Bi-directional Wireless Power Flow for Medium-Duty Vehicle-to-Grid Connectivity

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June 12, 2019 Project ID: ELT188

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

Overview

Timeline

- Start – May 2017
- End – December 2019
- Budget Period I completed in May 2018
- Budget Period II to be completed in Fall 2019

Barriers

- 11 inches magnetic airgap for 20kW wireless power transfer (most applications are for 6-8 inches)
- Achieving bidirectional wireless power flow between grid and vehicle
- Achieving high-efficiency (≥85%) at 20kW with 11 inches airgap
- Meeting the grid and utility standards at the grid side while meeting power density and reliability targets

Budget

- Total project funding
  - DOE share – $1.95M
  - Cost share from partners – $712K
- Project spending BP1: $500K
- Project spending for BP2 (to date): $650K

Partners

- CALSTART (Project lead)
- ORNL (Technical lead), **(Jason Pries, Gui-Jia Su, Veda Galigekere, Cliff White, Larry Seiber, Erdem Asa, Randy Wiles, Jonathan Wilkins)**
- UPS
- Workhorse
- Cisco

Project Objectives and Relevance

Overall Objectives

- Design, model, simulate, build, integrate, and test a bidirectional wireless power transfer (BWPT) system for medium duty delivery trucks
  - A vehicle integrated >20 kW wireless power transfer system with bidirectional operation
  - High-efficiency (85%) with a nominal magnetic airgap of 11 inches
  - Vehicle-to-grid mode 6.6 kW wireless power transfer to building or grid loads (grid support or ancillary services)
  - Integration of the WPT system into the vehicle
  - Modeling and analysis of BWPT systems

FY 2019 Objectives:

- Develop the grid interface converter (rectifier/inverter) hardware
- Develop the primary side high-frequency inverter/rectifier hardware
- Develop the vehicle side rectifier/inverter hardware
- Develop the electromagnetic coupling coils and resonant tuning components
- Integrate auxiliary components (sensors, contactors, fuses, pre-charge circuitry, connectors, controllers, power supplies, etc.)
- Test system power stages individually
- Integrate the whole system together and validate functionalities

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

Project Milestones

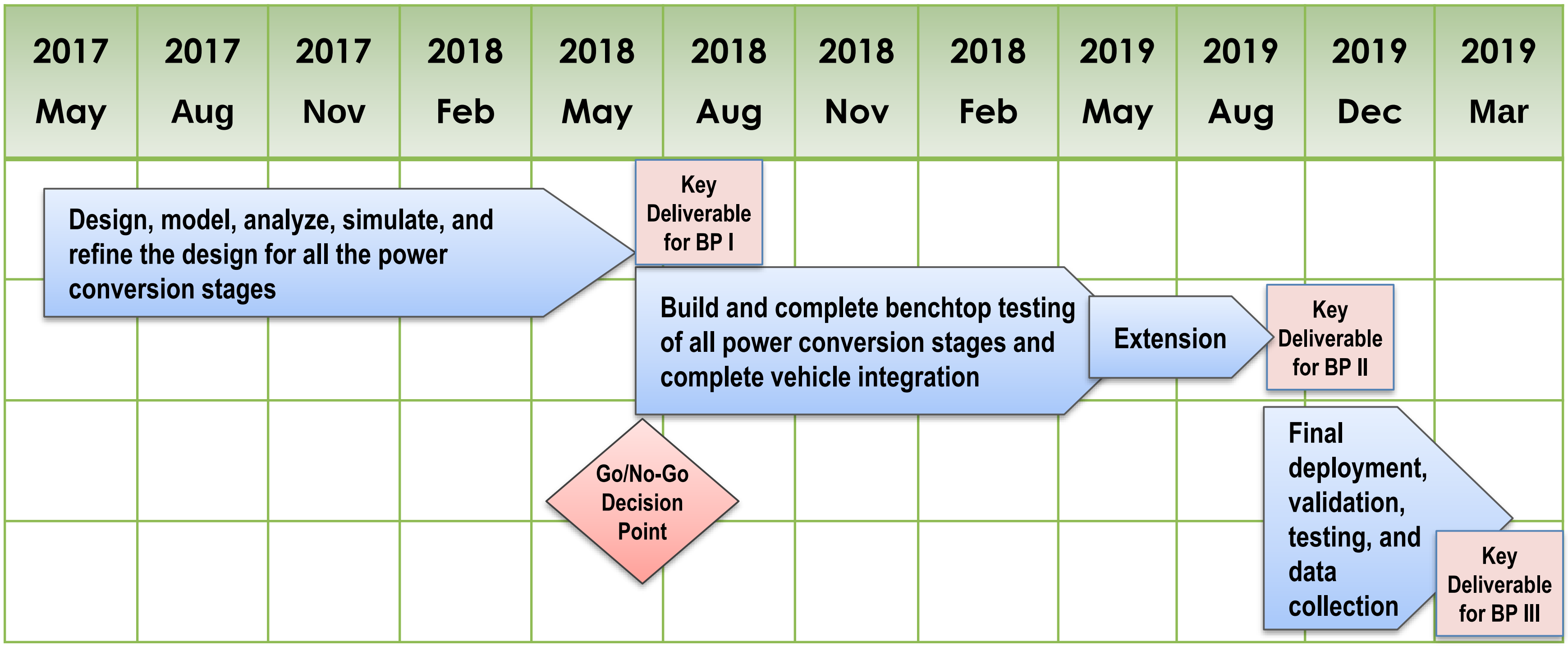
Date	Milestones and Go/No-Go Decisions	Status
May 2018 **Budget Period I**	Milestone: Design, model, simulate, analyze system components. Determine system power architecture and control strategy for the BWPT system.	Completed
May 2019 **Budget Period II**	Milestone: Develop (build) and test all the BWPT hardware for vehicle and grid sides, test all power conversion stages individually, complete benchtop tests, and integrate the system into the vehicle. Address the impact of BWPT on vehicle ESS, analyze the BWPT system benefits	Nearing completion
December 2019 **Budget Period III**	Milestone: Full vehicle level testing and demonstration of the BWPT technology, deployment of the vehicle and system to the test site, perform operations, collect data	On-track

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

Approach / Strategy

- Iterative design and the use of finite element analysis based modeling for the design optimization of the electromagnetic coupling coils.
- Vehicle battery and grid voltage and power levels are used for the proper system design and cascaded down to the appropriate subsystems and components.
- Built system power conversion stages in an integrated approach for an optimal system design in terms of complexity and compactness.
- Validated that system components meet the design parameters.
- Building two sets of stationary and vehicle side power electronics hardware.
- All the power conversion stages are being independently tested for functionality and validation of the performance.
- Entire system will be tested using grid and battery emulators before vehicle integration.
- Integrated system will be tested and validated on the test truck.

Project Timeline



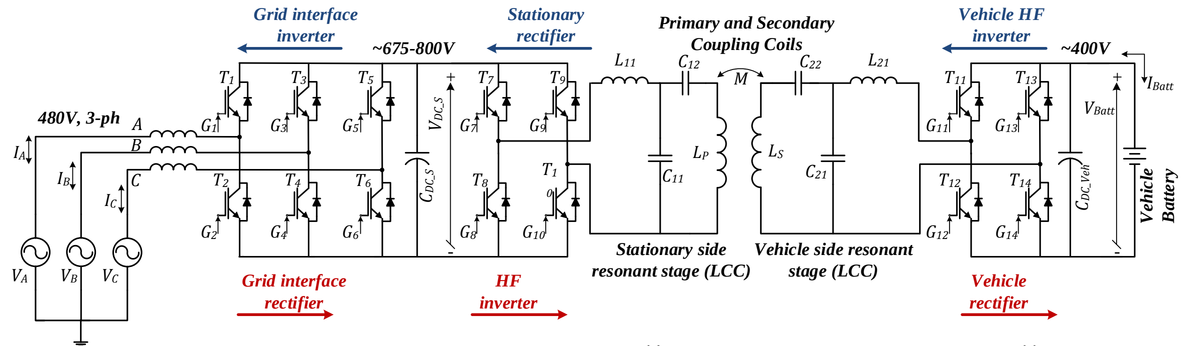
Go/No-Go Decision Point: Weather the system design, models, and simulations indicate the feasibility of 20 kW wireless charging operation over 11 inches magnetic airgap with at least 85% efficiency

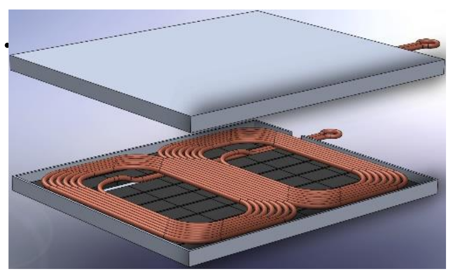
Key Deliverable for BP II: Complete results of benchtop system experimental tests and vehicle integrated operational test results.

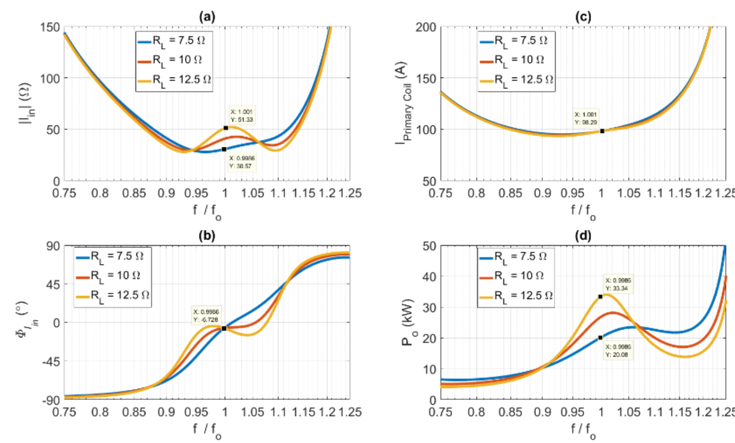
Any proposed future work is subject to change based on funding levels

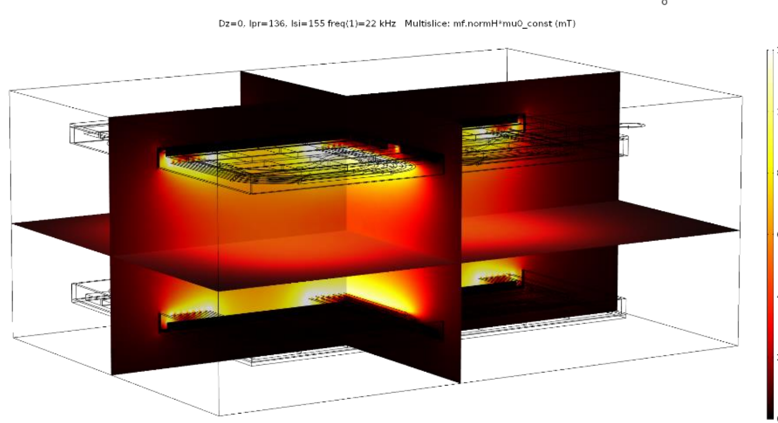
Technical Accomplishments – Summary of BP I

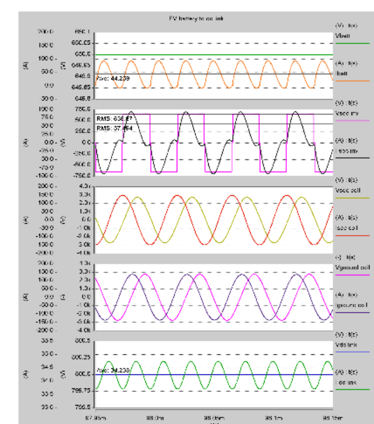
- Modeled, simulated, and analyzed power conversion stages and the whole system in both power flow directions.
- System architecture determined and designed
- Developed control systems both for charging and discharging operating modes.
- Designed the electromagnetic coupling
- Completed system characterizations.
- Completed resonant tuning configuration and tuning parameters.
- Completed the design of all the passive components.
- Completed power stage designs.

