OAK RIDGE National Laboratory

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

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U.S. DEPARTMENT OF ENERGY

Overview

Timeline

- Start – May 2017
- End – December 2021 (expected)
- Budget Period I completed in May 2018
- Budget Period II Go/No-Go completed in Feb. 2020
- Project completion by Dec. 2021

Budget

- Total project funding
  - DOE share – $1.95M
  - Cost share from partners – $712K
- Project spending BP1: $650K
- Project spending for BP2: $1.2M

Barriers

- 11 inches magnetic airgap for 20kW wireless power transfer (most applications are for 6-8 inches)
- Achieving bi-directional 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

Partners

- CALSTART (Project lead)
- ORNL (Technical lead)
- UPS
- Workhorse
- Cisco

Project Objectives and Relevance

Overall Objectives:

- Design, model, simulate, build, integrate, and test a bi-directional wireless power transfer (BWPT) system for medium duty delivery trucks
  - A vehicle integrated ≥20 kW wireless power transfer system with bi-directional 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 2020 Objectives:

- Complete the development of system power conversion stages
- Integrate auxiliary components (sensors, contactors, fuses, pre-charge circuitry, connectors, controllers, power supplies, etc.) and communication systems
- Test system power stages individually on laboratory benchtop setup
- Integrate the whole system together and validate functionalities
- Complete vehicle integrations and perform a vehicle integrated demonstration

FY 2021 Objectives:

- Site preparation, final deployment, testing and data collection at the UPS facility

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
February 2020 **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	Completed
December 2021 **Budget Period III**	Milestone: Deployment of the vehicle and system at the UPS Roswell, GA facility, full vehicle level testing and demonstration of the BWPT technology, perform operations, collect data	On-track

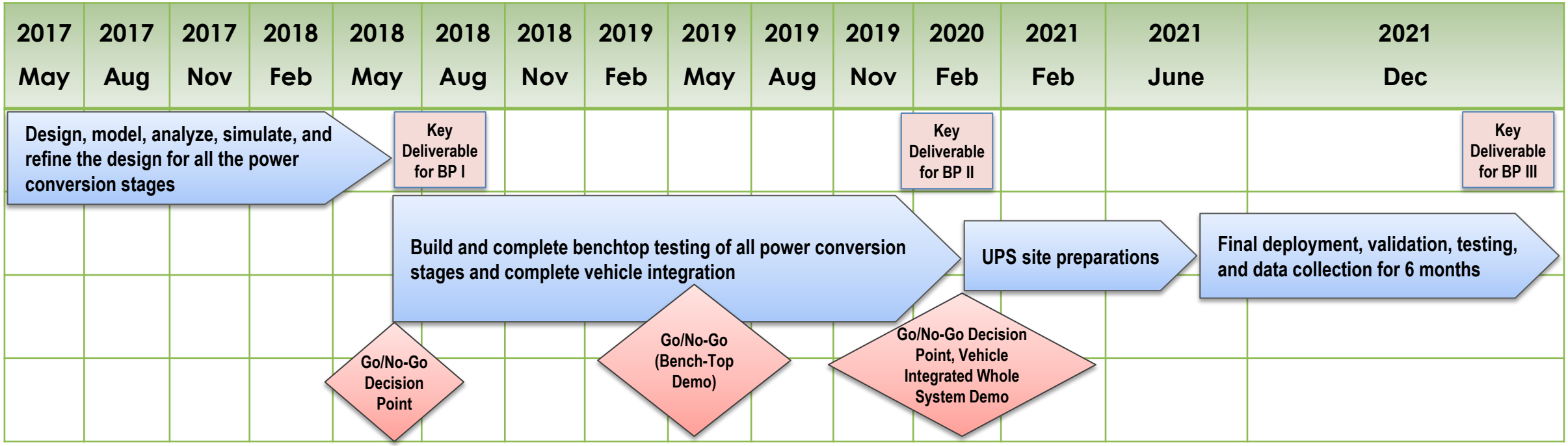
Any proposed future work is subject to change based on funding levels

Approach / Strategy

- Target operating conditions (power level, input grid voltage, vehicle battery voltage range, airgap, maximum current, etc.) are used for proper system level design and cascaded down to the appropriate subsystems and component designs
- Iterative design and the use of finite element analysis (FEA) based modeling for the design optimization of the electromagnetic coupling coils
- Build system power conversion stages in an integrated approach for an optimal system design in terms of complexity and compactness
- Validate that system components met the design parameters
- Test all the power conversion stages independently for functionality and validation of the performance
- Evaluate entire system using grid and battery emulators before vehicle integration
- Test and validate the integrated system on the test truck
- Site preparation and deployment for testing at the UPS facility and data collection

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

Project Timeline



Go/No-Go Decision Points:

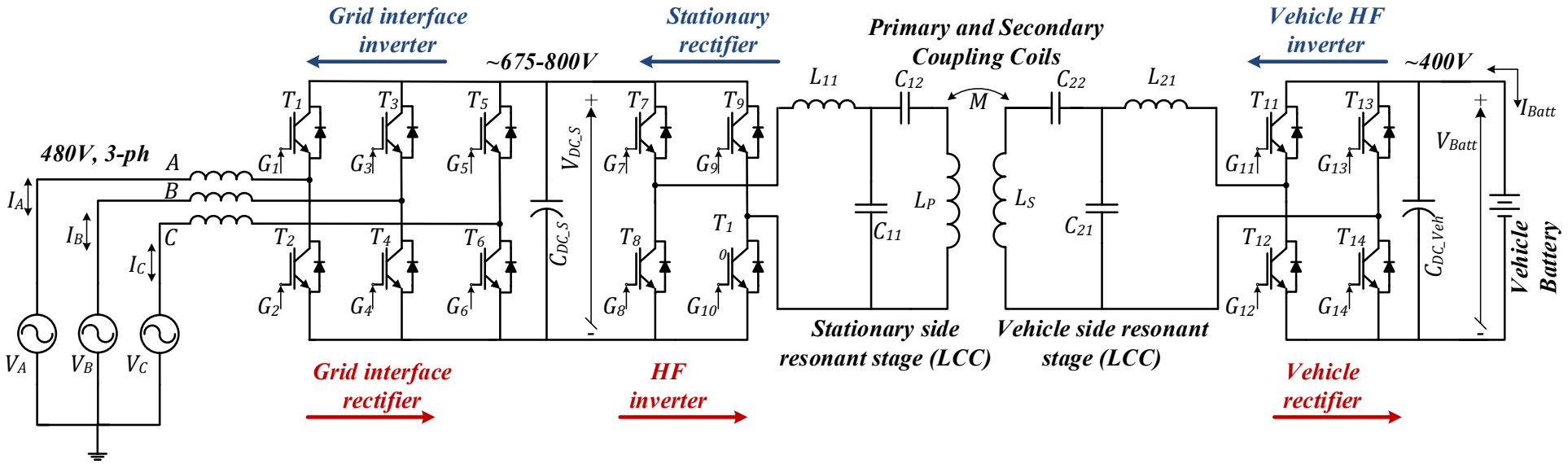
- Whether the system design and models indicate the feasibility of 20 kW wireless charging operation over 11 inches magnetic airgap with at least 85% efficiency (May 2018, BP I)
- Limited objective (bench-top) demo with 20 kW operation for the bi-directional wireless power transfer system (May 2019, BP II)
- **Vehicle integrated complete system demonstration in both power flow directions with all the targets met (February 2020, BP II)**

Key Deliverable for BP III: Final deployment at the UPS Roswell, GA facility, validation, demonstration, testing, and data collection (June - December 2021)

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

Summary of Technical Accomplishments

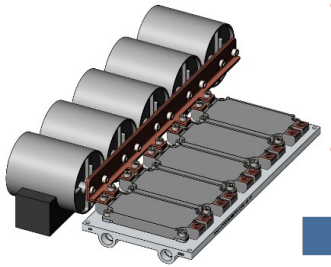
- Completed modeling, analysis, simulations, design and component selections in BP I (May 2018)
- Completed hardware development in BP II (October 2019)
- Modified the resonant tuning network to accommodate ~400V vehicle battery voltage due to the unavailability of all-electric truck with 650V battery voltage
- Demonstrated the dc-to-dc operation (without grid interface converter) with two dc emulators on each end (May 2019)
- Integrated the grid interface converter and started benchtop tests (November 2019)
- Individually tested the power stage and tested parameters and functionality of each subsystems and components
- Completed vehicle integrations, testing, and validations of the system on the truck (February 2020)
- UPS internal approval process started followed by site preparations (February 2021)



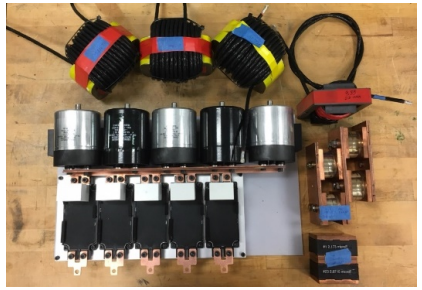
System level block diagram

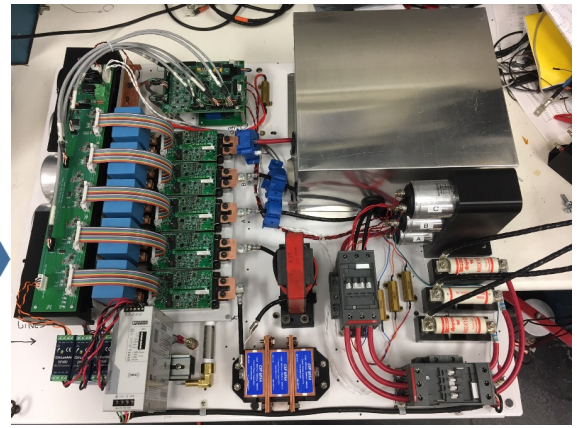
Technical Accomplishments – BP II

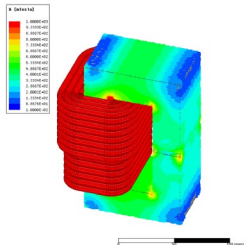
Power stage and resonant stage development



Primary-side power stage

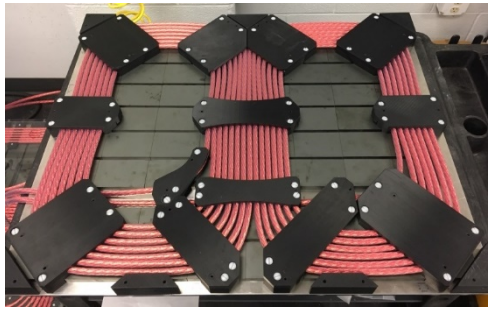




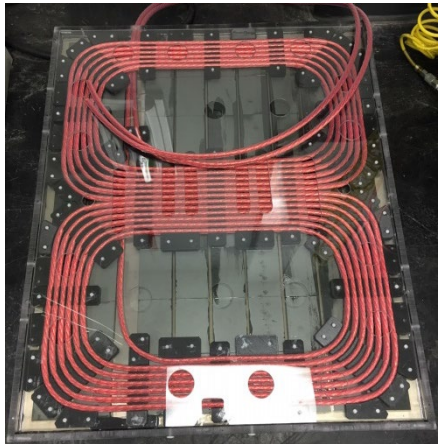




Grid interface inductors (3)

