Technology Requirements and Evaluations for High Power Applications of Wireless Power Transfer

Omer C. Onar, PI
Email: onaroc@ornl.gov
Phone: 865-946-1351

P.T. Jones, Project Manager
Email: jonespt@ornl.gov
Phone: 865-946-1472

Oak Ridge National Laboratory

U.S. DOE Vehicle Technologies Office
2015 Annual Merit Review and Peer Evaluation Meeting
June 10, 2015

Project ID: VSS152

ORNL is managed by UT-Battelle
for the US Department of Energy

Overview

Timeline	Barriers
• Project start date: October 2013 • Project end date: September 2015 • 65% Complete	• Risk Aversion – Partner/Industry engagement • Cost – Inherently high cost of heavy duty & high power equipment, higher kVA rating for devices and converters • Lack of Standardized Test Protocols • Lack of previous work & state-of-the-art for high power • Other technical challenges with high power
Budget (DOE share)	**Partners**
• DOE funding : $300K FY14 : $250K FY15 • Partner funding : $0K	• Oak Ridge National Laboratory (Project Lead) – Power Electronics & Electric Machinery Group – Center for Transportation Analysis

Project Objective and Relevance

- Advance technology maturity, identify commercialization, standardization and safety of wireless charging technology.
- Address barriers, technical challenges, issues, and risks with the detailed technology analysis, evaluation, and design.
- Support J2954/2 Bus and Heavy Duty Wireless Charging Standards Development Taskforce with development, test data, experimental lessons learned, and design experience.
- Design and build a high power wireless power transfer components meeting heavy duty vehicle expectations of overall WPT technical targets.
- Design, model, and simulate system architecture after initial analysis and evaluations.
- Then build test bench-top system for future integration to an MD application in collaboration with partner(s).

Objective- Design, Model, and Simulate a High Power Wireless Power Transfer System

"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"

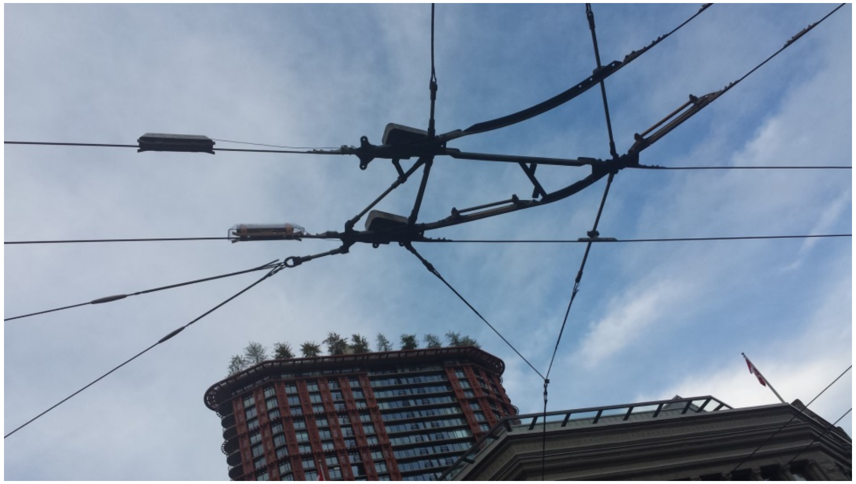
- Research and report on existing power electronics architectures and magnetic coupling technologies,
- Develop and validate methods of high power wireless power transfer for high power– ongoing and future focused standards support,
- Address design and operation challenges through modeling and simulations,
- 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,
- 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.

Why md/hd & High Power wireless charging?

- Low hanging fruit of transportation electrification:
  - The fuel economy of a heavy duty vehicle is much less than a passenger vehicle; i.e., 5-6 MPG according to a commuter bus service in California.
  - Considerably higher fuel consumption – more petroleum displacement if electrified
  - Much higher average fleet emissions
- Very heavy and extremely expensive battery packs required:
  - High power rating / high energy storage capacity
- Often a known route, predictable installation locations and power ratings and infrastructure usage.

Why MD/HD High Power wireless charging?

- Ugly, un-inspiring infrastructure when powered by wires.



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 J2954/2 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 (new start)

Date	Milestones and Go/No-Go Decisions	Status
Sept. 2015	Milestone: Design, model, and simulate a high power WPT system. Go /No-Go Decision: Achieves >100 kW power transfer at >85% efficiency, without circulating current issues at the inverters.	Initial model and electrical simulation of the system is complete. Preliminary simulation results obtained.
Sept. 2016	Milestone: Complete the physical design and build of the magnetic structure and the power electronic converters. Go/No-Go Decision: Integrated magnetic structure successfully couples the inverters to achieve higher power.	Future development.
Sept. 2017	Full integration with a commercial electric bus in collaboration with our partner(s).	Future development.

Approach and Strategy

- Through the literature review, modeling, design, and simulations, address the issues and barriers of high power wireless charging systems with design validation.
- Challenges and needs for high power – wireless charging systems:
  - If larger airgap that results in reduced coupling factor.
  - Reduced coupling factor reduces the mutual inductance.

$$M = k\sqrt{L_1 L_2}$$

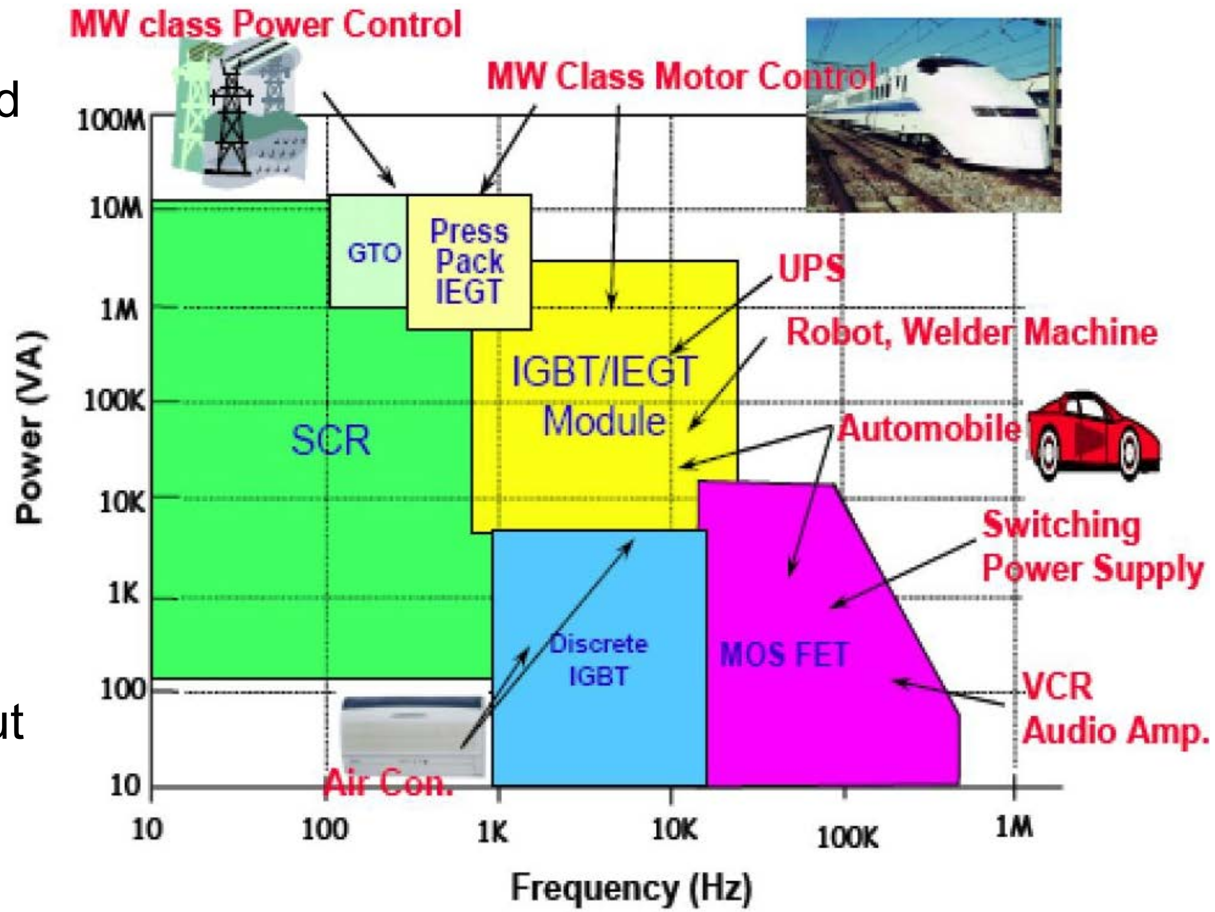
  - Lower mutual inductance requires highly reactive relatively larger primary coil current that the inverter has to deliver. Inverter device rating and coil wire current rating are stressed.
  - More reactive power rating from the tuning capacitors is needed.

