Wireless Plug-in Electric Vehicle (PEV) Charging

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Project ID: VSS061

2012 U.S. DOE HYDROGEN and FUEL CELLS PROGRAM and VEHICLE TECHNOLOGIES PROGRAM ANNUAL MERIT REVIEW AND PEER EVALUATION MEETING

Overview

Timeline

- Start – Oct. 2010
- Finish – Sept. 2012
- 75% complete

Budget

- Total project funding
  - DOE share – 100%
- Funding received for FY12
  - $1,000K

Partners/Advisors

- ORNL Fusion Energy RF experts

Barriers and Opportunity

- Plug-in Electric Vehicles (PEV) are burdened by the need for cable and plug charger, galvanic isolation of the on-board electronics, bulk and cost of this charger and the large energy storage system (ESS) packs needed.
- Wireless charging opportunity:
  - Provides convenience to the customer.
  - Inherent electrical isolation.
  - Regulation done on grid side.
  - Reduce on-board ESS size using dynamic on-road charging.
- Program targets
  - Level II charging at 3.6kW to 19kW level
  - On road stationary charging (stop sign, lay-by)
  - On road dynamic charging (vehicle in motion)

Objective

Objective for FY12

- Extend prior ORNL work based on air core, copper tube, high current Wireless Power Transfer (WPT) to SAE level 2 stationary charging at 6.6 kW and >90% overall efficiency in a test and demonstration vehicle
  – Loosely coupled magnetic resonant transformers having air core cannot meet health and safety targets, therefore, novel soft ferrite cores are employed
  – Target for Vehicle application: Level 2 charging, 6.6 kW, 150 < z < 200mm

Overall program

- Demonstrator vehicle operational with WPT at 6.6 kW power level and radio communications in the regulation feedback path to grid-tied power inverter
  – Demonstrate short range communications in bidirectional communications path
  – Comply with international emissions guidelines of 6.25uT average body exposure and <27.3uT peak magnetic field exposure in the public zone.
  – Demonstrate CAN gateway to vehicle BMS for control and regulation signals.

Milestones

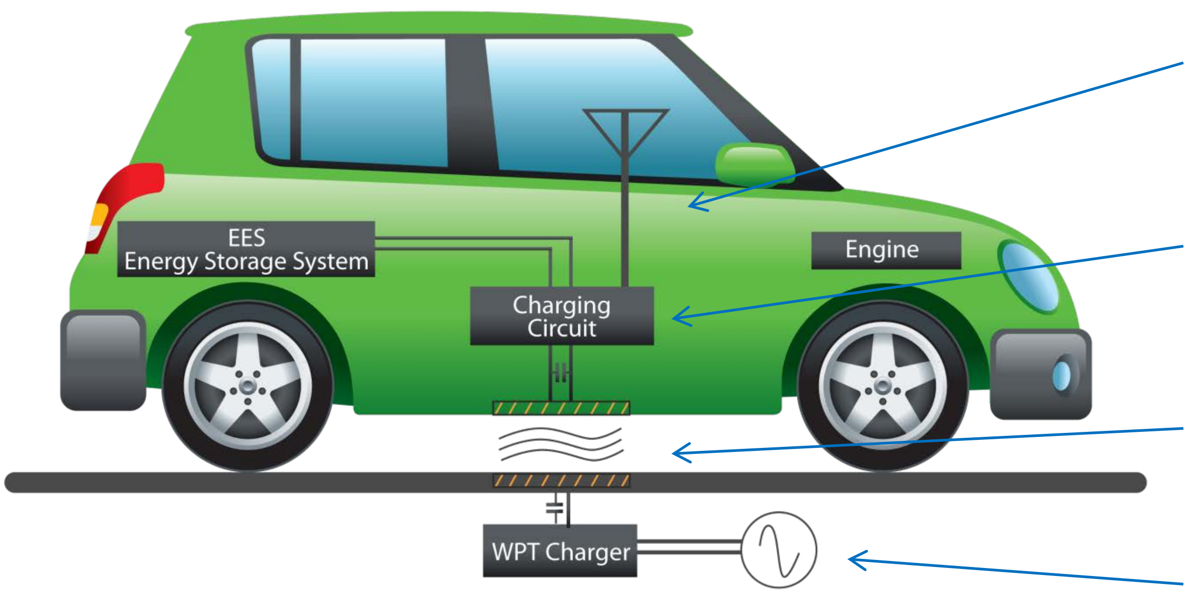
Month/Year	Milestone or Go/No-Go Decision
April-2012	Milestone: coils designed and tested for 7kW power level Milestone: power inverter fabricated and tested using new coupling coils and loaded using battery eliminator at 7kW Milestone: power flow control algorithm validated on bench with prototype inverter, coupling coils and rectifier-filter
July-2012	Milestone: Functional demonstration WPT equipped vehicle tested in laboratory Go/No-Go Decision: Primary side power control algorithm maintains desired regulation at vehicle battery pack
Sept-2012	Milestone: Demonstrate vehicle wireless charging with radio in feedback loop and CAN gateway to vehicle BMS Milestone: Demonstrate WPT control metrics: charge initiation, charge regulation vs SOC, charge termination, safety shut-down

Approach

- **Development activities focused on demonstration of highest efficiency, most compact, and lightest WPT system for future commercialization**
  - **Power inverter based on best available silicon IGBT technology, but including assessment of next generation devices**
  - **Coupling coil design supported with detailed EM FEA to guide material and structural design to be mechanically robust, magnetically shielded and electrically lowest loss**
  - **Minimized mass and size of vehicle mounted secondary coil, rectifier, filtering, cabling and disconnect components**
  - **Control strategy is primary side regulation of power flow based on vehicle BMS messages and algorithm tailored to primary coil excitation voltage (duty cycle) and frequency inner loops**

Approach (contd.)