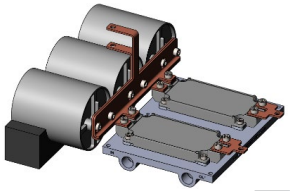


Primary coil

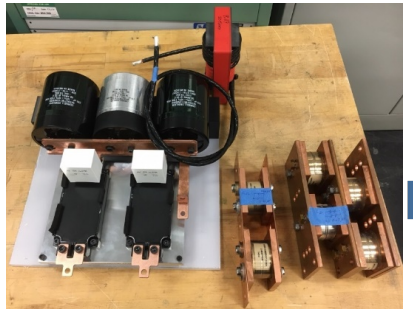


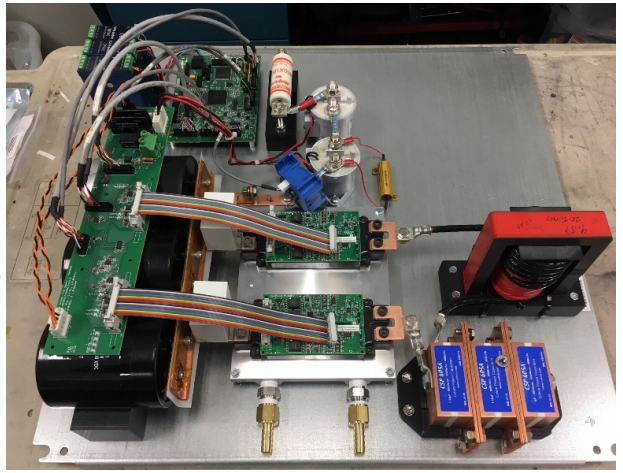
Secondary coil

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

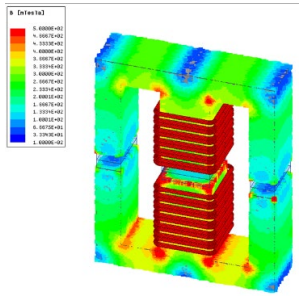


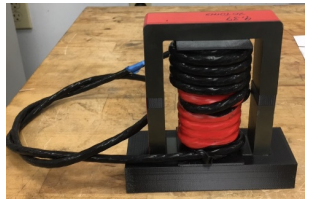
Secondary-side power stage



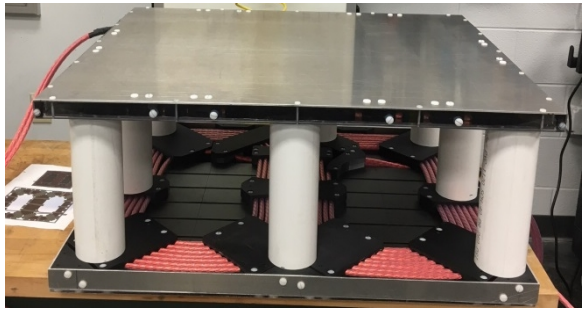


System hardware development progress





Primary and secondary side tuning inductors; design and physical build

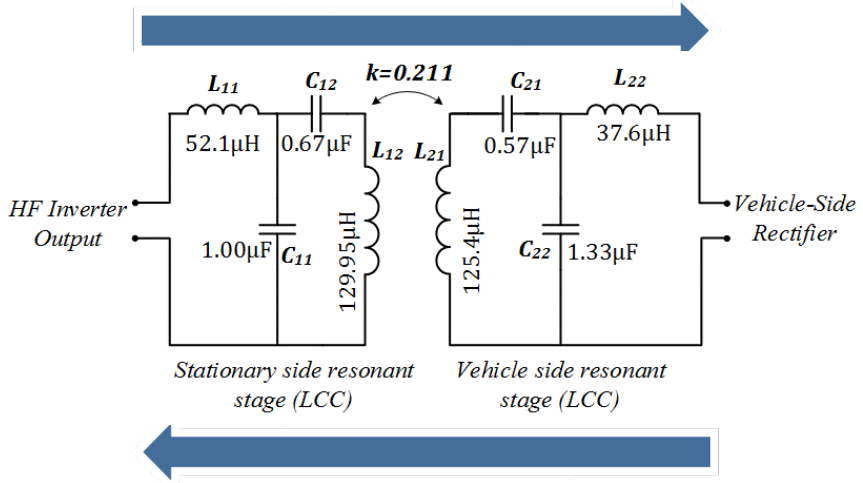


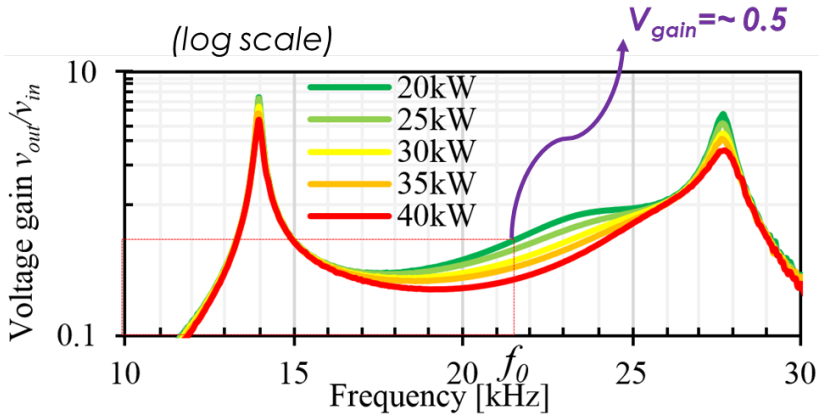
Coils with the required airgap

Technical Accomplishments – BP II

Performed voltage-gain analysis to validate the modifications

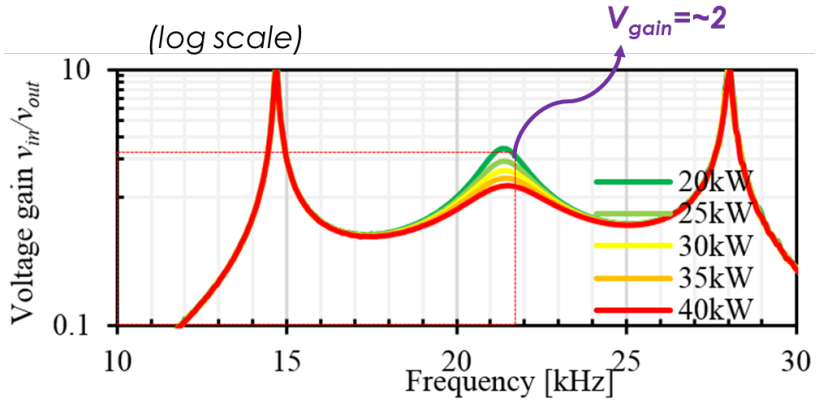
- ~800V bus to ~400V bus **(charging)**



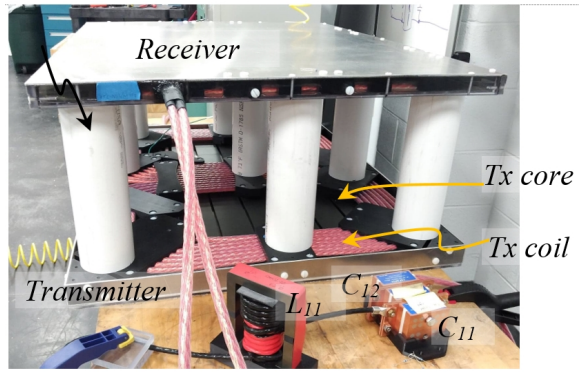


Voltage gain characteristic when charging the vehicle battery

- ~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

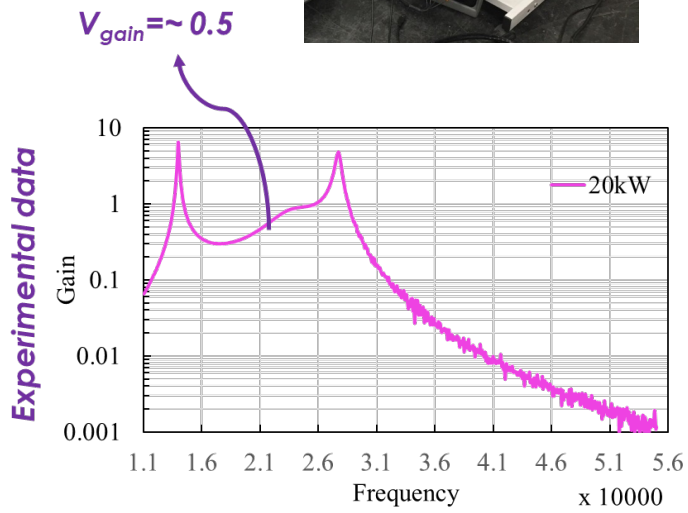


Voltage gain characteristic when discharging the vehicle battery



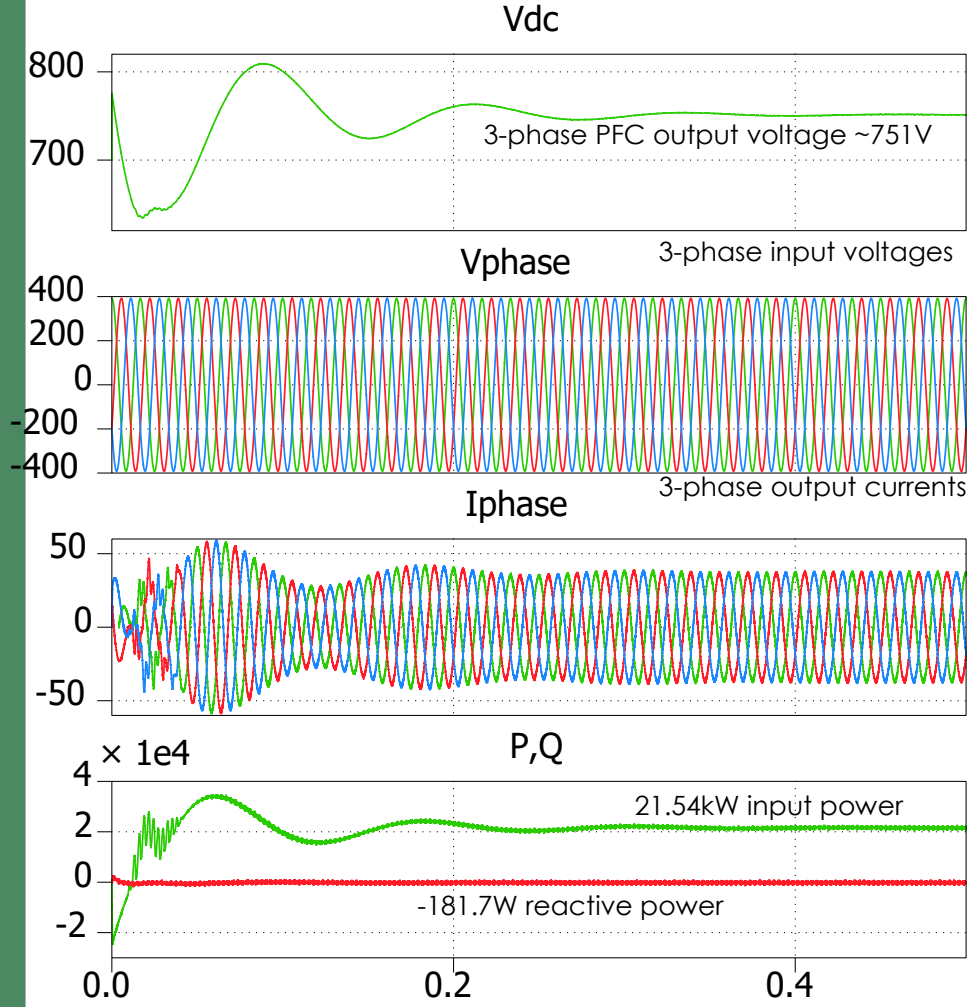
Experimental validation of the gain characteristics



