Tomorrow



Objective

- **Objective for FY15:** Coordinate multi-party team activities to integrate the technology developed during the phase I to the vehicles with different WPT charging levels (WPT Level I-II) and different vehicle ESS and interface requirements.

- **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 guidelines (ICNIRP) on high frequency electromagnetic fields and all the other UL and NRTL certification requirements. ORNL interacts with standardization committee -SAE J2954 Task Force for WPT standards development.

Objective–Phase II: Transfer Laboratory Development of Wireless Power Transfer (WPT) Technologies into Vehicle based Test Platforms

"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,
- Develop safety and protection systems in hardware and software to protect the equipment and operating people in the case of a fault or if an over-voltage, over-current, short-circuit, or over-temperature event occurs.
- Research and report on cost savings potential of production run rates of system components.
- Integrate technology into OEM supported vehicles to evaluate technology performance,
- Identify and provide solutions for the integration requirements of different vehicles in terms of voltage range, current range, power level, ramp rates, ripple restrictions, and other OBC and ESS requirements.

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

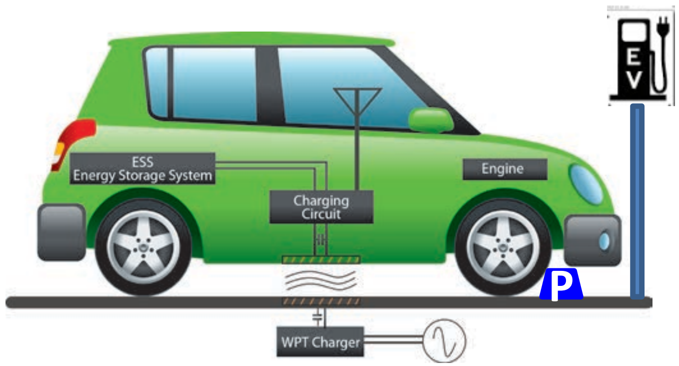
Milestones

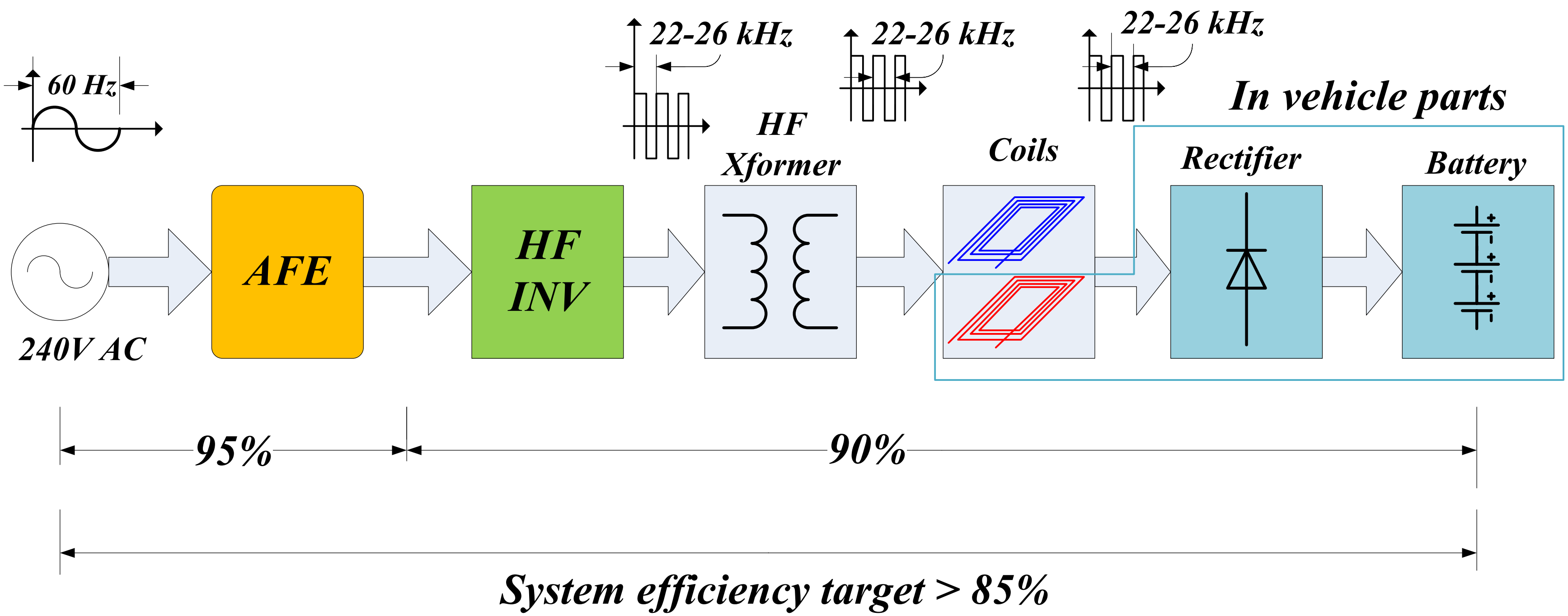
Date	Milestones and Go/No-Go Decisions	Status
Nov-2013	Milestone: WPT efficiency >85% wall to battery (or equivalent) at 6.6 kW power Go /No-Go Decision: Achieves 6.6 kW continuous power at >85% efficiency	DOE and NETL were in attendance at ORNL for bench top demonstration of technology at > 85% @6.6kW, and 10kW non-PFC 89% Efficiency
June-July (TBD) 2015	Milestone: Integrate WPT System into commercial PEV's. Demonstrate 85% efficiency is retained at >160mm airgap at >6.6kW power transfer to the load. Go/No-Go Decision: Vehicle battery charging power regulation performed using dedicated radio communications and message set	Initial Integration designs complete, CRADA completed. Toyota delivered all vehicles. ORNL and Evatran are completing vehicle integrations.
July – August (TBD) 2015	Milestone: Deploy and demonstrate 6.6 kW WPT charging facilities as required to meet Test and Evaluation plans	Working towards vehicle integrations, control system design, and hardware modifications to fit all vehicles with different input requirements.