Project Goals

- The strategy is to have the system expectations as close as possible to the ideal conditions:
  - Compact, light-weight coupler design,
  - **Highly efficient (>80%),**
  - **>100kW power rating,**
  - **Misalignment tolerant up to 10-15%,**
  - Low flux density / smaller fringe fields, meeting international guidelines,
  - Electrically safe, having built-in protection features for the equipment, vehicle, and people.

Project Goals – Address Power Electronic Device Restrictions

- Typically, device voltage and current ratings go down as the switching frequency increases.
- MOSFETs can switch at 100kHz but power rating cannot exceed a few kilo-Watts.
- SCR (silicon controlled rectifier) and GTO can handle MW level powers, but their switching frequency is restricted to les than a kHz.
- For effective field generation, ideally >20kHz is needed.



* Hongfang Wang, "Investigation of power semiconductor devices for high frequency high density power converters," Virginia Tech.

- IGBTs with smaller voltage-current ratings (<300V, <100A) can switch up to 25-30kHz but 4500-6500V devices can only handle a few kilo-Hertz.
- Advanced PE architectures are needed to overcome these issues.

Project Goals – Focus on Power Transfer Efficiency

- **Power transfer efficiency**: The overall end-to-end system efficiency should exceed 80%. For high power, most critical power conversion efficiency is the coil-to-coil efficiency that is defined by (ideally):

$$\eta = \frac{1}{1 + \frac{R_2}{R_L} + \left(\frac{R_L + R_2}{\alpha.\omega.L_2} \right)^2 . \frac{R_1}{R_L}}$$

- where R_1 and R_2 are the primary and secondary winding resistances, α is the coupler turns ratio, which is defined as $k\sqrt{L_1 L_2}$; k is the coupling factor which is defined as $M/\sqrt{L_1 L_2}$; M is the mutual inductance, ω is the angular frequency, and L_1 and L_2 are the primary and secondary self-inductances.
- Inverter efficiency depends on the switching (turn-on and turn-off) losses and the conduction losses of the semiconductor device and also the reverse-recovery losses of the internal body diodes.

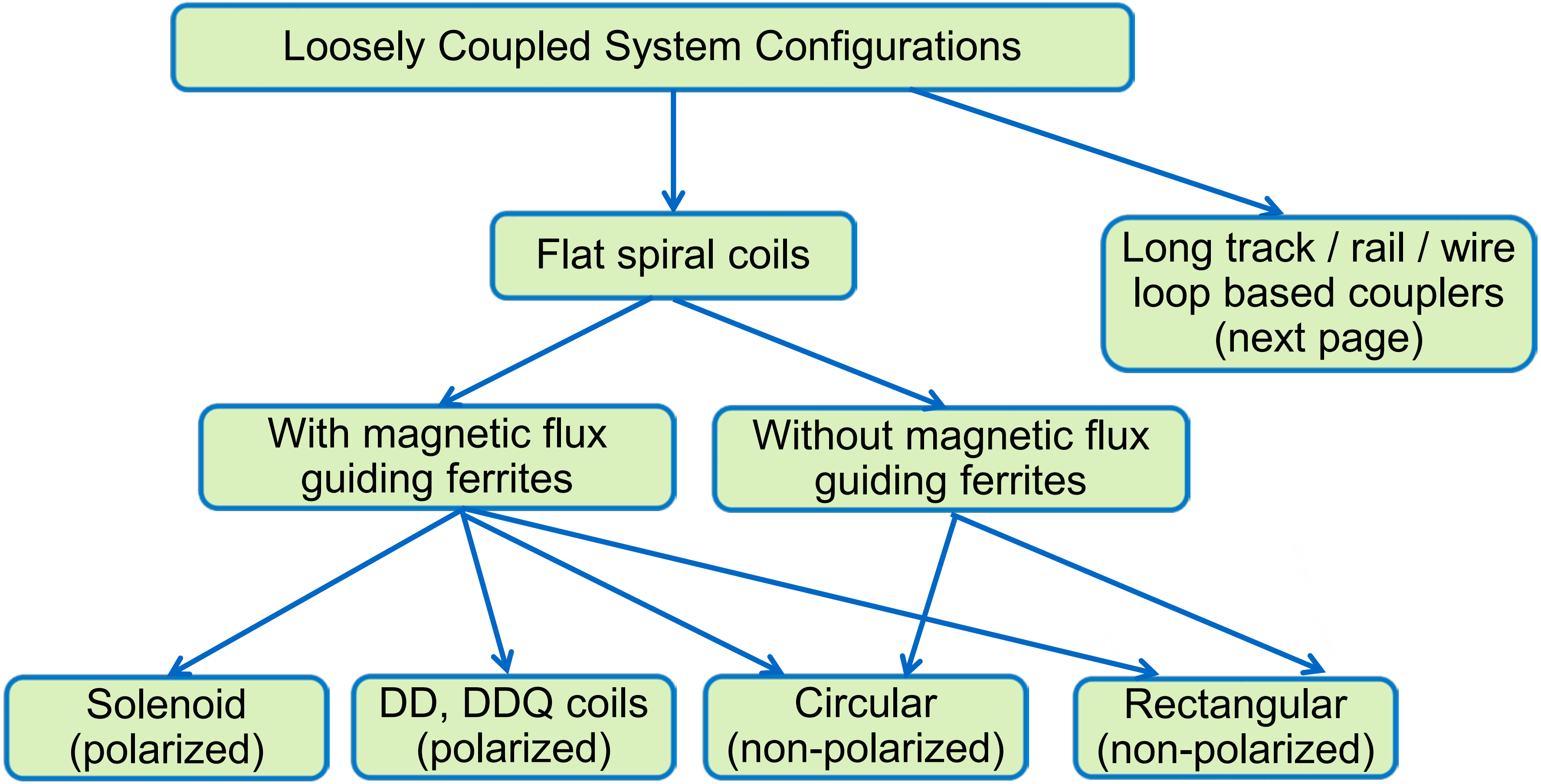
Project Goals – Focus on Airgap and Magnetic Field

- **Magnetic flux density**: Relatively higher airgap → flux linkage between primary and secondary is very low hence large leakage flux is emitted to the air from the primary.
- Field emissions should be less than 6.25 μT at all locations where the human may be exposed to magnetic field at frequencies 0.8 to 150kHz.
- According to IEC (International Electrotechnical Commission) 62110, the field radiation is evaluated at three locations; 20cm away from the surface of the source and 50, 100, and 150cm vertically above from the ground.
- Field emission normally depends on frequency, number of turns on primary, primary current, and the primary inductance.
- Ferrite layout or magnetic core design of the couplers is of significant importance to reduce field emissions and increase efficiency.

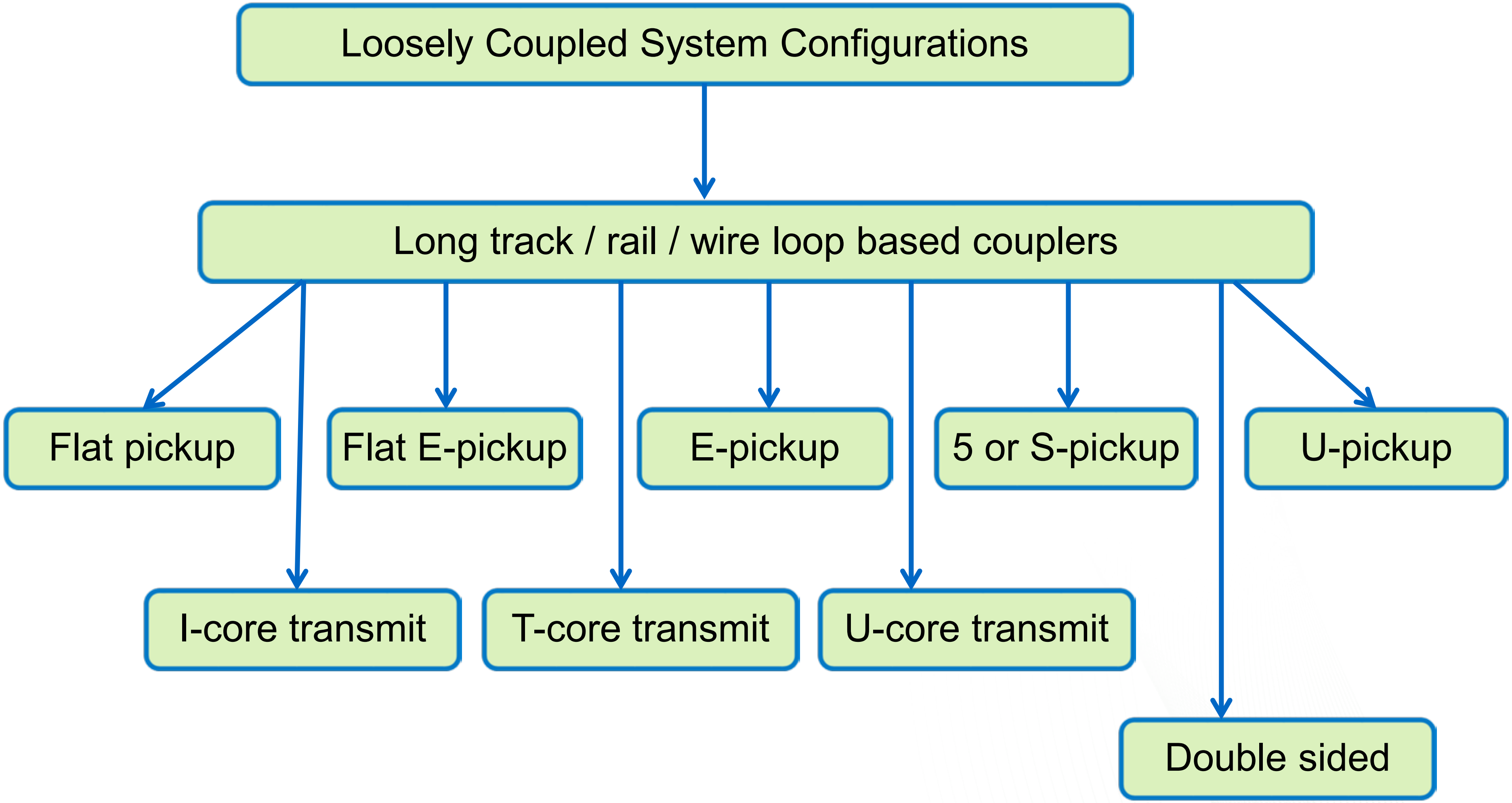
Project Goals– Focus Power Electronics Restrictions

