Oak Ridge National Laboratory

High-Power Inductive Charging System Development and Integration for Mobility

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

David E. Smith, Group Leader, Vehicle Systems Research
Email: smithde@ornl.gov
Phone: 865-946-1324

2019 U.S DOE Vehicle Technologies Office Annual Merit Review
June 13, 2019 Project ID: ELT239

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

U.S. DEPARTMENT OF ENERGY

Overview

Timeline

- Start – October 2018 (FY19)
- End – September 2020 (FY21)
- 3 budget periods

Barriers

- Achieving 100kW and 300kW charge rates for light-duty passenger vehicles to meet the 3C charge rates (50% increase in SOC in 10 minutes)
- Maintaining high power quality on the grid side
- High operating efficiencies ≥ 90% (end-to-end) for both cases
- Interoperable stationary side power electronics hardware

Budget

- Total project funding
  - DOE share – $2.2M
  - Cost share from partners – $3.0M
- Project spending BP1: $350K

Partners

- ORNL (Project lead), **(Jason Pries, Gui-Jia Su, Veda Galigekere, Cliff White, Larry Seiber, Erdem Asa, Randy Wiles, Jonathan Wilkins)**
- ChargePoint
- Hyundai-Kia America Technical Center
- SF Motors

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

Project Objectives and Relevance

Overall Objectives

- Design, model, simulate, build, integrate, and test an inductive XFC system.
  - Design a high power, modular, scalable, interoperable, high-efficiency plug-less extreme fast charging system.
  - Have minimal grid level disruptions with <5% harmonic distortions on the grid current and >95% grid power factor.
  - Design and develop a compact and light-weight poly-phase electromagnetic coupling coils that can be scaled up to 300 kW power transfer,
  - Achieve high charging efficiencies greater than 90%.
  - Integrate vehicle to infrastructure charging communication protocols such as 15118 over wireless.
  - Understand and address vehicle integration issues of XFC technology, including energy storage impacts and thermal management considerations.

FY 2019 Objectives:

- Analyze and evaluate state-of-the art XFC systems.
- Model and simulate the proposed inductive charging system.
- Complete the design of the power conversion stages including the integration design of the grid interface converter, high-frequency AC link, poly-phase electromagnetic coupling coils, vehicle-side power converters, and resonant tuning components and filters.

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

Project Milestones

Date	Milestones and Go/No-Go Decisions	Status
BP1 (FY19) 10/2018-09/2019	[*Research and design phase*] Design, model, simulate, and analyze system components. Size and design all of the subsystems and components.	On track, nearing completion
BP2 (FY20) 10/2019-09/2020	[*System development and integration*] Build all the system components, subsystems, and power conversion stages and integrate with each other. Validate system up to 100kW power transfer on a Hyundai-Kia vehicle.	On track
BP3 (FY21) 10/2020-09/2021	[*Integration and testing*] Complete system integration and perform necessary modifications, optimize system design, fine tune components and controllers. Integrate system into an SF Motors vehicle, validate 300 kW power transfer. Test and collect data and demonstrate the proposed concept.	On track

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

Technical Scope Summary

- **Budget Period 1 – Research and Design (M1-M12)**
  - Task 1.1: Technology Benchmarking and Evaluation (M1-M4)
  - Task 1.2: System Modeling, Simulations, and Design (M3-M12)
- **Budget Period 2 – System Development (M13-M24)**
  - Task 2.1: Development of Subsystems and Components with Testing and Validation (M13-M18)
  - Task 2.2: System Integration and Tests up to 100kW on a test vehicle (M16-24)
- **Budget Period 3 – System Integration, Deployment, and Testing (M25-M36)**
  - Task 3.1: System Integration and Tests up to 300 kW (M25-M29)
  - Task 3.2: Testing and Evaluations, Data Collection (M30-M36)

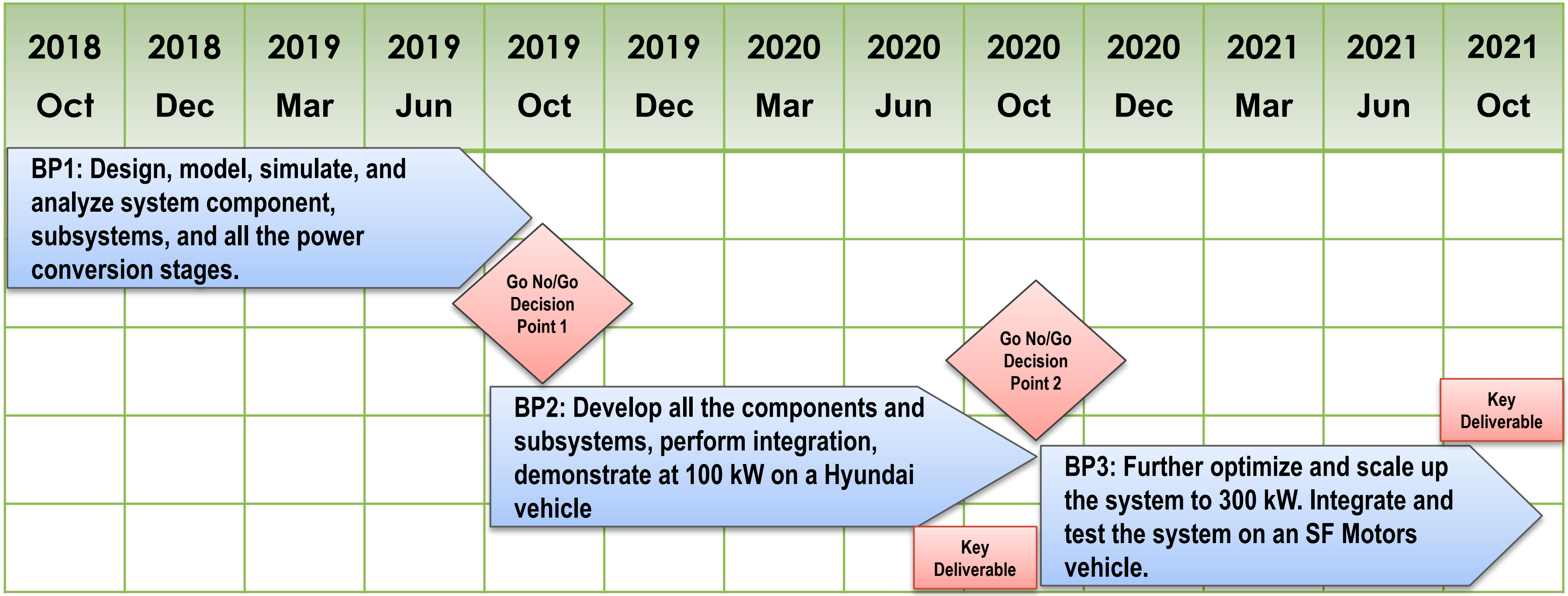
Any proposed future work is subject to change based on funding levels

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.
- Modeled and simulated the grid interface (front-end) power blocks based on the DC link voltage requirements of the proposed system and the grid infrastructure parameters.
- Designing system power conversion stages in an integrated approach for an optimal system design in terms of complexity and compactness.
- All of the power conversion stages will be tested and validated individually before the full system integration (for functionality and performance).
- Entire system will be tested using grid and battery emulators before vehicle integration.
- Designed and developed a prototype for proof of concept before designing and developing the high power scaled couplers and converters.

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

Project Timeline



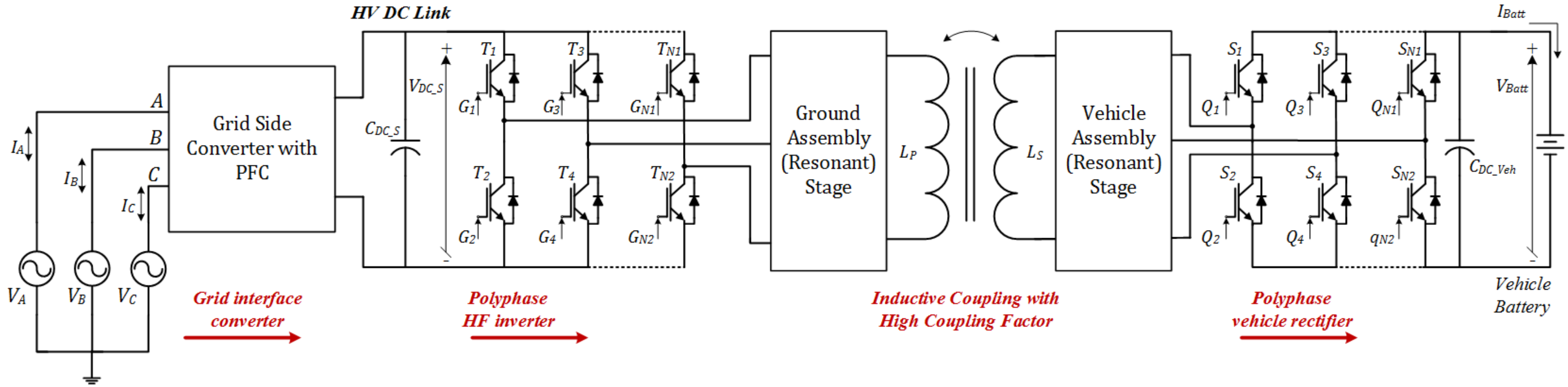
- **Go/No-Go Decision Point 1**: Weather the system design, models, and simulation indicate the feasibility of the proposed XFC system.
- **Go/No-Go Decision Point 2**: Weather the proposed system can be experimentally validated or not.
- **Key Deliverable for BP 1**: Complete design of the proposed system for 100kW power transfer to the vehicle side including all of the power conversion stages and coupling coils.

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

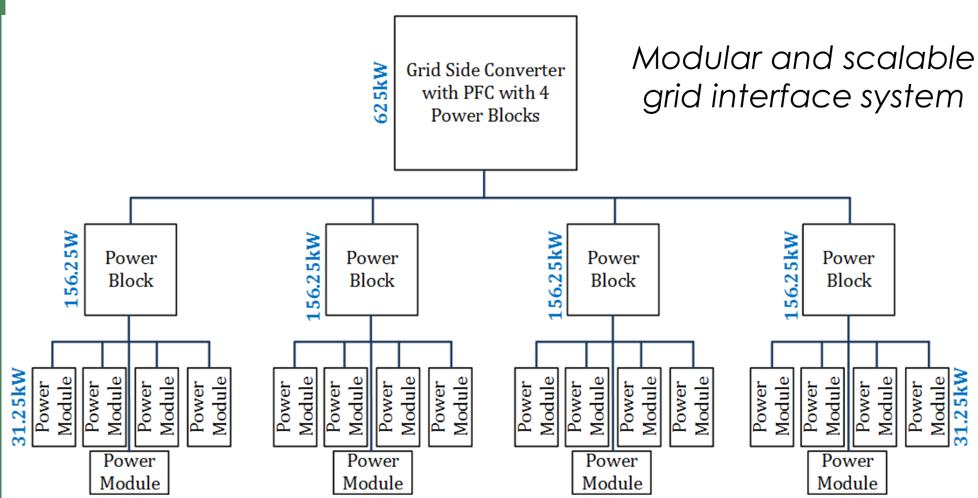
Proposed Technology

- System level diagram

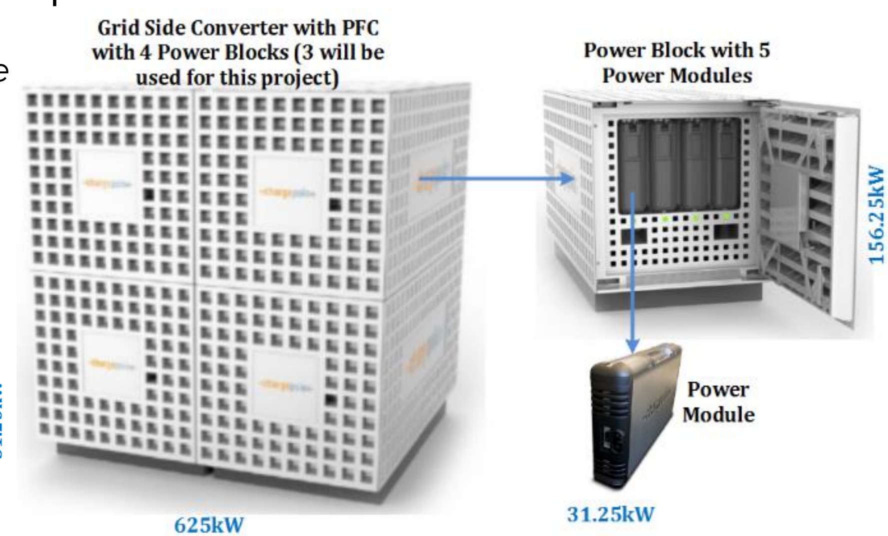
Proposed XFC system



- Modular grid-interface architecture with power blocks



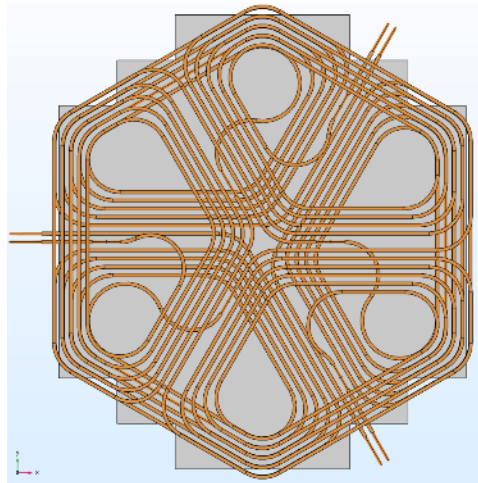
Modular and scalable grid interface system