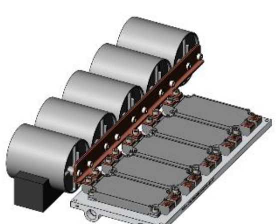








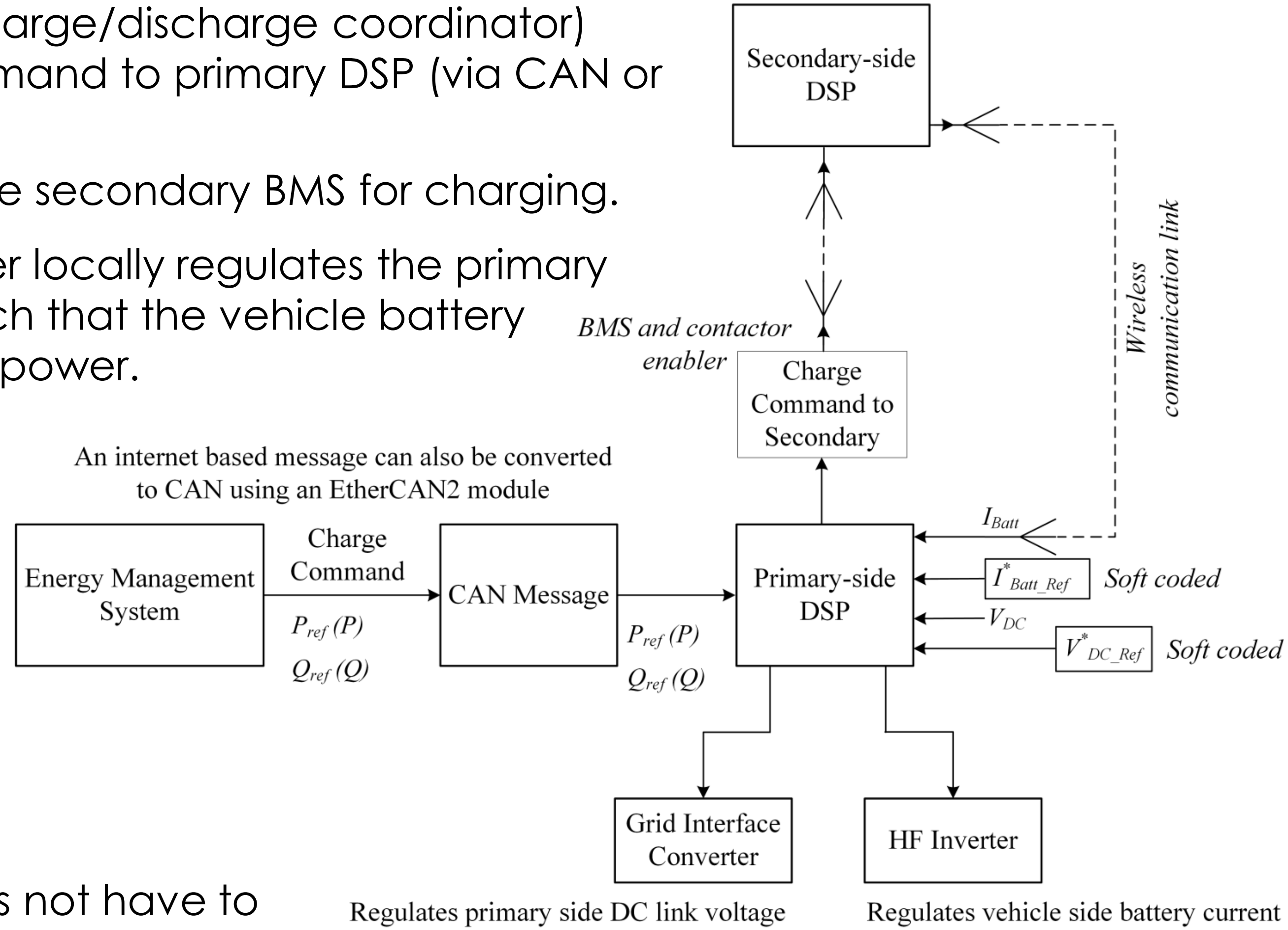




Technical Accomplishments – BP II

Designed and determined the operational features of the power flow control

- Energy manager (or charge/discharge coordinator) sends the charge command to primary DSP (via CAN or Ethernet).
- Primary side enables the secondary BMS for charging.
- Grid interface converter locally regulates the primary side DC link voltage such that the vehicle battery receives the reference power.
- HF inverter runs with fixed duty cycle or just for fine tuning the power.
- Vehicle-side rectifier runs as a passive diode bridge rectifier when charging.
- Wireless feedback does not have to be fast thanks to the LCL tuned resonant network both on primary and secondary.

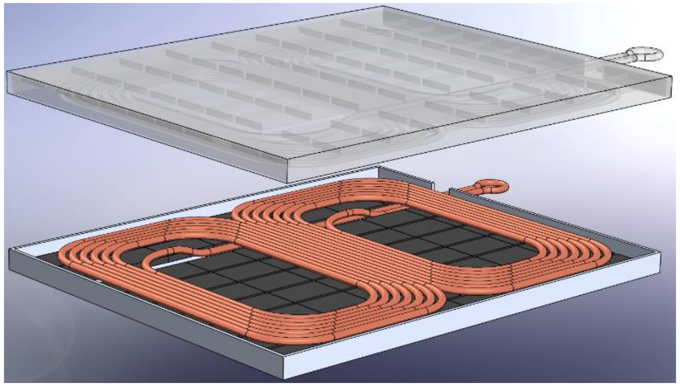


Operational block diagram of the bidirectional WPT power flow controller.

Technical Accomplishments – BP II

Finalized the development of coupling coils
Finalized the design of the resonant tuning components

- Asymmetric voltages drive asymmetry in coils and resonant stage
  - 800Vdc/420Vdc
  - 420Vdc/800Vdc



3D rendered image of coupling coils

	Primary	Secondary
Inductance	133 μH	123μH
Dimensions	34" x 28.5" x 1.5"	34" x 28.5" x 1.5"
Turns	7	6.5
Ferrite Mass	59.8 lbs.	59.8 lbs.
Litz Wire Mass	15.2 lbs.	14.3 lbs.
Plate Mass	109 lbs./in thickness	109 lbs./in thickness
Total Mass	102 lbs. (1/4" plate)	101 lbs. (1/4" plate)

Coupling coil specifications

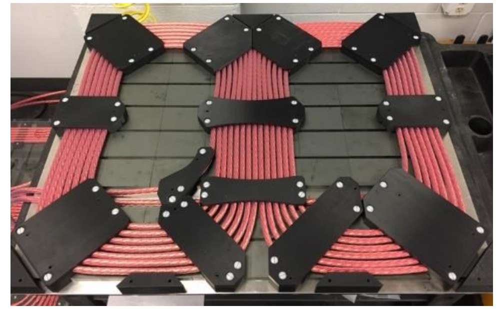
	Value	Nominal V or I	Rated V or I
L_{11}	40.4 μH	39.6 Arms	140 Arms
C_{11}	1.33 μF	753 Vrms	900 Vrms
C_{12}	0.68 μF	1100 Vrms	1800 Vrms
L_{12}	133 μH	100.6 Arms	150 Vrms
L_{22}	40.4 μH	77 Arms	80 Arms
C_{22}	1.33 μH	558 Vrms	900 Vrms
C_{21}	0.57 μF	1201 Vrms	1400 Vrms
L_{21}	123 μH	93.4 Arms	150 Arms

Parameters of the resonant tuning components

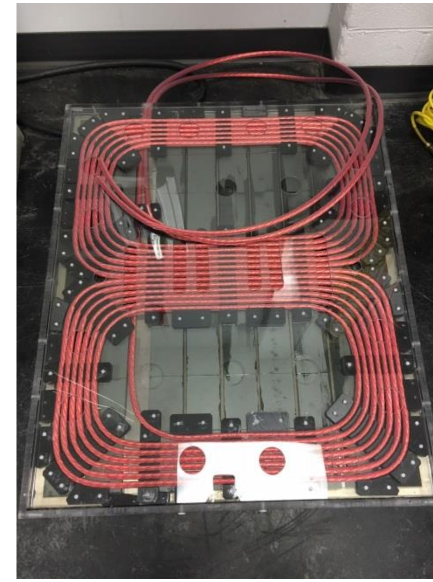
Technical Accomplishments – BP II

Developed (built) coupling coils as well as the resonant tuning components – closely matched the design parameters

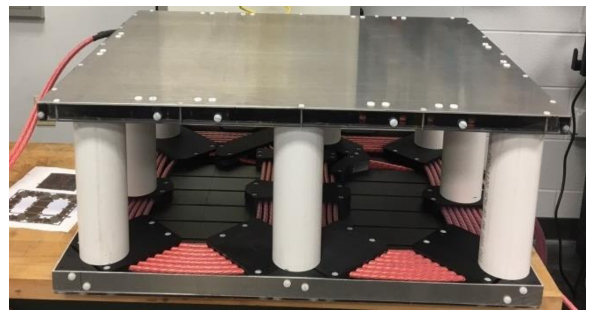
- FEA based modeling and design
- Target inductances
- L_P=133.4 μH, 39.3 mΩ for primary and
- L_S=123 μH, 37.1 mΩ for secondary
- Designed k = 0.21
- Actual inductances:
- L_P = 129.95 μH, 28.7 mΩ for primary
- L_S = 125.4 μH, 39.6 mΩ for secondary.
- Actual k_{ps} = 0.2130, k_{sp}=0.2105