- **Power electronics kVA rating and thermal management**: Ideally, tuning capacitors should eliminate the reactive power (VAr: Volt-Amp-reactive).
- But, the pickup circuitry feeding a voltage-source-based load (i.e., battery) through a rectifier requires reactive power that is reflected back to the primary side inverter.
- This means that the inverter should be oversized/overrated to compensate for all the additional VAr loads that can be presented from secondary or multiple pickups.
- Current rating for devices are defined for 25°C temperature.
- However, even at 97% efficiency, while transferring 100kW, the total power converted to heat is 3kW which increases the device temperatures well above 100°C and current rating is reduced.
- Either very advanced controlled chillers or the overrated systems should be utilized.

Technical Accomplishments: Review of SOA Coupling Devices

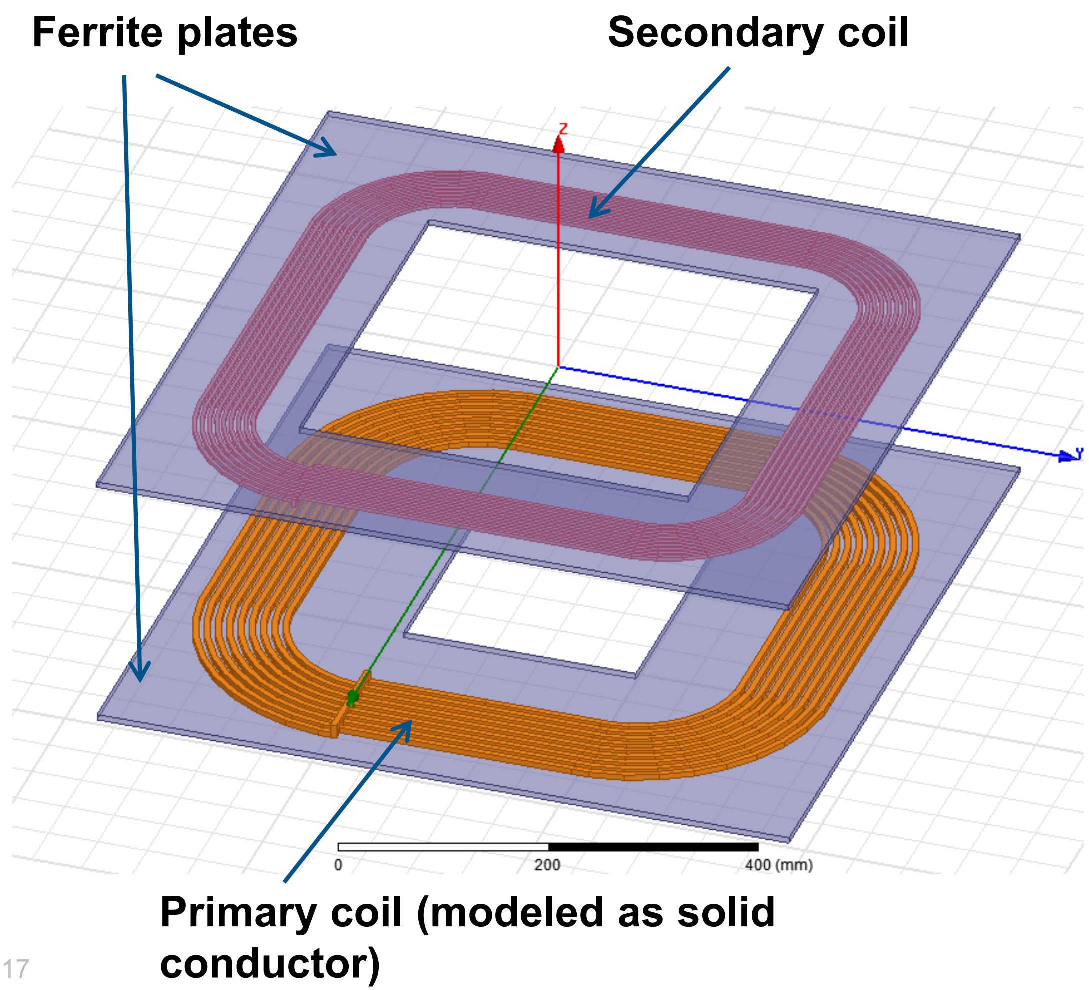


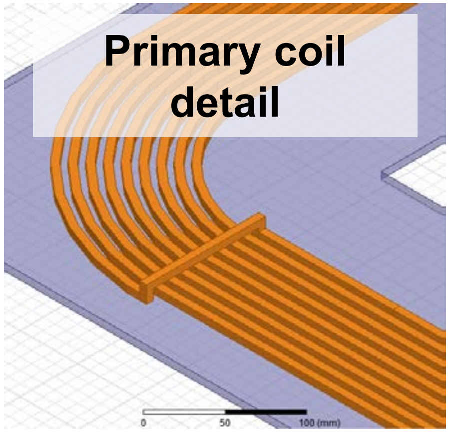
Technical Accomplishments: Review of SOA Coupling Devices

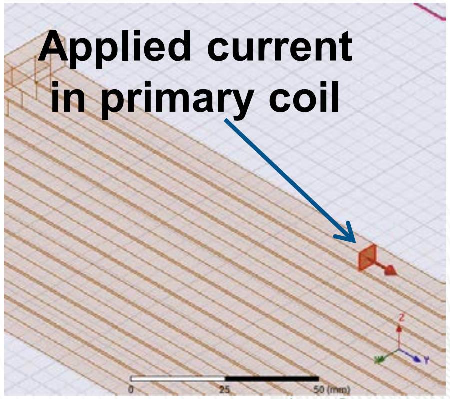


Technical Accomplishments: Design Validation of ORNL WPT couplers

- Completed the Eddy current model (frequency domain analysis, Ohmic and core loss calculation)
- Completed the magneto-static model (inductance and coupling factor calculations)