- **Design and develop a minimal complexity system suitable for vehicle integration for stationary wireless charging.**
  - **Technically: a non-radiating, near field reactive zone power transfer method**
  - **Practically: a convenient, safe and flexible means to charge electric vehicles.**



Vehicle to WPT base unit communications (radio) in regulation outer loop

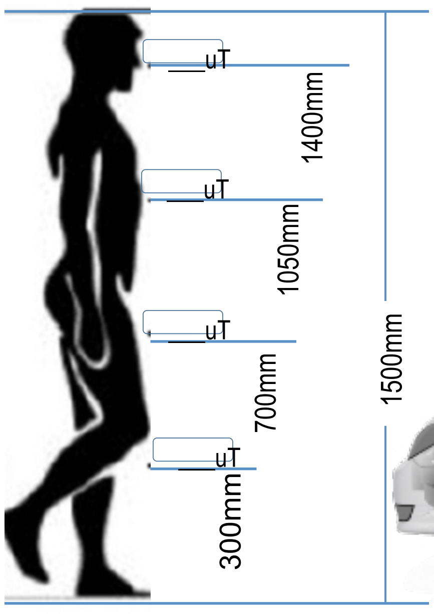
Lightest, most compact secondary coil, rectifier, filter and CAN/BMS interface to radio

Active to public zone field meets international standards (ICNIRP) at 4 measurement points

Smart grid compliant utility feed and modern power electronics

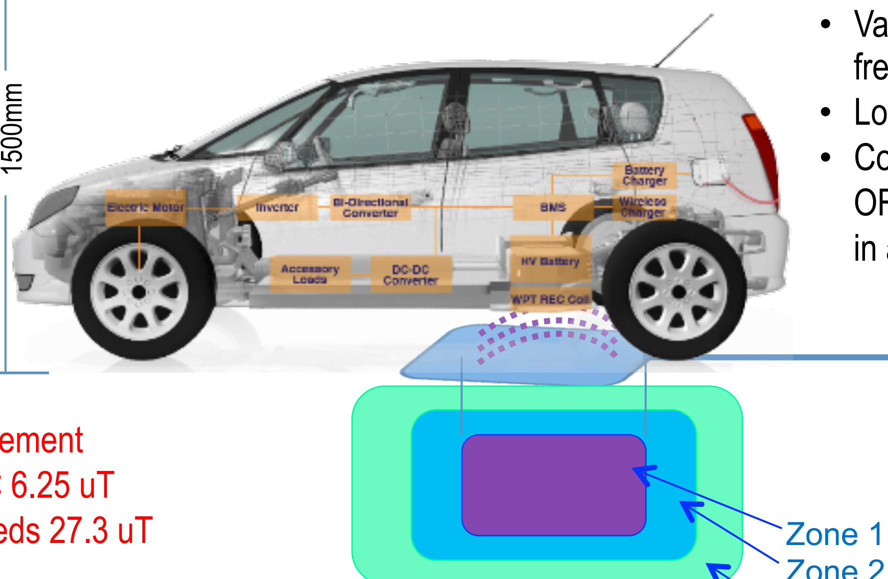
Approach (contd.)

- **Health and safety paramount in all aspects of WPT development work: high voltages, magnetic fields, high power**
  - **Primary coil field shaping, vehicle chassis/wiring shielding, alignment tolerance**
  - **Validation of fringe field levels using Narda EHP-50D EH Field Analyzer**



Also of interest:

- Validation of WPT harmonics and frequency interference
- Long term effect of magnetic field on tires
- Concrete and asphalt characterized by ORNL and show minimal added loss when in active zone

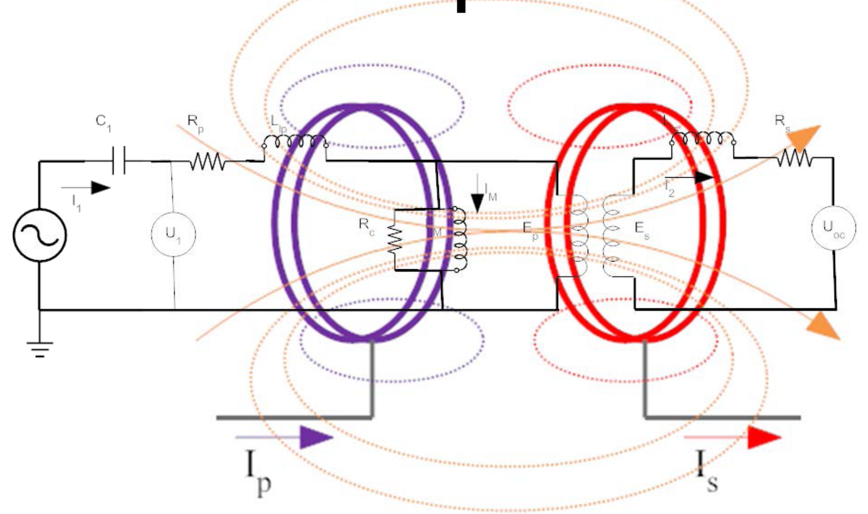


Record average of 4 measurement points and validate ______ < 6.25 uT
No field point recorded exceeds 27.3 uT

Zone 1: Active field, ~1m2, <500uT
Zone 2: Transition:300mm boundary
Zone 3: Public zone: Field focusing & shielding <62.5mG (incl.cabin)

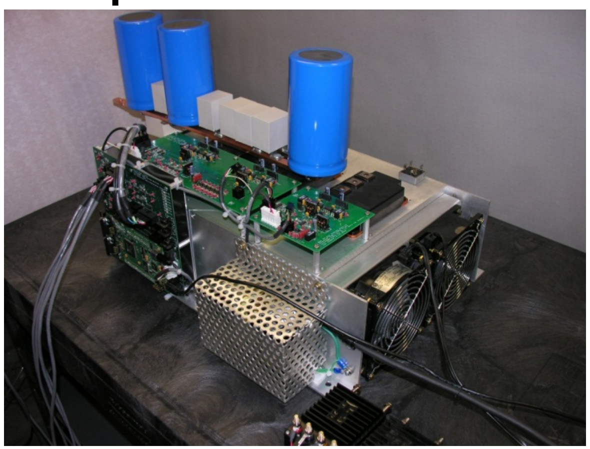
Technical Accomplishments and Progress - Overall