Note: FY14 milestone: 6.6 kW successful demonstration at ORNL with DOE and NETL representatives present and observing the 85% system efficiency at 160mm airgap.

Approach and Strategy

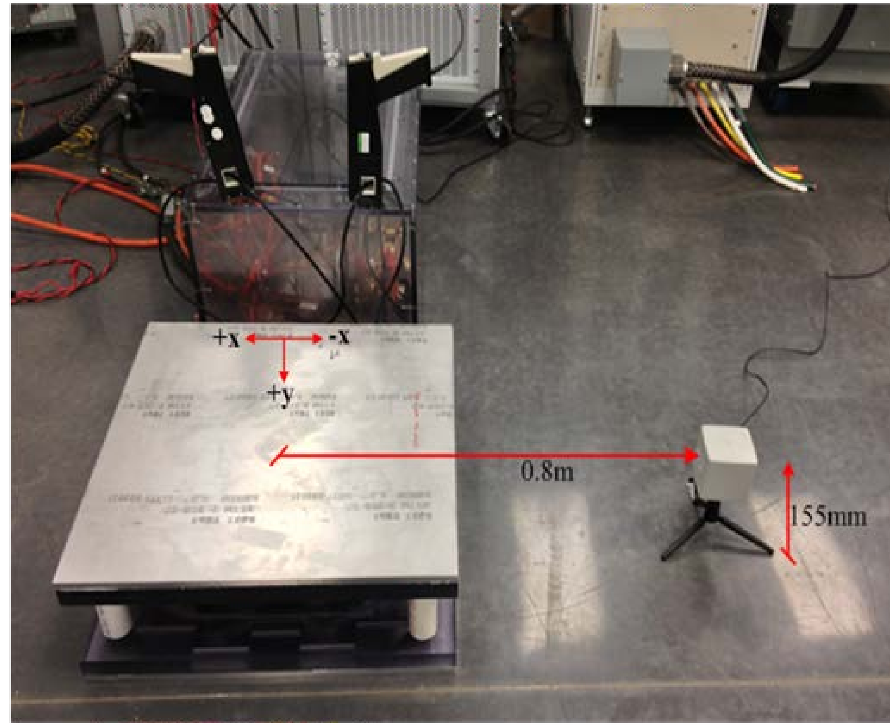
- **National Laboratory Role in Wireless Charging Technology R&D**
  - Intra-lab coordination on WPT R&D
  - Support standards creation thru R&D
  - Assessment of leakage fields
  - Consensus on system efficiency measurement, where measured, and what vehicle functions are to be included in the measurements.





FOA #667 Project Goals

- Complete vehicle integrations
- Validate coupling coil fringe field emissions <6.25 uT and <87V/m at 0.8m from primary coil center.
- Implement bidirectional radio communications that closes the loop on battery charge power regulation
- Integrate WPT technology into demonstration vehicles and evaluate in field testing



FOA #667 Project Goals

- Complete vehicle integrations

1) **Chevy Volt: Need to go through the OBC. It can work with 220V AC and can work with 185-265V DC input. -3.3kW.**

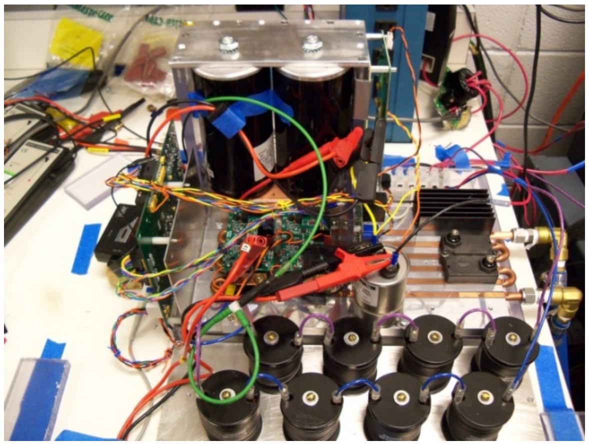
2) **Toyota Prius Plug-in: Cannot work with DC input. Only works with regulated 220-240V RMS AC voltage input with 50/60Hz frequency. -2.1kW.**

3) **Scion IQ EV: Nominal battery voltage is 277V, CHAdeMO connector input needs >277V, need to respond quickly after receiving charging request, need to be within the current ramping time limits and . -6.6kW.**

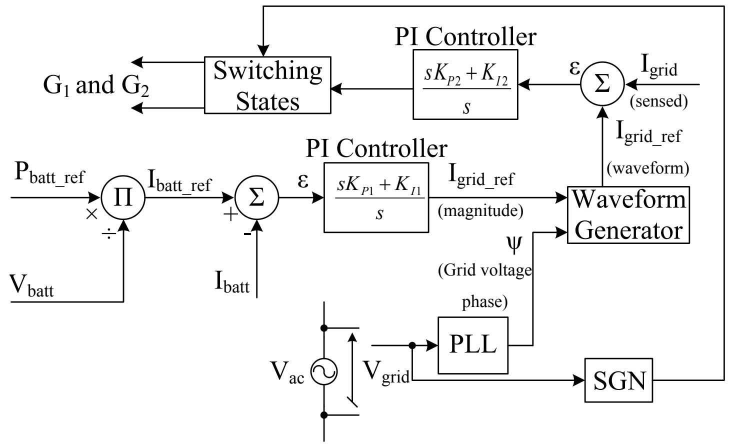
4) **Toyota RAV4: 392.5V add-on battery pack nominal voltage, direct battery connection, most likely voltage applied to battery terminals should be 400-420V for rated power charging. -6.6kW**

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

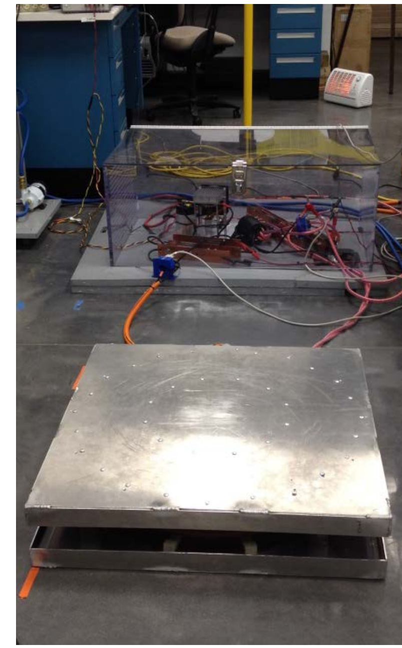
- SiC Active Front-end Rectifier (AFER) with power factor correction (PFC)



