High-Power Inductive Charging System Development and Integration for Mobility

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2020 U.S DOE Vehicle Technologies Office Annual Merit Review
June 4th, 2020 Project ID: ELT239

Overview

Timeline

- Start – October 2018 (FY19)
- End – September 2021 (FY21)
- 3 budget periods

Budget

- Total project funding
  - DOE share – $2.2M
  - Cost share from partners – $3.0M
- Project spending BP1: $350K
- Project spending BP2: $450K

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 (≤5% on current harmonics)
- High operating efficiencies ≥ 90% (end-to-end) for both cases
- Interoperable grid side power electronics and electromagnetic hardware

Partners

- ORNL (Project lead), (Omer C. Onar, Jason Pries, Gui-Jia Su, Cliff White, Larry Seiber, Veda Galigekere, Erdem Asa, Randy Wiles, Jonathan Wilkins, Subho Mukherjee, Mostak Mohamad, Lincoln Xue)
- ChargePoint
- Hyundai-Kia America Technical Center
- SERES Automotive (SF Motors)

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

Project Objectives and Relevance

Overall Objectives:

- 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 power transfer levels that correspond to 3C charge rates
- Achieve high charging efficiencies greater than 90% (end-to-end)
- Integrate vehicle to infrastructure charging communication protocols (wireless)
- Understand and address vehicle integration issues of XFC technology, including energy storage impacts and thermal management considerations

FY 2020 Objectives:

- Complete the design and hardware development of a 100 kW inductive XFC system including the grid interface converter, high-frequency inverter, poly-phase electromagnetic coupling coils, vehicle-side power converters, and resonant tuning components and filters
- Integrate system into a Hyundai-Kia provided research vehicle
- Technology demonstration, validation, test and data collection

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.	Completed
BP2 (FY20) 10/2019-09/2020	[*System development, integration, and testing up to 100 kW*] 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	[*System development, integration, and testing up to 300 kW*] Complete system integration and perform necessary modifications, optimize system design, fine tune components and controllers. Integrate system into a SERES vehicle, validate 300 kW power transfer. Test and collect data and demonstrate the proposed concept.	On track

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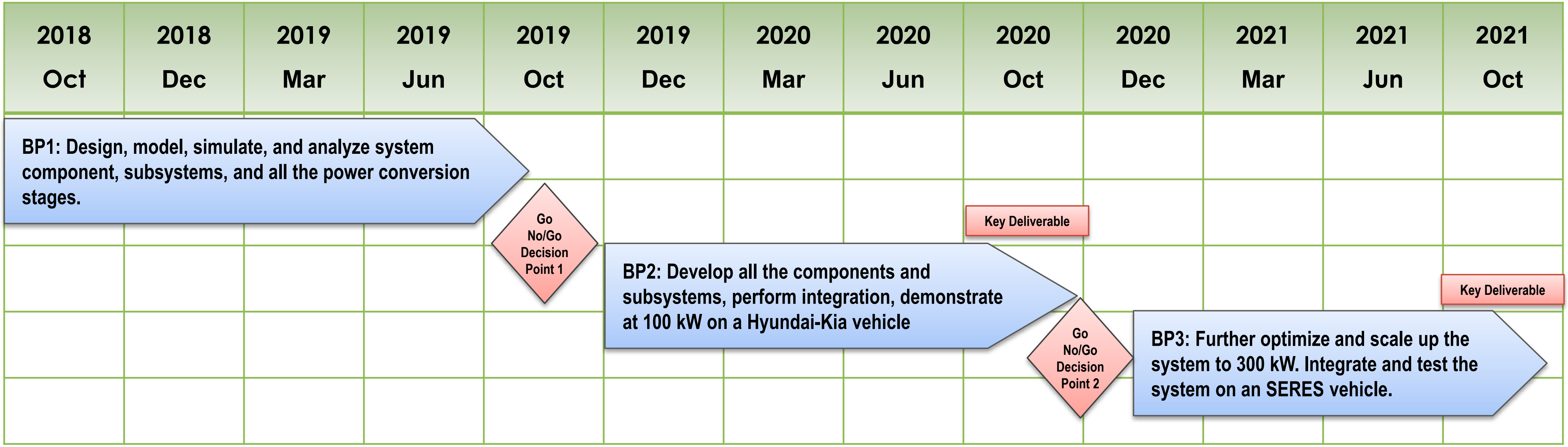
Approach / Strategy