Primary coil

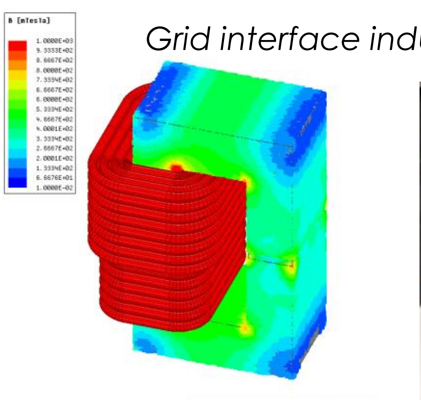


Secondary coil

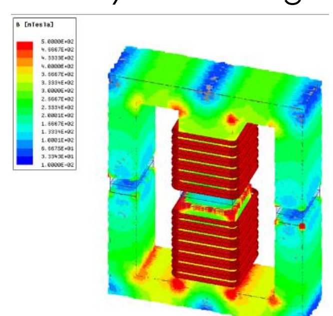


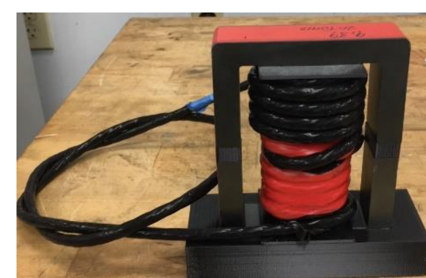
Coils with the required airgap

Grid interface inductor (3)



Primary and secondary side tuning inductors; design and physical built

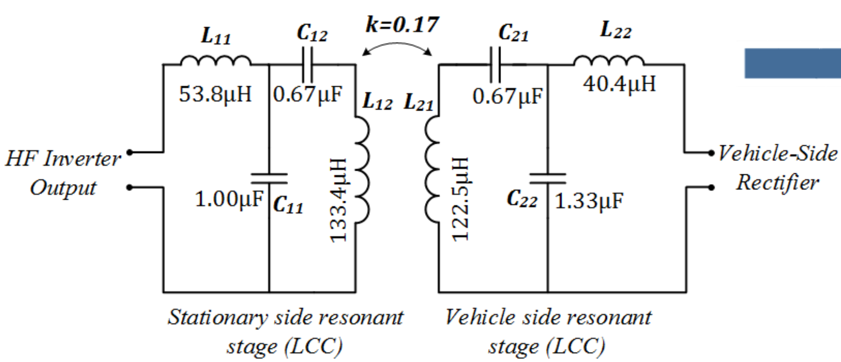




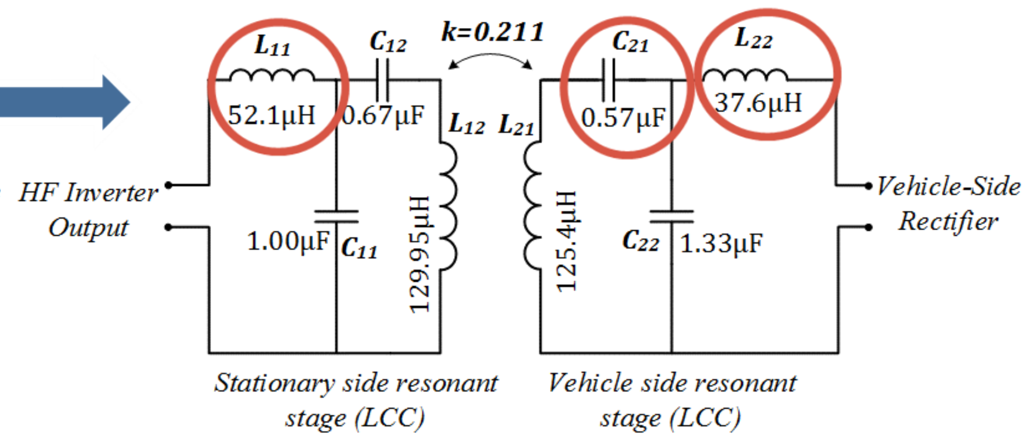
Technical Accomplishments – BP II

Modified the resonant tuning components for ~400V battery pack nominal voltage

- Issue: Full EV truck with 650V battery pack would not be available.
- Range extended hybrid (plug-in hybrid) with 420V nominal battery pack.
- Two options:
  - Modify the coupling coils that were already built – which would require the modification of the resonant tuning components anyways
  - Do more design work and simulations to modify the resonant tuning components
- New inductor values, new capacitor values
- Took the opportunity to redesign the capacitors and integrate the two capacitors in the LCC.



Previous resonant tuning components

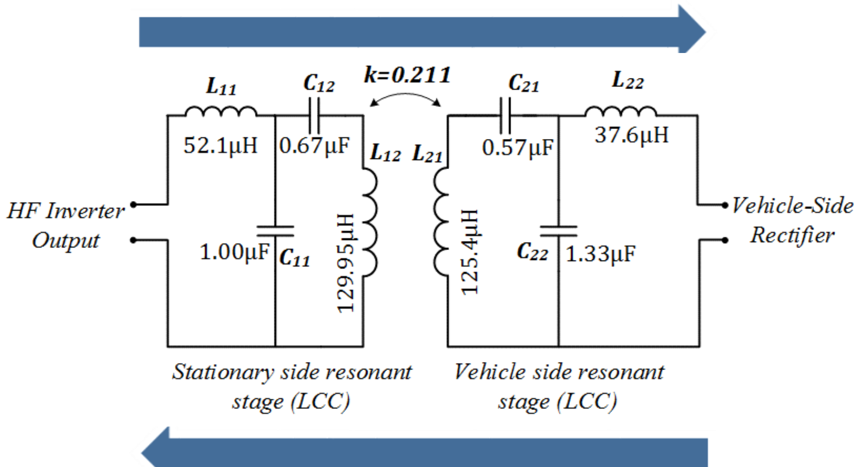


Modified resonant tuning components

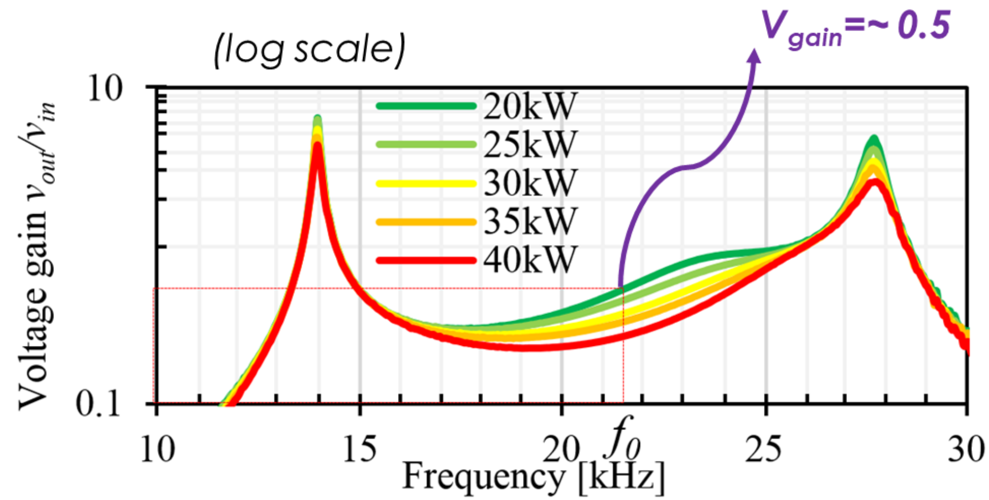
Technical Accomplishments – BP II

Performed voltage-gain analysis to validate the modifications

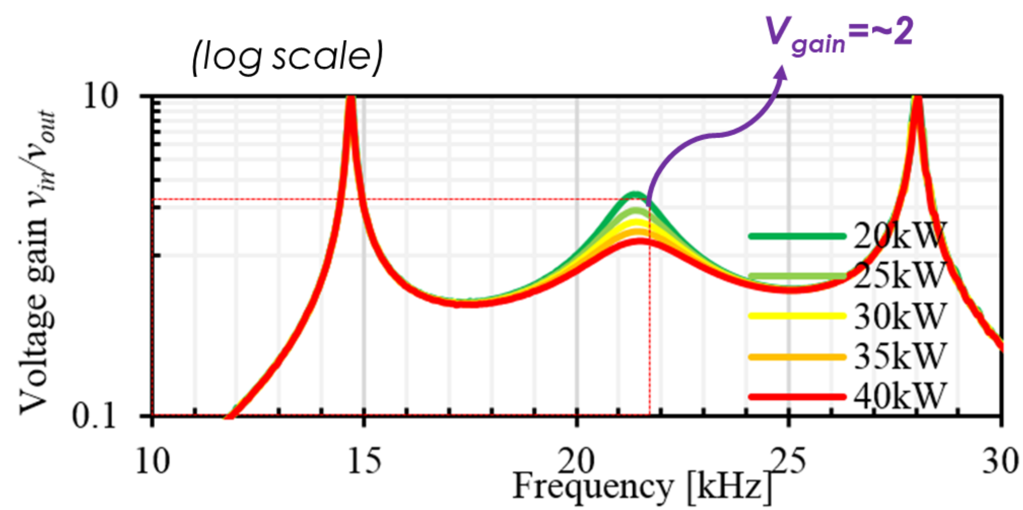
- ~800V bus to ~400V bus **(charging)**



- ~400V bus to ~800V bus **(discharging)**
- Voltage gains are properly designed to reduce the control stress on the power devices.
- Resonant gain provides most of the voltage conversion, power electronics only fine tunes the set points.