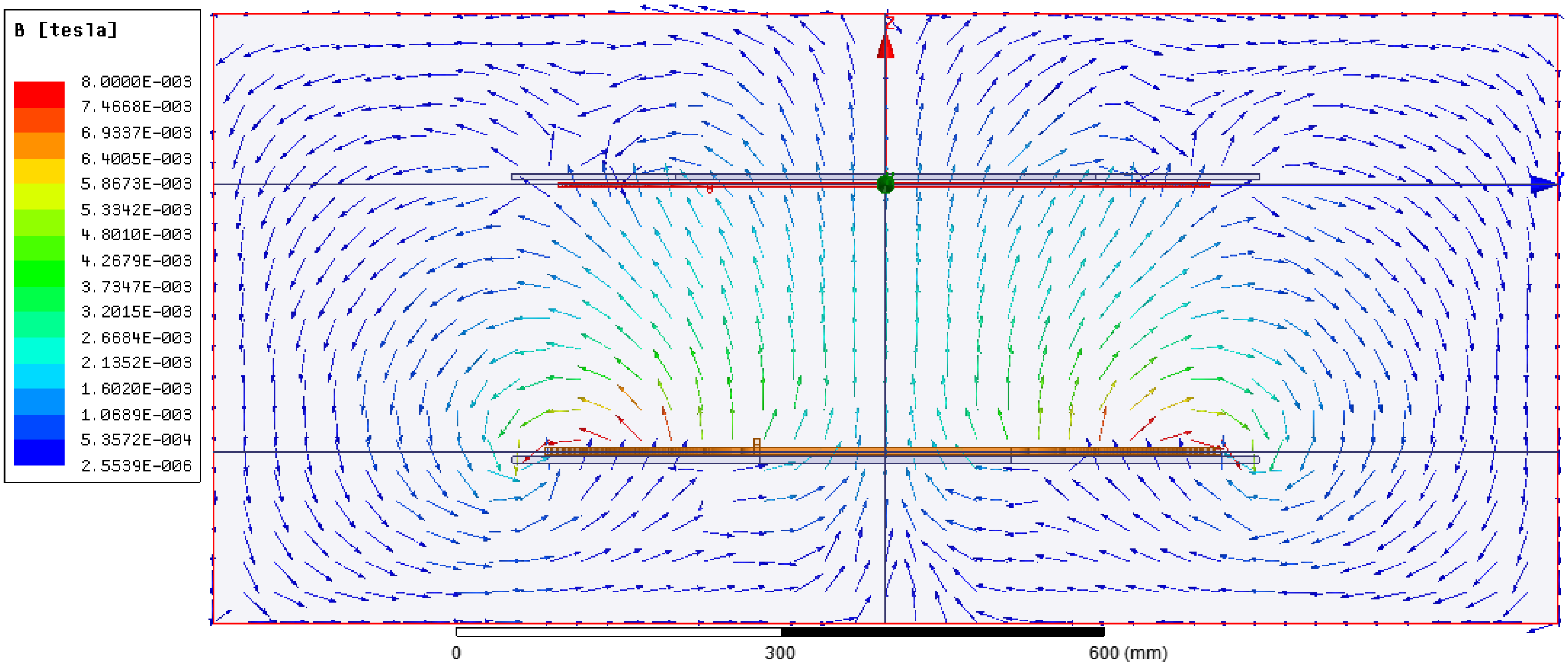






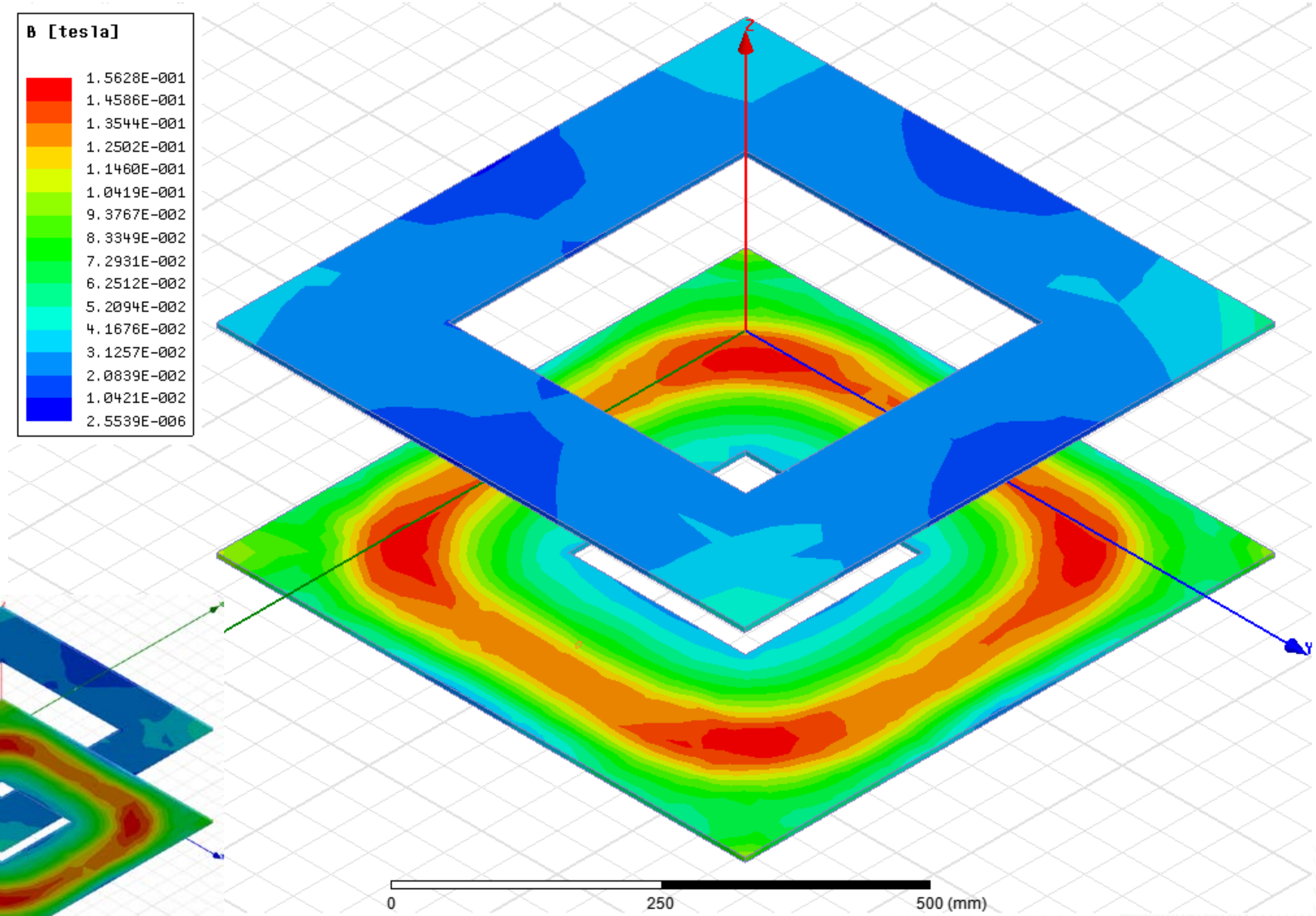
Technical Accomplishments: Design Validation of ORNL WPT couplers

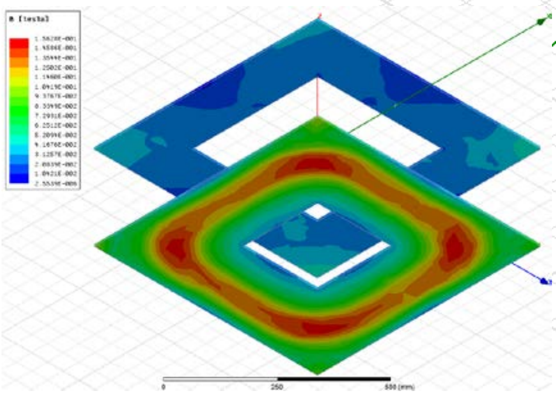
- B-vector in the crossectional plane



Technical Accomplishments: Design Validation of ORNL WPT couplers

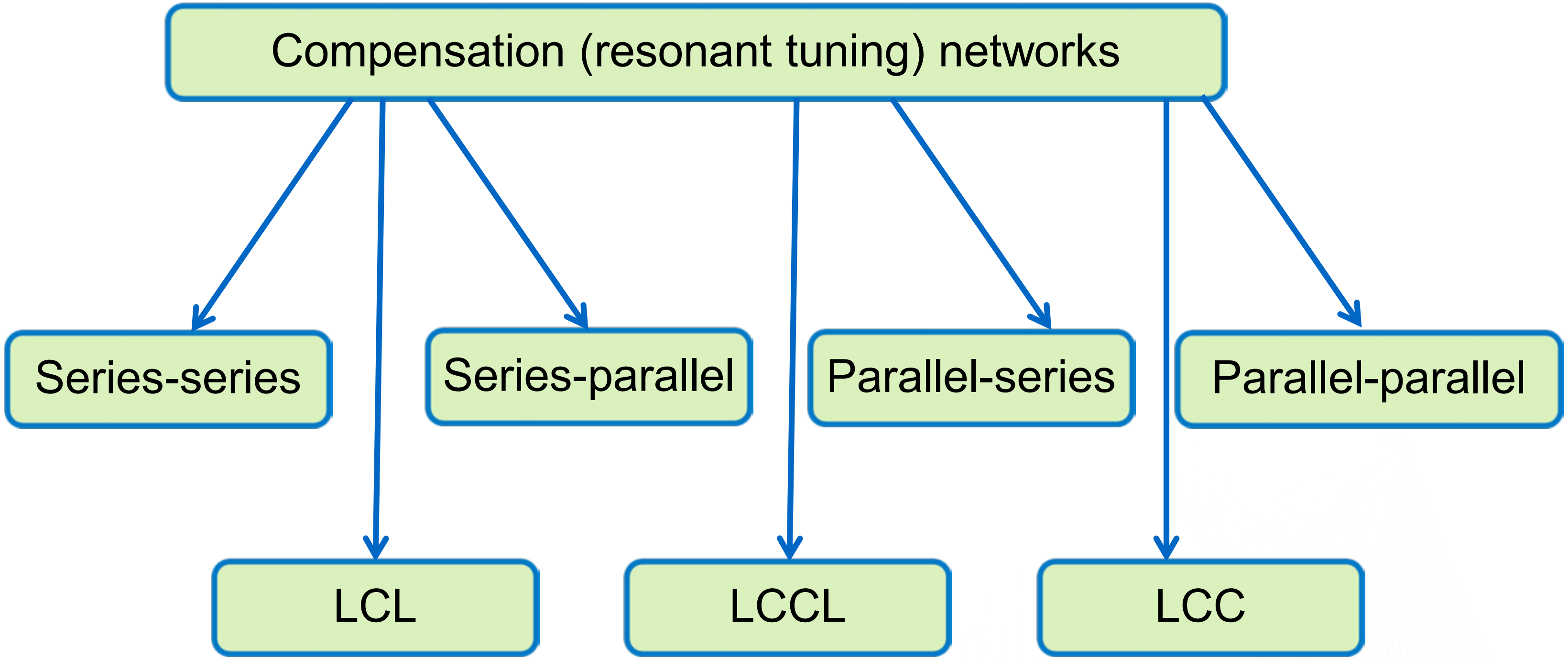
- B-field magnitude of the flux guiding Ferrite plates