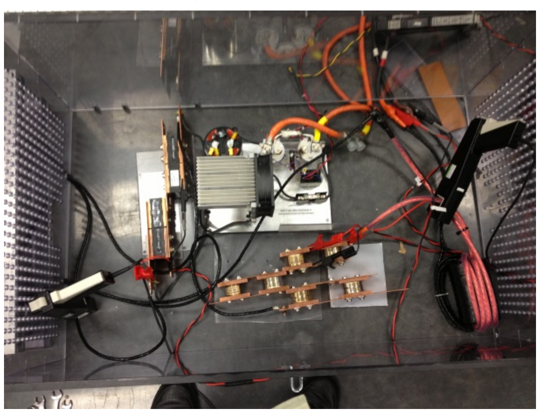
- PFC converter control system



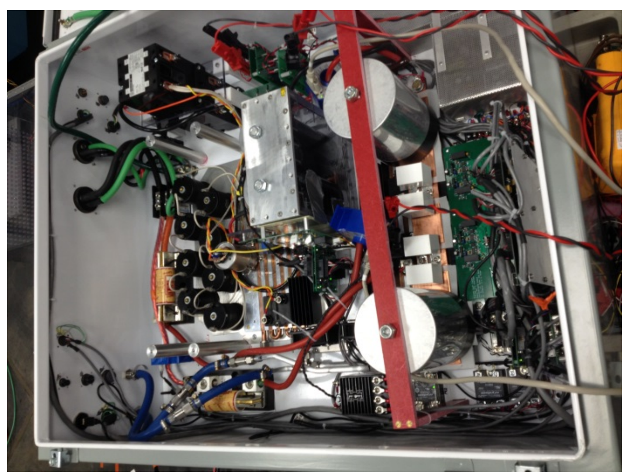
- Primary and secondary coils



- Tuning capacitors and HF transformer

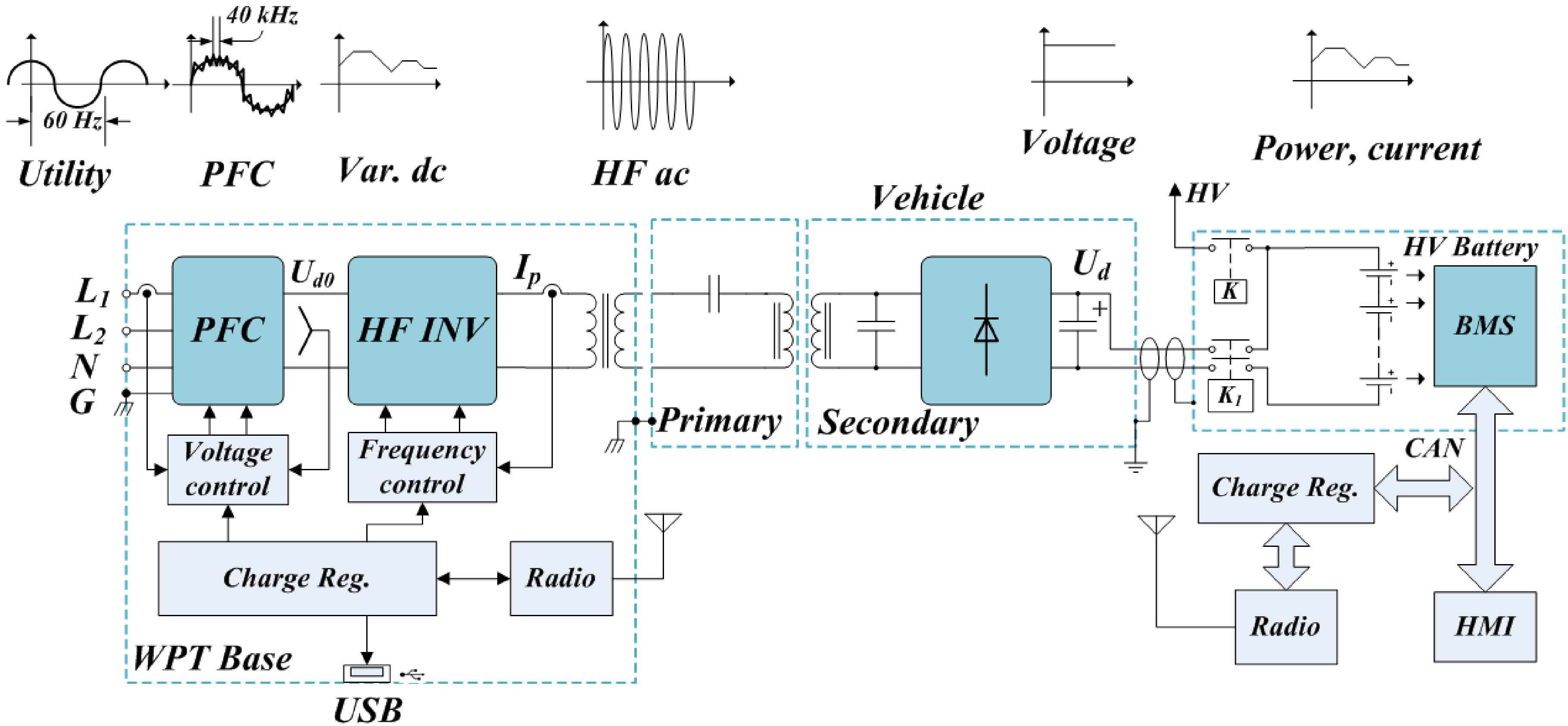


- Integrated PFC and HF power inverter



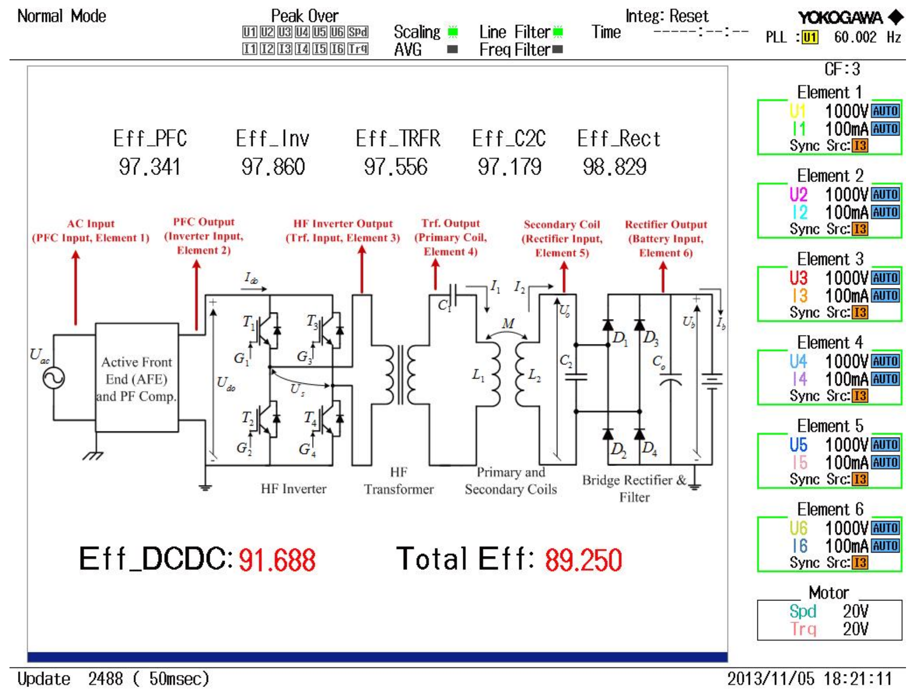
Technical Accomplishments: Complete System Integration for Test Bench Demo- FY13/14 Milestone

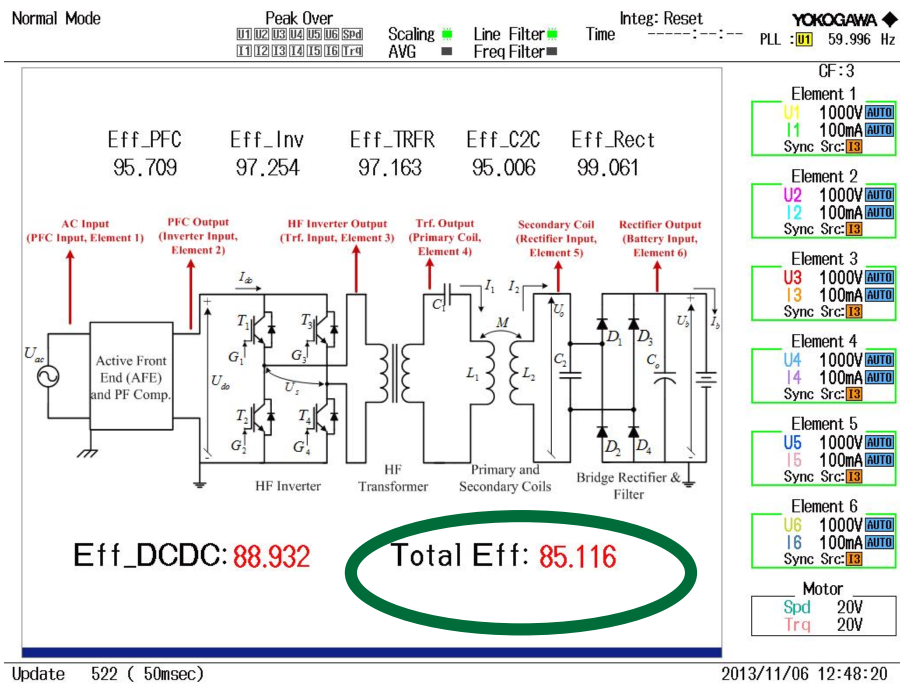
- Targeting grid side regulation with a single grid side unit adapting the requirements from different vehicles with minor hardware modifications on each vehicle.
- Built a control system in collaboration with Evatran that allow fully automated operation, control, monitoring, and switch between operating modes.



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 – FY15