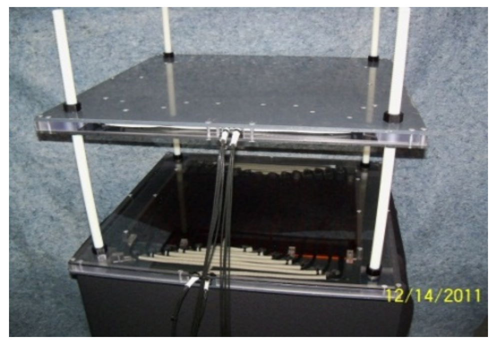
- ORNL team gave highest priority to grid-tied converter control and coupling coil design highest priority this period.
  - The coupling element is a transformer. Like all transformers it has leakage.
  - Primary and secondary capacitors are used to “cancel” this leakage and thereby admit highest possible primary current for power level it’s designed for.
  - Concrete and metal objects in the primary active and transition “fringe” zones act as lossy elements in the magnetizing branch of the equivalent circuit (Rc below)
- WPT requires dynamic manipulation of primary voltage and inverter frequency to meet load and gap changes
- Vehicle integration activities present new challenges

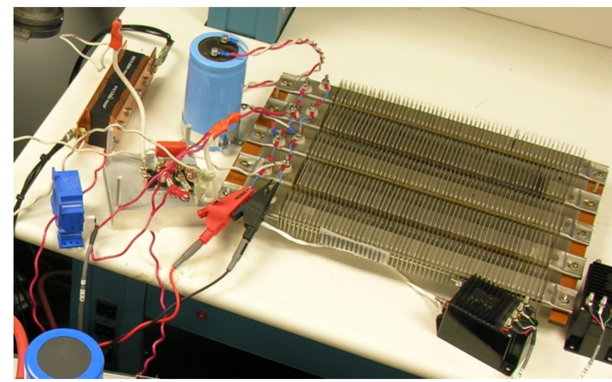


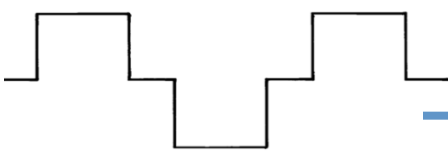
Technical Accomplishments and Progress – FY12 (contd.)

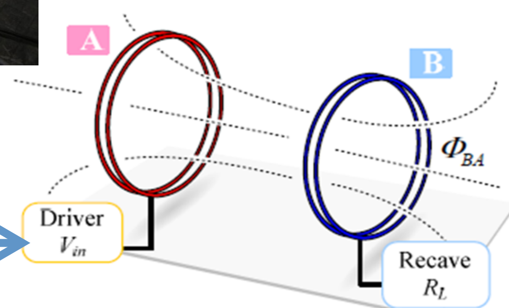
- Power inverter based on best available silicon IGBT technology, now includes assessment of next generation devices. WPT experimental hardware shown for reference
  - Experimental inverter   new coupling coils   5 kW dc load and filters

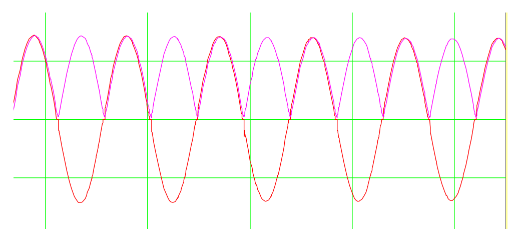












$$U_1(t) = \frac{4U_{dc}}{\pi}\sin\left(d\frac{\pi}{2}\right)\cos(\omega t)$$

3 control parameters: U_{dc}, d, ω

Technical Accomplishments and Progress – FY12 (contd.)

- **Future WPT grid-tied power converters have opportunity to use new ultra-thin IGBT's with 10x switching speed of IGBT modules in our present design**

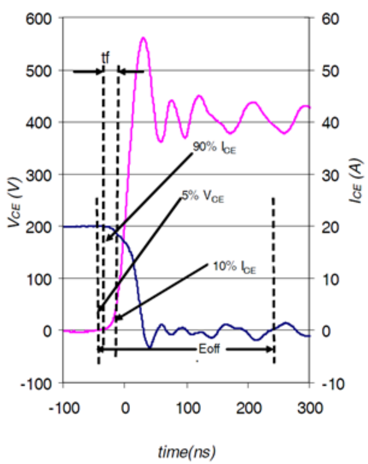


Fig. WF1 - Typ. Turn-off Loss Waveform
@ T_J = 175°C using Fig. CT.4

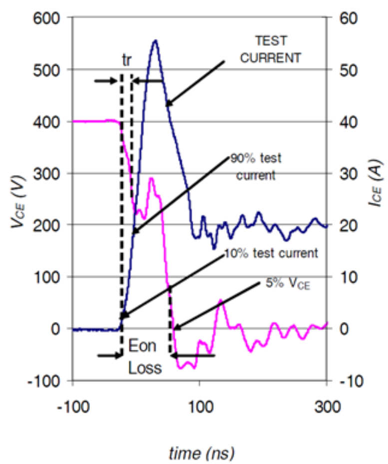
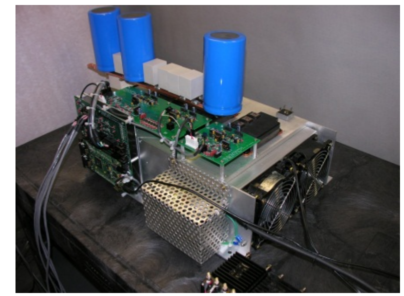
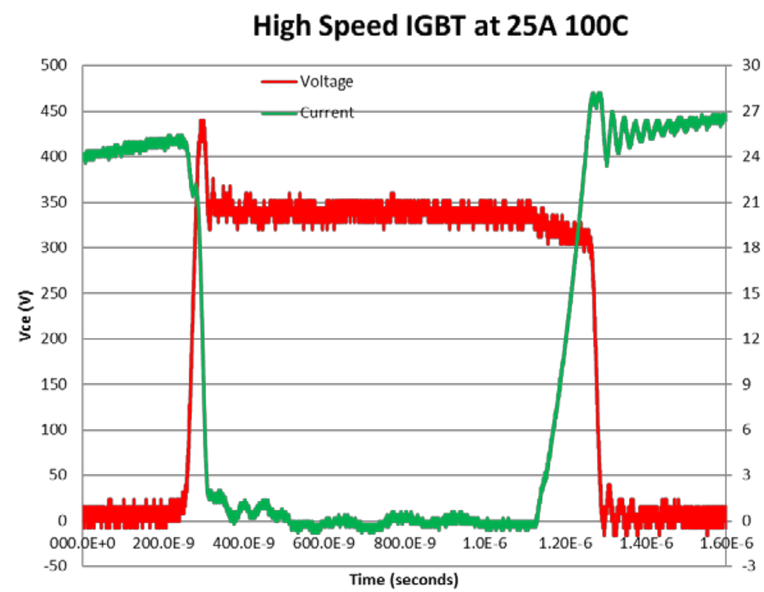