OAK RIDGE National Laboratory

Technical Accomplishments: Review of SOA Resonant Tuning Configurations

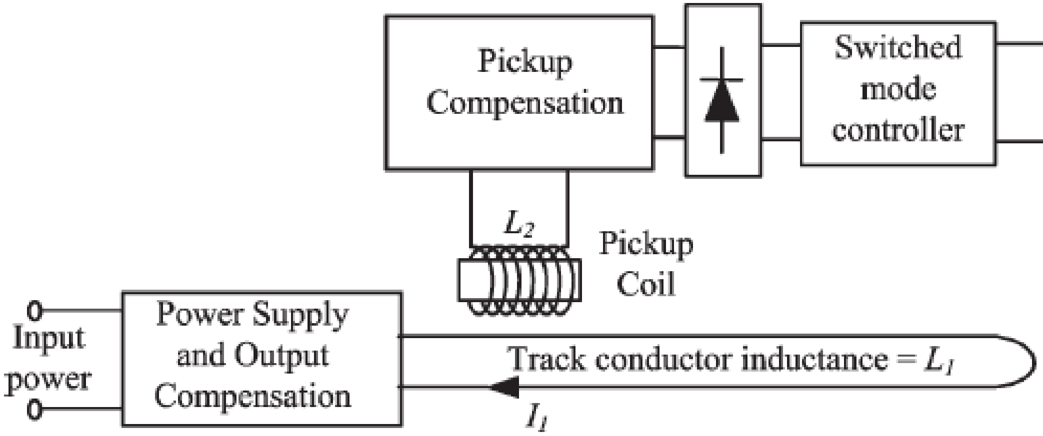


Technical Accomplishments: Comparison of SOA Resonant Tuning Configurations

	Series-parallel	Series-series	Parallel-series	Parallel-parallel
Dependence on load and coupling factor	Secondary side tuning capacitor depends on load and coupling factor	Primary and secondary tuning capacitors are not a function of load and coupling factor	Primary side compensation capacitor depends on load and coupling factor.	Both primary and secondary side compensation capacitor depends on load and coupling factor.
Inverter device voltage rating	Lower DC link voltage is required. – lower inverter efficiency if a transformer is not used	Lower DC link voltage is required (higher than SP). –lower inverter efficiency if a transformer is not used	Higher voltage is needed than SS and SP	Higher voltage is needed than SS and SP
Inverter device current rating	Equals to the primary coil current	Equals to the primary coil current	Equals to the active component of the primary coil current (ideally)	Equals to the active component of the primary coil current (ideally)
Restriction on flux linkage	Magnetic field independent of the load current since secondary is parallel compensated	Secondary coil current is equal to the load current, field is limited by load current	Secondary coil is equal to the load current, field is limited by load current	Magnetic field independent of the load current since secondary is parallel compensated

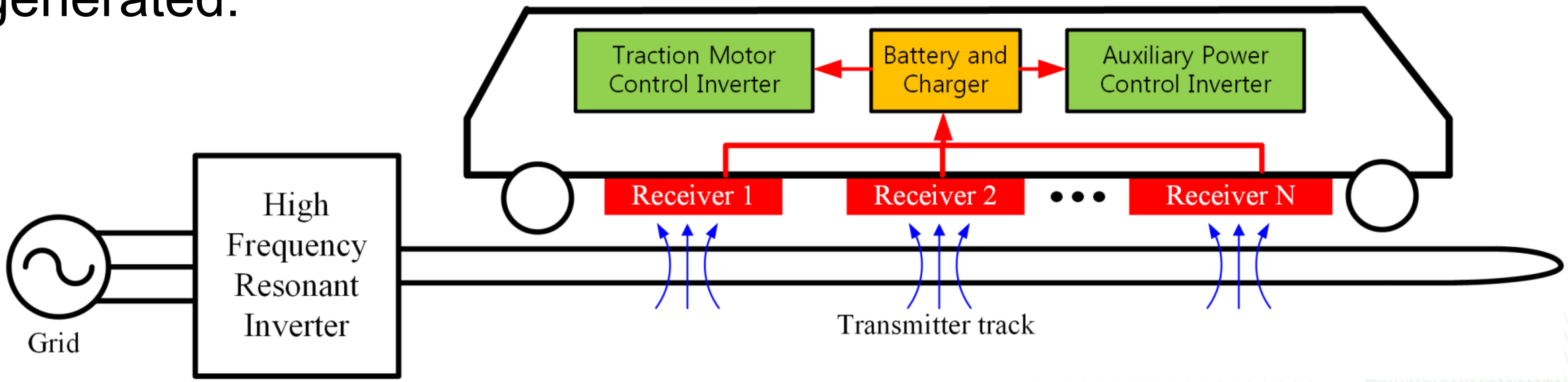
Existing System Architectures

- Typical system that is powered from a track loop (long wire loop or HF rail system):



*N. A. Keeling, G. A. Covic, and J. T. Boys (University of Auckland, New Zealand), “A unity power-factor IPT pickup system.”

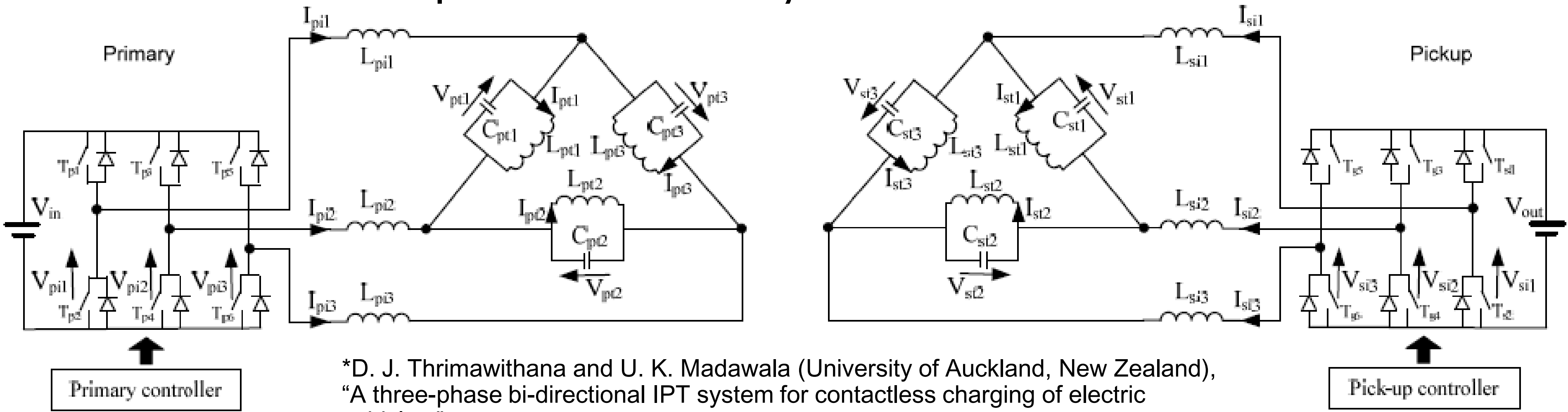
- Multiple pickup coils approach for better utilization of the field generated:



*S. –H. Lee, et. al, Korea Railroad Research Institute study.