- OEM agreement, collaboration, and support for technology integration connection points and mounting
- Prius Plug-in Integration

- Radio (on top)
- Vehicle side electronics: Evatran control module, radio interface, minimum load resistor, protection system, relays and contactors, interface to the OBC

Technical Accomplishments and Progress – FY15

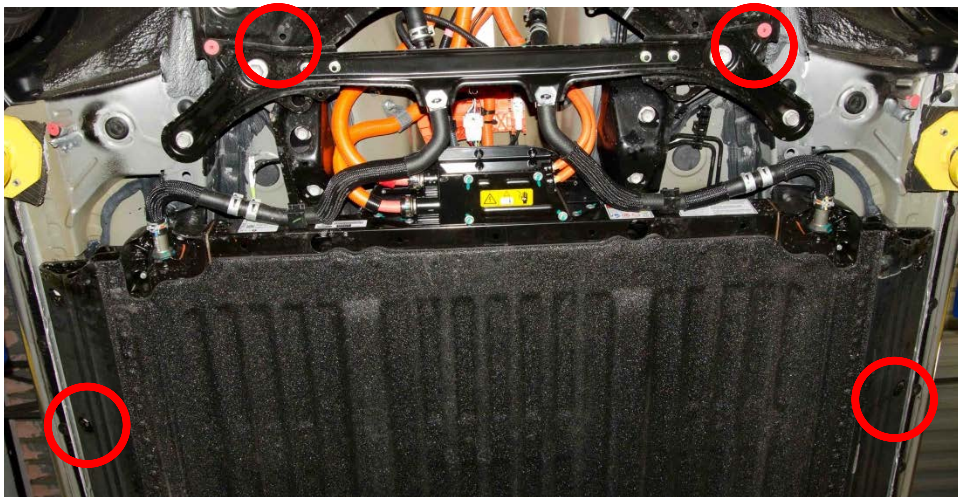
- OEM agreement, collaboration, and support for technology integration connection points and mounting
- Scion IQ-EV Integration

- CHAdeMO connector with contactor interface.
- DC output of the WPT system at the vehicle (after rectifier) is connected to the CHAdeMO that makes the interface to the vehicle battery.
- System needs to timely respond to the charging request, needs to tightly regulate the reference charging current, current needs to be within certain ripple limits.