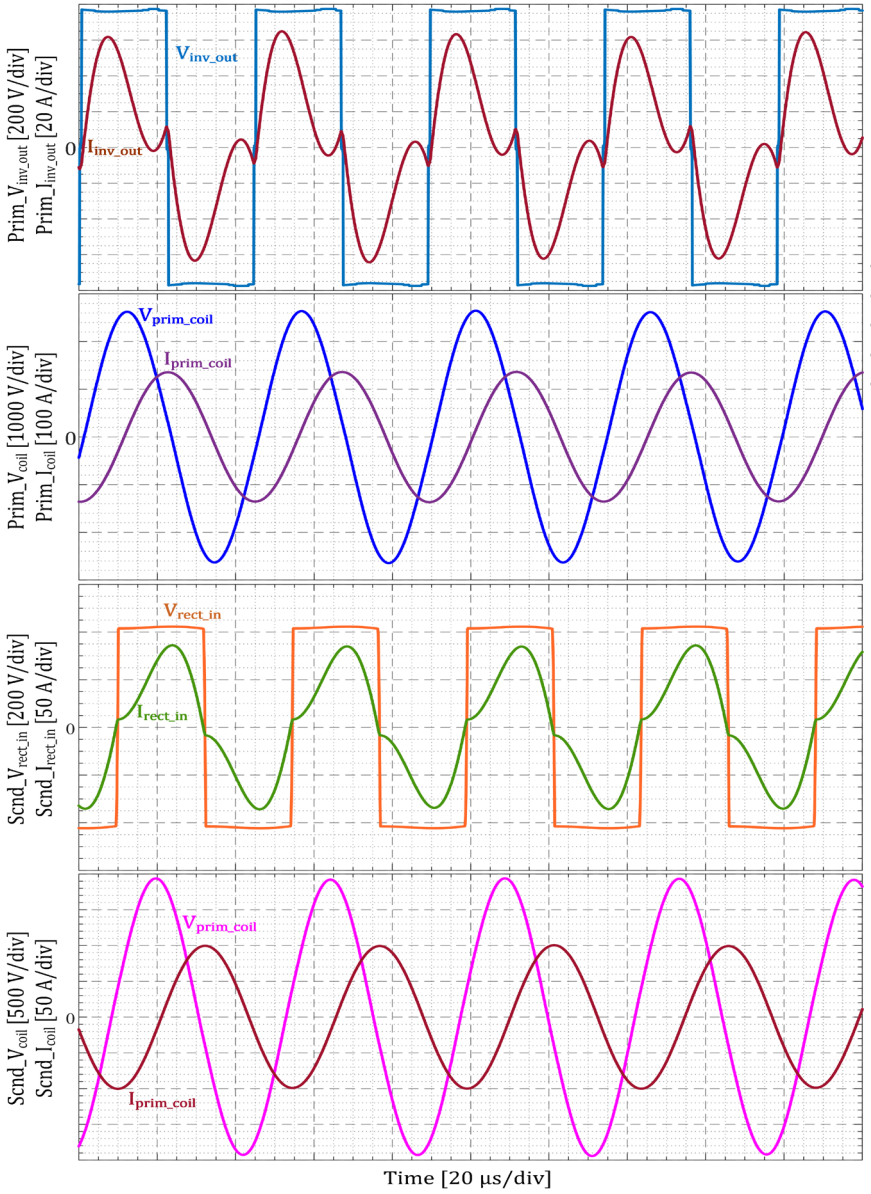


Entire system simulations with closed loop control: Charging

Input currents: 26A_{rms}, Input current THD: ~1%
Input power factor: 0.999, 20kW battery power

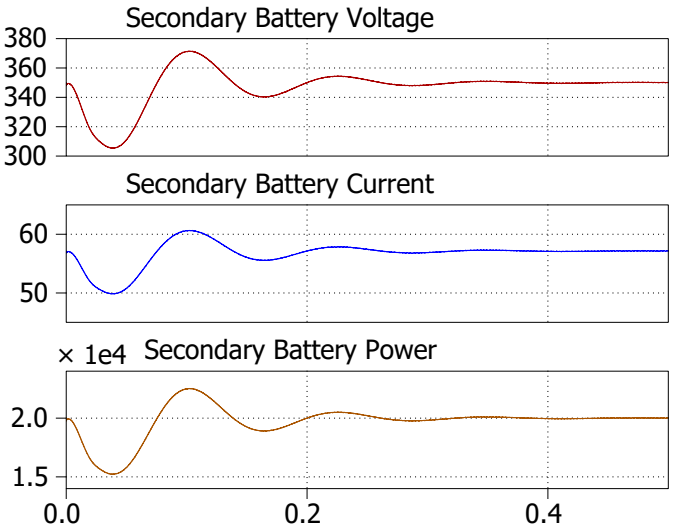


Grid-side measurements for charging mode



Resonant stage measurements for charging mode

Complete system model with full functionality in both power flow directions that validates the design and provides confidence for the hardware operation.

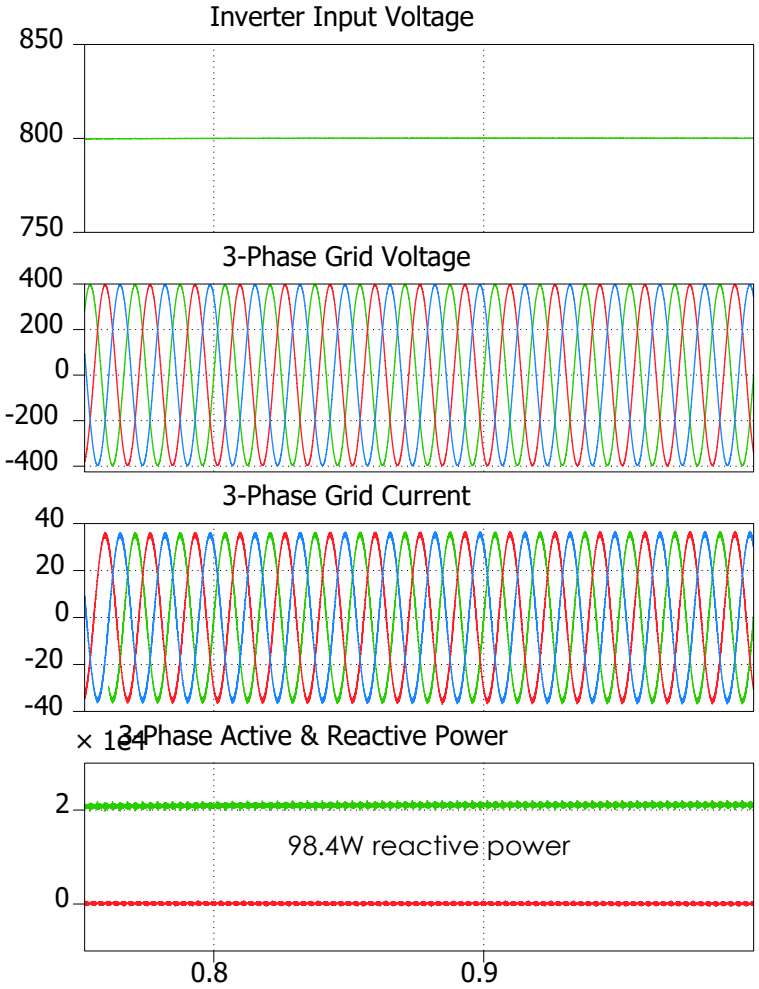


Vehicle-side measurements for charging mode

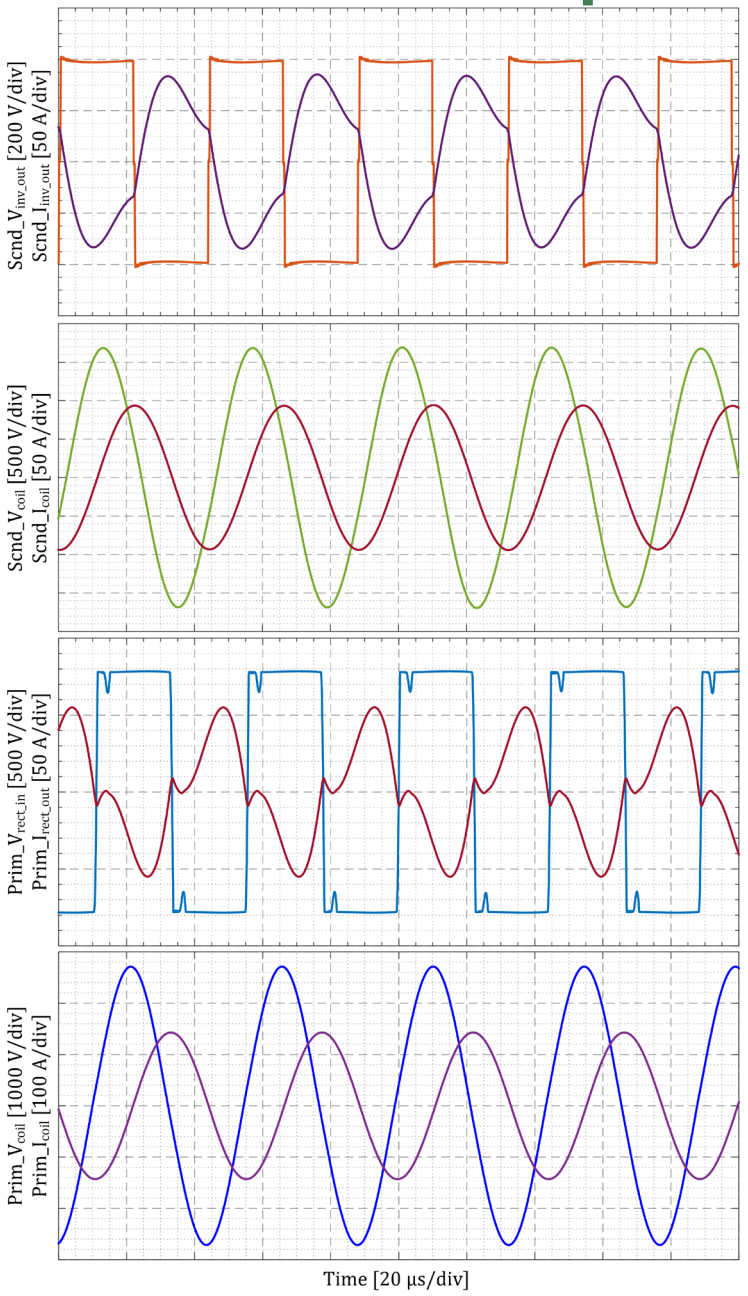
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Entire system simulations with closed loop control: Discharging