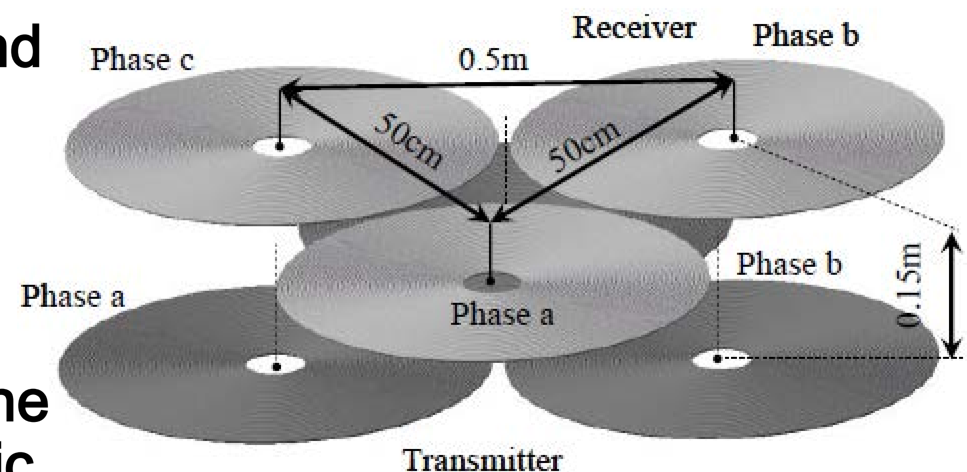
Existing System Architectures

- Three-phase transmit and three-phase receive coils with three-phase inverter and three-phase rectifier systems.



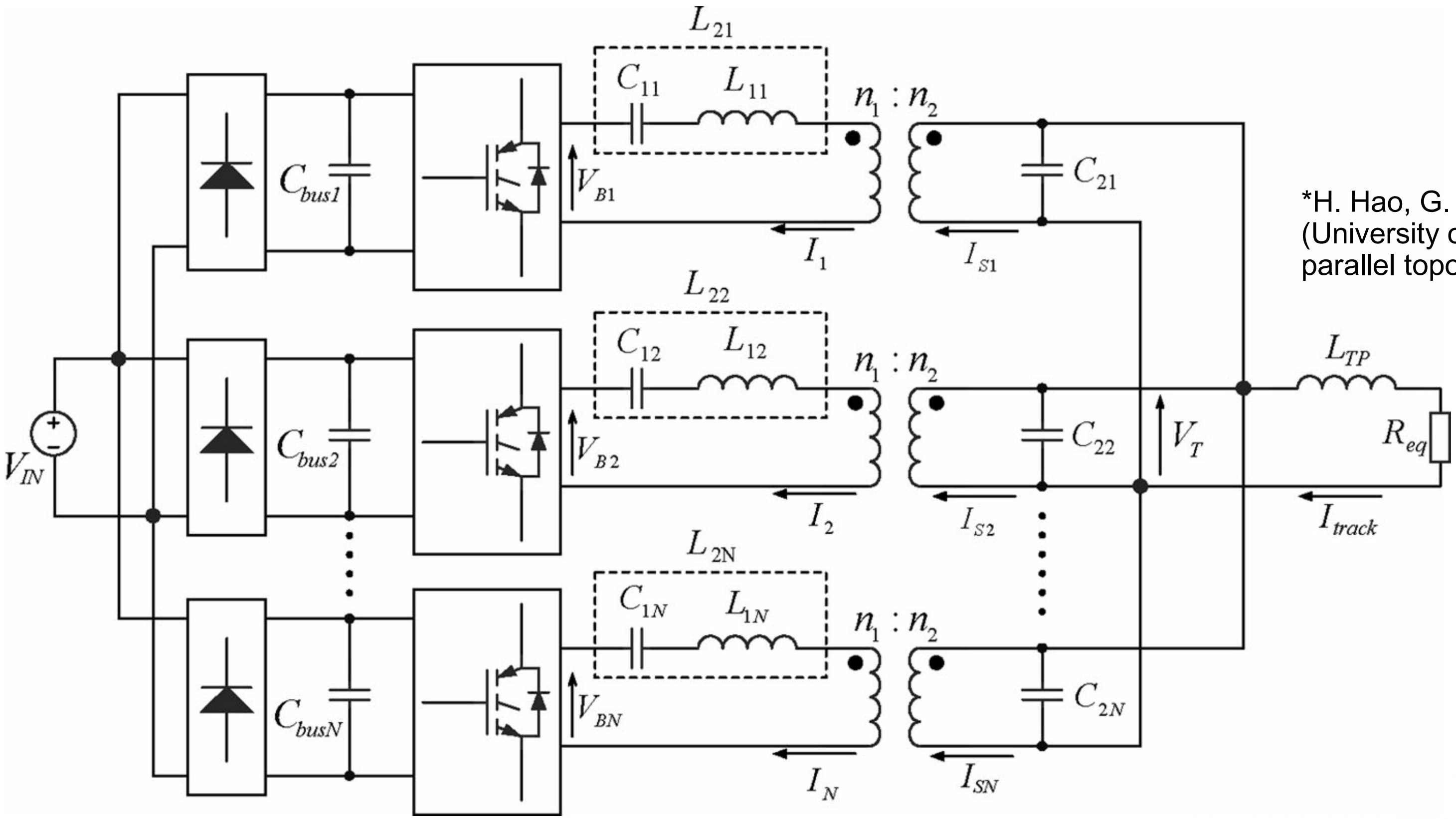
*D. J. Thrimawithana and U. K. Madawala (University of Auckland, New Zealand), "A three-phase bi-directional IPT system for contactless charging of electric vehicles."

- **Distance between transmit and receive coils, winding direction, and complicated phase-controlled inverter is needed.**
- **There will also be mutual inductance between all three transmit coils which may reduce the efficiency and may cause magnetic flux cancellation.**



Existing System Architectures

- Parallel architecture for increased power rating:

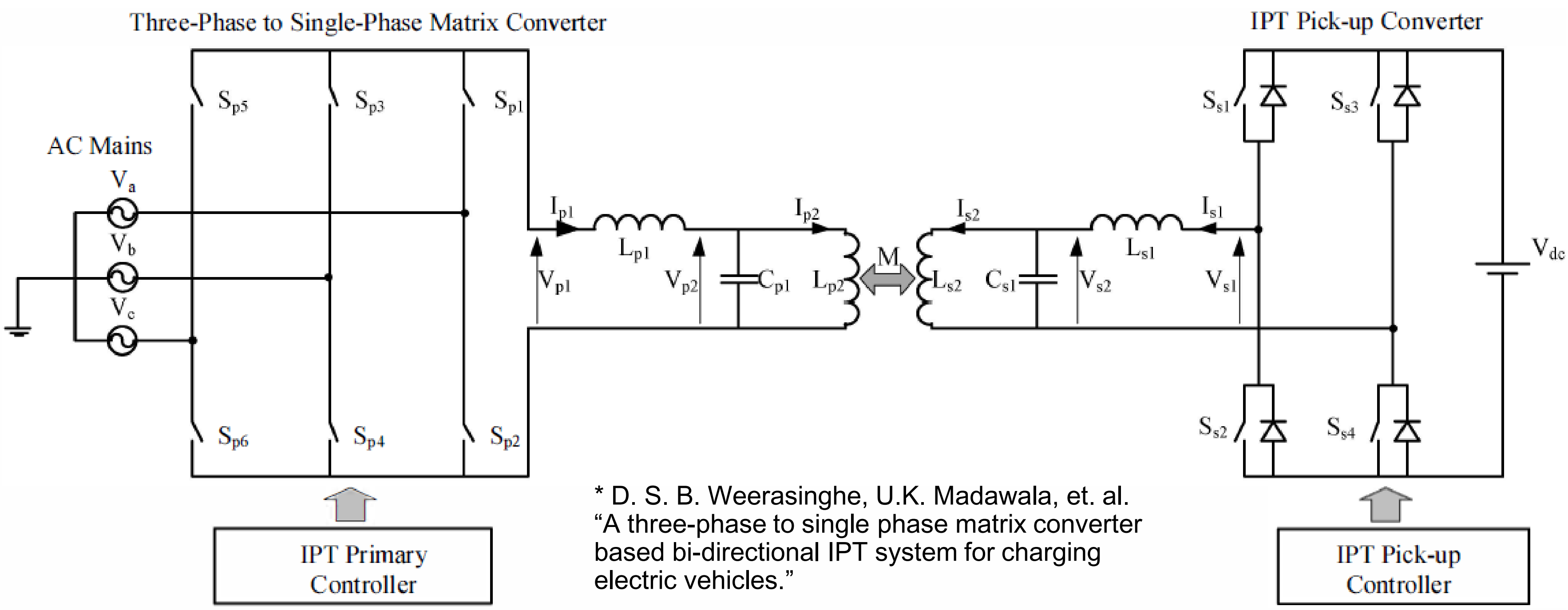


*H. Hao, G. A. Covic, and J. T. Boys (University of Auckland, New Zealand), "A parallel topology for IPT power supplies."