- Iterative design and the use of finite element analysis (FEA) based modeling for the design optimization of the electromagnetic coupling coils.
- 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.
- Model and simulate the grid interface (front-end) power blocks based on the dc link voltage requirements of the proposed system and the grid infrastructure parameters.
- Design the system power conversion stages in an integrated approach for an optimal system design in terms of complexity and compactness.
- Test and validate all the power conversion stages individually before the full system integration (for functionality and performance).
- Test the entire system using grid and battery emulators before vehicle integration.
- Design and develop a prototype for proof of concept before designing and developing the high power scaled couplers and converters.
- Complete vehicle integrations, evaluations, and validation of the proposed system.

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

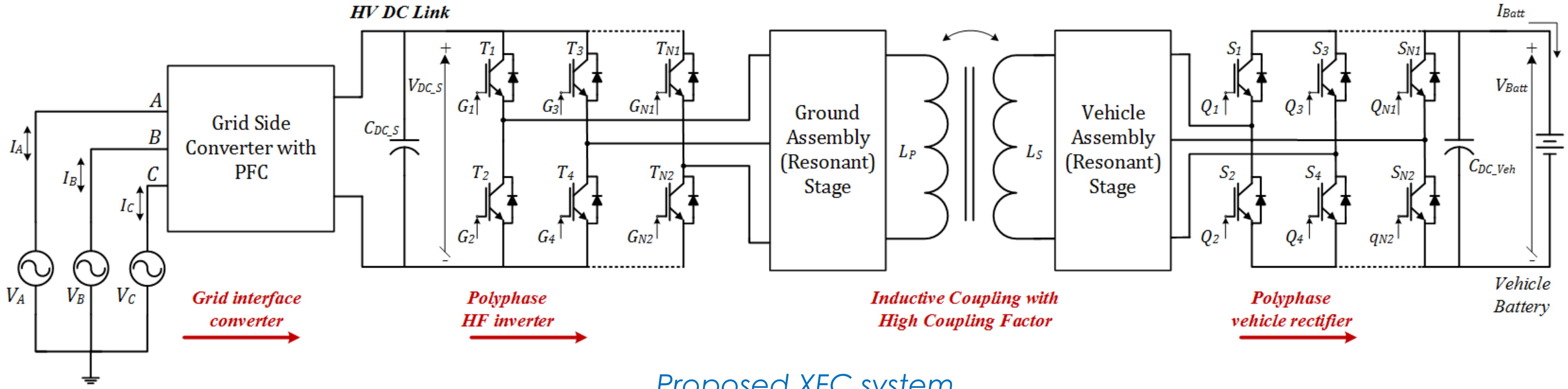
Project Timeline



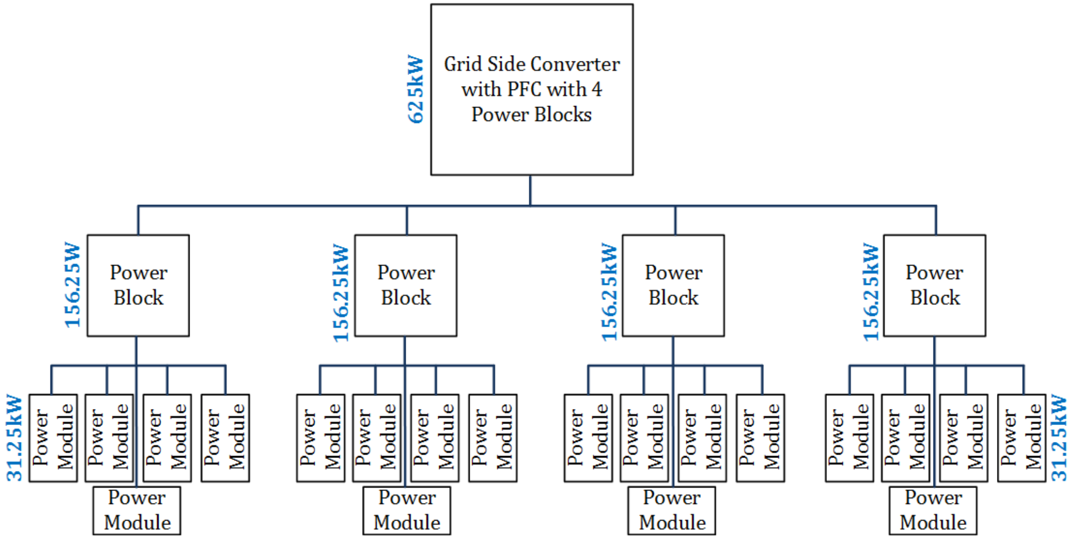
- **Go/No-Go Decision Point 1**: Whether the system design, models, and simulation indicate the feasibility of the proposed XFC system.
- **Go/No-Go Decision Point 2**: Whether the proposed system can be experimentally validated with 100 kW power transfer to the Hyundai-Kia provided test vehicle.
- **Key Deliverable for BP 2**: Complete design, development, integration, and testing 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