Voltage gain characteristic when charging the vehicle battery

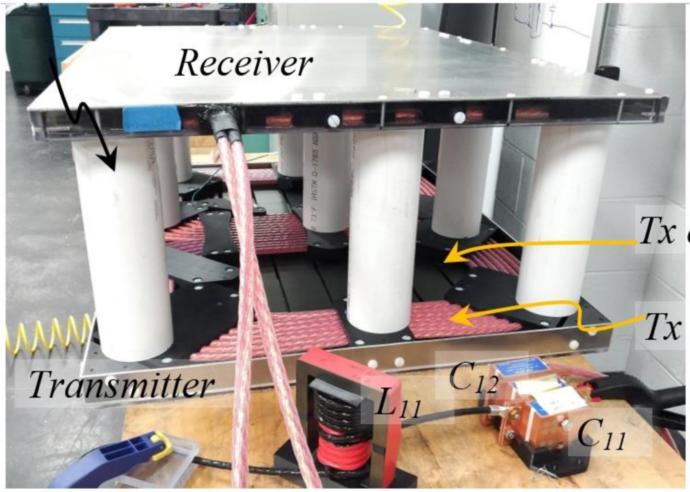


Voltage gain characteristic when discharging the vehicle battery

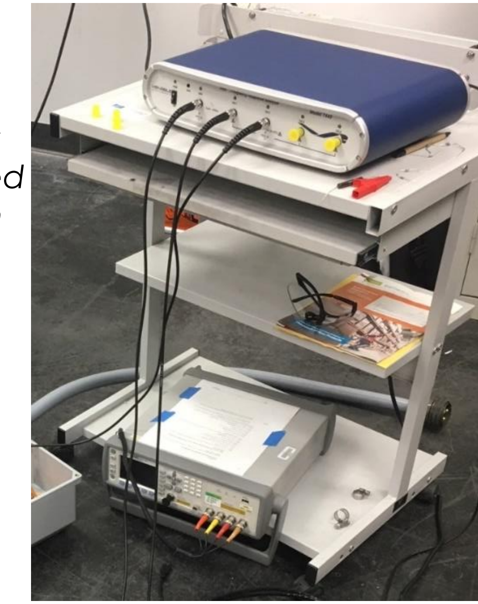
Technical Accomplishments – BP II

Experimentally validated the voltage gain of the system

- Coupling coils and resonant tuning components



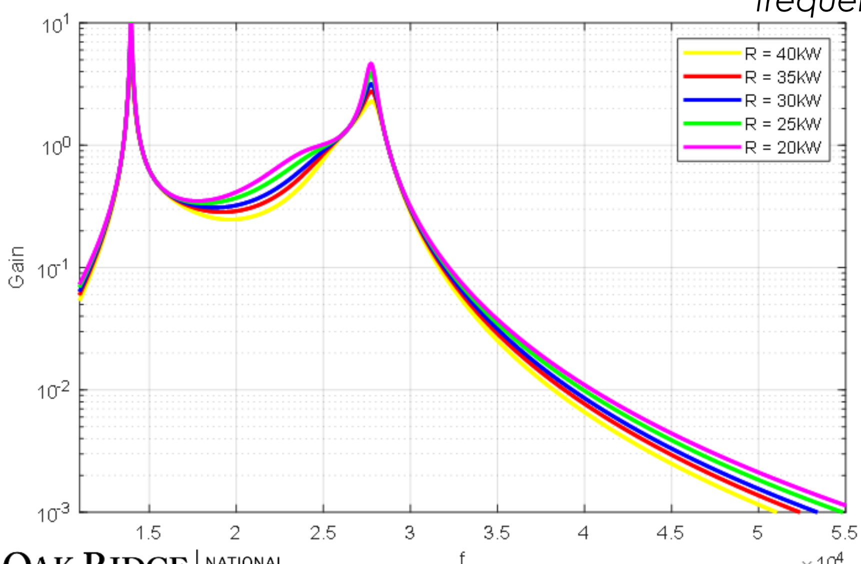
Bode 100 frequency response analyzer used for validating system characteristics.



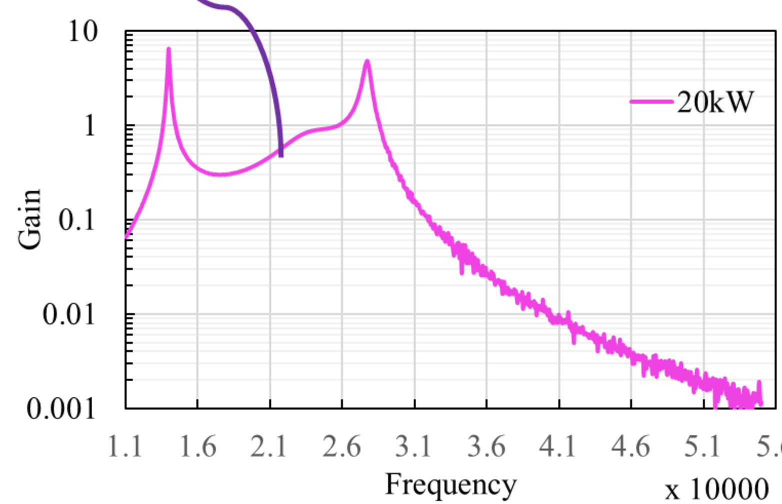
System voltage gain with respect to frequency

V_{gain}=~ 0.5

Simulation



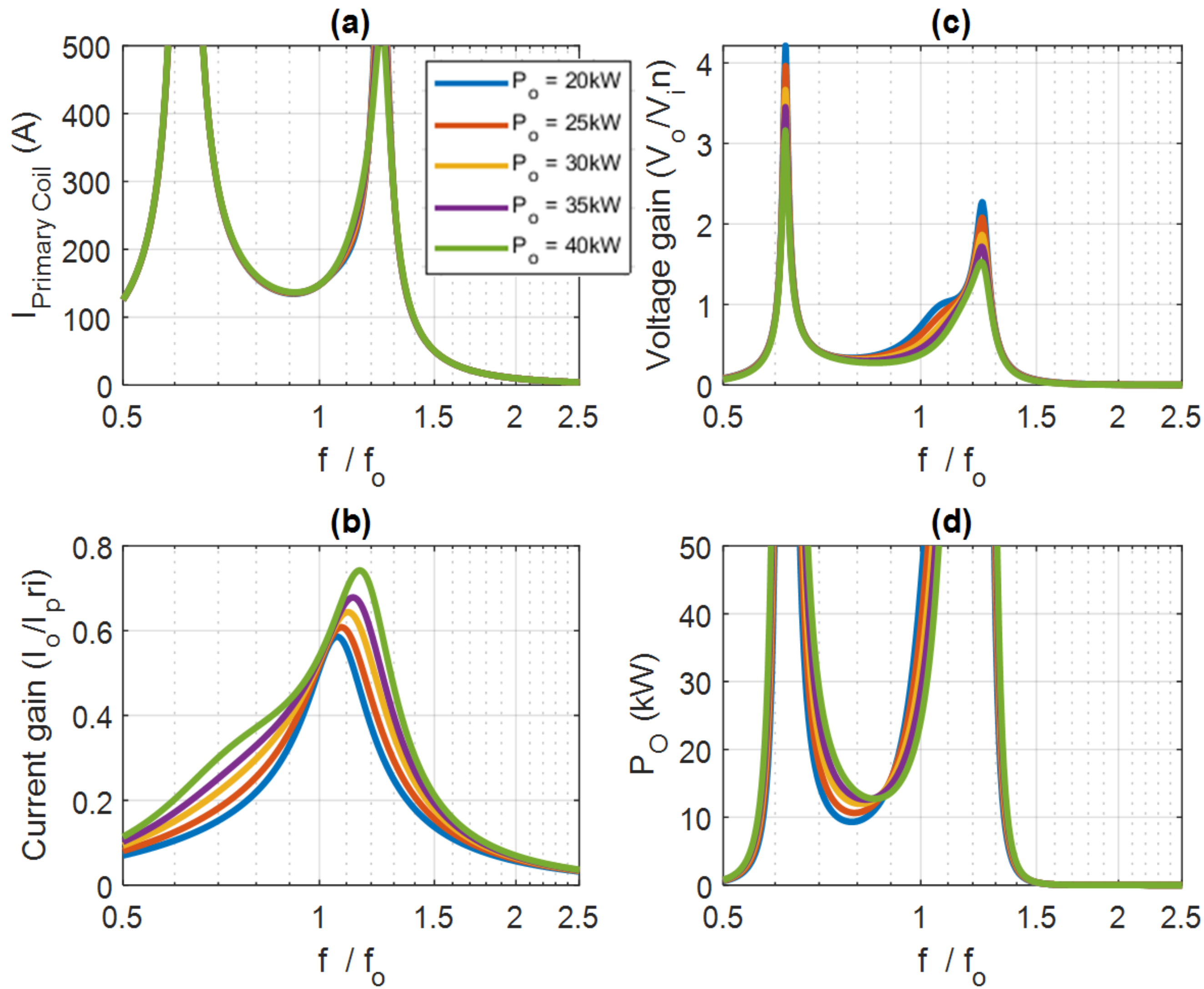
Experimental data



Technical Accomplishments – BP II

Analyzed system sensitivity for the modified resonant stage

- Analytical sensitivity characteristics of the
  - (a) primary current,
  - (b) voltage gain (v_o/v_{in}),
  - (c) current gain (i_o/i_{in}), and
  - (d) the output power with the variation of nominal output power and frequency variation.