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

Proposed Technology

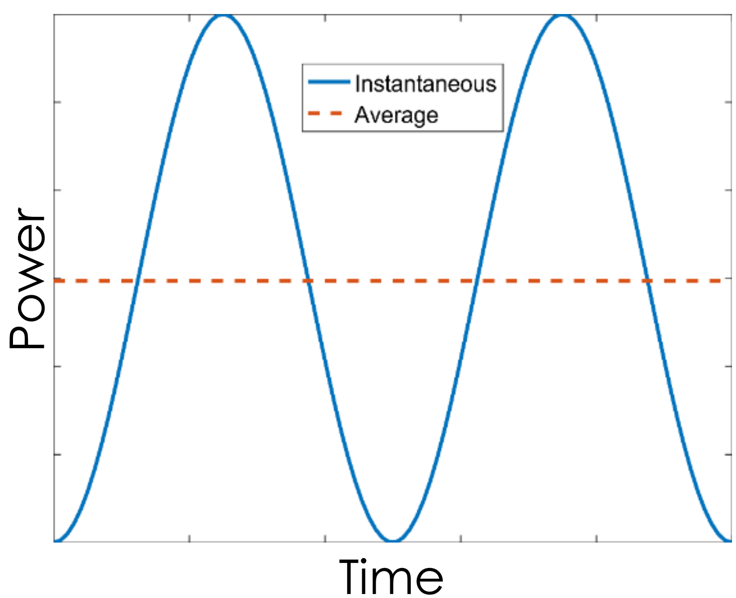
- Polyphase WPT Systems
  - Single-phase systems “pulse” power across the airgap
  - Low space-time average utilization since fields oscillate between peak values and zero



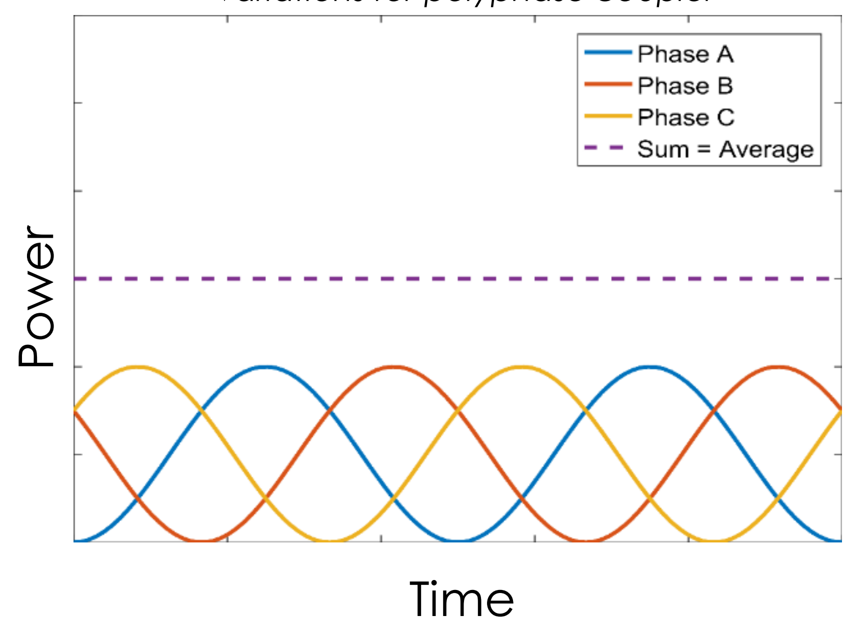
Polyphase coupler wiring

- Polyphase systems using rotating fields for constant power transfer
- Phase shifted excitation and spatially shifted coils
- Much higher power density due to improved space-time field utilization
- Lower current ripple

Instantaneous and average power variations for conventional circular couplers



Instantaneous and average power variations for polyphase coupler

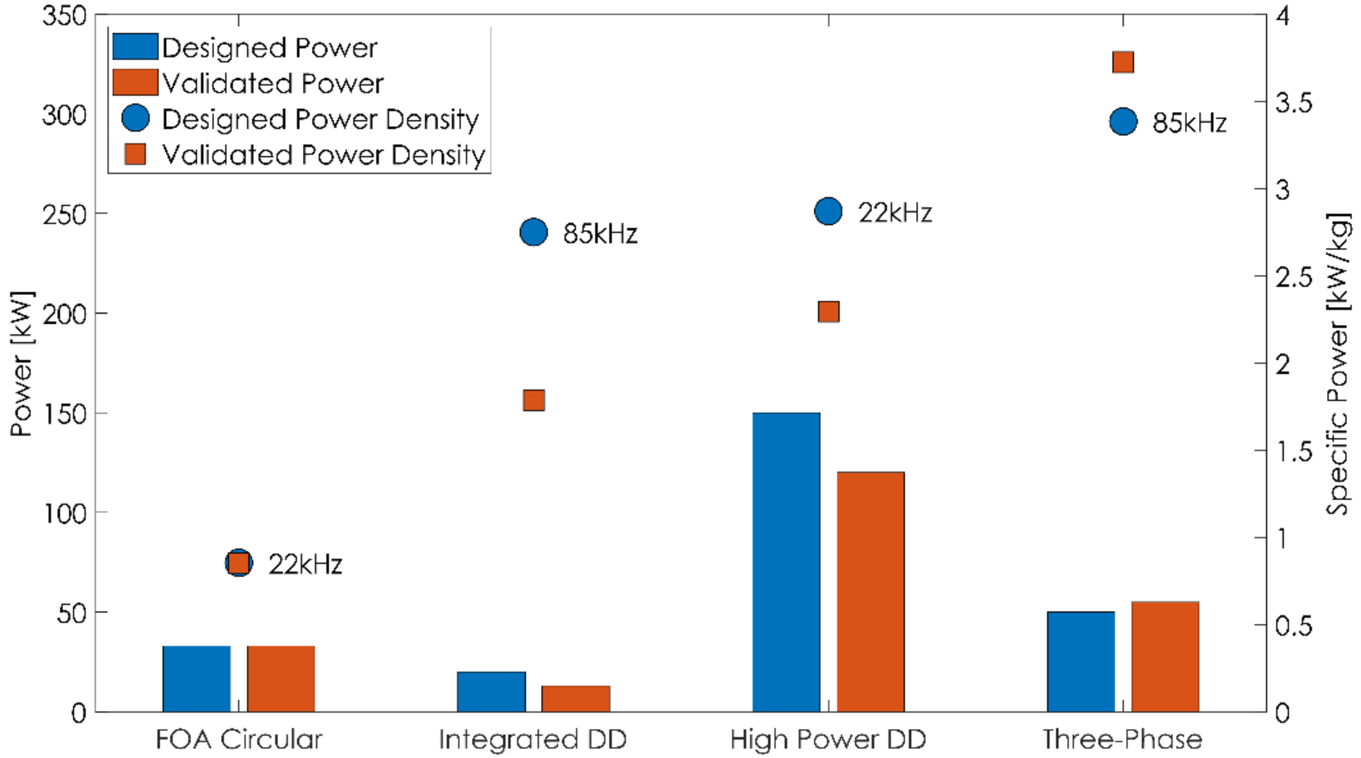


Any proposed future work is subject to change based on funding levels

Technical Accomplishments – BP I

Specific power analysis of the proposed system and comparisons with conventional approaches

- Power density comparisons of:
  - FOA circular coil (project ended in 2016)
  - Integrated charger DD coil
  - High power DD coils (recently demonstrated the operation at 120 kW), and
  - Proposed poly-phase coupler



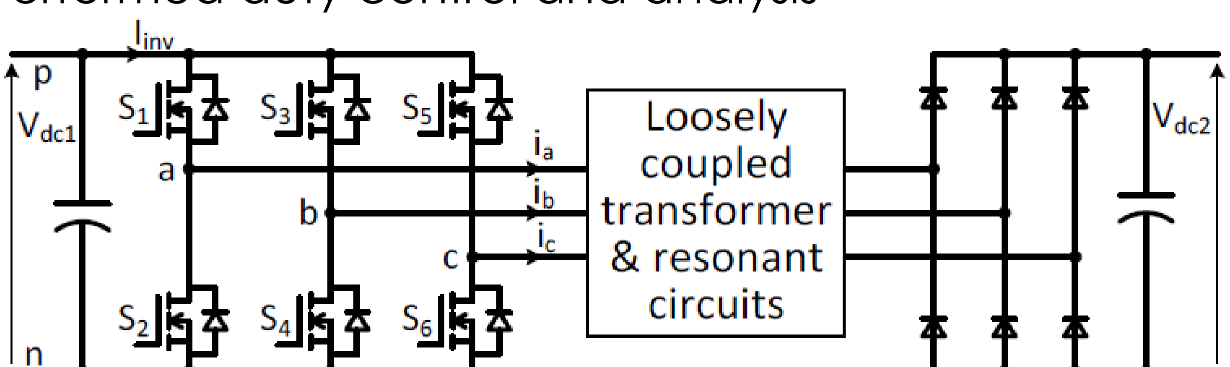
Specific power comparisons of the proposed technology with previously developed systems.

OAK RIDGE National Laboratory | NATIONAL TRANSPORTATION RESEARCH CENTER

Technical Accomplishments – BP I

Modeled and analyzed 3-phase inverter variable duty cycle control

- ChargePoint power blocks provide 200-1000V dc variable regulated output power which can be used to control the bulk power.
  - ORNL system determines the reference DC link voltage, communicates to the ChargePoint power block.
- Fine tuning the power, supporting the charging profile management will be controlled by ORNL 3-phase inverter.
- Controllability – circulating currents in non-unity duty cycles
- 3 single-phase inverters vs. a 3-phase inverter
  - 3-phase offered much less DC link ripple currents
  - Significant reduction in DC-link capacitance for the 3-phase inverter
- Performed duty control and analysis



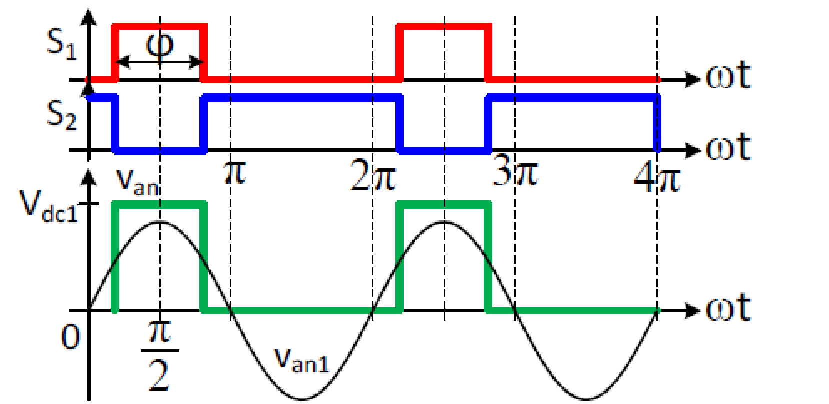
Three-phase inverter driving the polyphase coupler and resonant tuning circuitry.