Fig. WF2 - Typ. Turn-on Loss Waveform
@ T_J = 175°C using Fig. CT.4





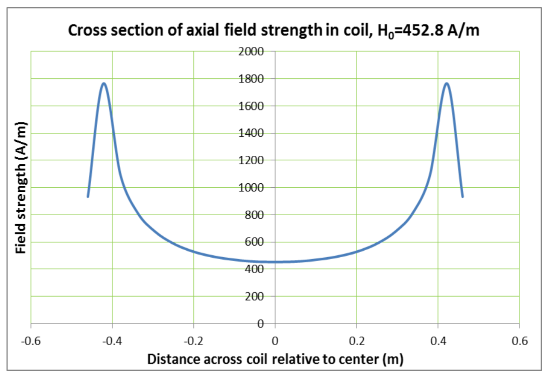
Silicon IGBT's tested over full current, voltage and temperature range and demonstrate feasibility for WPT at any frequency in the available spectrum.

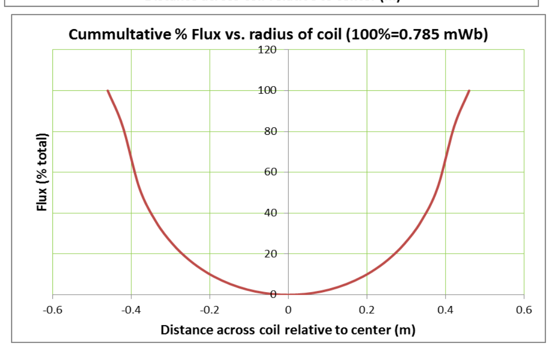
Technical Accomplishments and Progress – FY12 (contd.)

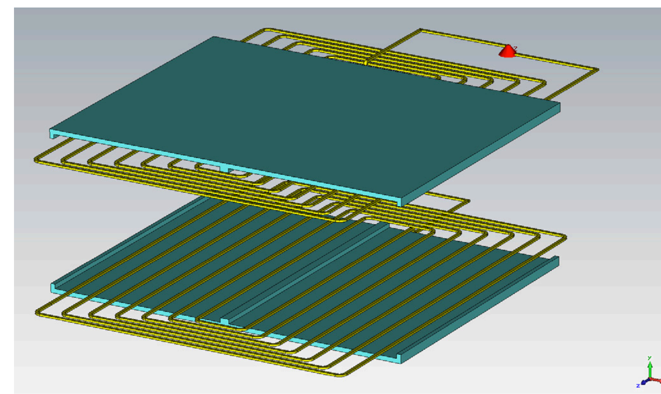
- **Coupling coil design supported with detailed EM FEA to guide material and structural design to be mechanically robust, magnetically shielded and electrically lowest loss**
  - Coupling coefficient, k, is a key parameter in WPT coil performance and represents the fraction of primary coil flux captured by the secondary coil
  - The fraction (1-k) is leakage flux that must be "tuned out" using capacitors

$$k = \frac{\Psi_P}{\Psi_0} = \frac{0.149}{0.785} = 0.189$$

Coupling coefficient z=200mm







k = 0.199 (calculated from FEA)
= 0.203, 0.201, 0.xxx (measured)

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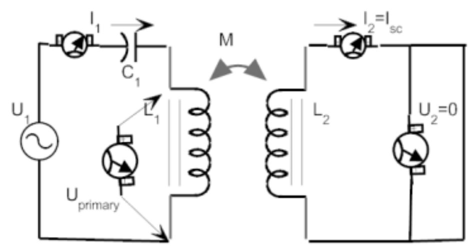
Technical Accomplishments and Progress – FY12 (contd.)

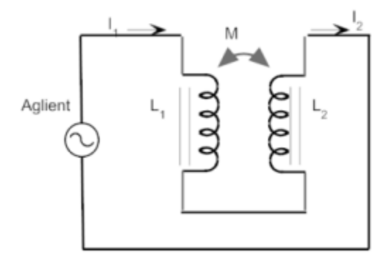
- **ORNL's coupling coil performance has been used to validate SAE J1954 Wireless Charging Task Force method and results shown here have been shared with SAE**

Validation of the ORNL coil pair coupling coefficient.

Open/short circuit test

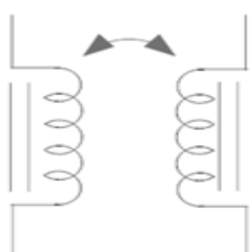


Inductance aiding



$$k = \left.\frac{U_2}{U_p}\right|_{\substack{U_2 = U_{oc} \\ I_1 = 10A_{rms}}}$$

$$k = \frac{L_{aid} - (L_1 + L_2)}{2\sqrt{L_1 L_2}}$$



Loosely coupled transformer
ferrite core back iron

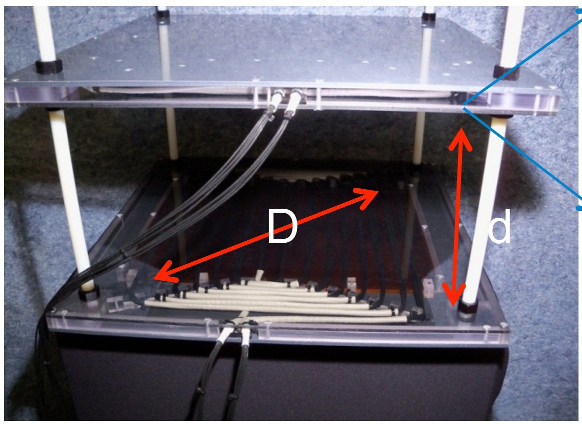
Coupling coefficient, k, results

z= (mm)	200	175	150	125	100
Open Ckt	0.203	0.2506	0.312	0.389	0.488
Induct Aid	0.201	0.251	0.308	0.385	-

Result of SAE J2954 method for k not disclosed here

Technical Accomplishments and Progress – FY12 (contd.)