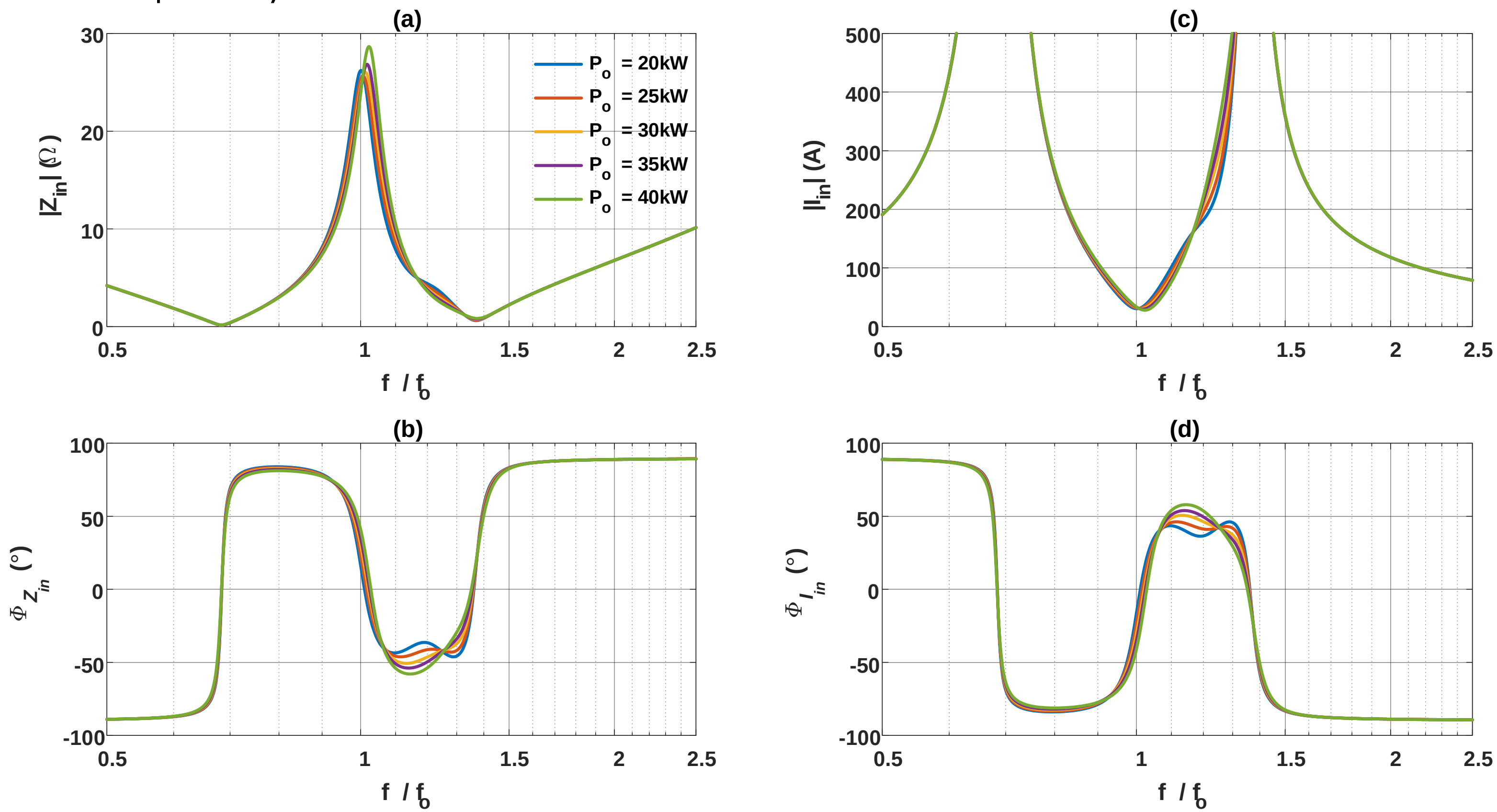


System characteristics as a function of frequency at different load levels.

Technical Accomplishments – BP II

Analyzed system sensitivity for the modified resonant stage

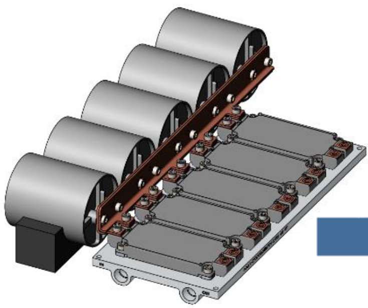
- Analytical sensitivity characteristics of the
  - (a) magnitude,
  - (b) (b) phase of the input impedance, (Z_{in}),
  - (c) magnitude, and
  - (d) phase of input current (i_{in}), with the variation of nominal output power and frequency variation.



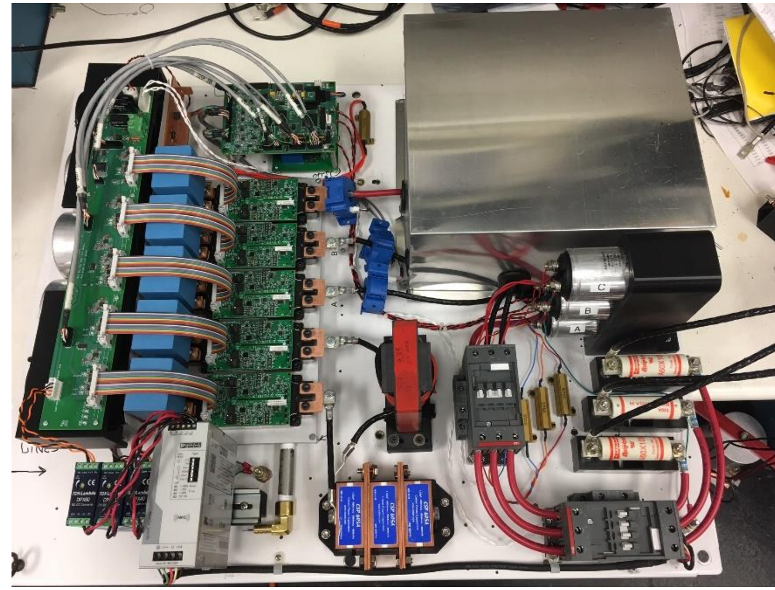
System characteristics as a function of frequency at different load levels.

Technical Accomplishments – BP II

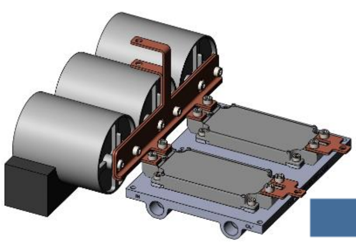
Power stage development



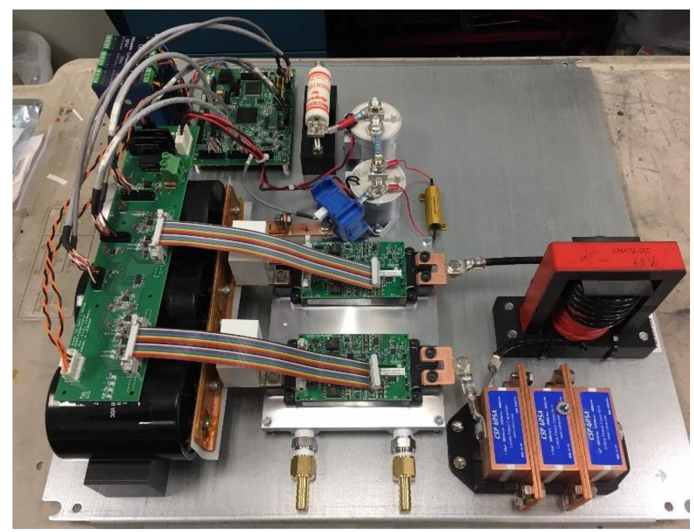
Primary-side power stage



May 2018 **October 2018** **March 2019**



Secondary-side power stage

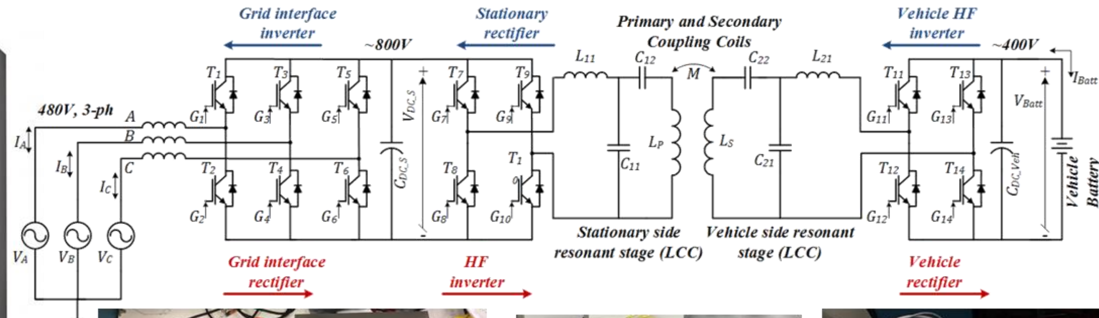


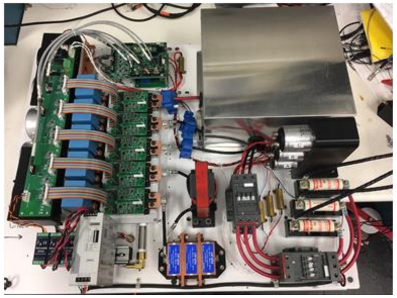
System hardware development progress.

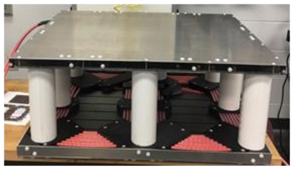
Test Plans for BP II

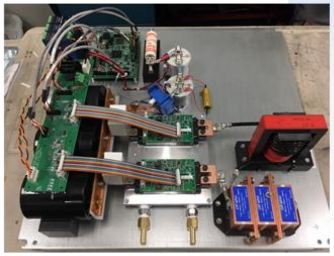
- All components have been individually tested, validated the parameters / functionalities.
- Resonant stage characteristics have been tested
- Tests being performed:
  - Test the HF inverter feeding a resistive load,
  - Test the resonant stage in loaded condition, transferring 20 kW power with 11 inches airgap separation,
  - Test the grid-interface converter feeding a DC resistive load,
  - Test the grid-interface converter feeding the HF inverter and resonant stage
  - Reverse the power flow and repeat the functionality tests