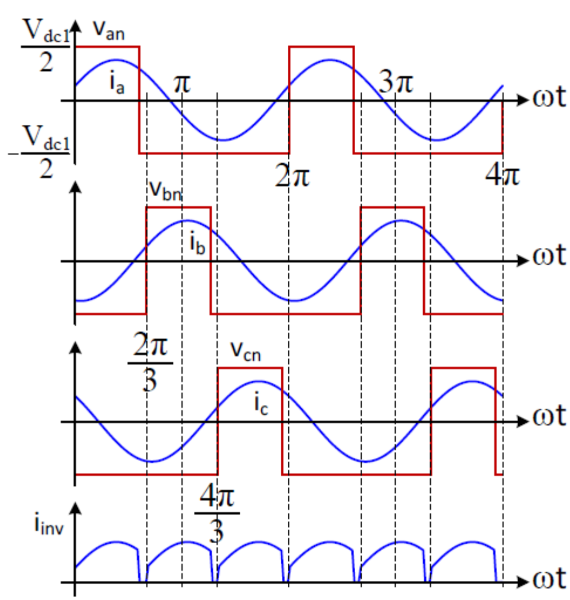
Technical Accomplishments – BP I

Modeled and analyzed 3-phase inverter variable duty cycle control

- Derived the modeling equations for the 3-phase inverter duty cycle, output voltage, and the fundamental component of the output voltage.
- Analyzed the inverter output phase currents and the dc component of the dc link current.
- Analyzed the condition of continuous and discontinuous DC link current.
- Compared dc link ripple currents with a single-phase inverter.

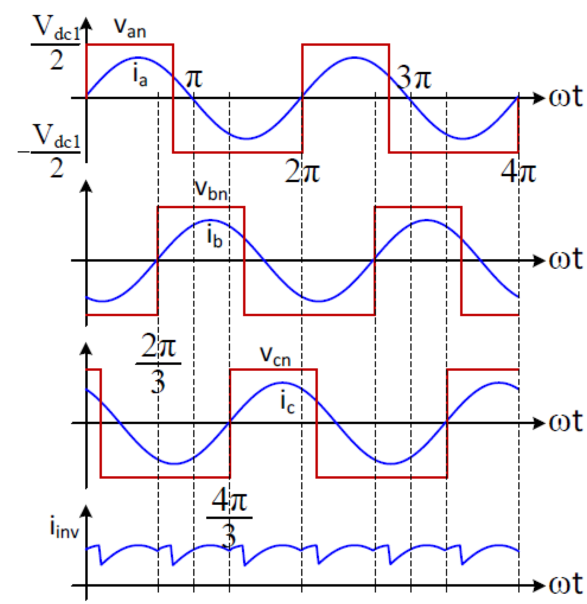
Inverter duty cycle, output voltage, and switching signals.





(a) $d<2/3$

Discontinuous dc link current.



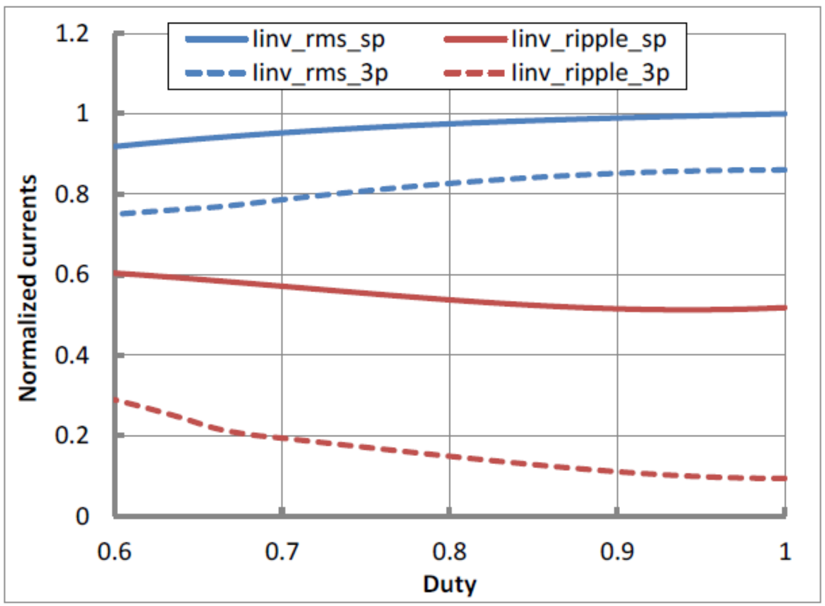
(b) $d\geq 2/3$

Continuous dc link current.

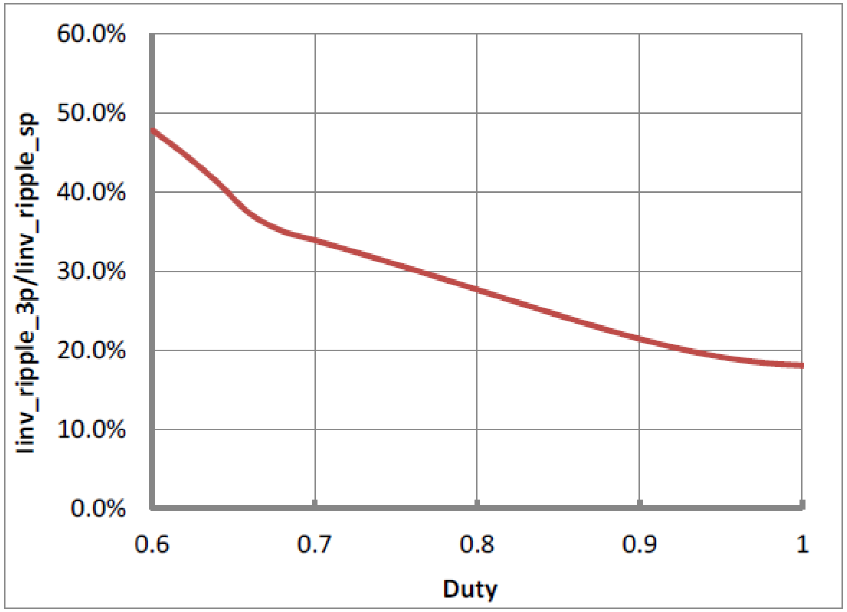
Technical Accomplishments – BP I

Analyzed and compared and 3-phase inverter dc link ripple currents

- Comparison of RMS and ripple currents if the 3-phase and single-phase inverter dc link currents at a pf=0.95.
- Significant reductions in the inverter dc link ripple current (52% to 82% as the duty increasing from 0.6 to 1)
- Significant reduction in the dc link capacitance requirement for the 3-phase inverter



3-phase and single-phase inverter RMS and ripple current comparisons



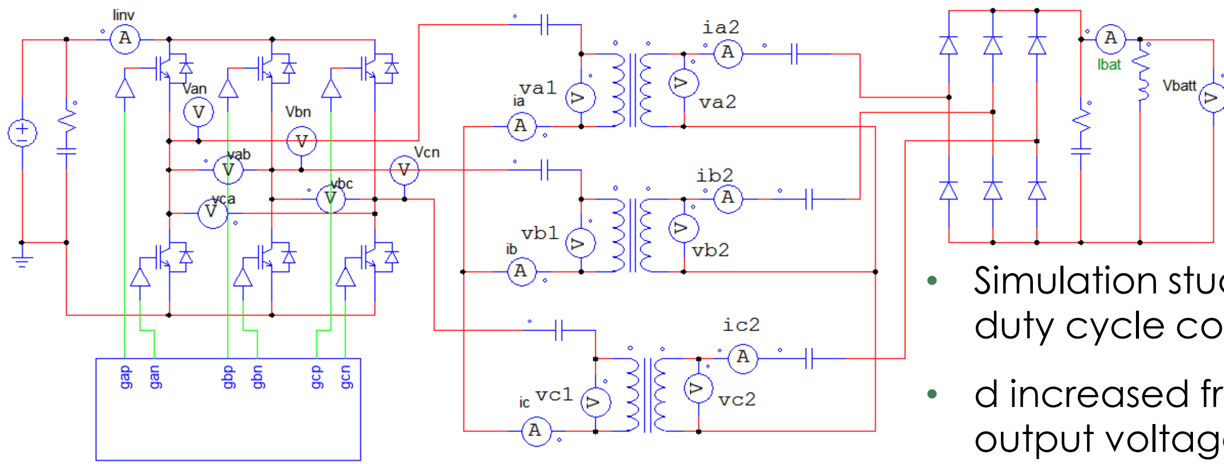
3-phase and single phase ripple current rates

Technical Accomplishments – BP I

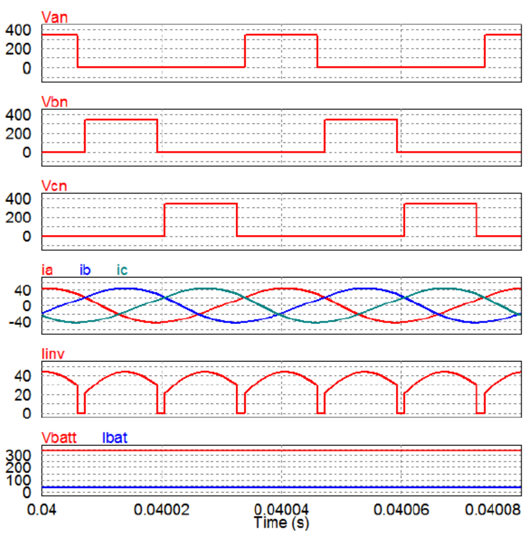
Modeled and simulated 3-pjase inverter for duty cycle controllability validation

- Developed a 3-phase inverter simulation model.
- Polyphase couplers are modeled as 3 coupled inductors.

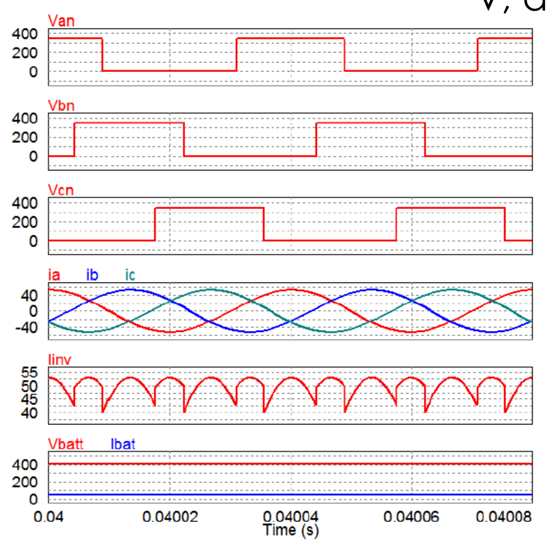
Simulation model of 3-phase inverter driving 3-coupled inductors



- Simulation study for a VSI-based WPT under duty cycle control
- d increased from 0.6 to 0.9 resulting in output voltage increase from 340 V to 416 V, a 49% increase in output power

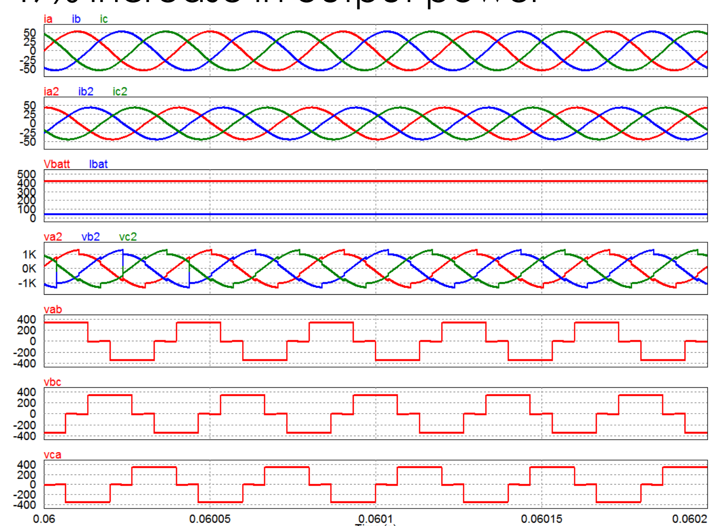


(a) d=0.6



(b) d=0.9

Operational waveforms for d=0.6 and d=0.9 cases



Operational waveforms for unity duty cycle

Technical Accomplishments – BP I

Designed and prototyped a 3-phase high-frequency inverter

- Design is based on the ORNL 120kW HF/HP inverter that was single-phase

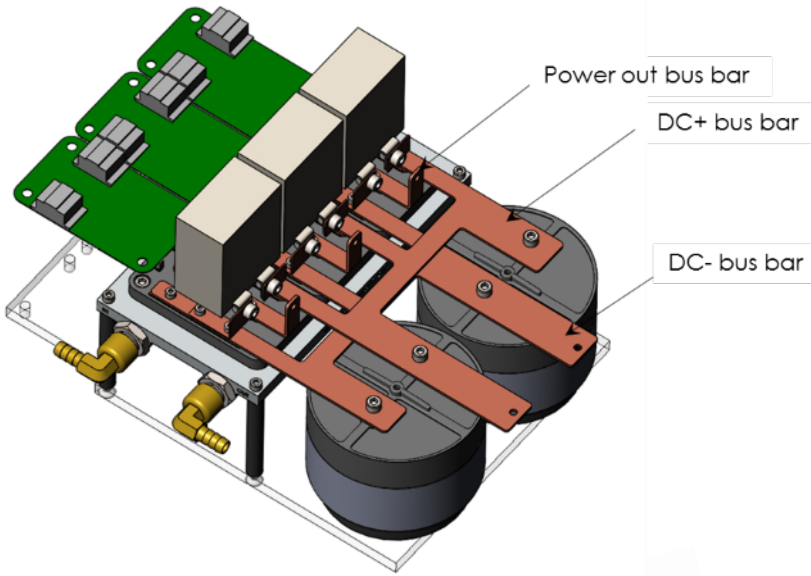
Parameter	Value
Phase leg	CAS325M12HM2
Cold plate	CP3009
Gate driver	CGD16HB62LP
DC link capacitor	947D601K901DCRSN 900 V Polypropylene high energy density