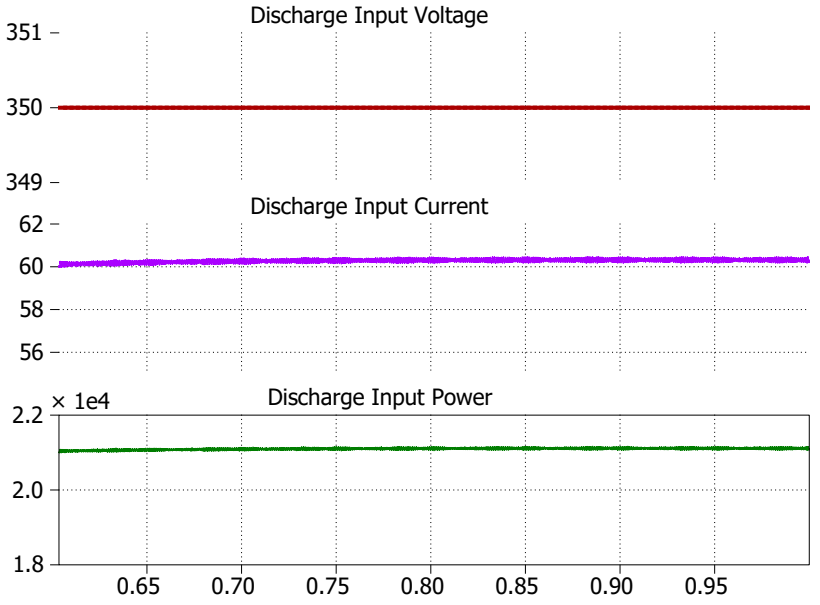
Grid currents: 25A_{rms}, Grid current THD: ~1%
Grid power factor: 0.999, ~21.5kW battery power, ~20 kW grid power



Grid-side measurements for discharging mode



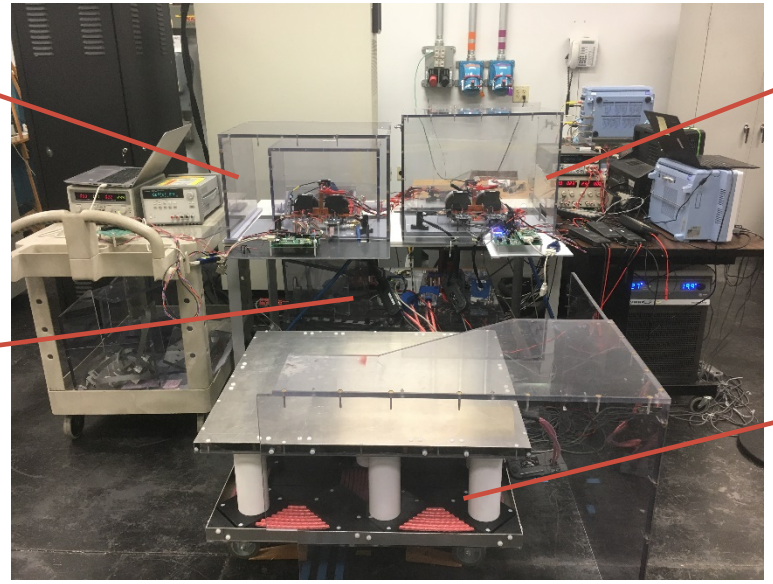
Resonant stage measurements for discharging mode



Vehicle-side measurements for discharging mode

Technical Accomplishments – BP II

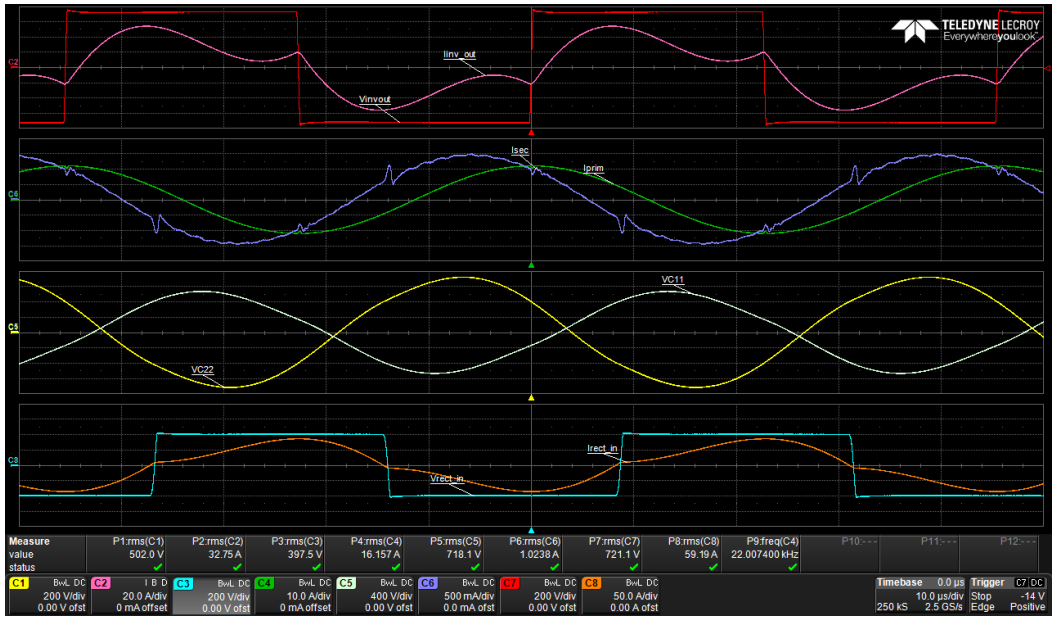
Experimental test setup and results of the resonant stage (dc-to-dc)



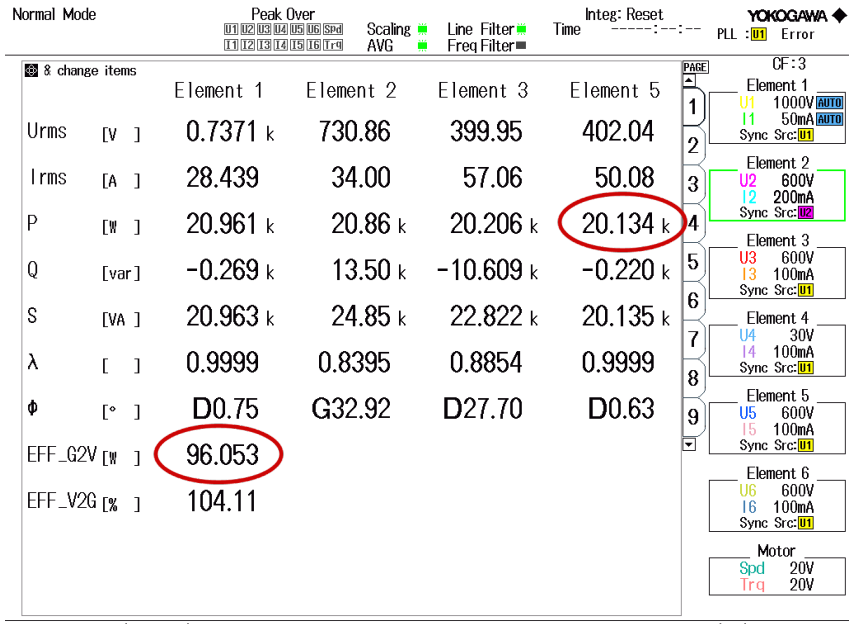
Experimental test setup

- **~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



Operational waveforms for charging mode

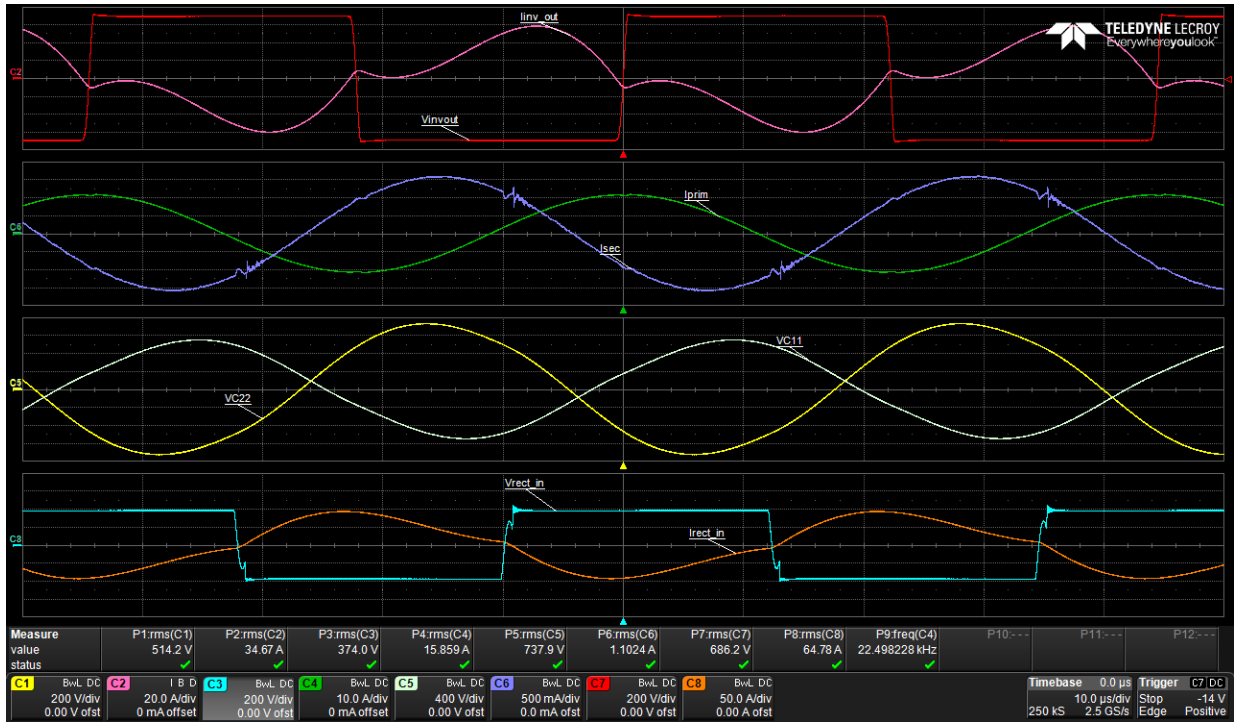


Power analyzer screenshot for charging mode test results

Technical Accomplishments – BP II

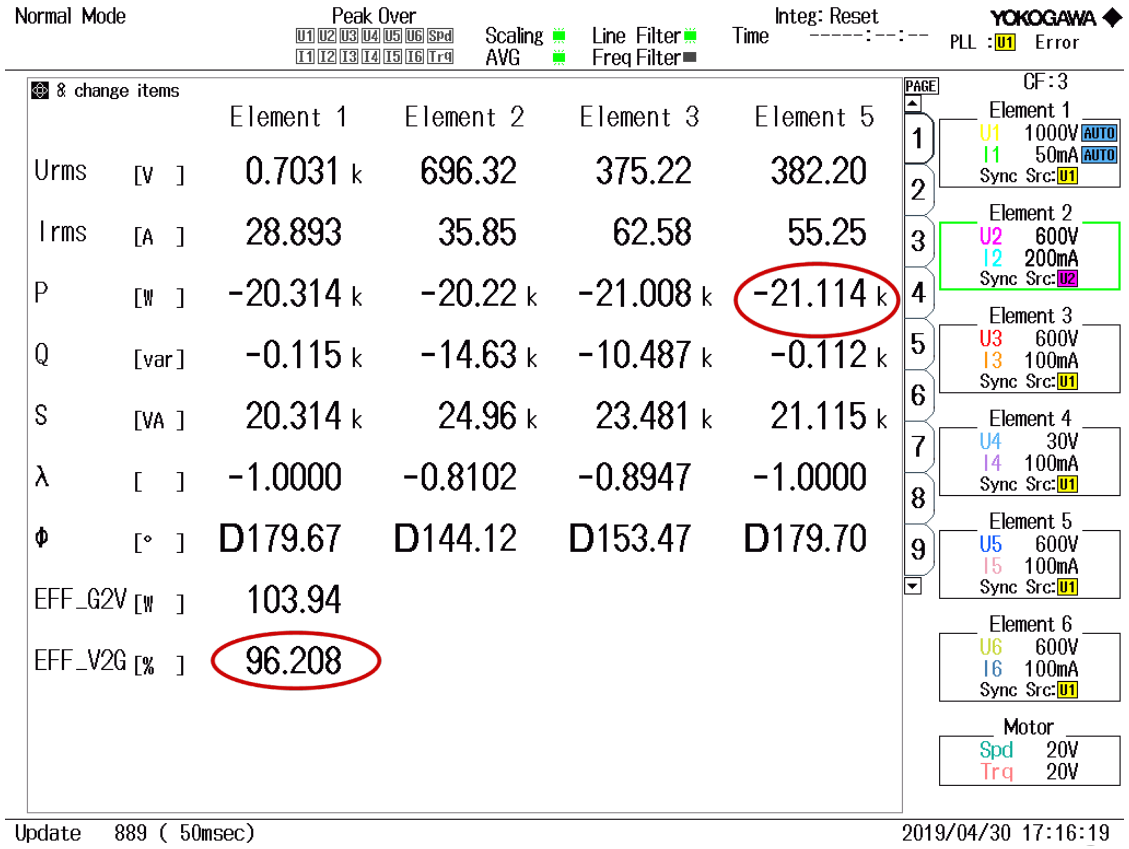
Experimental test setup and results of the resonant stage