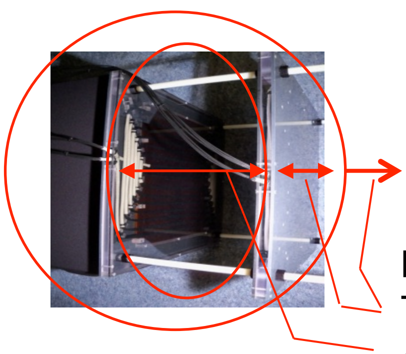
- Quantified key form-fit-function parameters of WPT coupling coils
  - The previously stated coupling coefficient, k
  - Coupling coil diameter, D, must be on the order of 4 times the active zone gap, d
  - Core and winding geometry play a key role in meeting fringe field constraints



Procedure: Equate the field point radial and co-elevation magnetic flux and solve for D/d

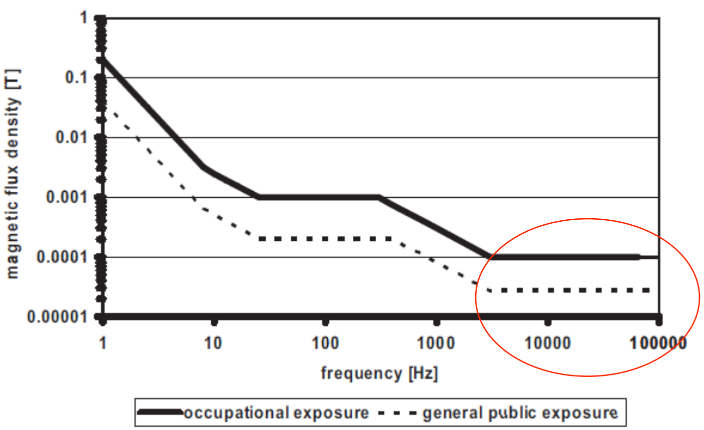
$$\frac{\mu_0 N_1 I_1 a_1^2}{2r^3}\cos\theta = \frac{\mu_0 N_1 I_1 a_1^2}{4r^3}\sin\theta$$

$$2\frac{d}{r} = \frac{a_1}{r};\quad \therefore d \le \frac{D}{4}$$



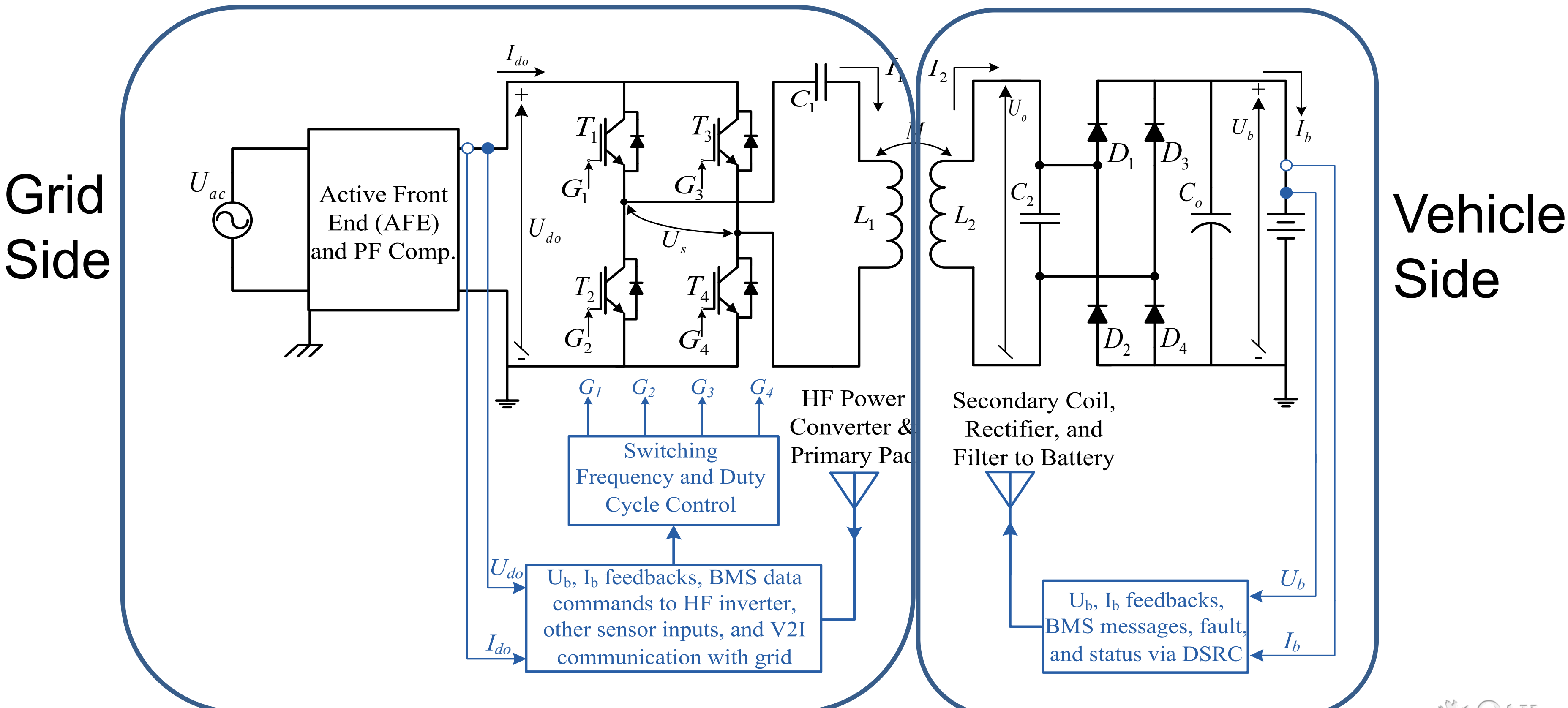
Public zone – ICNIRP
Transition zone – attenuate field
Active zone – strong H-field

Health Physics December 2010, Volume 99, Number 6



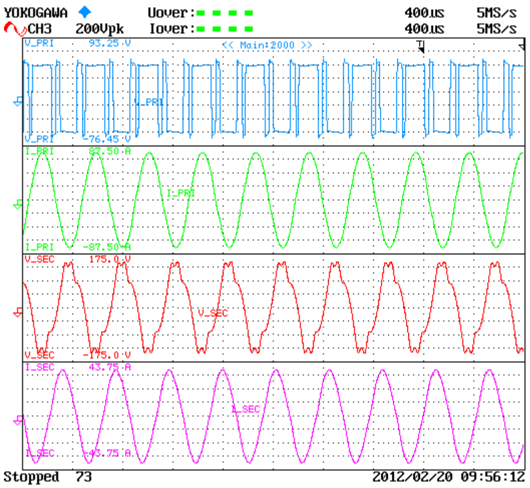
Technical Accomplishments and Progress – FY12 (contd.)