- 1200V / 256A (@175°C junction and 125°C case) or 444A @175°C junction and 25°C case)

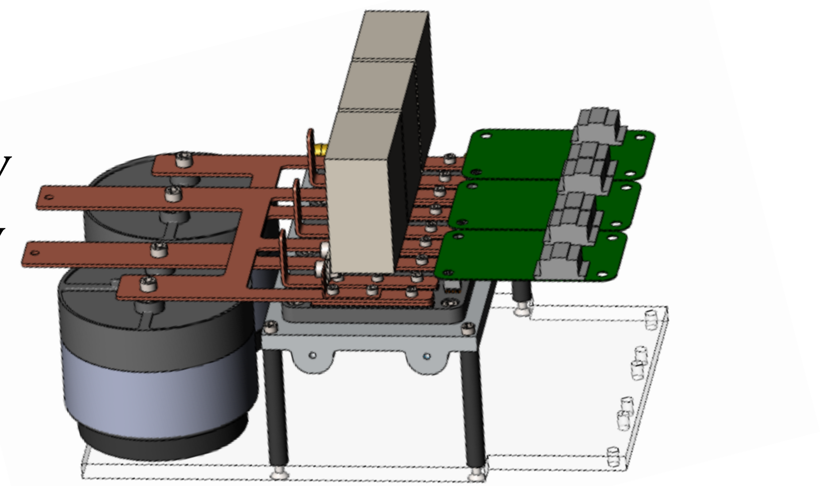
$$P_{out\_1} = 600V \times \sqrt{3} \times 125A \times 0.9_{\eta} \times 0.95_{pf} = 111{,}067\ kW$$

$$P_{out\_2} = 850V \times \sqrt{3} \times 250A \times 0.9_{\eta} \times 0.95_{pf} = 314{,}691\ kW$$

- Dimensions: 13" × 11" × 8"
- 1144 cubic inches (18.74 ℓ → **16 kW/ℓ**)
- VTO 2020 Target for HV PE: **13.4 kW/ℓ**)



3-phase inverter design rendered image



Technical Accomplishments – BP I

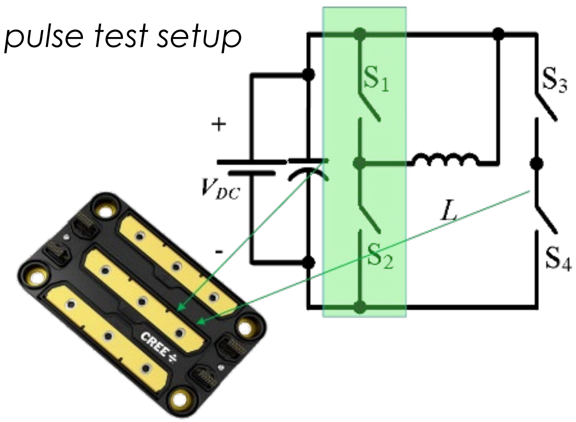
Designed and prototyped a 3-phase high-frequency inverter

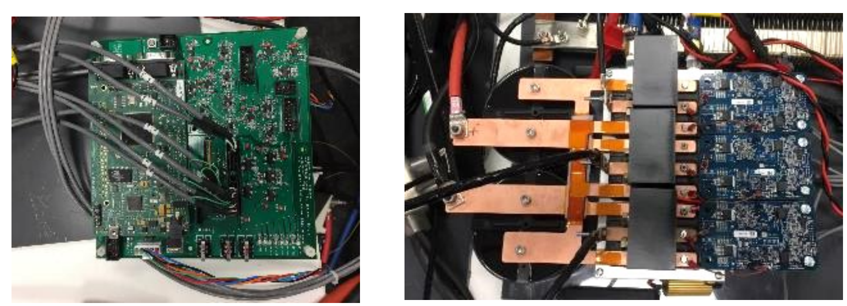
- Analyzed inverter switching characteristics to ensure safety and protection
  - Tested for power module performance and operation
  - Drain to source voltage oscillations observed to protect the device and passives
  - Drain current oscillation
- Lab prototype integrated wit a TMSF320F28335PGFA DSP from TI with a CAN interface through a host computer for controls.
- Gate driver loop inductance improved based on initial double-pulse test results.
- Also tested the device protection functionalities (short-circuit protection), response time of 3.88 μs.

Parameters for double pulse set-up

Parameter	Values
Inductance (L)	150 μH
Gate Voltage (V_{OFF} / V_{ON})	– 2 V/ +18 V
V_{DC}	600 V

Schematic of the double pulse test setup





Laboratory prototype of the inverter and the controller

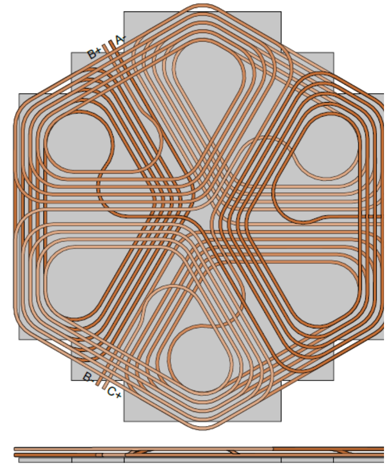
Technical Accomplishments – BP I

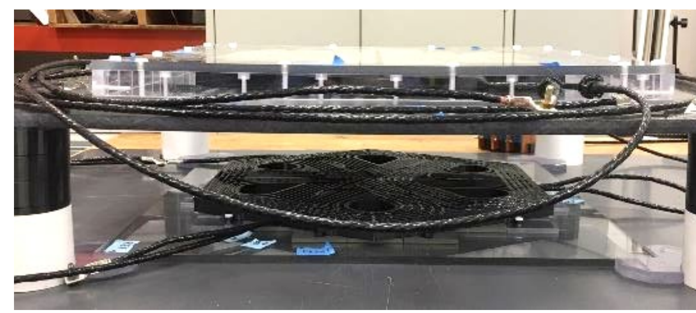
Designed and prototyped a 3-phase, 2-layer, polyphase couplers

- Polyphase coupler design
- Inductance readings @170mm airgap

		Aligned Sim.	Aligned Exp.	Δφ=30° Sim.	Δφ=30° Exp.
GA Self–Inductances	L_a	34.1	31.6	34.1	30.9
	L_b	34.3	32.3	34.3	30.6
	L_c	34.2	32.4	34.2	30.9
	M_{ab}	-11.2	- 9.8	-11.2	- 9.9
	M_{bc}	-11.3	- 9.8	-11.3	-10.2
	M_{ca}	-11.1	-10.2	-11.1	-10.6
VA Self–Inductances	L_a	34.1	31.1	34.1	30.9
	L_b	34.3	31.3	34.3	31.0
	L_c	34.2	31.6	34.2	30.7
	M_{ab}	-11.2	-10.0	-11.2	-10.2
	M_{bc}	-11.3	- 9.8	-11.3	-10.1
	M_{ca}	-11.1	- 9.9	-11.1	- 9.6
GA to VA Mutual–Inductances	M_{ga}^{va}	5.65	5.32	5.32	5.10
	M_{gb}^{va}	-3.64	-3.68	-1.08	-1.49
	M_{gc}^{va}	-1.85	-1.53	-4.29	-3.27
	M_{ga}^{vb}	-1.85	-1.23	-4.29	-3.57
	M_{gb}^{vb}	5.54	5.42	5.20	5.76
	M_{gc}^{vb}	-3.57	-3.50	-0.99	-1.73
	M_{ga}^{vc}	-3.64	-3.32	-1.08	-1.47
	M_{gb}^{vc}	-1.77	-1.30	-4.18	-3.97
	M_{gc}^{vc}	5.55	5.07	5.20	5.40

Design and hardware realization of 3-phase polyphase electromagnetic couplers





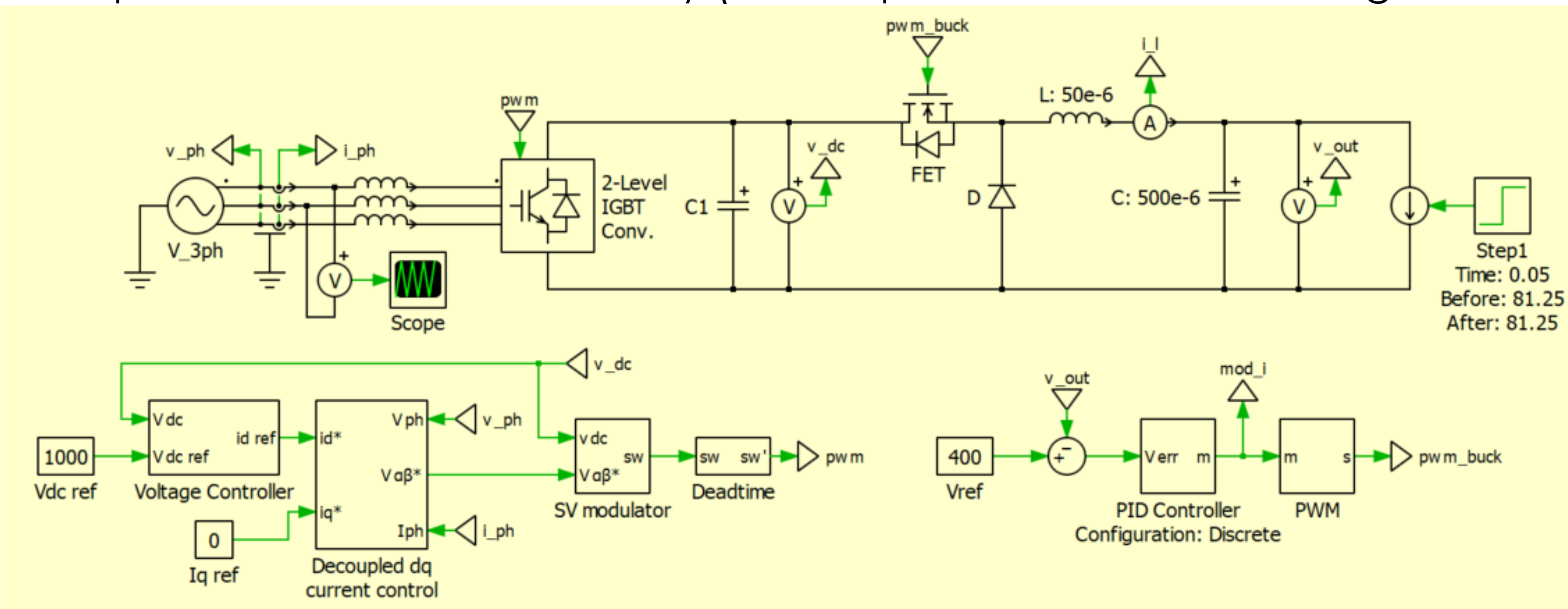
- Effective self and mutual inductances

	Aligned Sim.	Aligned Exp.	Δφ=30° Sim.	Δφ=30° Exp.	Δx=Δy=100 mm Sim.	Δx=Δy=100 mm Exp.
$L_{g,e}$	136.2	000.0	136.2	123.1	134.7	121.9
$L_{v,e}$	136.2	000.0	136.2	122.5	134.7	121.0
M_e	25.3	00.0	25.1	24.6	12.7	12.7
k_e	0.186	0.000	0.184	0.200	0.094	0.105