- Coil location and trunk area for vehicle side electronics.

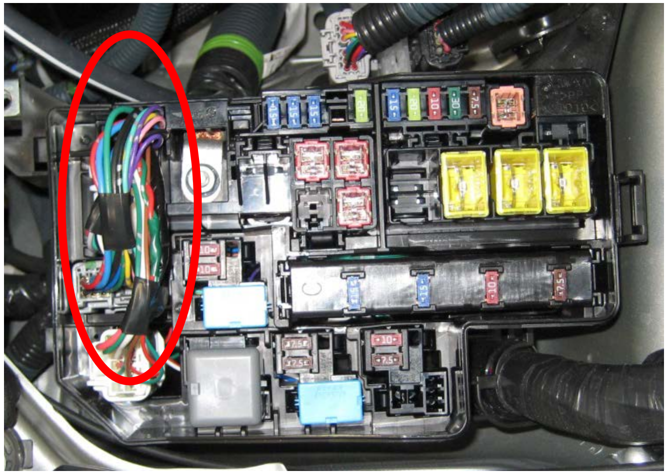
Technical Accomplishments and Progress – FY15

- OEM agreement, collaboration, and support for technology integration connection points and mounting
- RAV4-EV Integration



- Coil mounting location.

- Other electronics added by Toyota to have external charge & discharge path for the add-on battery pack (for integrity and as a back-up to wireless)



- Vehicle CAN bus connection location for closed loop feedback and controls.

Technical Accomplishments and Progress – FY15 cont'd

- Site Improvements

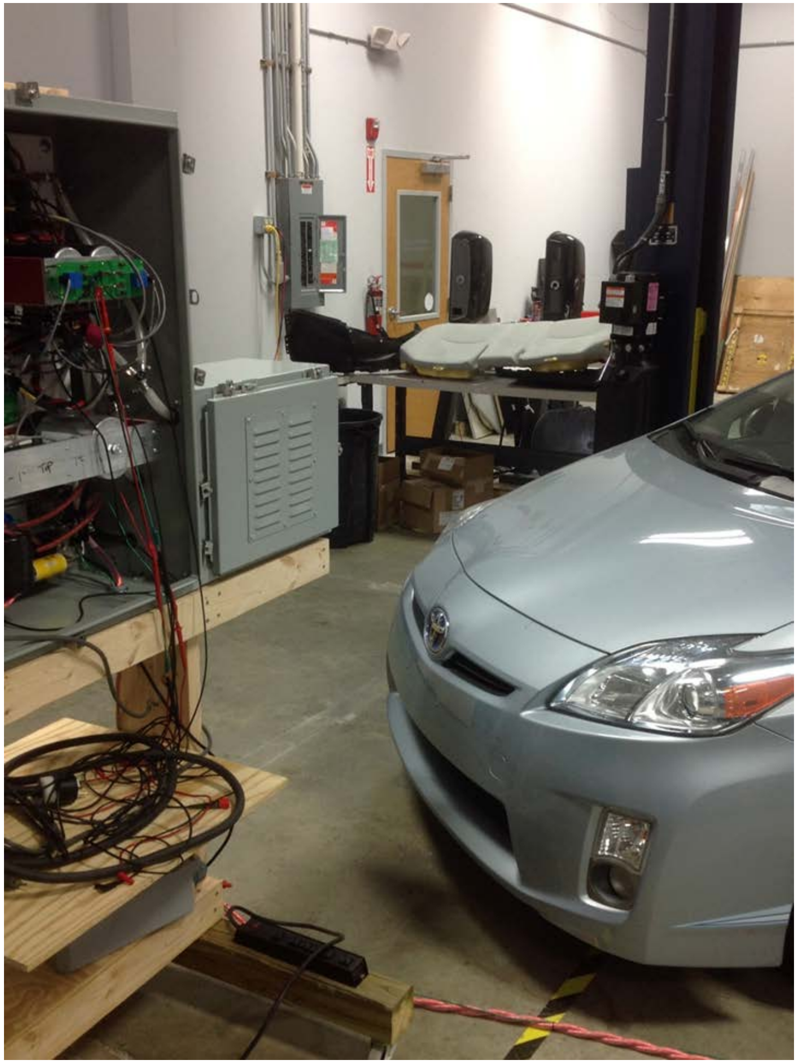
CUICAR
TOMORROW'S ENGINEER TODAY

- CU-ICAR resources supported by ITIC

- Communications development

Project Progress – FY15 cont'd

- Vehicle delivery and continued integration



TOYOTA

Response to Previous Year Reviewer's Comments

- **Q1)** One of the reviewers would like to see more emphasis on the "uniqueness" of ORNL's developed wireless power transfer technology. The reviewer thought it was a little "undersold" in the presentation. The commenter requested that presenter should have shown why ORNL is good at this, and why it is not coming from industry
- **A1)** Wireless power transfer system is a complex structure involving knowledge and experience on power electronics, magnetics design, energy storage system, and vehicle systems. One industrial organization may not have all of these capabilities at the same time. However, ORNL is the primary national laboratory in the field of advanced power electronics and electric machines. Due to the uniqueness of the project and the multi-disciplinary requirements, ORNL is a unique organization to develop the technologies that cannot easily designed, developed, built, integrated, and tested at the industry.
- **Q2)** The reviewer pointed out that the technical accomplishments were being met and that the project was on track. One thing that was not clear was whether the SAE decision to go with a different frequency would negatively impact this project going forward and whether Evatran would abandon the technology in favor of one that adheres to the SAE standard. The reviewer suggested that providing evidence of a contingency plan for this situation and a discussion of what the reasons are for the SAE decision would be good additions to future presentations.
- **A2)** ORNL is currently working on wide bandgap device technologies what will meet the 85kHz center frequency as indicated in the SAE J2954 TIR. Currently, ORNL designed SiC power converter is one of the very few developments that can meet high frequency requirements while still allowing to transfer high power (WPT Level-2) at target efficiencies. The inverter was tested at 10kW at 85kHz with an efficiency of >98%.