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



Operational waveforms for discharging mode

- **~21kW** 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



Power analyzer screenshot for discharging mode test results

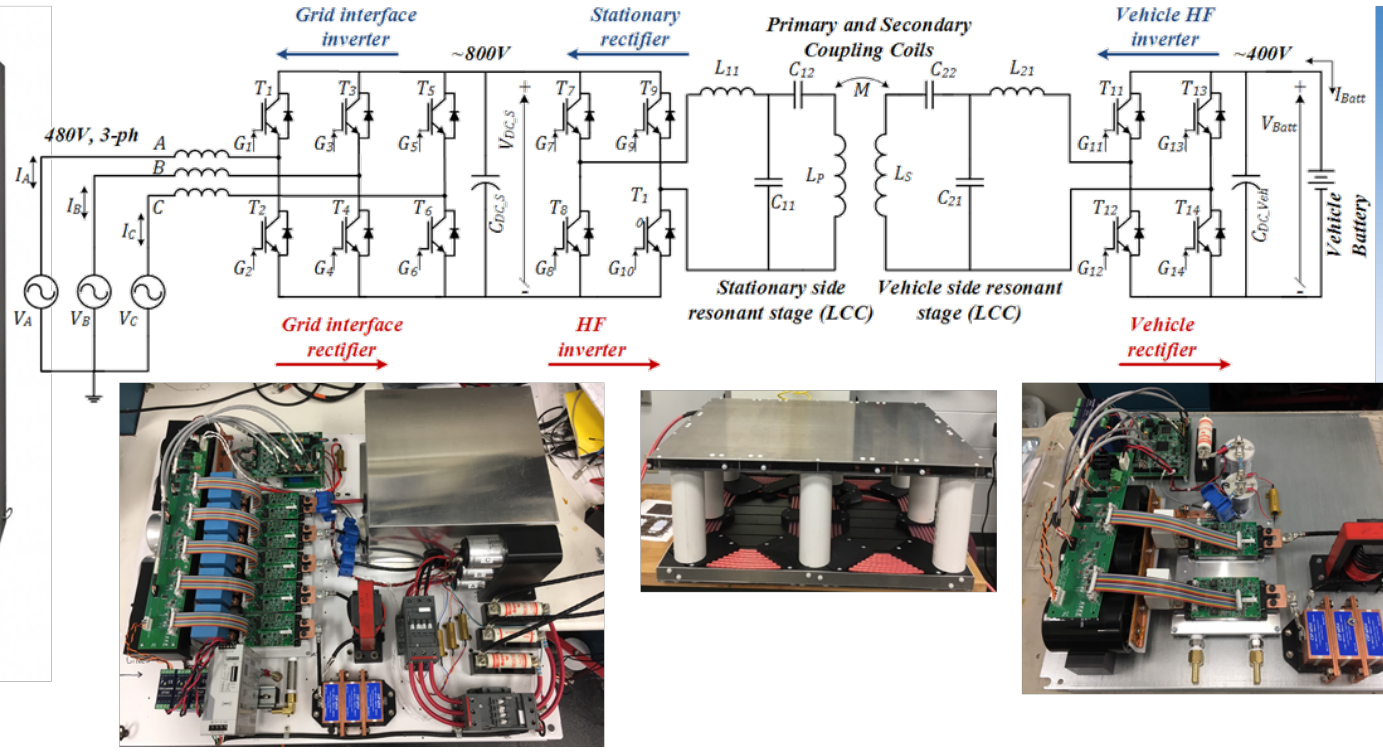
Technical Accomplishments – BP II

Benchtop test setup and validation of power conversion stages and the system as a whole

- Tested and validated parameters and functionalities (both component and subsystem level) of each power conversion stage
- Integrated whole system together
- Tested for both power flow directions
- Tested with communications link with closed loop operation

Ametek RS90 90kW AC Grid Emulator



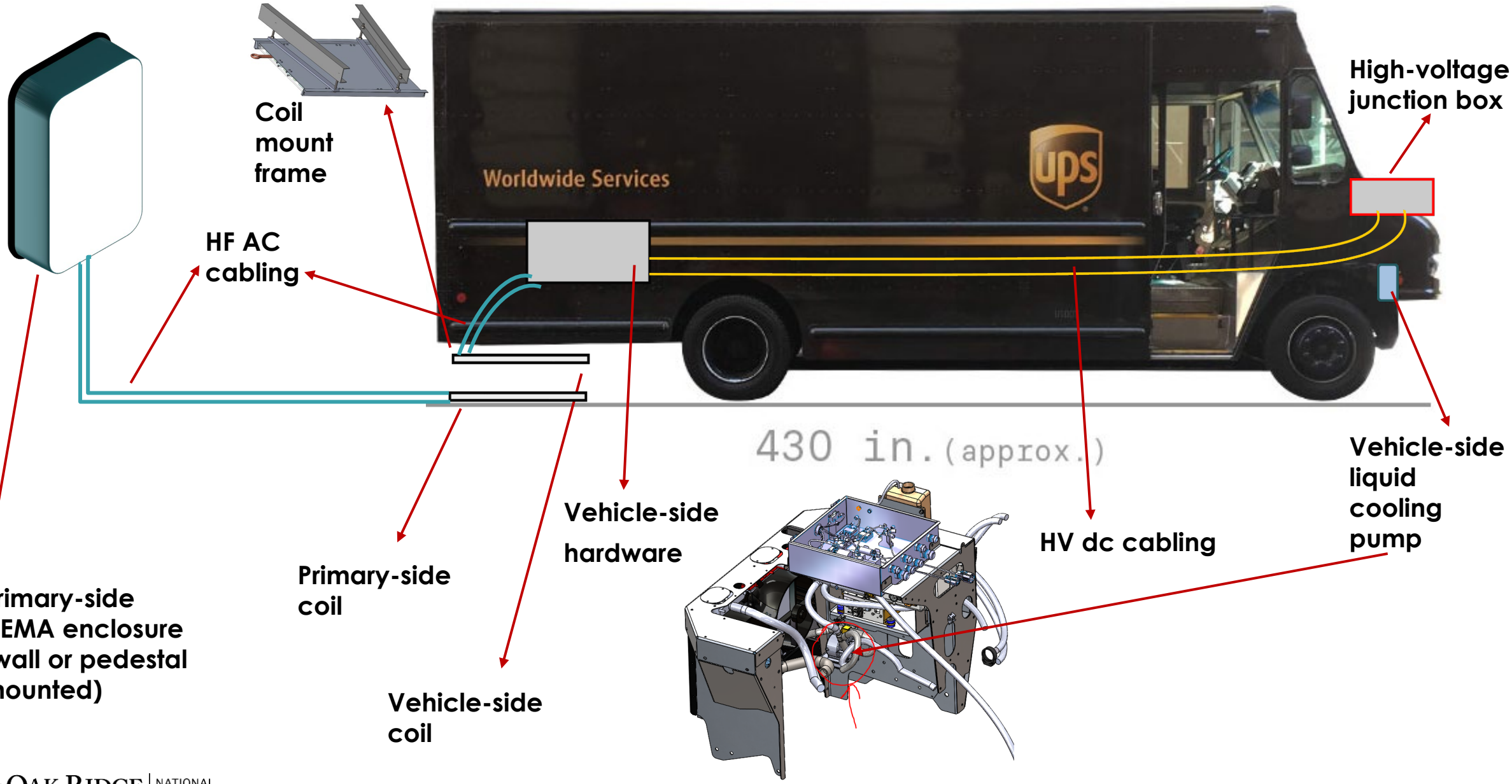




NHR 9300 100kW Battery Emulator

Benchtop setup diagram

Vehicle Integration Efforts – BP II



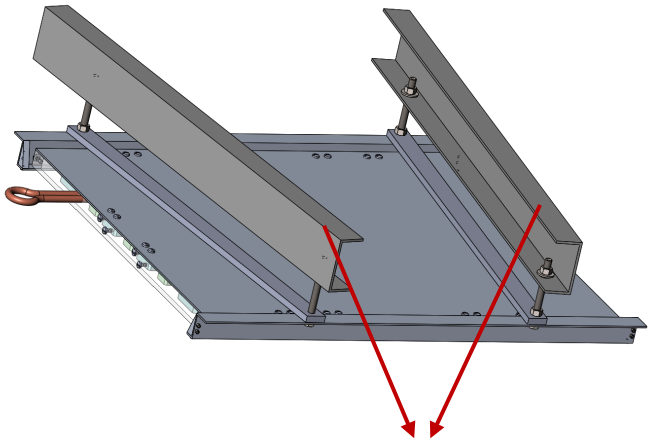
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Vehicle Integration Efforts – BP II

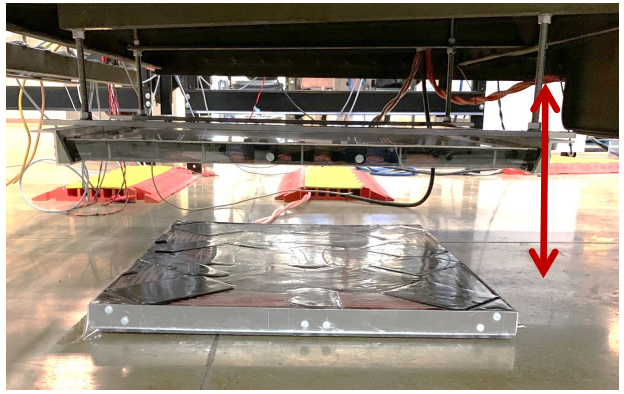


8” – minimum ground clearance, lowest point under the vehicle (coupling rod)