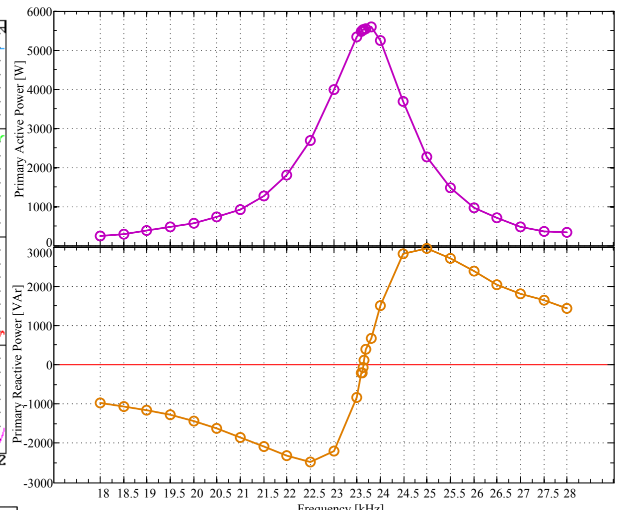
- **Minimized mass and size of vehicle mounted secondary coil, rectifier, filtering, cabling and disconnect components**
  - Minimizes vehicle complexity by adding only the basic tuning, rectification and filtering, plus reliance on primary side control

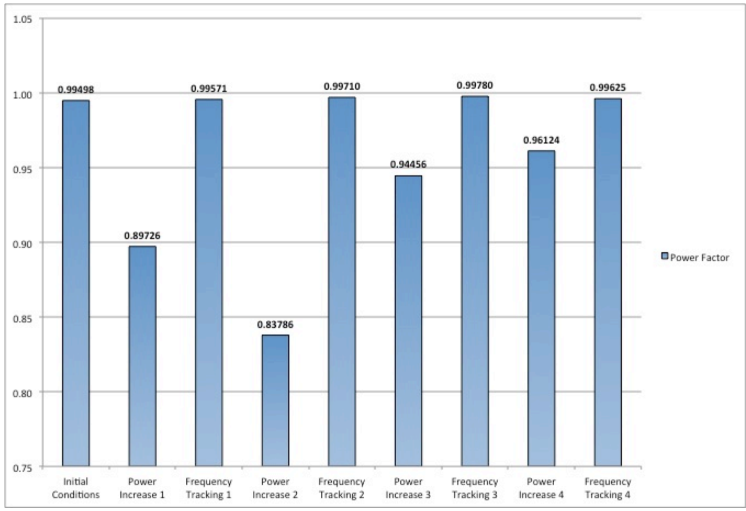


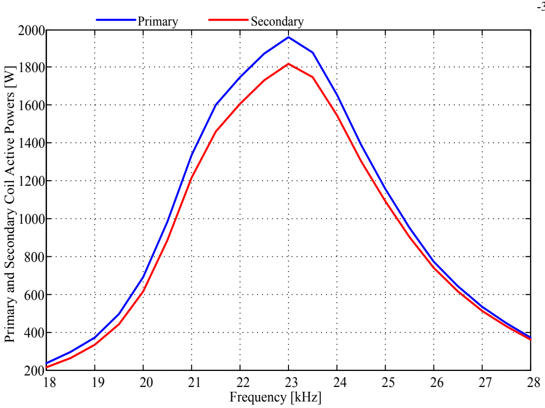
Technical Accomplishments and Progress – FY12 (contd.)

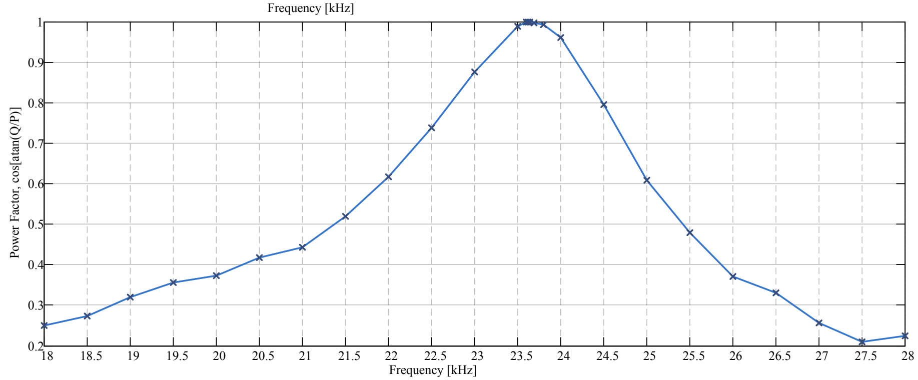
- Control strategy is primary side regulation of power flow
  - Load increase into constant voltage (battery) results in need for positive frequency shift in grid converter. Battery eliminator to mock-up vehicle battery.