Partners / Collaborators

Organization		Type of Collaboration/Coordination
Evatran	Evatran - Plugless Power	WPT packaging, vehicle integration, vehicle testing
CU-ICAR	Clemson University ICAR	Communications technology, demonstration site
TOYOTA	Toyota Motor Corp	Demonstration vehicles (Prius Plug-in, Scion IQ-EV, RAV4) and integration support, CAN
Duke Energy	Duke Energy	Grid readiness and interaction
CISCO	CISCO Systems	DSRC Communications

- **ORNL supports SAE J2954 Wireless Charging Standards Development Committee and its subcommittees.**

Proposed Future Work

- FY2015 (remainder)
  - Complete integration of WPT technology into OEM supplied vehicles, build and fine-tune control systems depending on vehicle charging protocols & requirements
  - Demonstrate technology integrated test vehicle and grid side unit meeting the Phase II requirements
  - Proceed with the T&E plan and identify procedures of industry interest and program maximum impact
  - Deploy for test and evaluation phase at ITIC in Greenville, SC

Summary

- **Previously achieved WPT of 6.6kW at full system efficiency of 85% made during benchtop demonstration in FY2014, and integrating system testing in FY2015.**

- **Integration designs approved by Toyota, vehicle deliveries are 100% complete and system integrations are 70% complete**

- **Continuing to support standards development with R&D**
  - Address vehicular interoperability at the system level (not only the coupling subsystem) and address vehicle side requirements for a range of vehicles with different voltage and power ranges, different connector types, and various charging profiles and protocols.
  - International interest in higher power transfer levels and initial dynamic deployment will provide research topics at testbed beyond phase III

Acknowledgments

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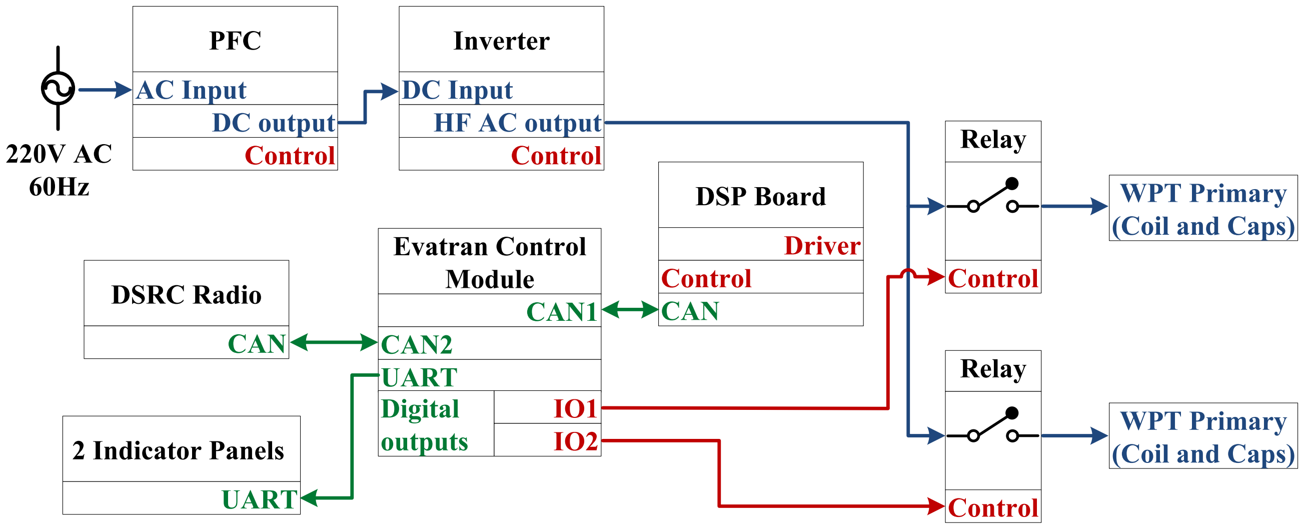
Technical Back-Up Slides

Grid Side Unit Operational Block Diagram



DSP Board Functions

Controls PFC operations
Controls inverter operations
Internal safety checks
(over-voltage, over-current, etc.)

Receives system status from Evatran controller
Receives secondary set points
Receives secondary feedback
Sends status information to Evatran controller
Regulates for secondary setpoints

WPT Primary Functions

Couple to secondary
Perform power transfer

DSRC Radio Functions

Establish radio rink
Verify system compatibility
Communicate to secondary side controller
Provide date and time