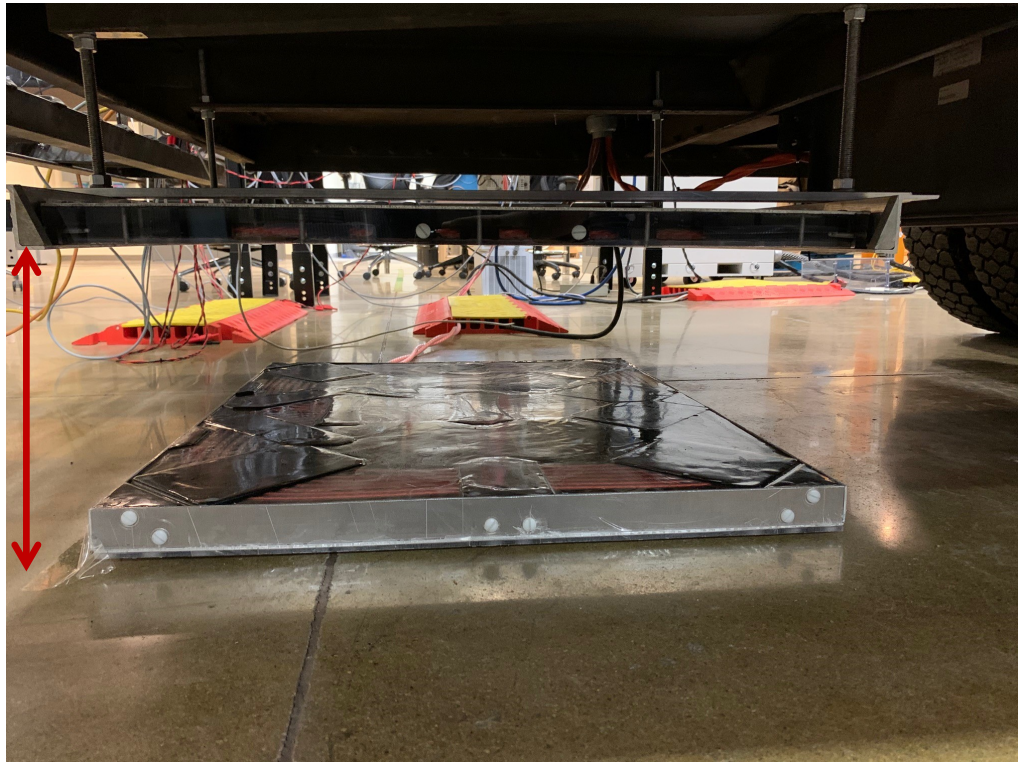




Mounts on the vehicle rails



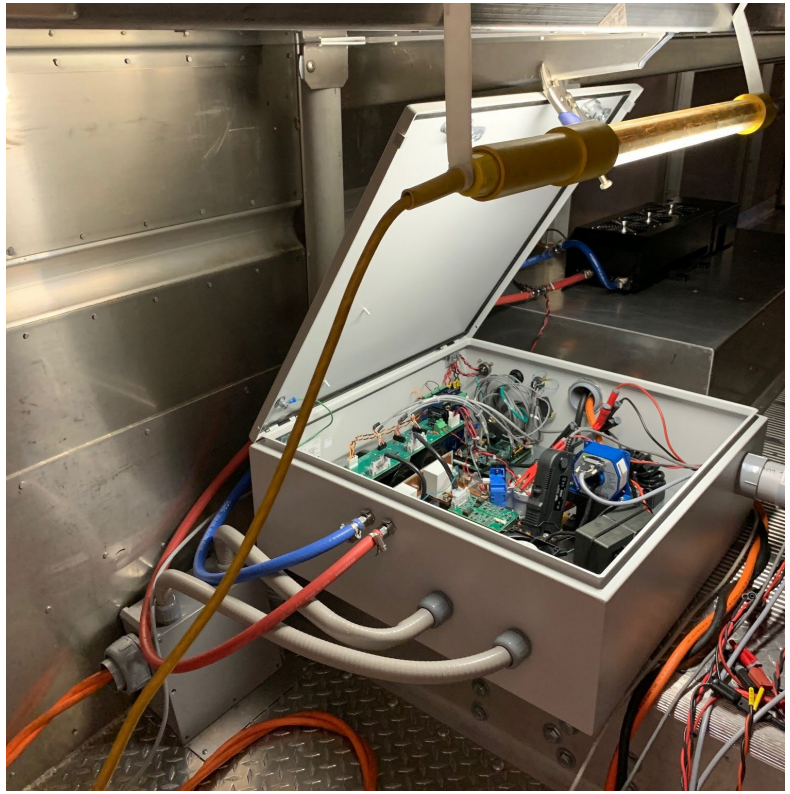
11” magnetic airgap, surface from secondary coil to the ground level



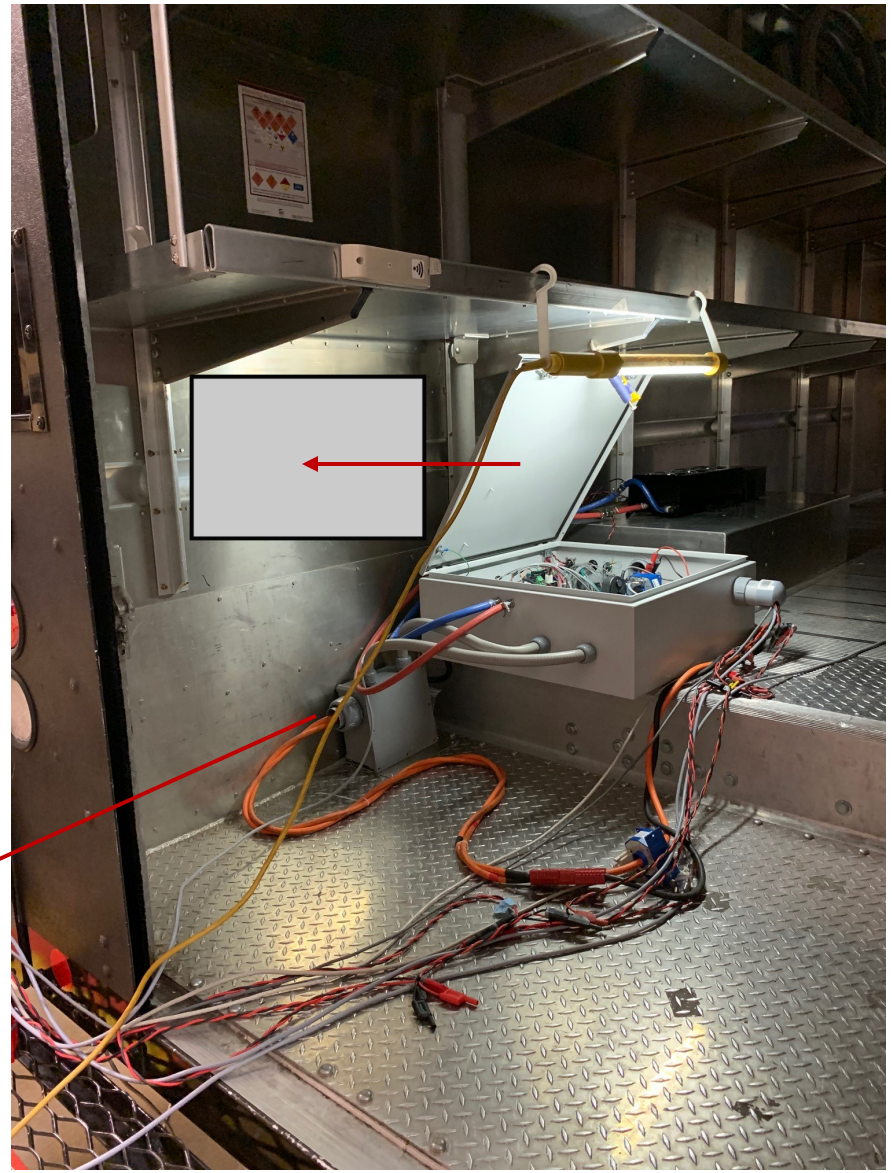
- Coil mounting rail frames
- Adjustable height
- ORNL design
- Fabricated in ORNL machine shop

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Vehicle Integration Efforts – BP II

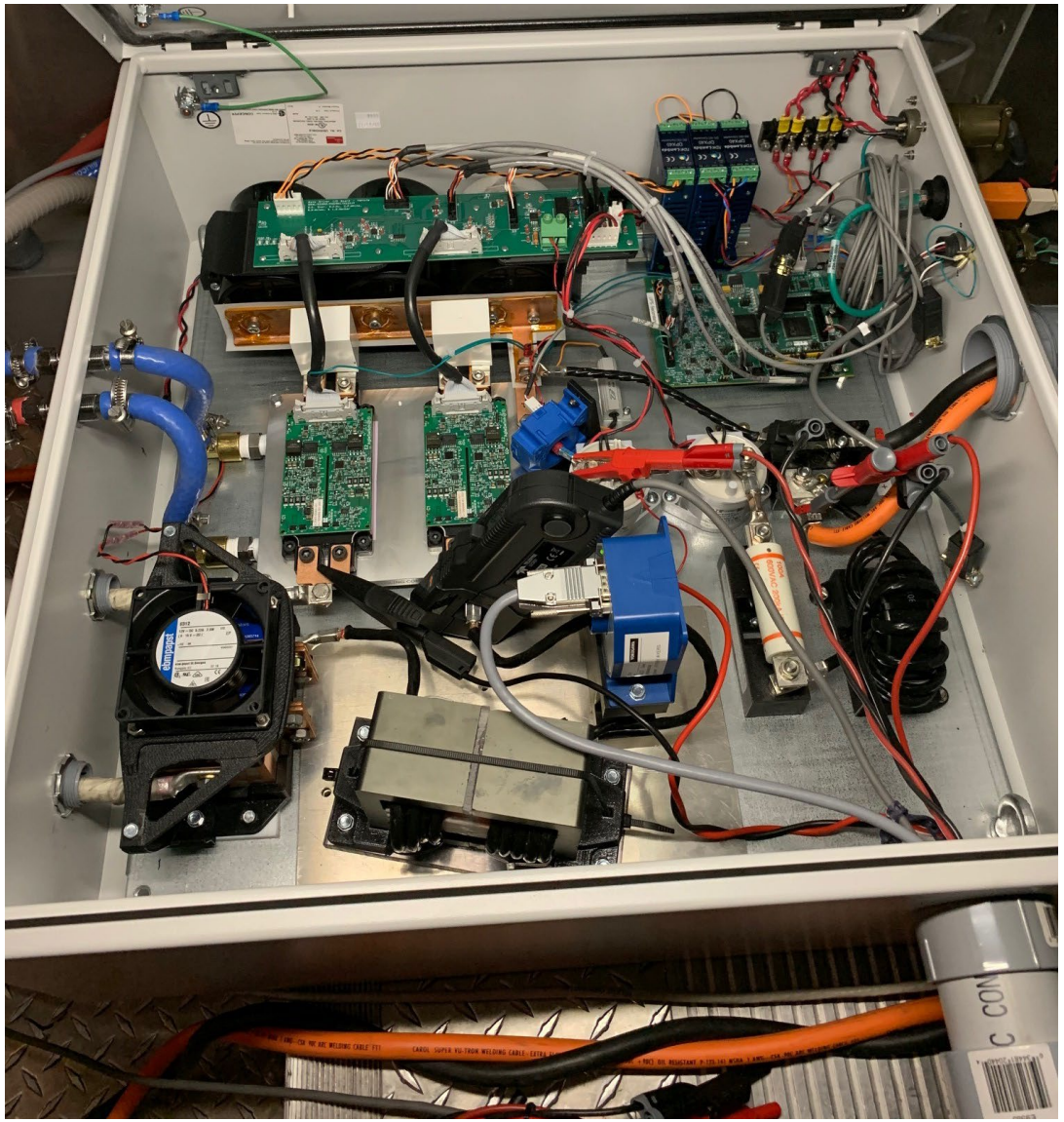


Vehicle-side hardware and HF ac and dc connections



Vehicle-side junction box, passage for HF ac and HV dc wiring

Vehicle Integration Efforts – BP II



Detailed view of the vehicle-side hardware

- Slightly larger than the vehicle's existing 11kW on-board charger (EDN EVO)
- EDN EVO: 90% efficient
- ORNL WPT: ~92% in charging (vehicle side is about ~99% efficient)
- Bi-directional rectifier/inverter
- Hardware modified with an additional 400V to 24V dc/dc converter to power the dc power supplies with +/-15V and 5V outputs instead of powering them with 12V vehicle battery
- Also added additional controls and functionalities in preparation for deployment