Technical Accomplishments – BP I

Developed a simulation model for closed-loop 3-phase PFC with step-down regulator

- The model of the front-end ChargePoint power blocks to understand control requirements and controllability (480V 3-phase to 200V-1000V regulated DC voltage)



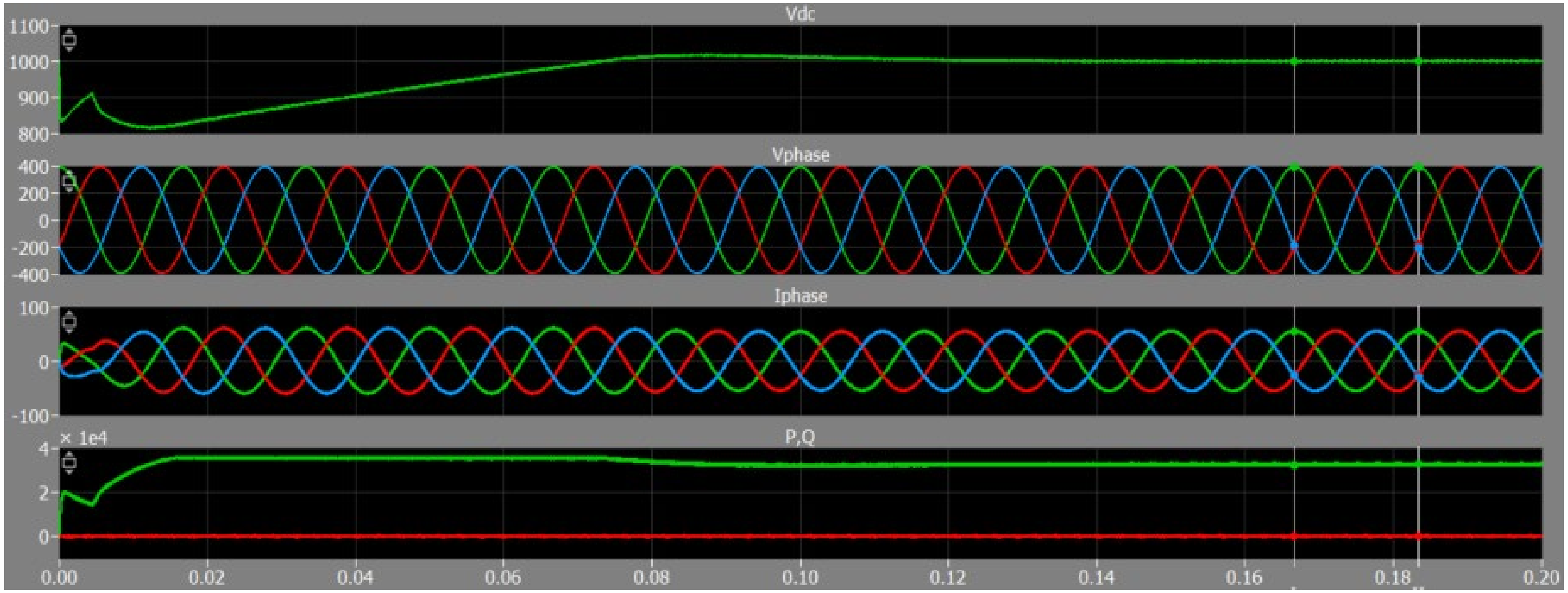
ChargePoint express plus – power block	
Input Rating (3-phase 4 wire)	400V AC, 3-phase, 256A, 50 Hz 480V AC, 3-phase, 222A, 60 Hz
Max Output Power	156 kW
Max Output Current	390A
Max Modules per Power Block	5

Simulation model for the front-end grid-tied PFC and dc/dc buck converter

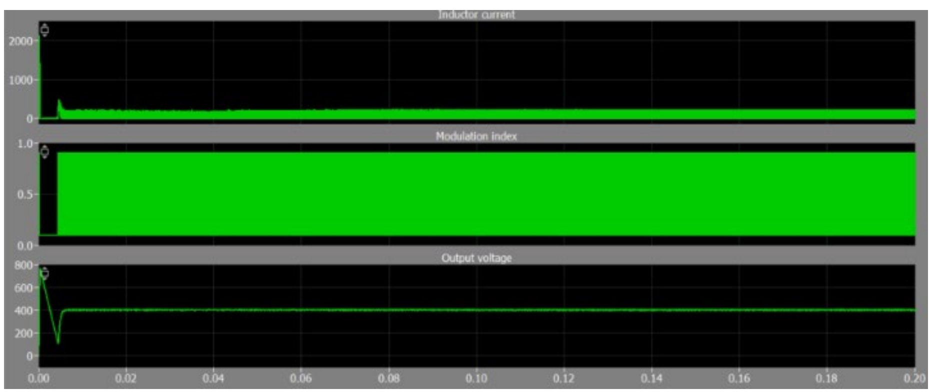
Technical Accomplishments – BP I

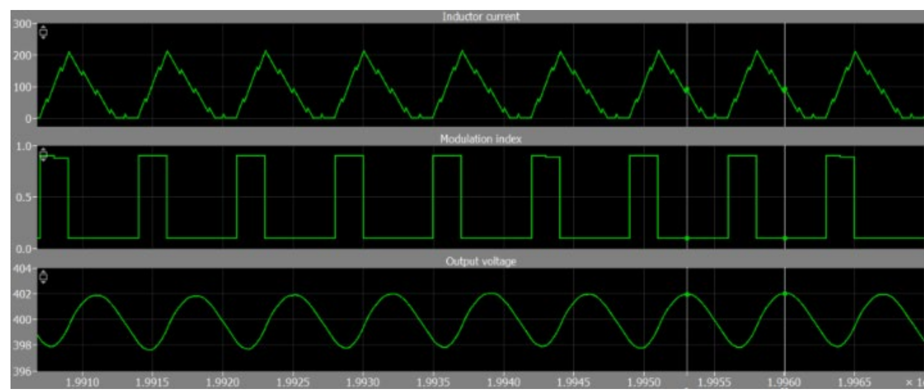
Developed a simulation model for closed-loop 3-phase PFC with step-down regulator

- Simulation results for 325kW output power



DC bus voltage (1000V), 480V 3-phase input voltages and currents and the active and reactive power from the grid.



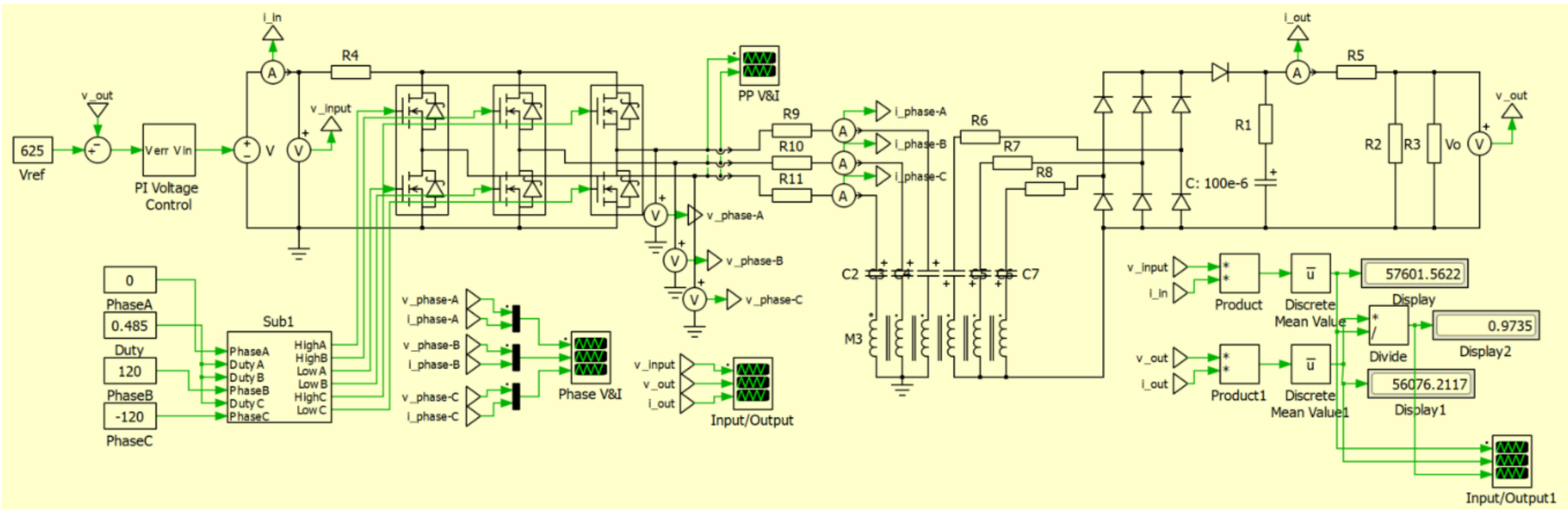


Operational waveforms and output DC bus voltage regulated to 400V.

Technical Accomplishments – BP I

Developed a simulation model for the 3-phase inverter model and the polyphase coil

- ~55kW simulations using the measured coil inductances from polyphase coupler prototype



Matrix model of the mutual and self-inductances of the polyphase coupler

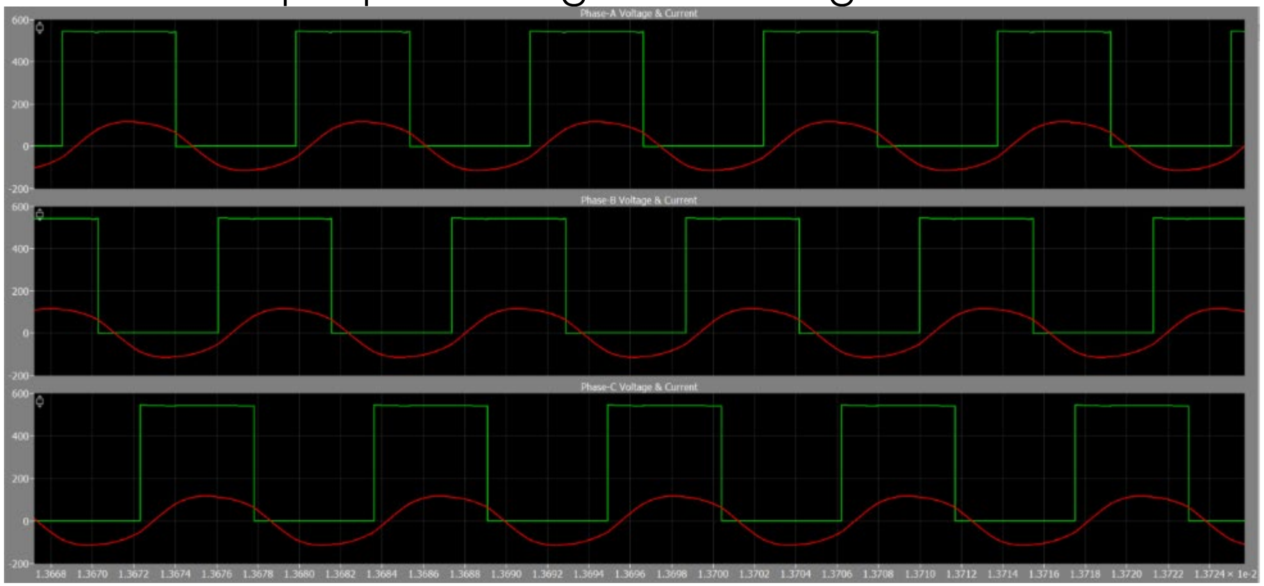
```
[34.22 -11.21 -11.21 -5.7 2.78 2.78;
-11.21 34.22 -11.21 2.78 -5.7 2.78;
-11.21 -11.21 34.22 2.78 2.78 -5.7;
-5.7 2.78 2.78 34.22 -11.21 -11.21;
2.78 -5.7 2.78 -11.21 34.22 -11.21;
2.78 2.78 -5.7 -11.21 -11.21 34.22]*1e-6
```

600μs deadband, 88.5 kHz switching frequency, 0.083μF series resonant tuning capacitors