Indicator Panel

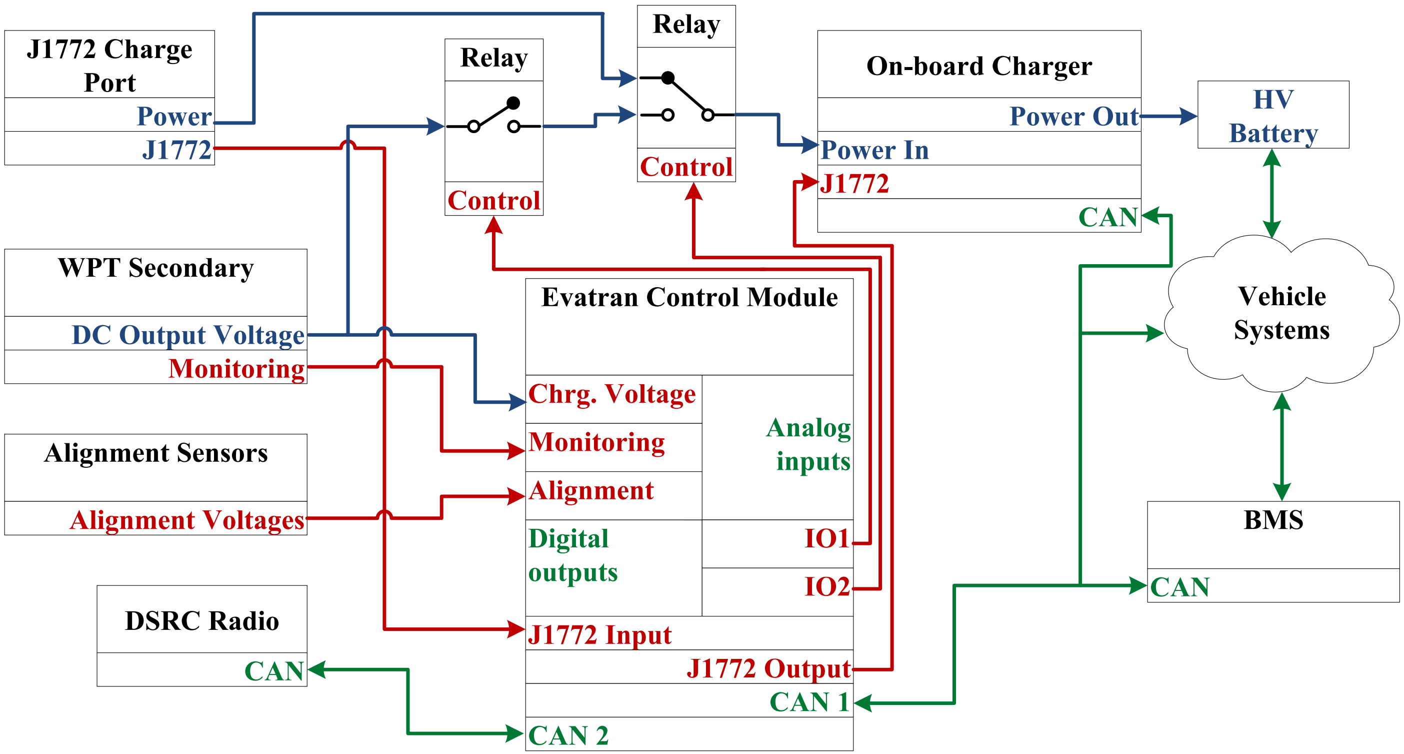
Alignment indications:
- Forward/Back/Left/Right
- Stop

System Status Indications
- Idle
- Charging
- Error

Evatran Controller Functions

Control indications
Control of charging pad relays
Control system state
(alignment, charging, idle)
Forward secondary set points to DSP
(DC voltage, DC current)
Forward secondary feedback to DSP
(AC voltage, DC voltage, DC current)
Receive status information from DSP
Receive CAN information from radio
Send vehicle side command to radio

Prius Plug-in Integration Through J1772 OBC



OBC Charger Functions

- High voltage DC output to battery
- Controls charge rate
- Communicate with BMS

DSRC Radio Functions

- Establish radio rink
- Verify system compatibility
- Forwards CAN messages from Evatran Controller
- Provide date and time

WPT Secondary (Coils/ Caps/Rect.) Functions

- Couple to primary
- Rectify voltage
- Bulk storage
- DC output
- Minimum load
- Pre-charge circuit
- Safety relay