Ametek RS90 90kW AC Grid Emulator







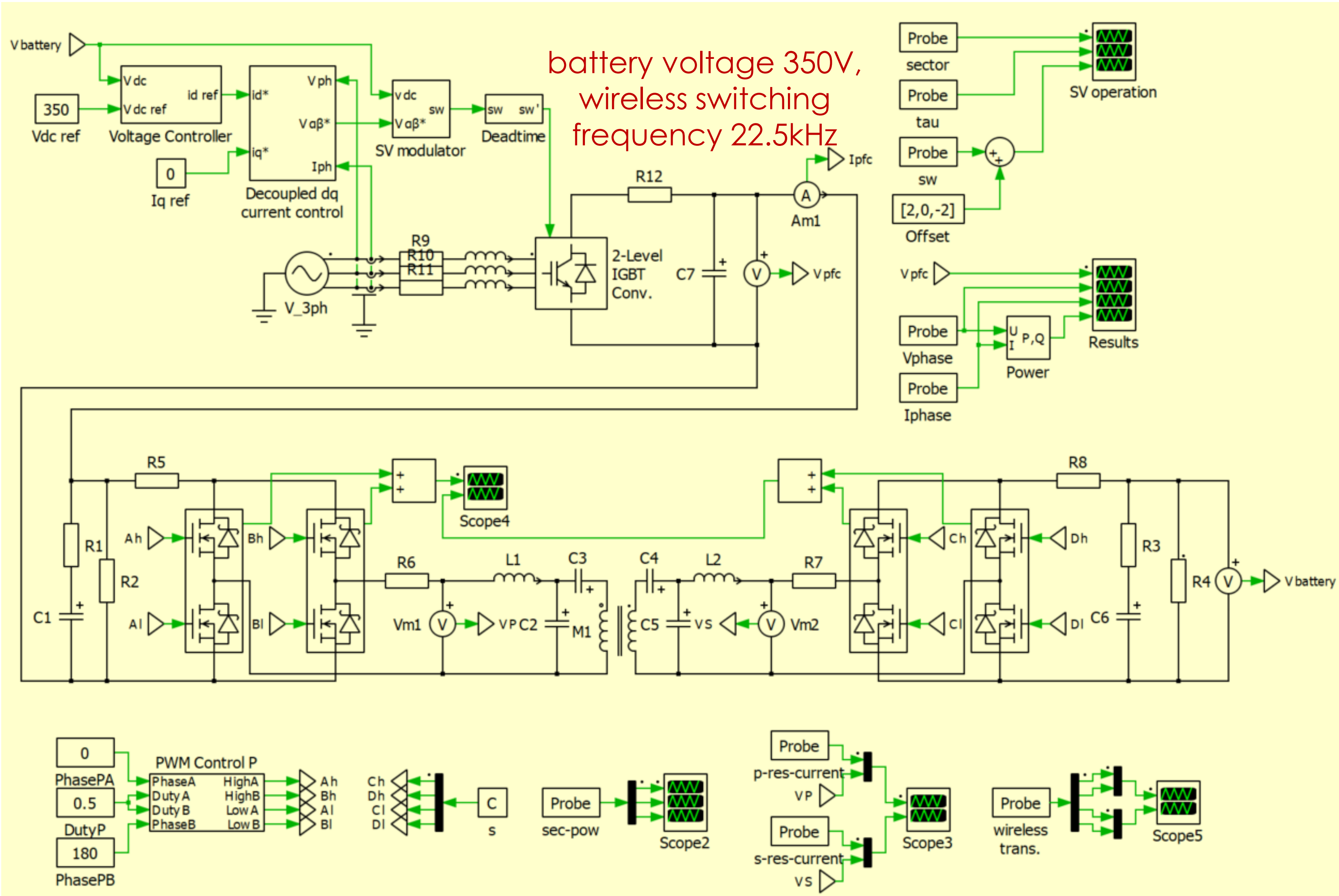


NHR 9300 100kW Battery Emulator

Test setup diagram

Technical Accomplishments – BP II

Entire system simulations with closed loop control: Charging



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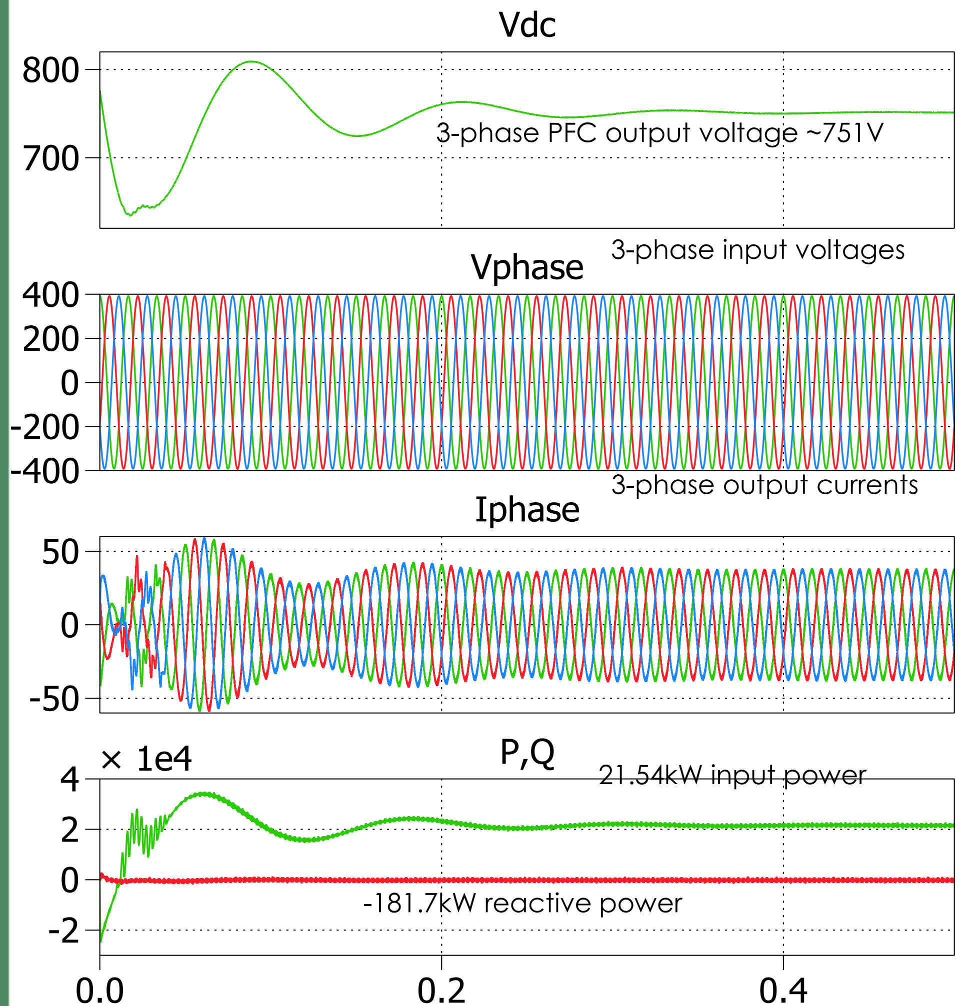
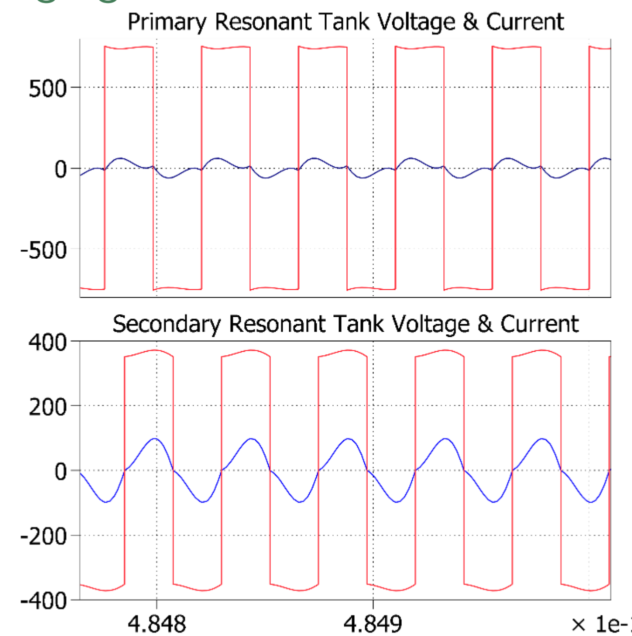
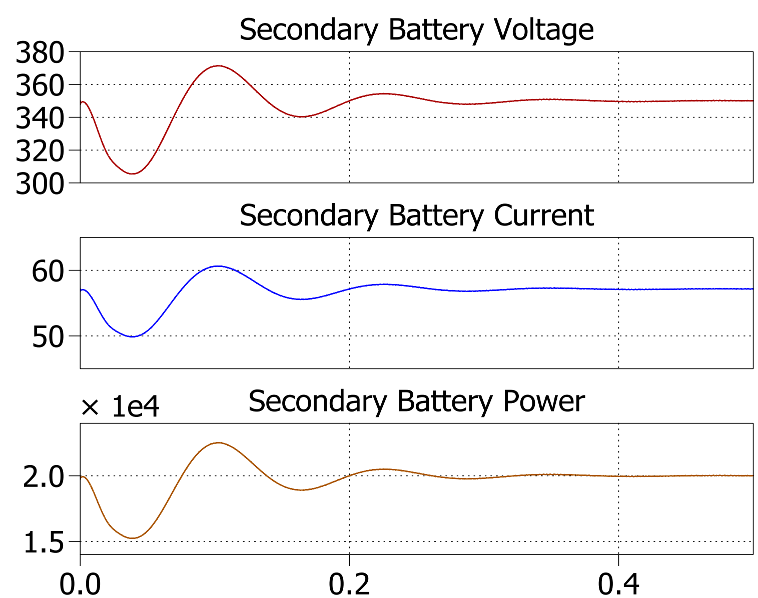
Technical Accomplishments – BP II