- Still the mutual inductance between each transmit coils might be an issue although the power rating is virtually triples. Since all the inductors are loosely coupled, one primary coil can couple to another primary coil almost as much as one primary couples to a matching secondary.

Existing System Architectures

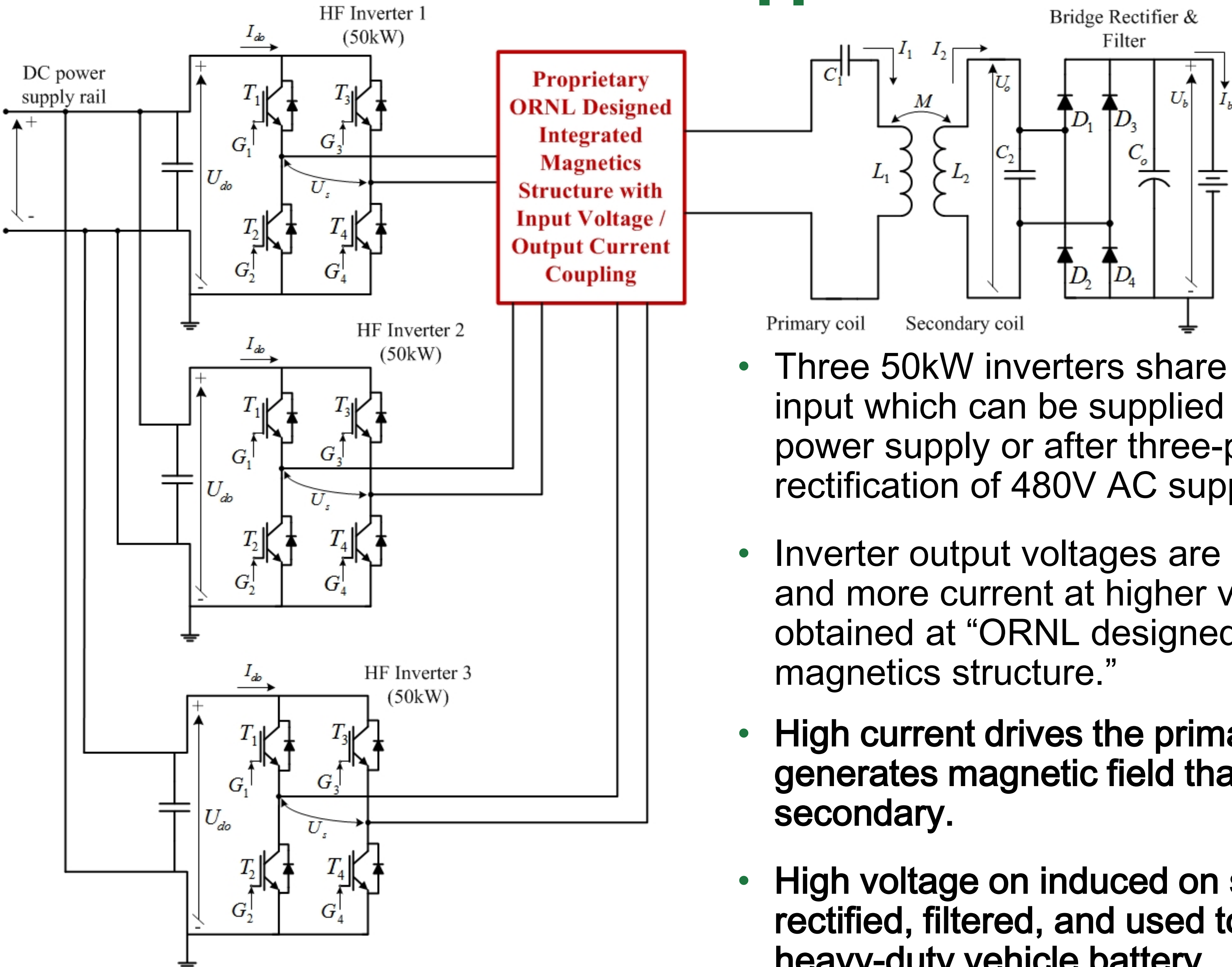
- Three-phase to single-phase matrix converter



* D. S. B. Weerasinghe, U.K. Madawala, et. al. “A three-phase to single phase matrix converter based bi-directional IPT system for charging electric vehicles.”

- Very complicated control system needed for primary.
- Very high kVA rating for the primary inverter and coil.

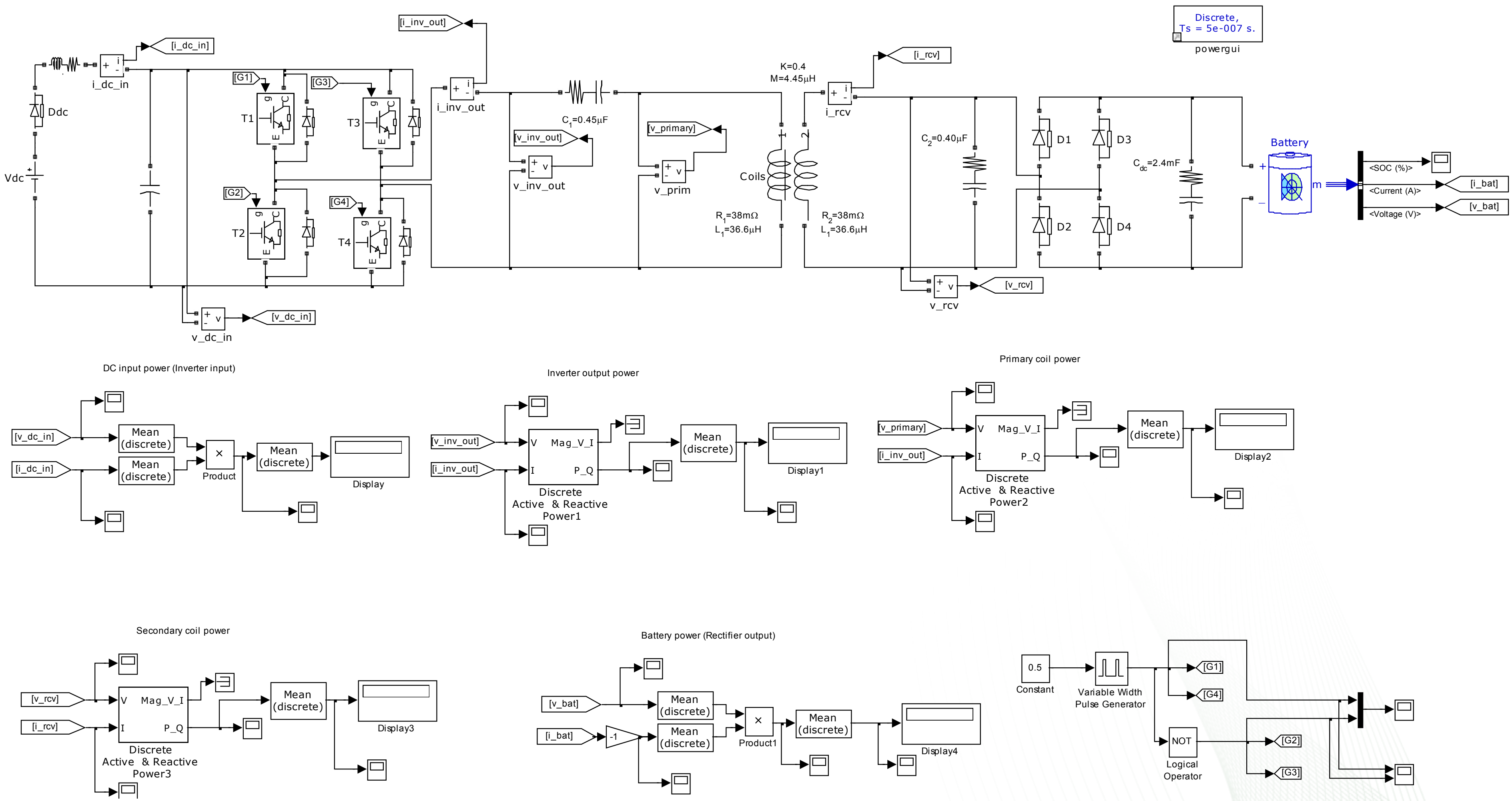
ORNL Power Electronics Approach



- Three 50kW inverters share the same input which can be supplied from a DC power supply or after three-phase rectification of 480V AC supply.
- Inverter output voltages are added up and more current at higher voltage is obtained at “ORNL designed integrated magnetics structure.”
- **High current drives the primary coil that generates magnetic field that is linked to secondary.**
- **High voltage on induced on secondary is rectified, filtered, and used to recharge heavy-duty vehicle battery.**

Example simulation system

- Simulink – SimPowerSystems Model – with lumped inverter, parameters designed for high power application up to 150kW