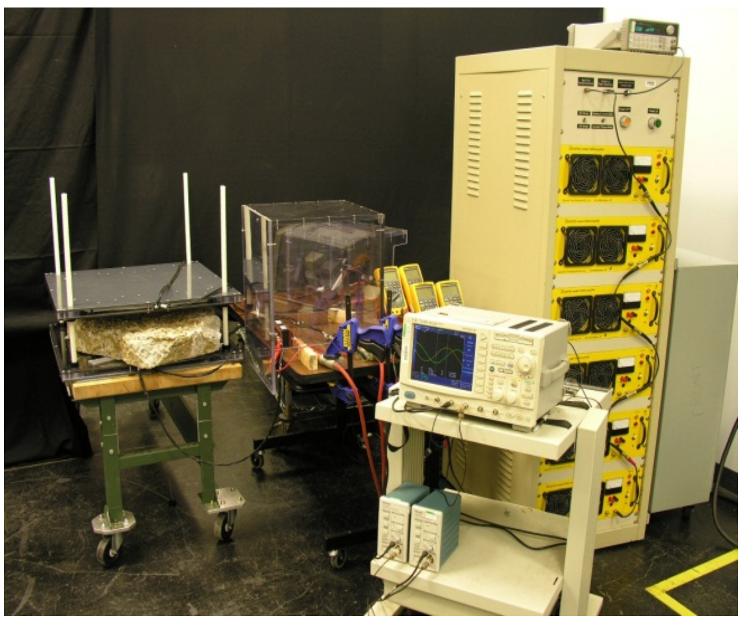




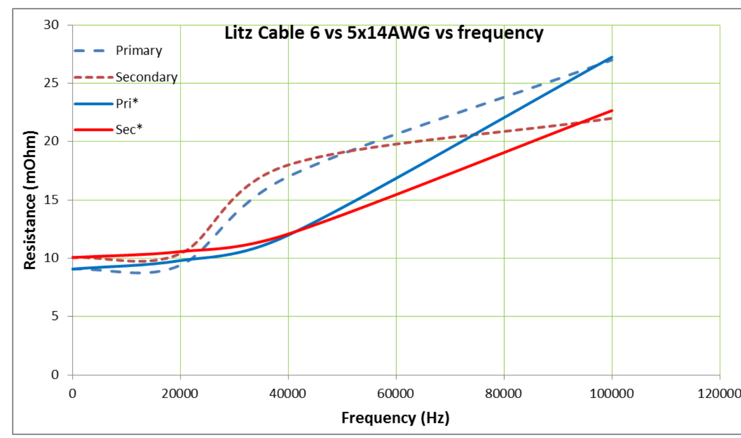


Technical Accomplishments and Progress – FY12 (contd.)

- **Characterized lossy materials in WPT active zone, plus assessment of Litz connecting cable**
  - Concrete and asphalt (full size of coils and 110mm thick) exhibit loss on the order of 6mm thick ferrite
  - Litz cable (6 AWG 1650 strands #38AWG) exhibits Rac increase that is different from (7 AWG 5x 14AWG Litz) and possible instrument error



Section of roadway concrete under test

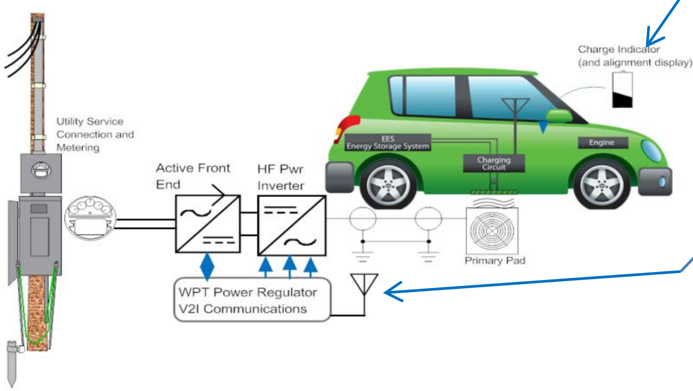


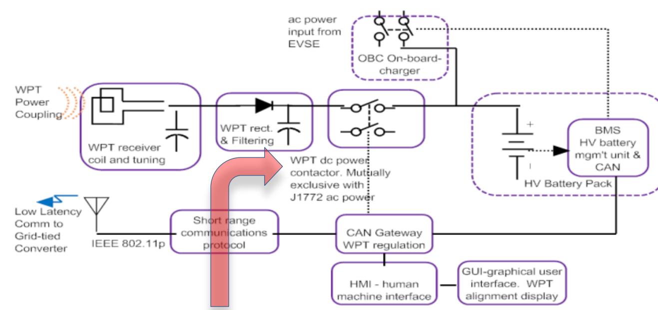
$$R_{ac} = R_{dc}\left[1 + 0.08\left\{\frac{f}{f_0}\right\}^2\right]$$

Technical Accomplishments and Progress – FY12 and Forward (contd.)

- **Communications channel latency and impact on fault management**
  - **Communications channel may have 1ms or more delay in message – latency issue**

How fast can a fault in the vehicle ESS trip the WPT charging to OFF?



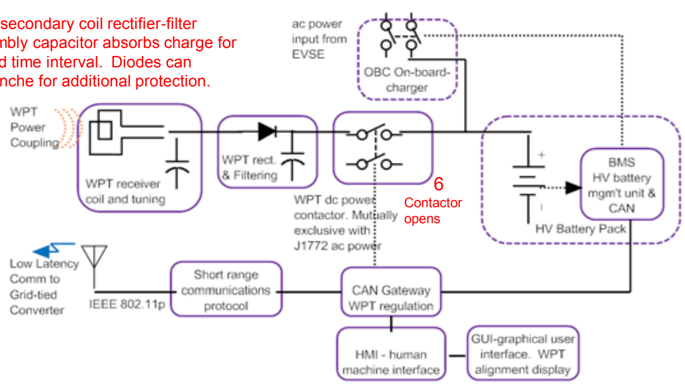


1
Time,t=t_0, BMS issues a STOP Charge message

2
t=$t_0+\varepsilon$, STOP CHARGE message to CAN Gateway results in disengage WPT power contactor signal

3
t=t_1, WPT power contactor responds, takes ~2-4ms, and wireless priority message sent to WPTB to inhibit HF power inverter

5 WPT secondary coil rectifier-filter assembly capacitor absorbs charge for limited time interval. Diodes can avalanche for additional protection.



4
At, t=$t_1+\delta$ the grid-tied power inverter inhibits and charging stops.

1
Time,t=t_0, BMS issues a STOP Charge message

The WPT team is investigating coil ring-up and down times impact on inverter inrush and secondary voltage ringing that must be dealt with during the BMS initiate charge interval and subsequent charge management interval based on DBC messaging.

Technical Accomplishments and Progress – FY12 and Forward (contd.)