Entire system simulations with closed loop control: Charging



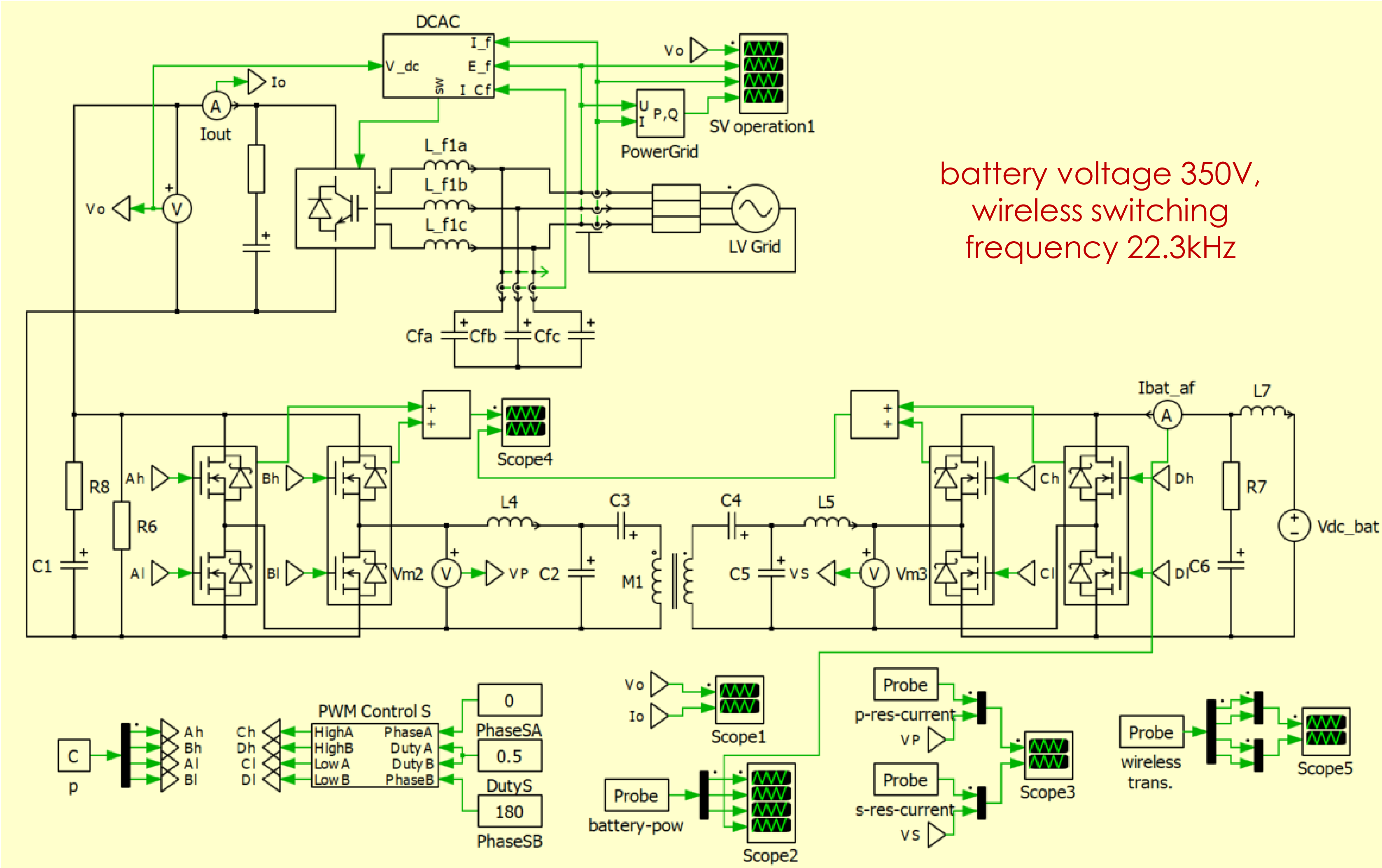




Input currents: $26A_{rms}$, Input current THD: ~2%
Input power factor: 0.999, 20kW battery power

Technical Accomplishments – BP II

Entire system simulations with closed loop control: Discharging



battery voltage 350V, wireless switching frequency 22.3kHz

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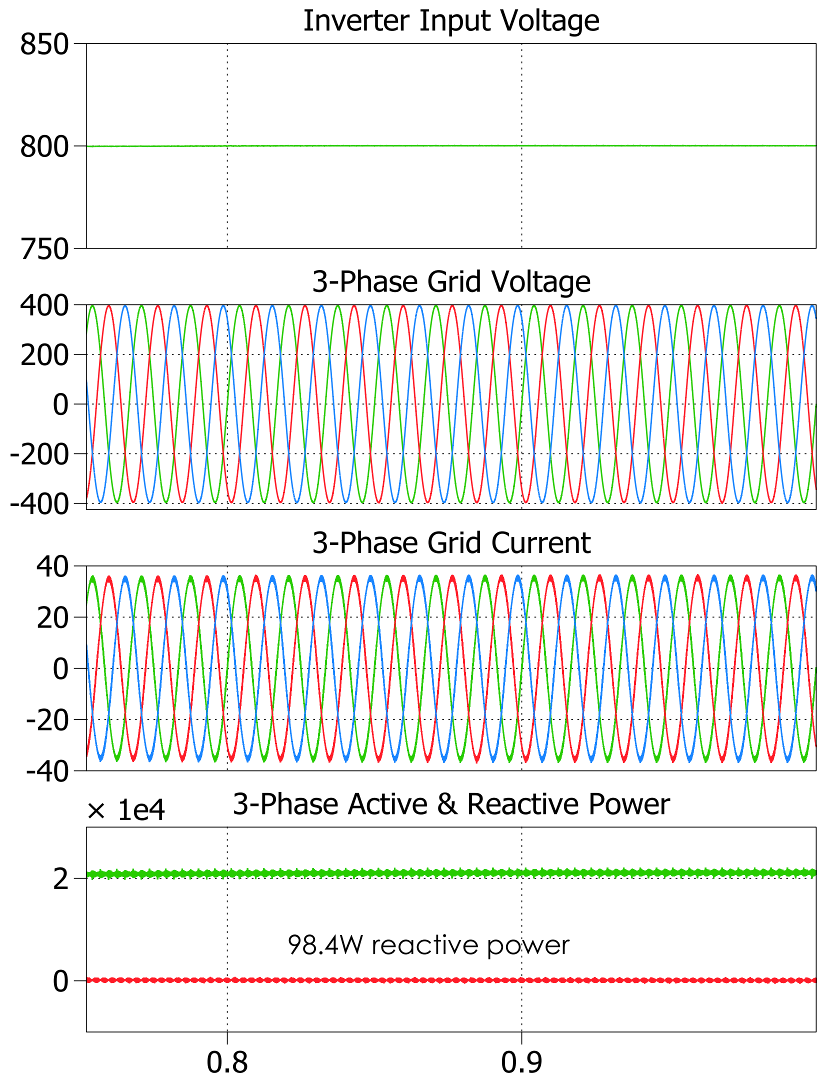
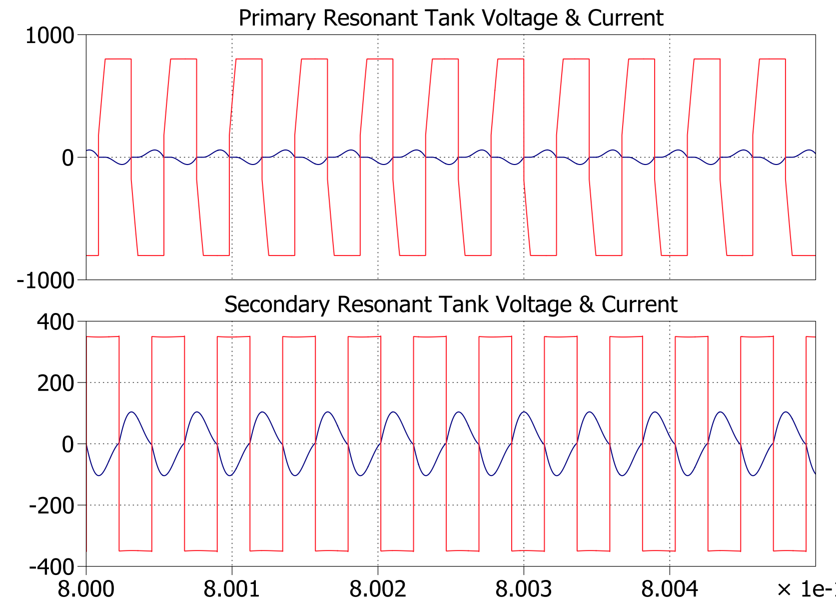
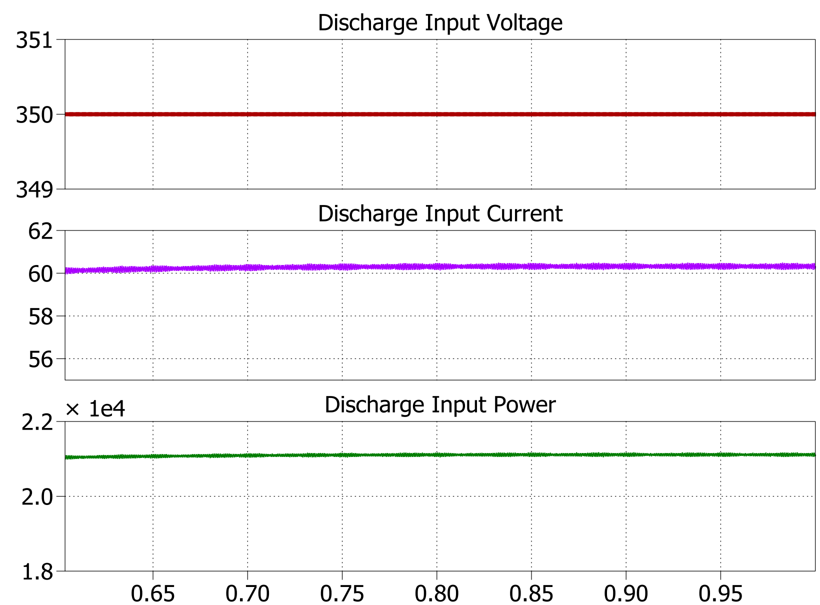
Technical Accomplishments – BP II

Entire system simulations with closed loop control: Discharging



Grid currents: $25A_{rms}$, Grid current THD: ~2%
Grid power factor: 0.999, 21kW battery power,
~20 kW grid power



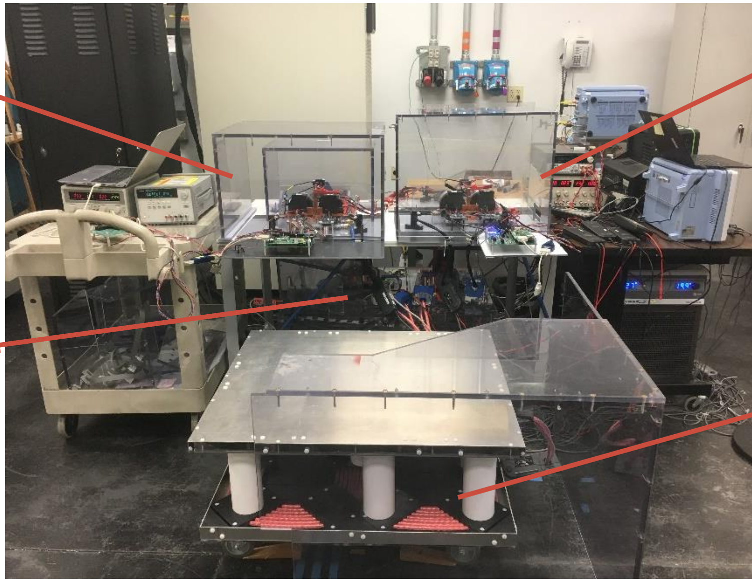


Technical Accomplishments – BP II

Experimental test setup and results of the resonant stage

Secondary-side hardware

LCC-LCC tuning components

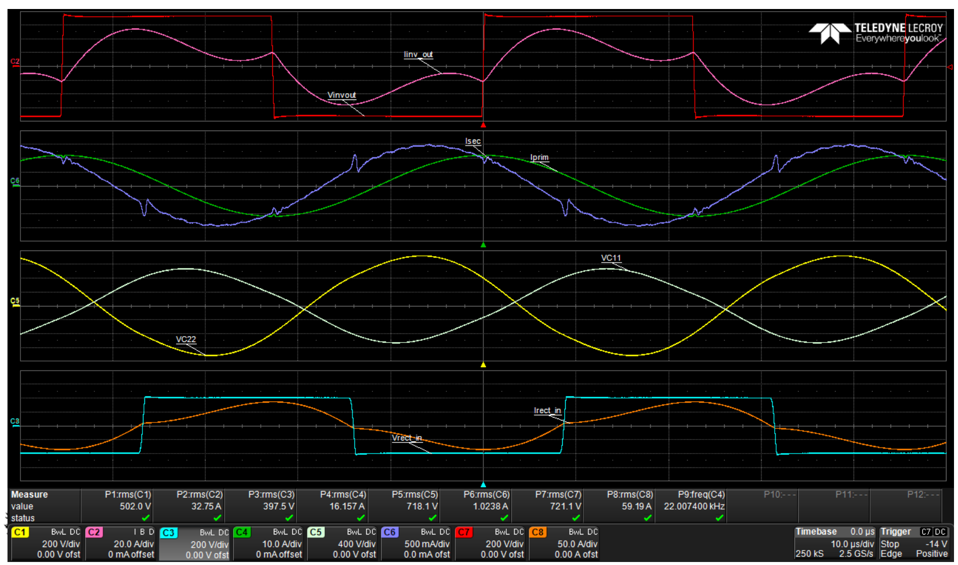


Primary-side hardware

Coupling coils with 11" airgap

- ~20kW power delivery to the battery emulator
- Grid-to-vehicle power flow
- ~737V_{in_dc}
- ~400V_{out_dc}
- 96% dc-to-dc efficiency
- Inverter, rectifier, coils, primary and secondary-side LCC tuning components