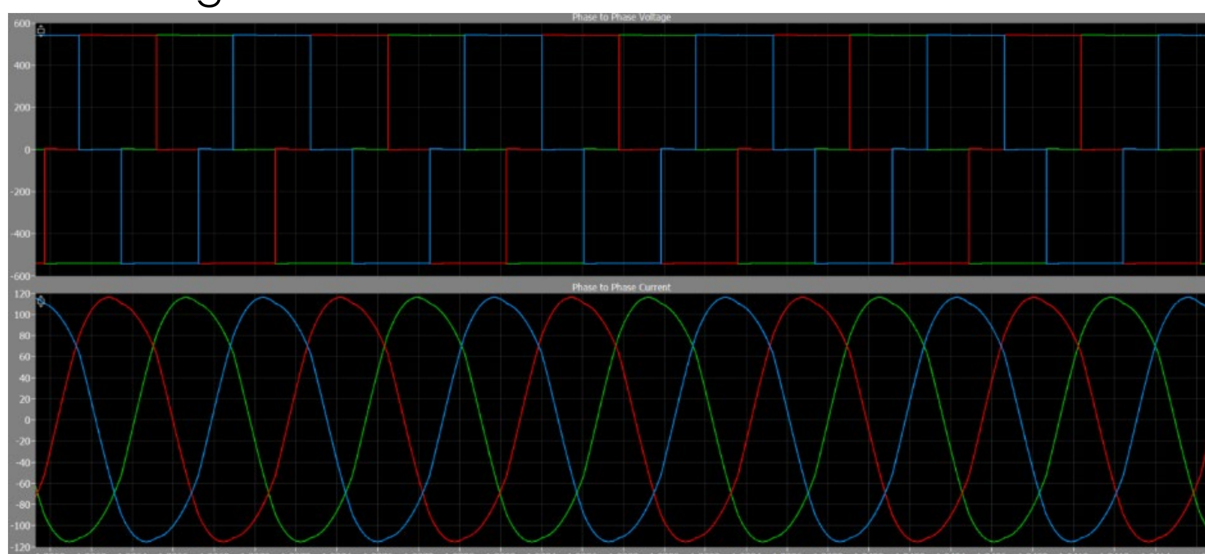
Technical Accomplishments – BP I

Developed a simulation model for the 3-phase inverter model and the polyphase coil

- Inverter output phase-to-ground voltage and current measurements



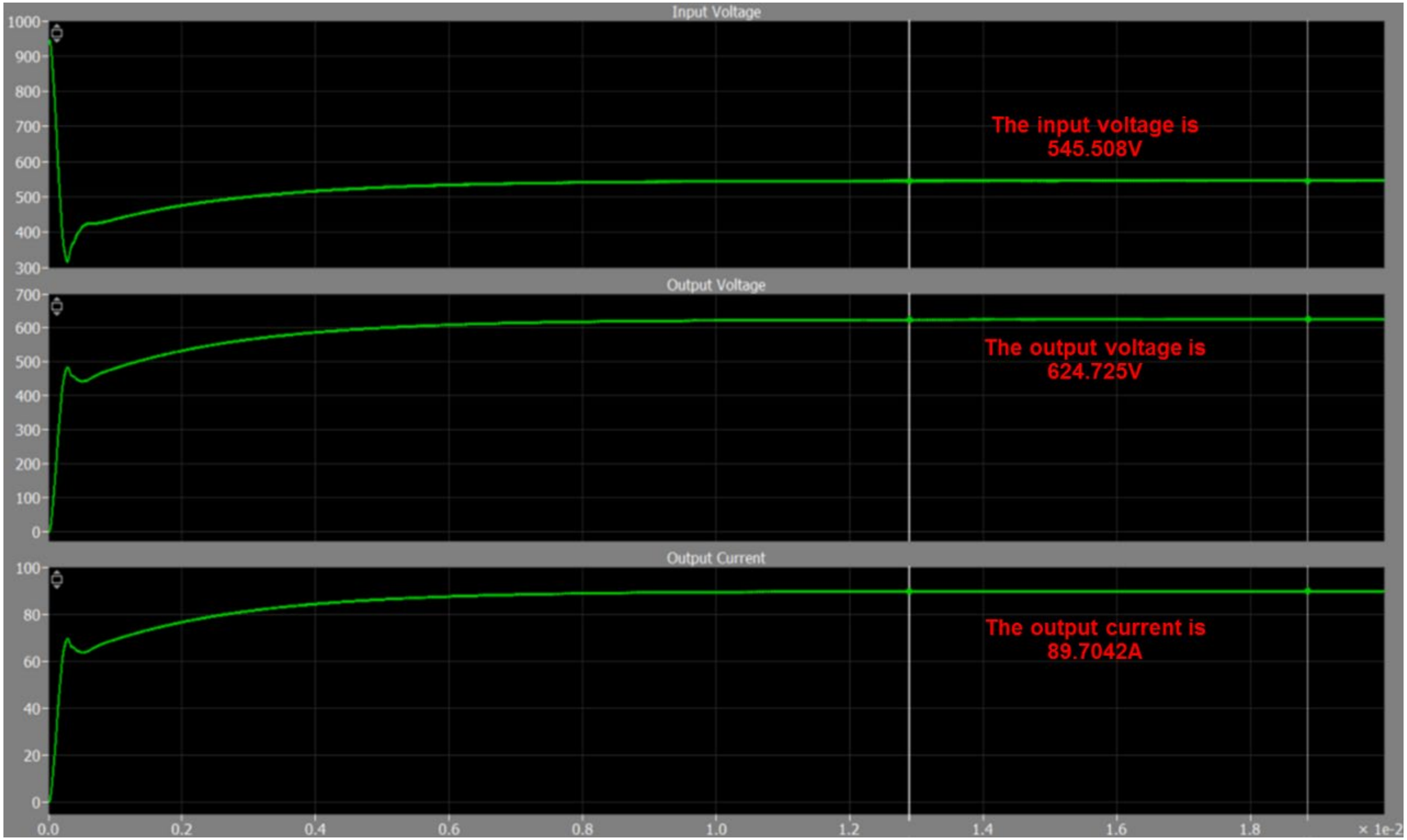
- Inverter output phase-to-phase voltages and currents



Technical Accomplishments – BP I

Developed a simulation model for the 3-phase inverter model and the polyphase coil

- Input and output voltage and current measurements

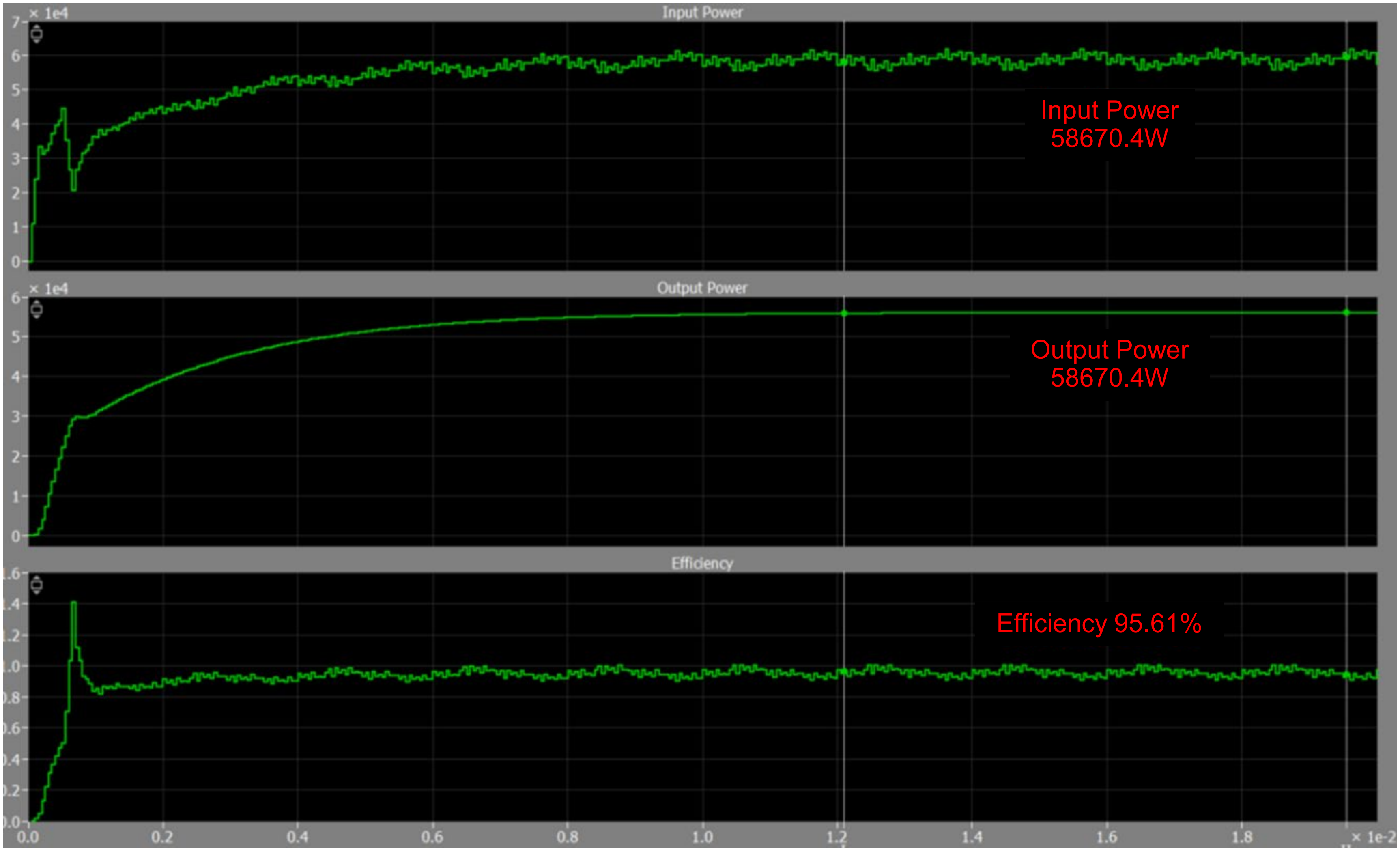


OAK RIDGE National Laboratory | NATIONAL TRANSPORTATION RESEARCH CENTER

Technical Accomplishments – BP I

Developed a simulation model for the 3-phase inverter model and the polyphase coil

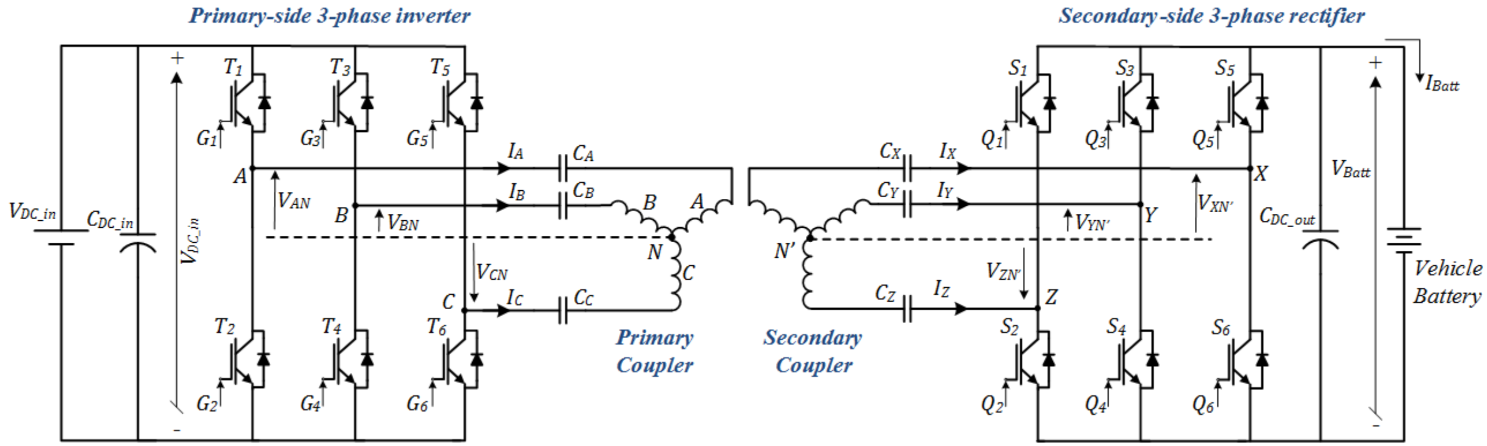
- Input and output power and efficiency measurements