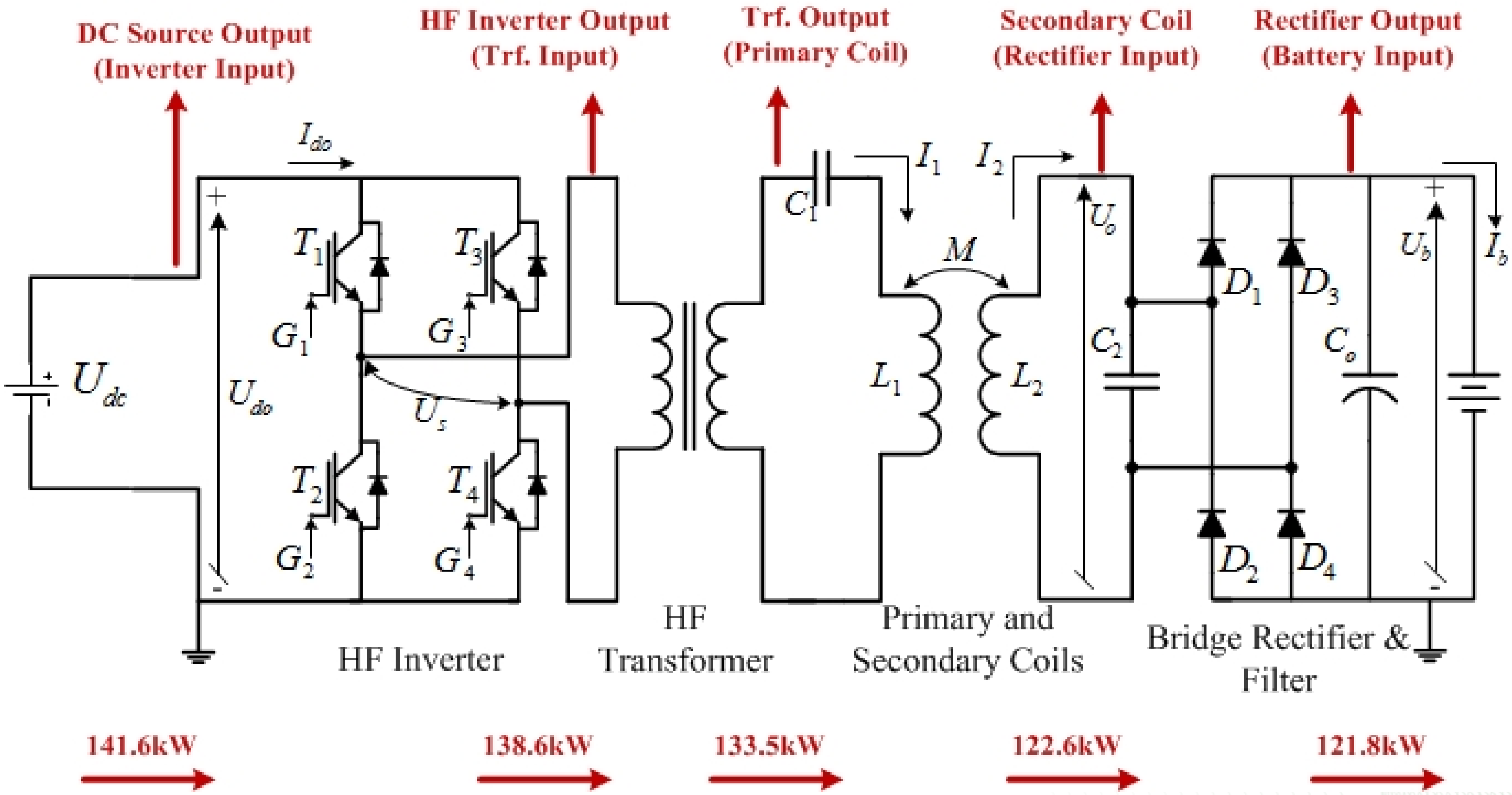
Example simulation system

- System parameters:

Parameter	Value
Source supply	480V, 3-phase rectified (675 Vdc)
Primary and secondary coupler inductance	$L_1 = L_2 = 447.08\mu H$
Primary and secondary tuning capacitor	$C_1 = C_2 = 117.06nF$
Capacitor internal resistance	$C_{R1} = C_{R2} = 3m\Omega$
Coil winding internal resistance	$L_{R1} = L_{R2} = 9.06m\Omega$
Coupling factor	$k = 0.19$
Mutual inductance	$M = 84.94\mu H$
Vehicle battery	Lithium-ion with 600Vdc nominal voltage
Switching frequency	22 kHz

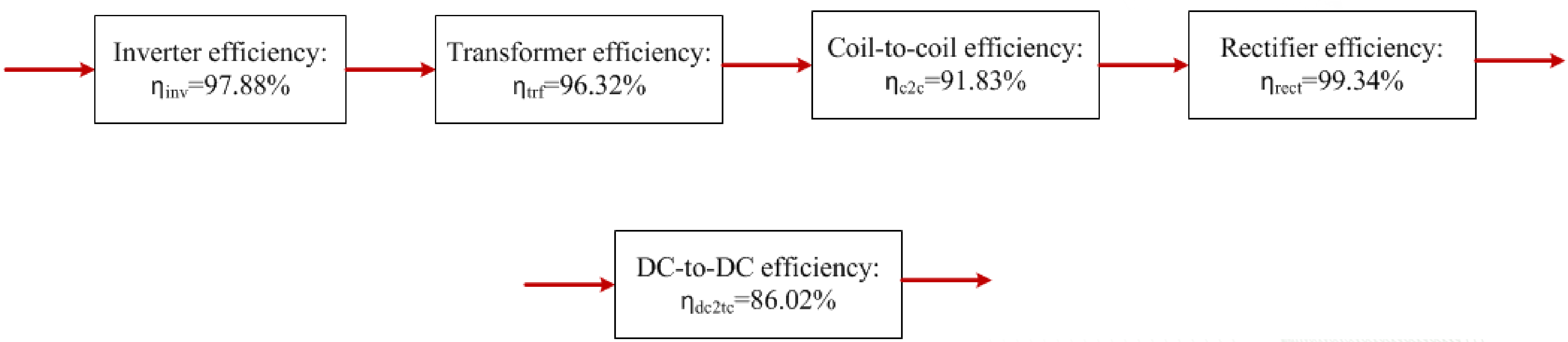
Example simulation system

- System power flow diagram:
  - DC source power: 141.6kW (inverter input)
  - Inverter output power: 138.6kW (transformer input)
  - Primary coupler power: 133.5kW (transformer output)
  - Secondary coupler power: 122.6kW (rectifier input)
  - Battery power: 121.8kW (rectifier output)



Example simulation system

- System power efficiency diagram:
  - When transferring 121.8kW to the heavy duty vehicle high voltage battery, stage by stage efficiencies obtained at each input-output pair of the power conversion stages:
  - Inverter efficiency: 97.88%
  - Transformer efficiency: 96.32%
  - Coil-to-coil efficiency (@k=0.19 coupling factor, due to high airgap): 91.83%
  - Vehicle side rectifier efficiency (using ultra-fast recovery Schottky barrier diodes): 99.34%
  - Overall end-to-end efficiency: 86.02%



Proposed Future Work

- FY2015 (remainder)
  - Improving coupling factor to reduce iron losses,
  - Improving coupler wiring with a thicker AWG wire to reduce copper losses,
  - Improving integrated magnetic structure (transformer) efficiency with different core material,
  - Improving inverter devices by evaluating wide bandgap device materials; i.e., SiC or other devices with reduced thermal stress.

Summary

- Performed a literature review on coupling technologies and resonant tuning configurations,
- Validated the design of the ORNL coupling coils with Eddy current model and the magneto-static model.
- Proposed an integrated magnetic structure for the combining three 50kW inverter,
- Modeled and simulated the proposed system and received state by stage efficiencies and evaluated the areas needing improvement,
- Hardware will be built in next phases for a high power design validation.

Acknowledgments

Lee Slezak
Lead, Vehicle and Systems Simulation and Testing
Office of Vehicle Technologies
US Department of Energy

David Anderson
Vehicle and Systems Simulation and Testing
Office of Vehicle Technologies
US Department of Energy

Contacts

P.T. Jones
Project Manager
Center for Transportation Analysis
Program Manager,
Advanced Vehicle Systems
(865) 946-1472
ptj@ornl.gov

Omer Onar
Project Principal Investigator
Power Electronics and Electric Machines (PEEM)
(865) 946-1351
ONAROC@ornl.gov

David Smith
Director
Center for Transportation Analysis (CTA)
Leader, Vehicle Systems Research Group
(865) 946-1324
smithde@ornl.gov

Publications and Presentations

- O. C. Onar and P. T. Jones, "**System Parameters, Modeling, Design, and Simulations of High Power Wireless Charging for Heavy Duty Vehicle Applications**," *SAE Hybrid and Electric Vehicle Symposium*, February 2015, Los Angeles, CA.

OAK RIDGE National Laboratory