Vehicle Integration Efforts – BP II







February 27th, 2020 Demonstration day

Primary-Side Hardware and System Instrumentation

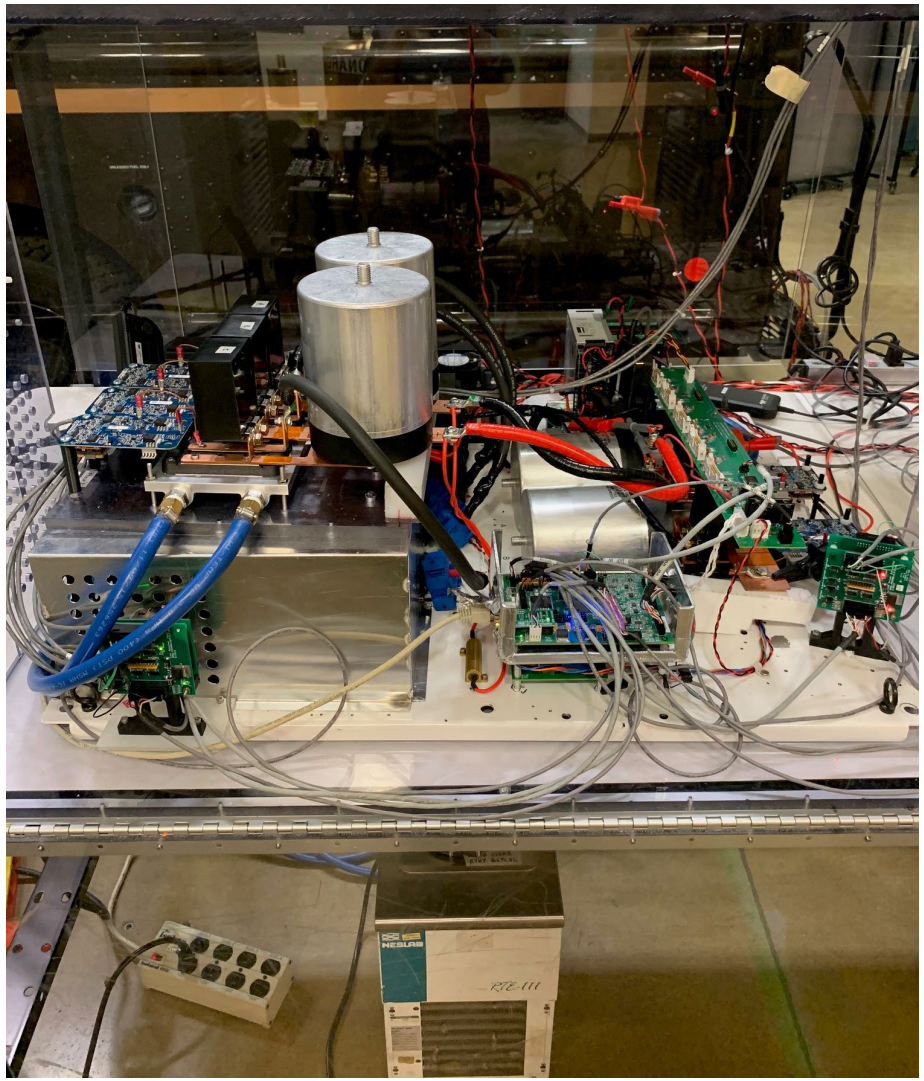
- 480V, 3-phase connection

(277V phase-to-neutral, 480V phase-to-phase)

- HF output cable feeding the transmit coil
- Liquid cooled

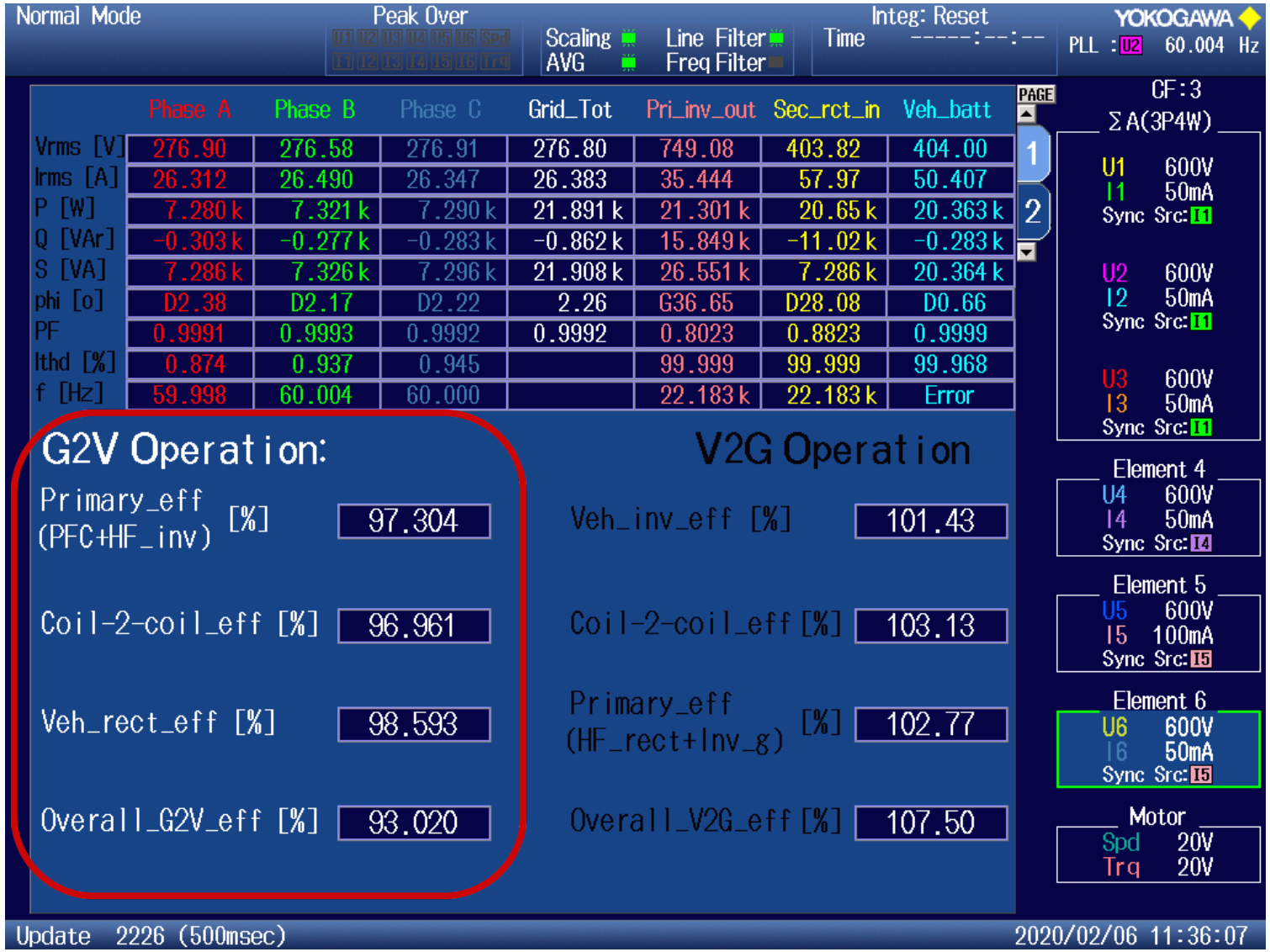


Instrumentation of the BWPT system for functionality and performance demonstration



Primary-side grid-connected hardware with output to the primary coupler

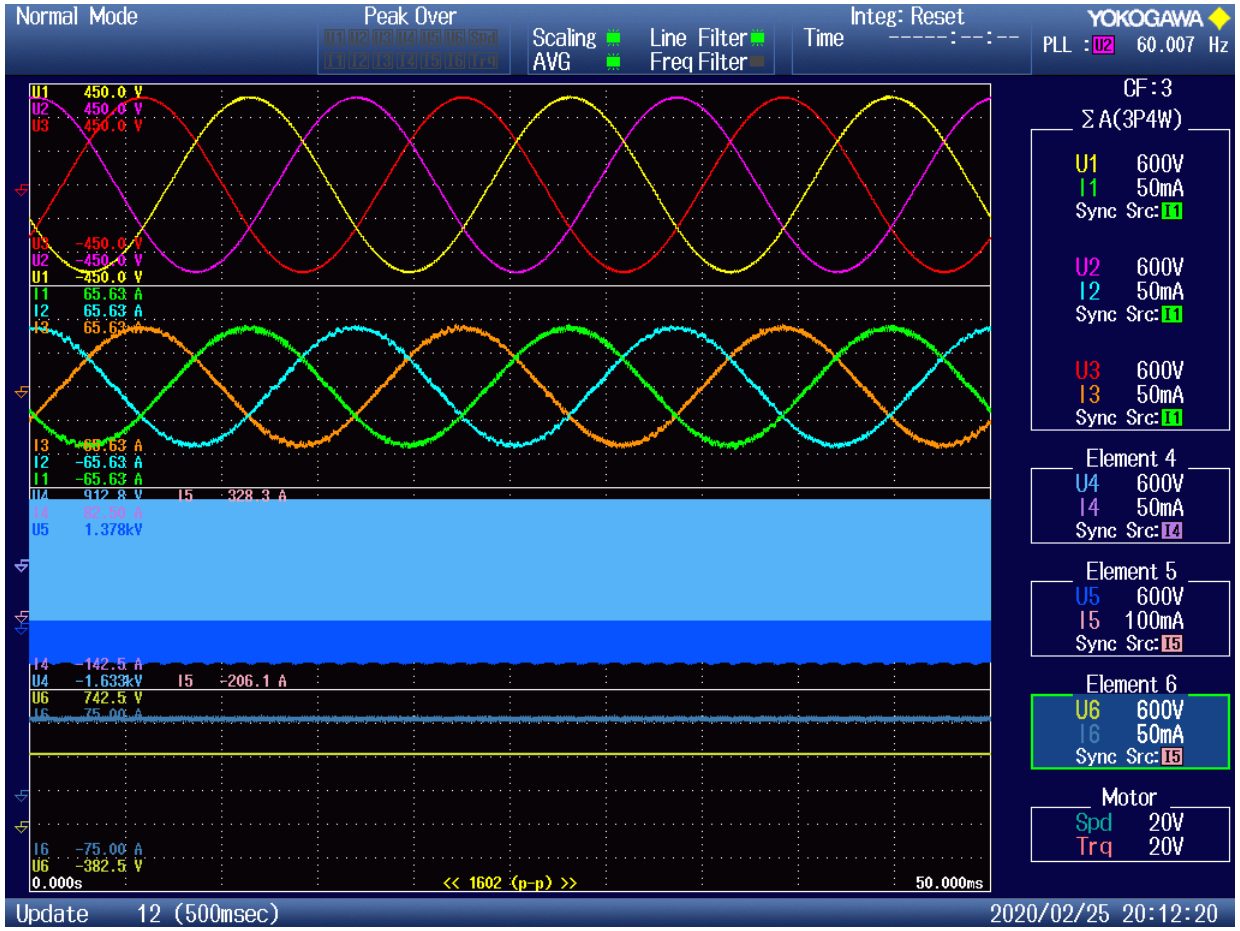
End of BP-II: Demonstration of the BWPT System – Charging Mode