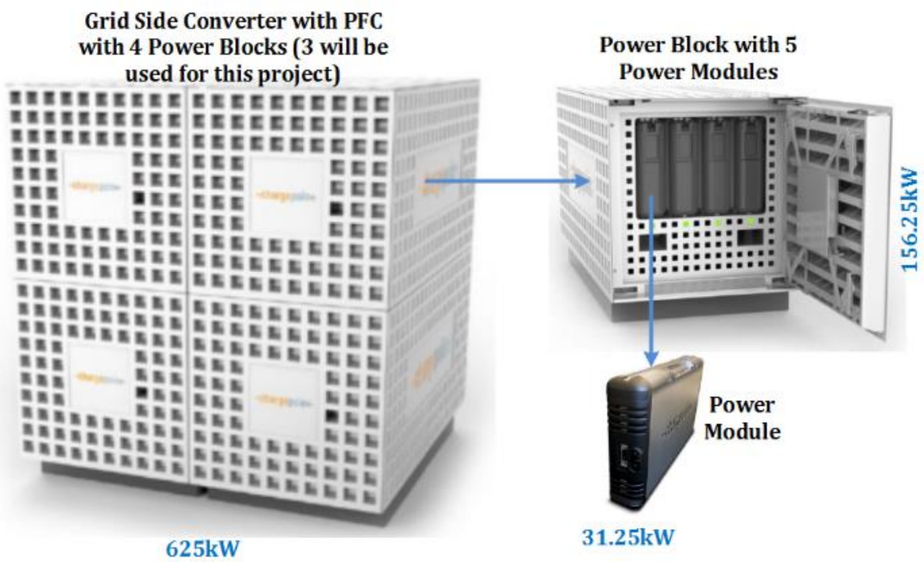
Proposed Technology



Proposed XFC system



Modular and scalable grid interface system

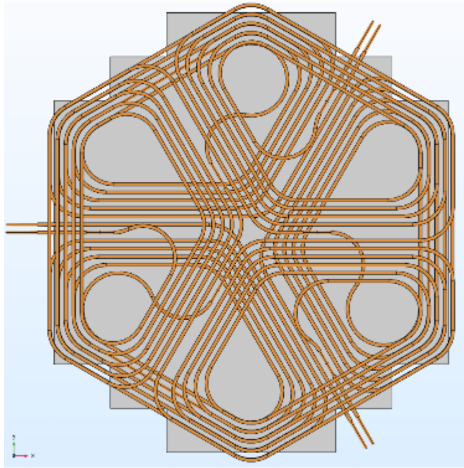


ChargePoint Power Blocks

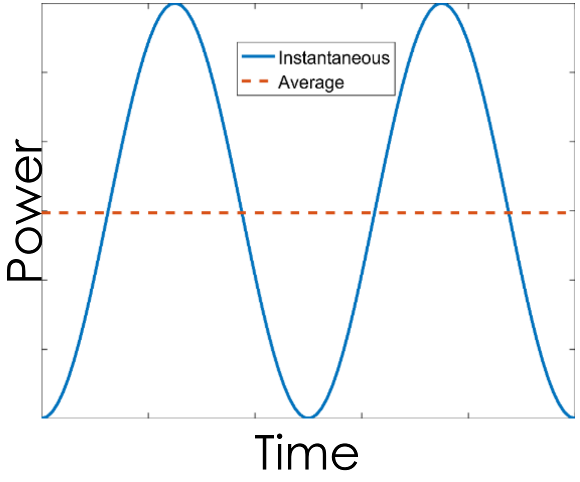
Any proposed future work is subject to change based on funding levels