- **WPT control will be crucial in burst mode operation**
  - Stationary charging installations must “ramp-up” the coil power to avoid primary (transmit) coil high voltage ringing
  - On-road dynamic installations requiring high burst power in short time intervals

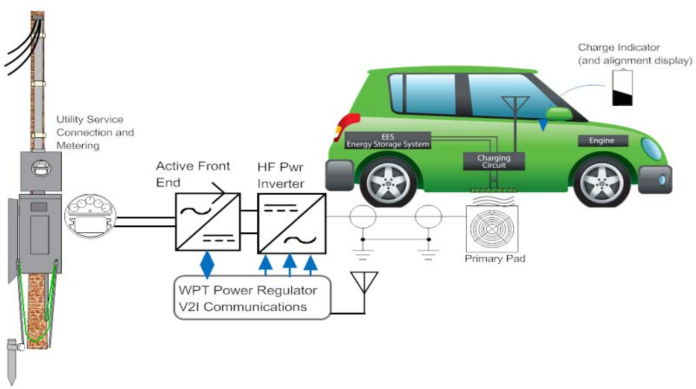
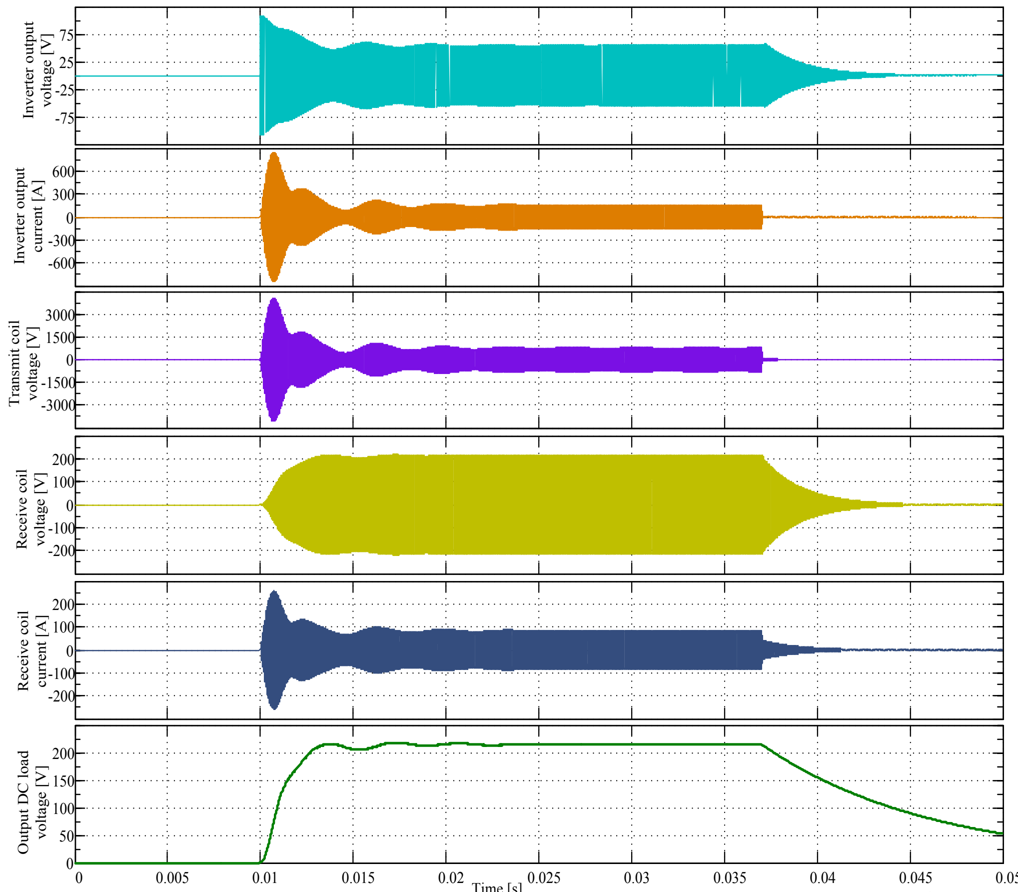


Illustration of a 27ms, 23.6kHz, 20kW power burst command to a 720mm primary coil representing an abrupt charge command in stationary setting or a vehicle pass-over at 55 mph for in-motion charging. Note the excessive primary coil over voltage and over current that would require over rated components. Controlled ramping is a system requirement for all WPT installations.



Collaborations

- ORNL Plasma Energy & Applications, Fusion Energy Division
  - Dr. John Caughman, Dr. Timothy Bigelow, Dr. Phillip M. Ryan for coupling coil simulation and fringe field studies that guide unique ORNL coil designs
- SAE J2954 Wireless PEV Charging Task Force
  - Mr. Jesse Schneider (BMW) chairman
  - Interactions with UL2750 on field measurement validation

Future Work

- Remainder of FY12
  - Procurement, fabrication, test of experimental hardware for vehicle integration (WPT to battery disconnect contactor and coordination with OBC)
  - Validated power flow algorithm that minimizes coupling coil reactive power flow to minimize losses
  - Coordinated vehicle to grid inverter control signals for stable power flow under load change and coil gap changes
- Beyond FY12
  - This project concludes in FY12
- Industry Concerns
  - Address vehicle to grid-tied inverter radio communications latency effect on regulation stability (and by extension, the limit imposed on vehicle speed for in-motion systems)
  - Resolution of interoperability issues and frequency interference
  - Scalability of WPT to dc fast charge equivalence (by extension, applicability to transit bus and in-motion burst charging)

Summary

FY12 Accomplishments

- WPT charging of PEV's is convenient, flexible, safe and autonomous, but
- Wireless power transmission must be adequately shielded and the hardware appropriately isolated
- ORNL has developed primary side only regulation of WPT charging that minimizes system complexity, is dependent on low latency wireless communications, and places the charge regulation burden in software rather than hardware
- Power management, whether on primary, secondary or both must be capable of rapid and safe disengagement in the event of an energy storage system fault
- A great deal of the experience and lessons learned from conductive charging apply to WPT

- Impacts
  - Wireless charging is a transformational technology that better meets customer needs in PEV's than other methods,
  - Is amenable to PEV charging at different rated WPT Base units (3.3, 6.6 kW…)
  - Can be scaled to shuttle, transit and other HD vehicle applications
  - New opportunity for material handling, drayage and future on road dynamic charging