Power analyzer test results for the charge mode of operation

- Power analyzer for stage-by-stage power flow and efficiency of the system
- **20.36 kW** to the vehicle battery
- **93%** efficiency
- Power factor: **0.999**
- ITHD on the grid side: **0.7-1%**

End of BP-II: Demonstration of the BWPT System – Charging Mode



3-phase grid voltages and currents for the charge mode of operation



Primary-side HF inverter output and vehicle-side rectifier input voltages and currents for the charge mode of operation

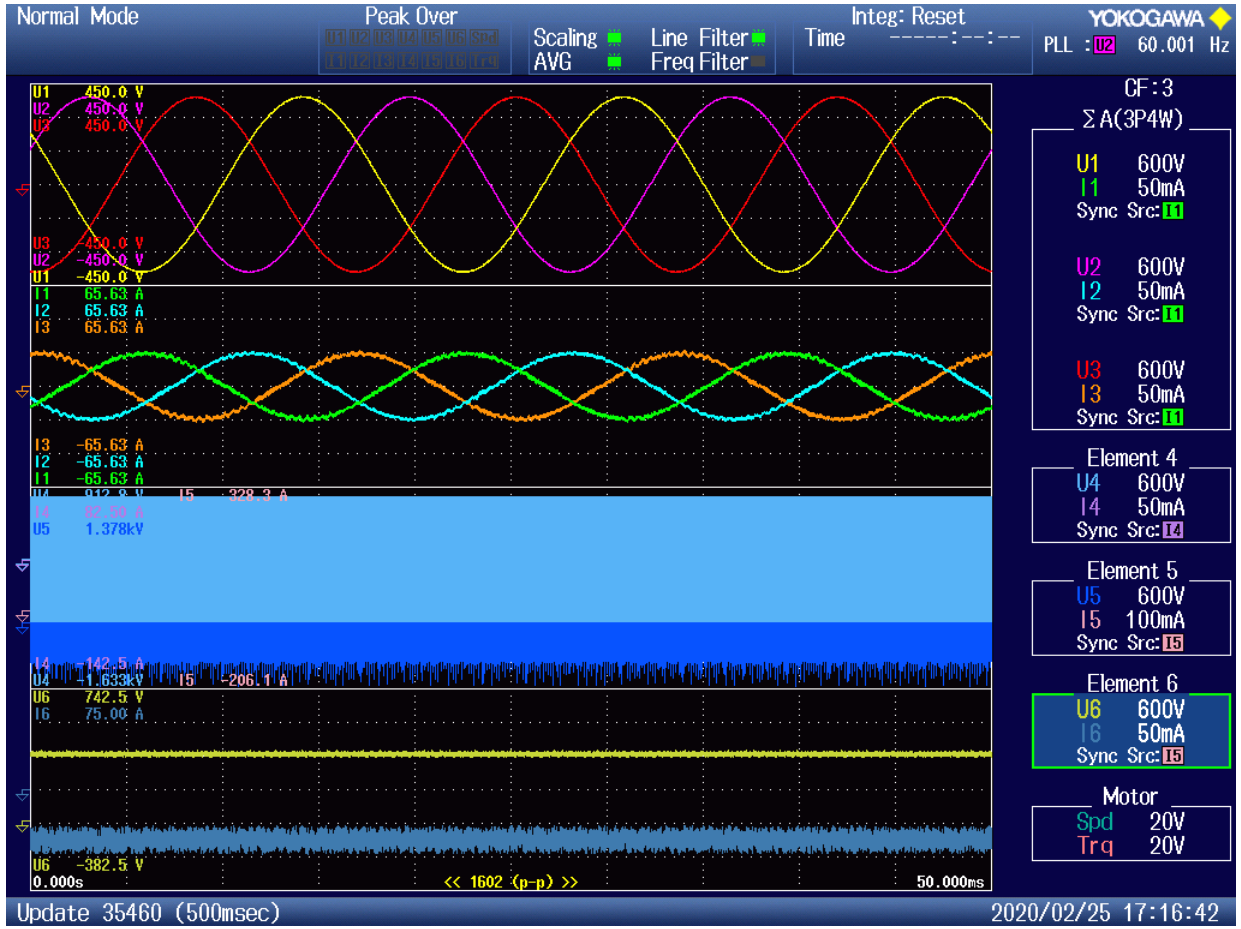
End of BP-II: Demonstration of the BWPT System – Discharging Mode



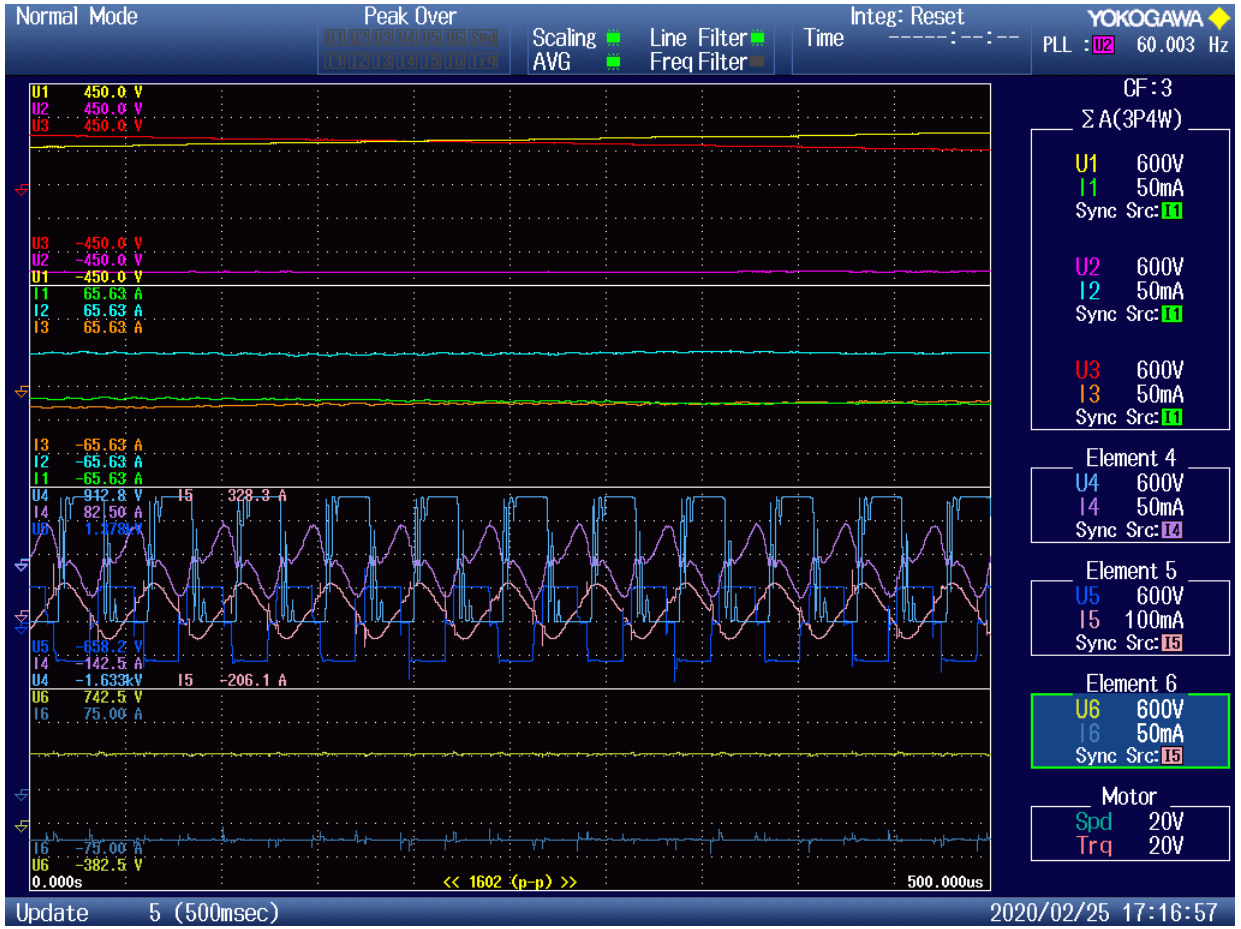
Power analyzer test results for the discharge mode of operation

- Power analyzer for stage-by-stage power flow and efficiency of the system in discharging operating mode
- **12.8 kW** to 480V power grid
- **89.1%** efficiency
- Power factor: **0.997**
- ITHD on the grid side: **1-1.6%**

End of BP-II: Demonstration of the BWPT System – Discharging Mode



3-phase grid voltages and currents for the discharge mode of operation (note the 180 degrees of phase-difference between voltages and currents)



Vehicle-side inverter output and primary-side HF rectifier input voltages and currents for the discharge mode of operation (note the 180 degrees of phase-difference between voltages and currents)

Response to Previous Year Reviewers' Comments

- Project team would like to thank all of the reviewers for the feedback and the comments.
- Some comments:
  - *The reviewer described the project as an excellent systematic approach.*
  - *"Project appears to continue to progress toward overcoming barriers outlined and approved previously, using logical framework and partners."*
  - *"Excellent progress has been made and a lot of hardware demonstrated."*
  - *"The future work is consistent with the overall project plan."*
  - *"Wireless charging is important for expanding future charging capabilities."*
  - *"Resources are sufficient."*

  - *"The reviewer did not have the full history of this project or DOE objectives that may be related, so more information from commercial project partners to clarify the value of success compared to the value of alternatives would have been ideal."*
  - *"It would be helpful to have the background and the value proposition from a commercial partner, such as United Parcel Service (UPS), as guidance and metrics for project success."*
    - *Response: This is a pilot demonstration project to prove the concept and evaluate the use cases. After 6 months of testing duration, UPS may decide to use the technology for future vehicles in collaboration with OEM partner and a Tier-1 manufacturer. In addition to the conveniences with WPT, bidirectional capability allows UPS to optimize their microgrid operations, provide time of use energy cost management (peak shaving and demand charge management), and renewables firming in addition to other grid support and ancillary services.*

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, deployment
- **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

Remaining Challenges and Barriers

- Site preparation and final deployment at the UPS Facility at the Roswell, GA
  - UPS internal project review and approval (March 2021)
  - Bidirectional (two-way radio) wireless communication system review and approval (April 2021)
  - Installation of a 480V 3-phase disconnect switch
- Shipping out the truck and bidirectional WPT hardware
  - Wiring and installation
  - Bolting primary-side coupler on the floor
  - Instrumentation
- Data collection for 6 months

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

Proposed Future Research

- **BP III (remainder of FY20 and a portion of FY21)**
  - Final deployment, validation, testing at the demonstration site and data collection for long term operation (6-months).
  - Business case analysis of bi-directional charging systems (CALSTART).

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 bi-directional 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, engineering support on vehicle integration
  - **Cisco**: Providing radio communication systems for commanding the system and to form feedback control loops
- **Future Work**:
  - Final deployment, validation, testing at the demonstration site and data collection for long term operation

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