Polyphase Coupler Technology

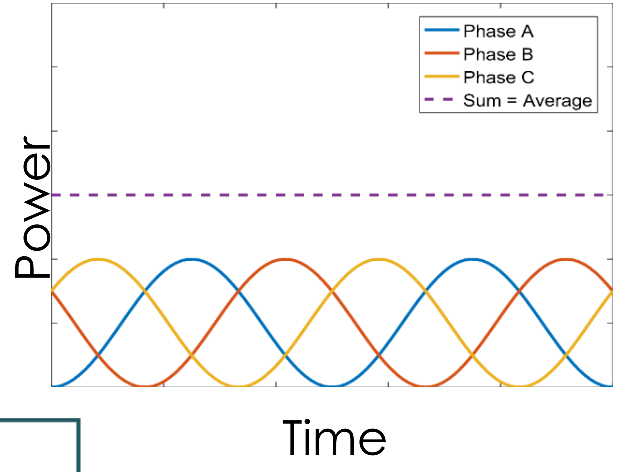
- Single-phase systems “pulse” power across the airgap
- Low space-time average utilization since fields oscillate between peak values and zero



Polyphase coupler wiring

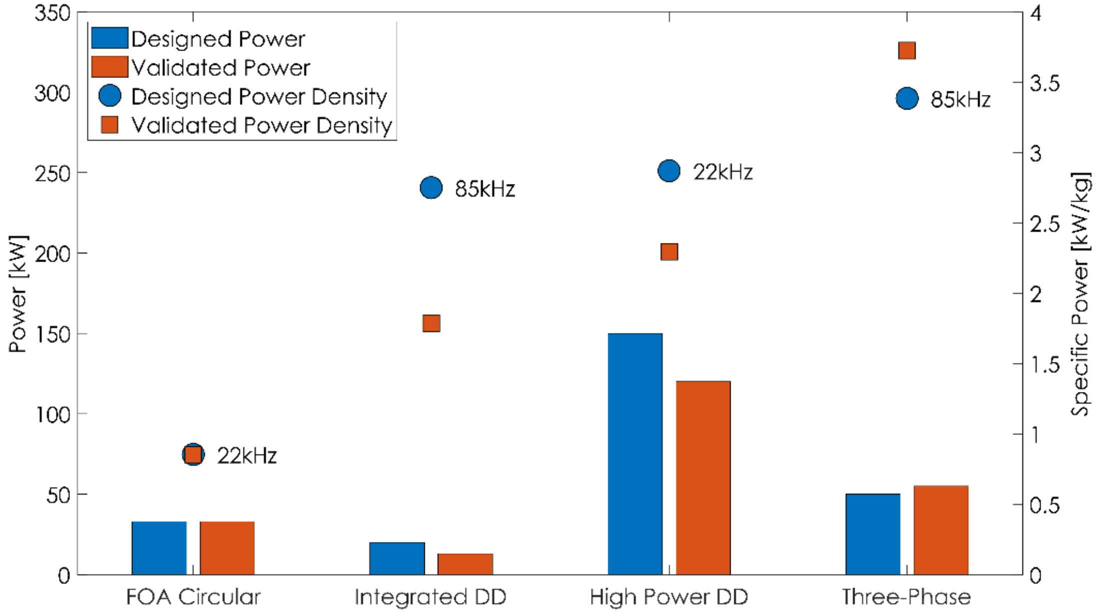


Instantaneous and average power variations for conventional circular couplers



Instantaneous and average power variations for polyphase coupler

- Polyphase systems use 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



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