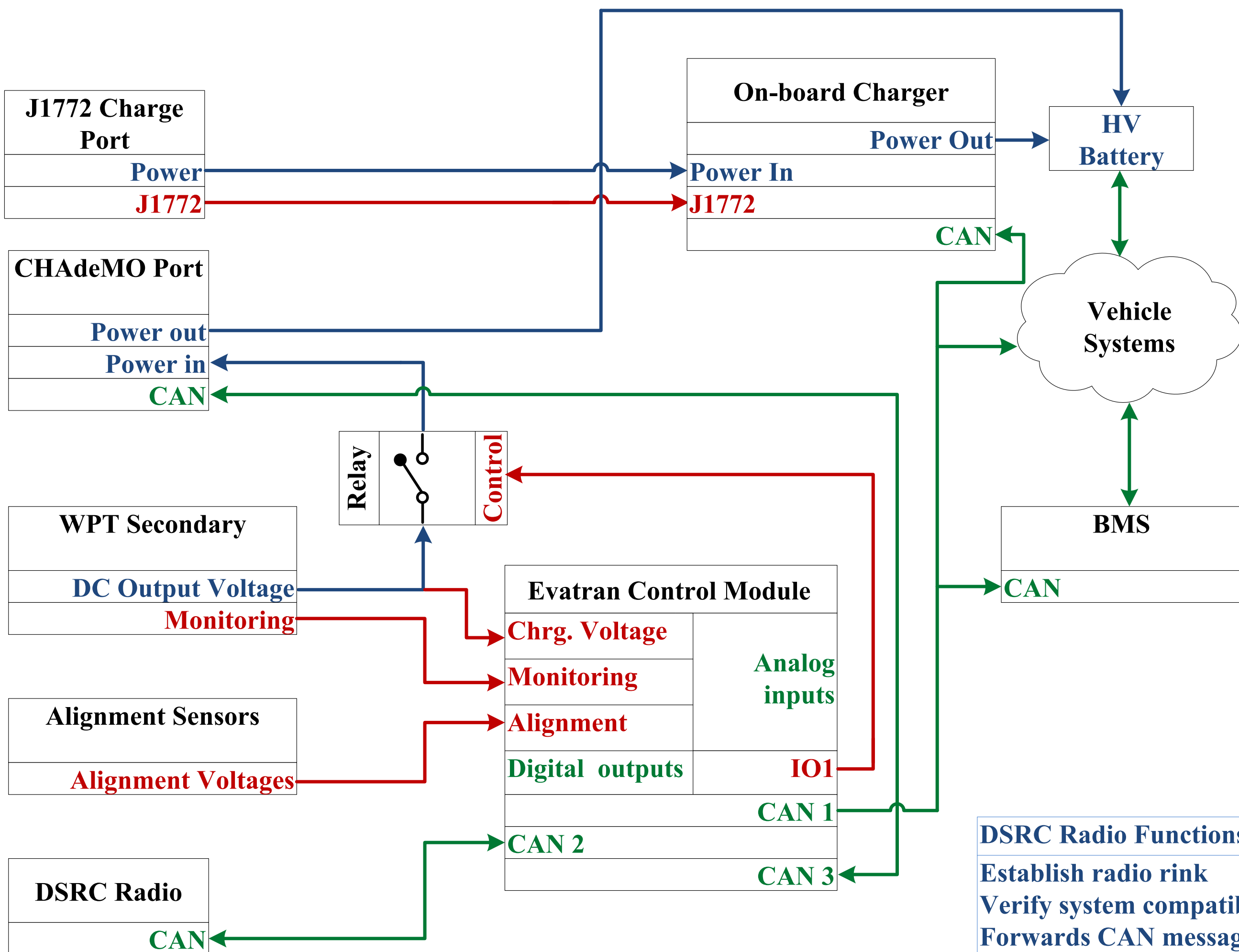
Evatran Controller Functions

- Measure secondary analog values (AC voltage/DC voltage/DC current/Temp.)
- Measure alignment signals
- Sends measurements to radio
- Sends status messages to radio
- Receives commands from radio
- J1772 protocol support
- Discrete outputs (relay control)
- OBD2 CAN monitoring

Safety interlocks:

- Close safety relay on over-voltage
- Open charging relays on over-voltage
- Close safety relay on over-current
- Open charging relays on over-current

Scion IQ-EV Integration Through CHAdeMO



WPT Secondary (Coils/Caps/Rect.) Functions

- Couple to primary
- Rectify voltage
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- DC output
- Minimum load
- Pre-charge circuit
- Safety relay

Evatran Controller Functions

- Measure secondary analog values (AC voltage/DC voltage/DC current/Temp.)
- Measure alignment signals
- Sends measurements to radio
- Sends status messages to radio
- Receives commands from radio
- CHAdeMO protocol support (CAN)
- Discrete outputs (relay control)
- OBD2 CAN monitoring

Safety interlocks:

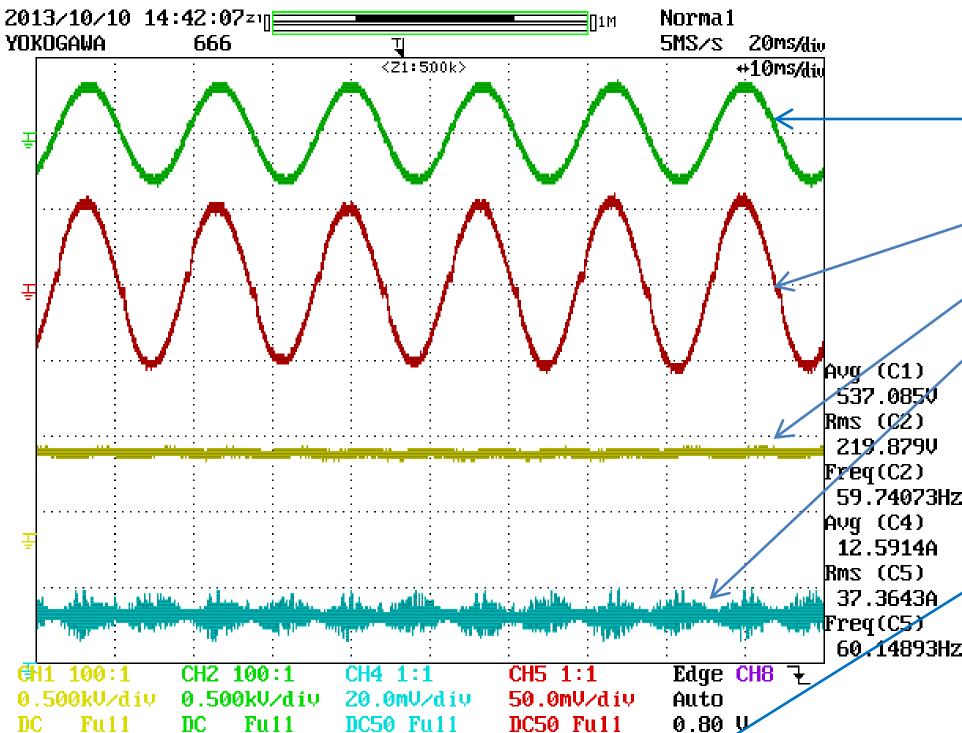
- Close safety relay on over-voltage
- Open charging relays on over-voltage
- Close safety relay on over-current
- Open charging relays on over-current

DSRC Radio Functions

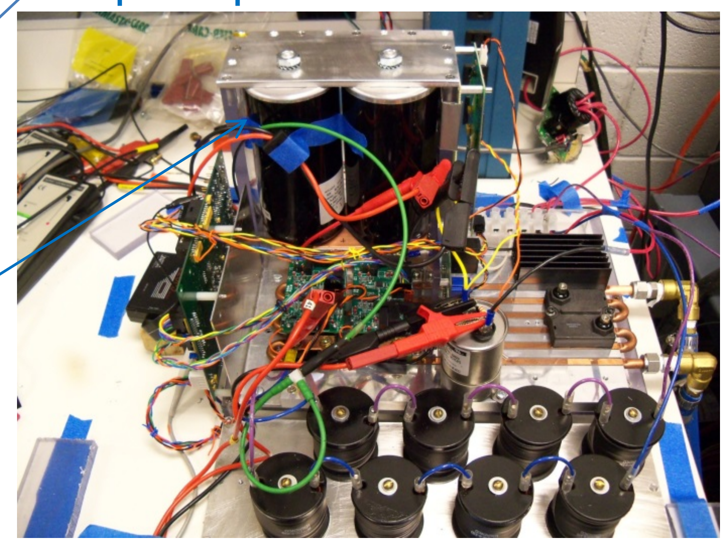
- Establish radio rink
- Verify system compatibility
- Forwards CAN messages from Evatran Controller
- Provide date and time

Active Front-End Rectifier with Power Factor Correction – Meeting Grid Power Quality Requirements

- 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