- Zero-voltage-switching (ZVS) operation



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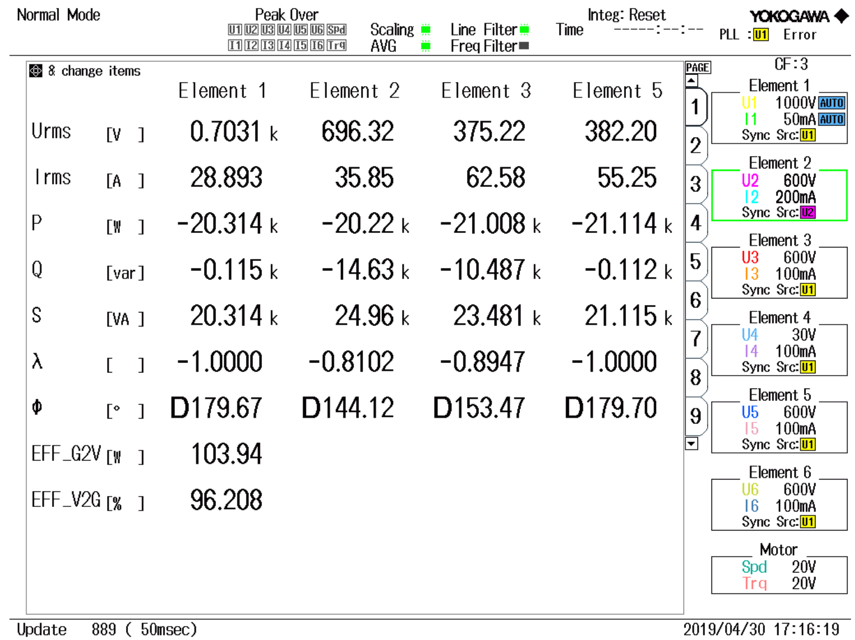
		Element 1	Element 2	Element 3	Element 5
Urms	[V]	0.7371 k	730.86	399.95	402.04
Irms	[A]	28.439	34.00	57.06	50.08
P	[W]	20.961 k	20.86 k	20.206 k	20.134 k
Q	[var]	-0.269 k	13.50 k	-10.609 k	-0.220 k
S	[VA]	20.963 k	24.85 k	22.822 k	20.135 k
λ	[ ]	0.9999	0.8395	0.8854	0.9999
Φ	[°]	D0.75	G32.92	D27.70	D0.63
EFF_G2V	[%]	96.053			
EFF_V2G	[%]	104.11			

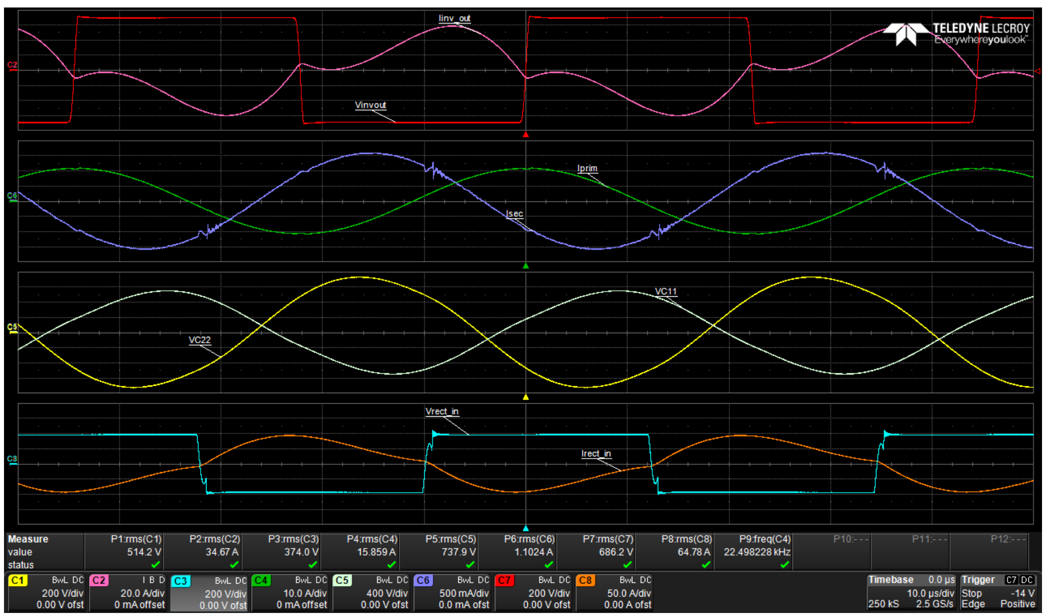
Update 1586 (50msec)

Technical Accomplishments – BP II

Experimental test setup and results of the resonant stage

- ~20kW power delivery from battery emulator to the input DC bus
- Vehicle-to-grid power flow
- ~700V_{prim_dc}
- ~382V_{batt}
- 96.2% dc-to-dc efficiency
- Inverter, rectifier, coils, primary and secondary-side LCC tuning components





- Zero-voltage-switching operation both on primary and secondary power converters

Response to Previous Year Reviewers' Comments

- **Comment**: "*Including a partner that would provide the true operational parameters provides realism to the design constraints and enhances the proof of concept.*"

Response: UPS is one of the project partners and the end-user of the proposed technology. UPS provides the required parameters for the design constraints and operational characteristics of the system.

- **Comment**: "*Great physical assessment will be necessary to confirm the efficiencies calculated.*"

Response: Now that the team completed the design and the hardware development, experimental tests are being performed to validate the efficiencies and all the functionalities.

- **Comment**: "*How about the robustness of the system for vibration and the possibility of radiation leakage caused by the large airgap.*"

Response: Team includes mechanical engineers working on the layout design of the system components and robust mounting methods for the components. The leakage field is measured during the tests and the aluminum plate shielding seems to be sufficient to keep the field emissions below the limits set by ICNIRP 2010 guideline.

- **Comment**: "*ORNL has been the primary organization energetically designing and building the system but there seems to be limited collaboration with partners.*"

Response: ORNL closely works with UPS and Workhorse who manufactures the plug-in hybrid truck that the technology will be integrated into. ORNL continuously receives information and data from partners for successful integration and demonstration of this technology.

- **Comment**: "*Demonstration delivery in 2019 is an aggressive target with all the hardware to be developed.*"

Response: The reviewer is right as we experienced some delays due to uncertainty on the vehicle battery voltage levels and the hardware was re-designed and modified multiple times for best optimization for the given battery voltage. However, now the team is back on the track performing tests and evaluations for a successful integration.

Collaboration and Coordination with Other Institutions

- **CALSTART**: Project lead, project management, budget management, reporting, overall coordination, V2G economic analysis, business case analysis
- **ORNL**: Technical lead, system design, development, integration, testing
- **UPS**: End-user, deployment site, integration coordination
- **Workhorse**: Vehicle manufacturer, vehicle systems integration and engineering support
- **Cisco**: Developed and provides communication interfaces from energy management system to the BWPT system and also the vehicle to grid / grid to vehicle communications.

CALSTART OAK RIDGE National Laboratory ups WORKHORSE CISCO

Remaining Challenges and Barriers

- The grid power and battery charger power should be accurately controlled to meet the requirements of the energy management system or facility operations engineer.
- The electric and electromagnetic field emissions should be less than the limit levels set by the ICNIRP 2010 guidelines inside and around the vehicle while transferring 20kW across 11 inches airgap.
- Meeting the utility and grid standards for the grid interface converter requires precise measurement and control system development.
- The thermal management system of the hardware requires utilizing cooling system designed for the vehicle's on-board charger. Controlling the cooling system as well as other on-vehicle auxiliary components including the BMS system requires input from the OEM.

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

Proposed Future Research

- **FY 2019**
  - Complete the entire system tests and modify control systems as needed. Also complete the vehicle integration and demonstrate the system operation on the vehicle.
  - Model and analyze the benefits of the BWPT systems.
  - Model and analyze the impact of the BWPT operation on the lifetime of the vehicle battery for a given use-case scenario or duty-cycle.

- **FY 2020**
  - Final deployment, validation, testing at the demonstration site and data collection.

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

Summary

- **Relevance**: Increase the benefits and reduce the barriers in vehicle electrification, wireless charging, and vehicle to grid integration for improved V2G operations.
- **Approach**: Proposed a bidirectional wireless power transfer system that operates at a high airgap for medium duty delivery trucks with high-efficiency and functionality through advanced power electronics and magnetics design, vehicle systems integration, and control system design.
- **Technical Accomplishments**:
  - Designed and developed all the system power conversion stages including all the subsystems and components.
  - Currently testing the whole system together for validations and functionalities.
- **Collaborations and Coordination with Other Institutions**:
  - **CALSTART**: Project lead and project management.
  - **UPS**: Test vehicle provider, end-user, final deployment site.
  - **Workhorse**: Plug-in hybrid and electric delivery truck manufacturer.
  - **Cisco**: Providing radio communication systems for commanding the system and to form feedback control loops.
- **Future Work**:
  - Complete tests of the entire system and vehicle integration.
  - Model and analyze BWPT V2G benefits.
  - Model and analyze impact of BWPTV2G operations on battery lifetime

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