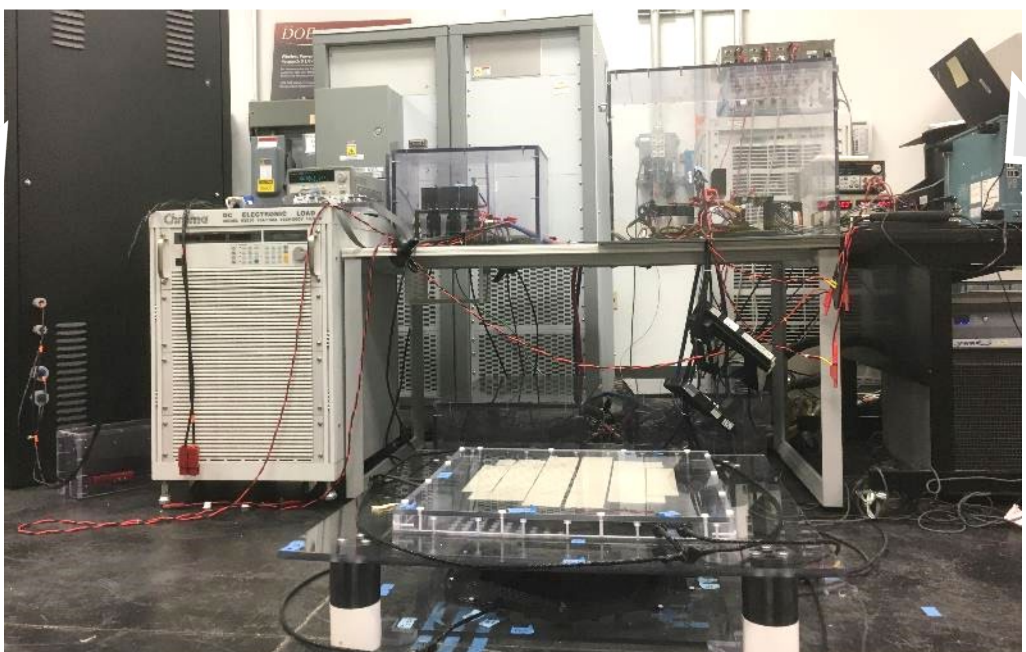
Technical Accomplishments – BP I

Developed a laboratory benchtop test setup to validate the concepts

- Hardware development and experimental test results



Circuit diagram of the proposed system

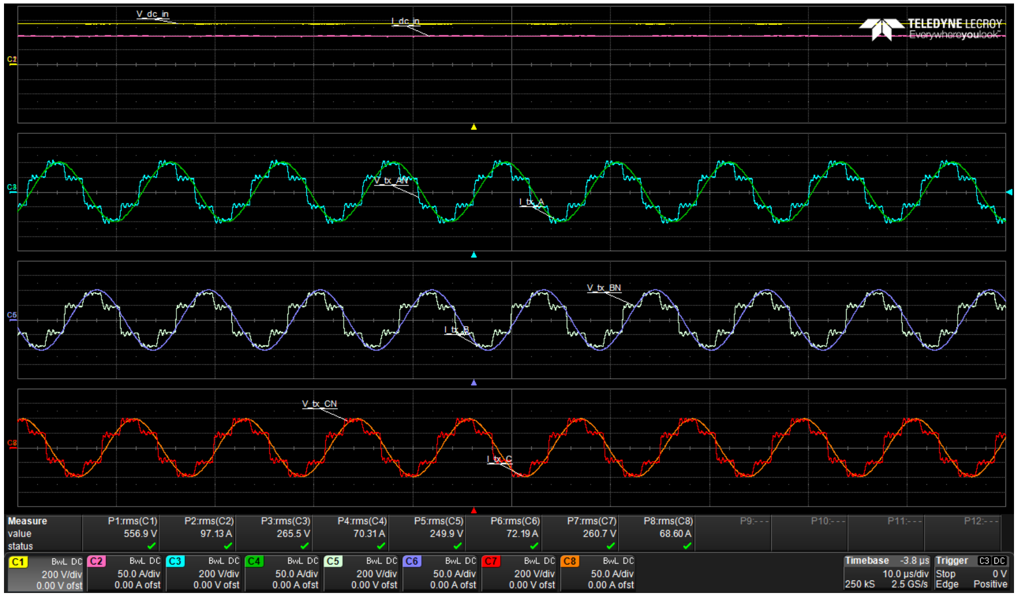


Experimental hardware of the proposed system

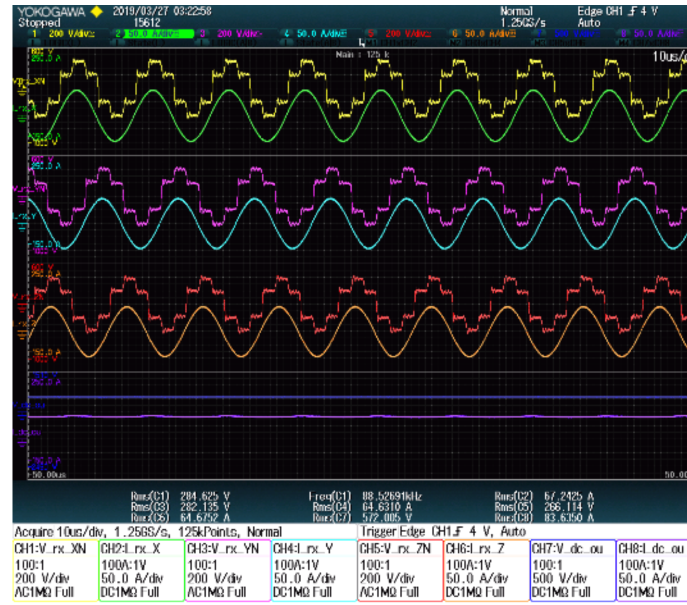
Technical Accomplishments – BP I

Developed a laboratory benchtop test setup to validate the concepts

- Hardware development and experimental test results



Primary-side voltages and currents



Secondary-side voltages and currents

OAK RIDGE National Laboratory | NATIONAL TRANSPORTATION RESEARCH CENTER

Technical Accomplishments – BP I

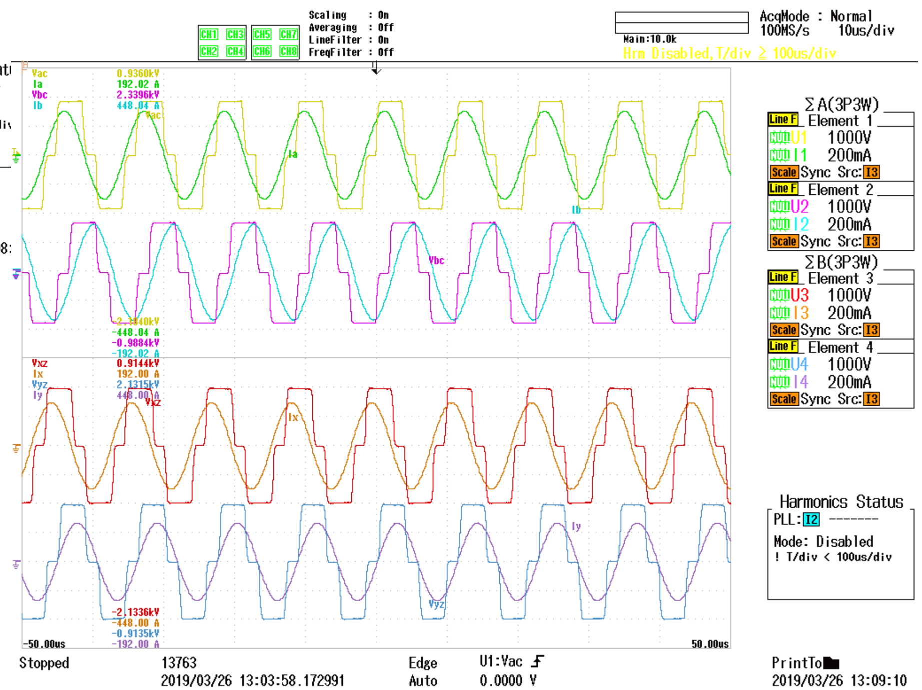
Developed a laboratory benchtop test setup to validate the concepts

- Hardware development and experimental test results: 99.49% coil-to-coil efficiency

	Element 1	Element 2	Σ A(3P3W)	Element 3	Element 4	Σ B(3P3W)
Urms [V]	0.4615k	0.4602k	0.4609k	0.4814k	0.4701k	0.4757k
Irms [A]	68.26	73.96	71.11	66.99	60.43	63.71
P [W]	27.20k	24.06k	51.26k	25.21k	25.79k	51.00k
Q [var]	-15.89k	24.08k	8.19k	-20.11k	-11.90k	-32.01k
λ [ ]	0.8634	0.7067	0.9030	0.7817	0.9080	0.9710
Φ [°]	D30.30	G45.03	25.44	D38.58	D24.77	13.84
V_CA [V]	491.04					
V_CX [V]	481.85					
η1 [%]	99.496					

Stopped 13763 2019/03/26 13:03:58.172991 Edge Auto U1:Vac 0.0000 V

3-phase couplers transmitter to receiver efficiency analysis with 2-wattmeter method



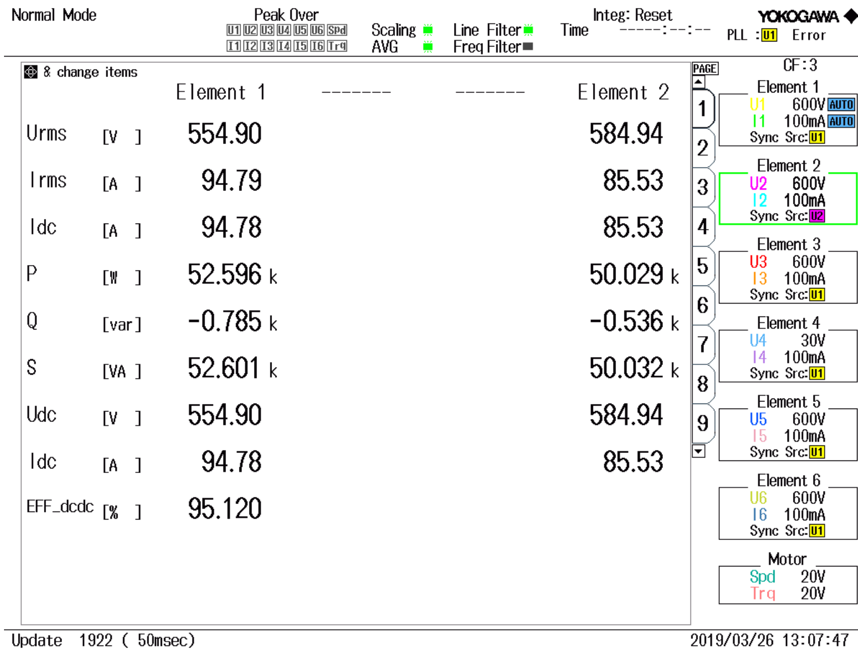
Primary-side V_{AB} and V_{AC} voltages, phase A and B currents, secondary-side V_{XY} and V_{XZ} voltages, and phase X and Y currents measured for 2-wattmeter method

OAK RIDGE National Laboratory | NATIONAL TRANSPORTATION RESEARCH CENTER

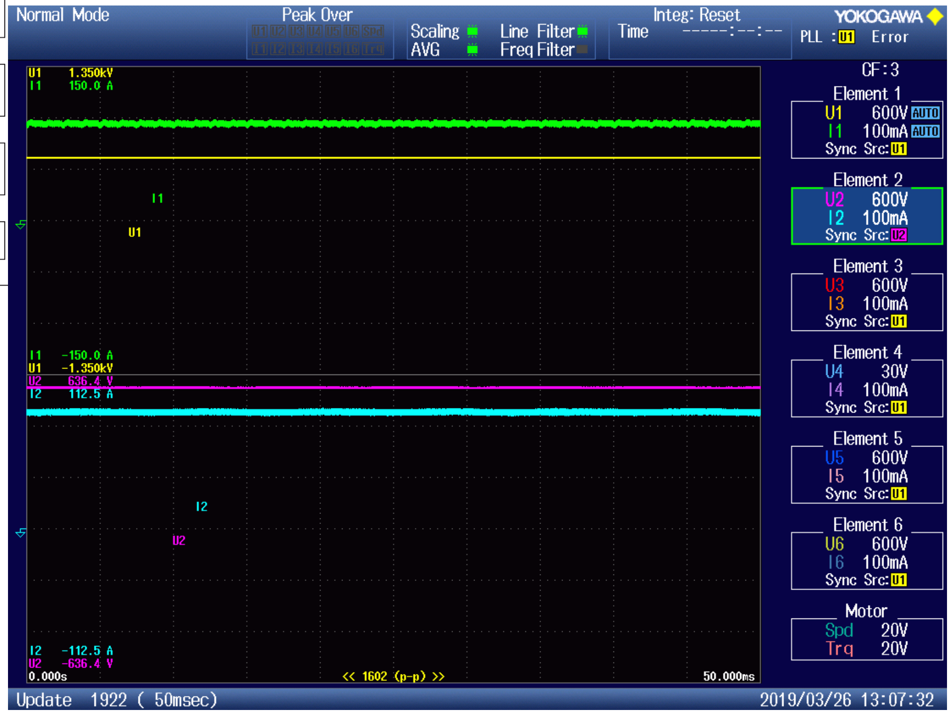
Technical Accomplishments – BP I

Developed a laboratory benchtop test setup to validate the concepts

- Hardware development and experimental test results: 95.12% dc-to-dc efficiency



DC input and DC output voltage, current, and power measurements for dc-to-dc efficiency analysis



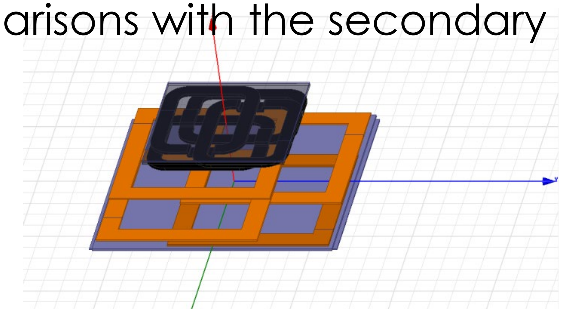
DC input and DC output voltage and current waveforms

- 97.5% inverter efficiency
- 98.1% rectifier efficiency
- 99.49% coil-to-coil efficiency
- 95.12% overall efficiency

Technical Accomplishments – BP I

Comparisons with the state-of-the-art systems

- Comparisons with WPT4 (WPT Level 4) 22kW coil proposal by KAIST
- Called 4-coil magnetic beamforming technology
- KAIST 4-coil coupler technology (VA): 780 mm × 630 mm × 38 mm, 5.29 ft^2, 1139.5 in^3
- ORNL polyphase coupler technology: 471 mm × 544 × 26 mm, 2.76 ft^2, 406.53 in^3
- Comparisons with the secondary (smaller) coupler



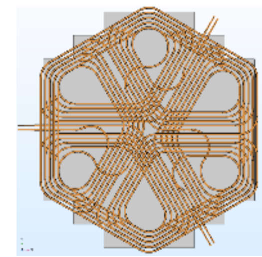
- Surface power density of 4-coil coupler:

$$d_{sp\_KAIST} = \frac{22kW}{5.29ft^2} = 4.16\ kW/ft^2$$

- Volumetric power density of 4-coil coupler

$$d_{vp\_KAIST} = \frac{22kW}{993.42\ in^3} = 19.31\ W/in^3$$

- Airgap: 120mm
- Efficiency: 92.95% (@z=120mm, 22kW)



- Surface power density of ORNL polyphase coupler:

$$d_{sp\_ORNL} = \frac{55kW}{2.76\ ft^2} = 19.93\ kW/ft^2$$

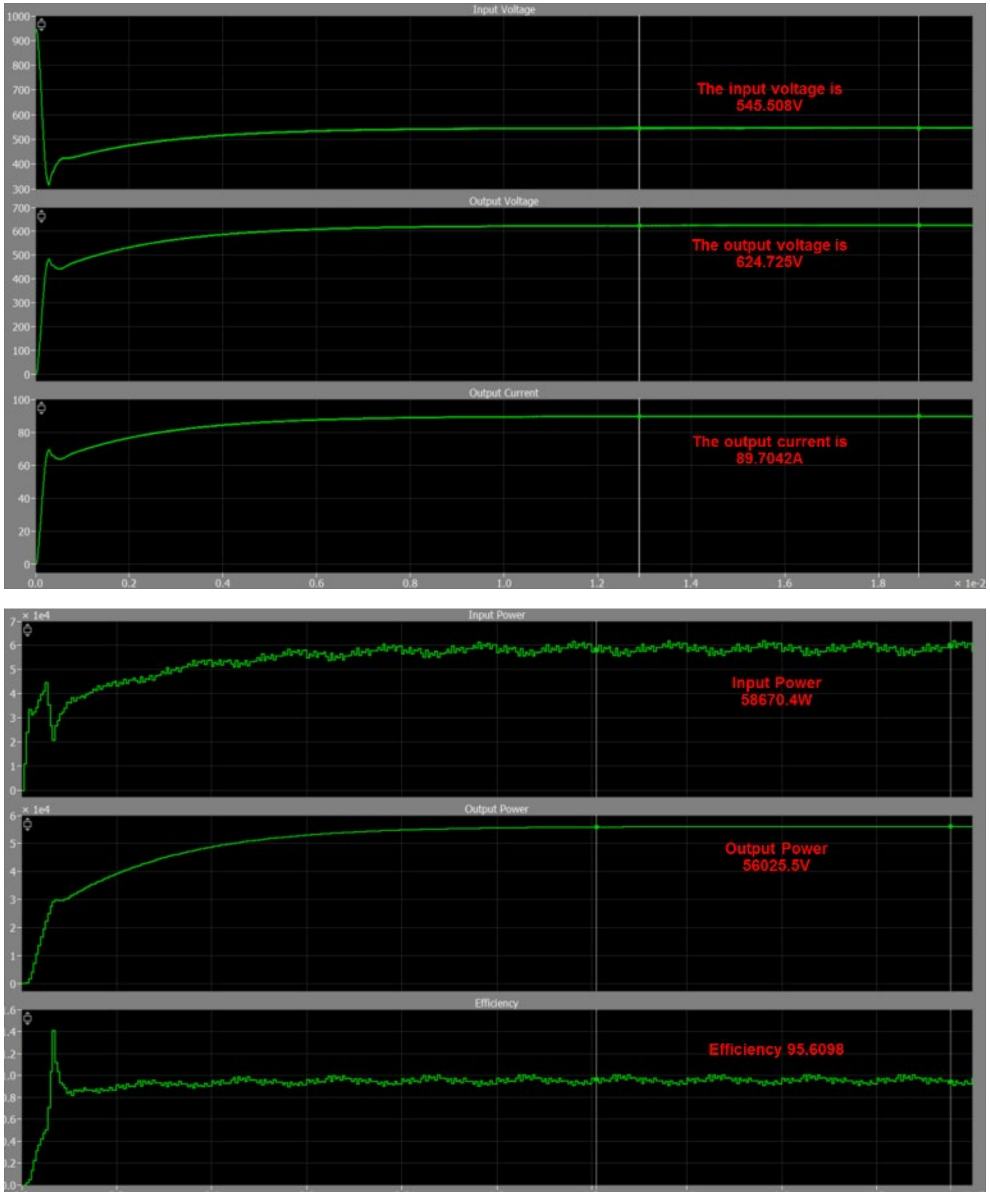
- Volumetric power density of ORNL polyphase coupler

$$d_{vp\_ORNL} = \frac{55kW}{406.53\ in^3} = 135\ W/in^3$$

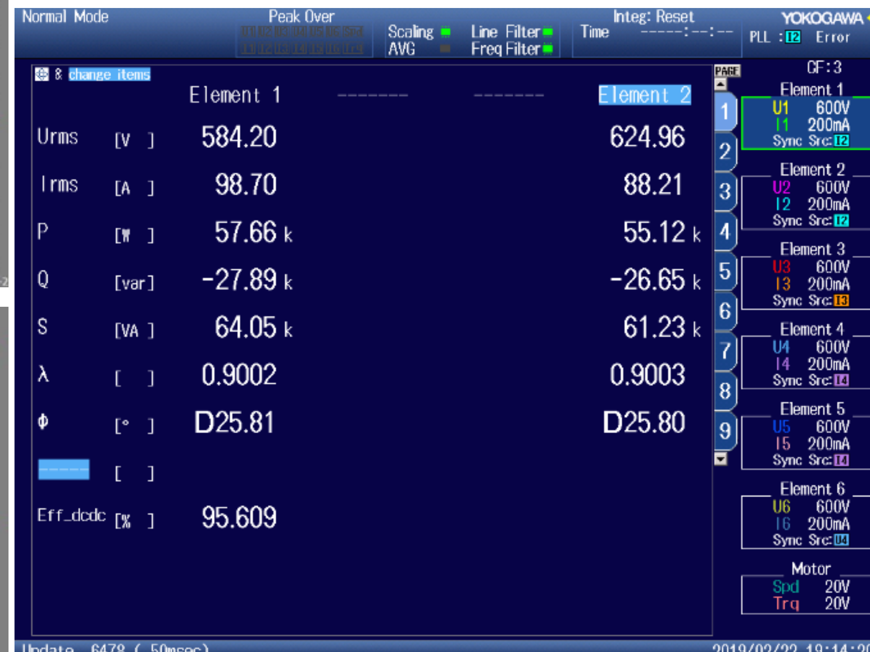
- Airgap: 170mm
- Efficiency: 95.61% (@z=170mm, 55kW)

Technical Accomplishments – BP I

Simulation model experimental verification



- Simulation results compared with the 55 kW experimental results.
- Input & output voltage and current
- 95.61% dc-to-dc efficiency



55 kW experimental test results (dc input / inverter input and rectifier output & load)

OAK RIDGE National Laboratory | NATIONAL TRANSPORTATION RESEARCH CENTER

Response to Previous Year Reviewers' Comments

- No reviewer comments from previous year.
- This is a new project started in FY19.

Collaboration and Coordination with Other Institutions

- **ORNL**: Project lead, project management, budget management, reporting, overall coordination, design, development, integration, testing, demonstration. Designer and developer of all the power electronics and electromagnetics components and subsystems.
- **ChargePoint**: Design and development of grid-interface converters, R&D on cybersecurity and active cooling technologies, engineering and integration support on grid-interface converters.
- **Hyundai-Kia**: Vehicle manufacturer; providing the research vehicle along with engineering and integration support, support on BMS, battery thermal management, and technical specifications for the 100kW tests and integrations.
- **SF Motors**: Vehicle manufacturer; providing the research vehicle along with engineering and integration support, support on BMS, battery thermal management, and technical specifications for the 100kW tests and integrations.

Remaining Challenges and Barriers

- The reference DC input voltage to the system should be accurately communicated to the front-end ChargePoint power blocks.
- 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 100 and 300 kW across 6-7 inches airgap.
- The thermal management system of the hardware requires utilizing cooling system designed for the vehicle's on-board electronics (traction drive inverter or on-board charger). Controlling the cooling system as well as other on-vehicle auxiliary components including the BMS system requires input from the OEM partners.

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

Proposed Future Research

- **FY 2019**
  - Scale the design polyphase electromagnetic couplers as well as the inverter/rectifier to 300 kW target power as well as the inverter with backward compatibility to 100 kW.
- **FY 2020**
  - Integrate the final design to a Hyundai-Kia vehicle (Kona or Ioniq) with 100kW power transfer demonstration (~30 kWh battery pack)
- **FY 2021**
  - Integrate the final design to an SF Motors vehicle (SF5) with 300kW power transfer demonstration (~96 kWh battery pack)

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, achieve extreme fast charging power levels with advanced and compact designs with user convenience.
- **Approach**: Proposed a polyphase electromagnetic coupler and high-power and high-frequency power electronic converters to meet high-power and high-efficiency targets.
- **Technical Accomplishments**:
  - Designed and developed a 55 kW proof of concept prototype for laboratory tests and evaluations to scale the system and provide a design guideline for 100 kW and 300 kW power levels.
  - Currently testing the whole system together at different operating conditions including x-y and rotational misalignments.
- **Collaborations and Coordination with Other Institutions**:
  - **ORNL**: Project lead and project management.
  - **ChargePoint**: EV charging equipment manufacturer and network operator, providing grid-interface converters.
  - **Hyundai-Kia**: Vehicle OEM. Providing a test vehicle and integration and engineering support and guidance.
  - **SF Motors**: Vehicle OEM. Providing a test vehicle and integration and engineering support and guidance.
- **Future Work**:
  - Scale the design to 300 kW target power level both for power electronics and polyphase electromagnetic couplers.
  - Commission the ChargePoint power block and integrate to the overall system with controls and communications.
  - Perform vehicle integrations and prepare for demonstrations.

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