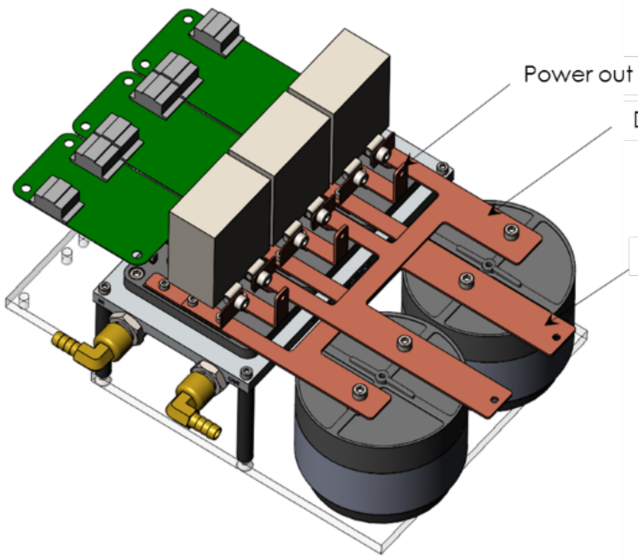
Any proposed future work is subject to change based on funding levels

Technical Accomplishments – BP I

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

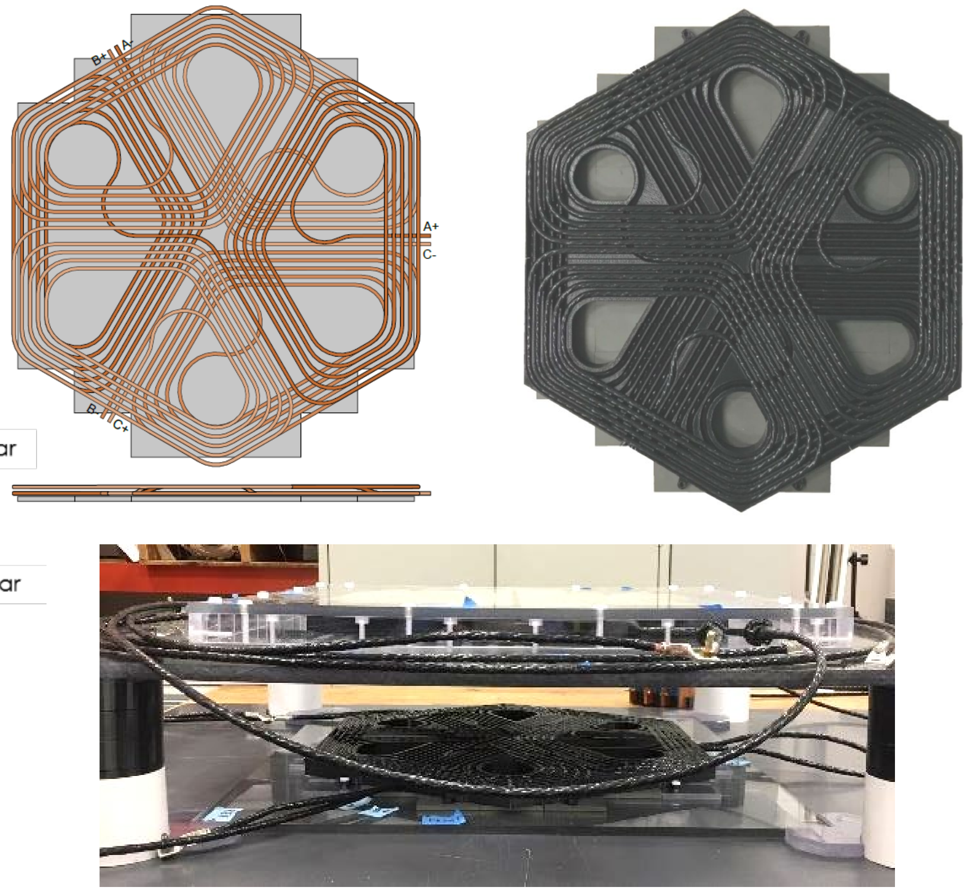
- Polyphase coupler design
- Inductance readings @170mm airgap

		Aligned		Δφ=30°	
		Sim.	Exp.	Sim.	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



3-phase inverter design rendered image

- 3-phase inverter design based on ORNL 120 kW WPT system
- Effective self and mutual inductances



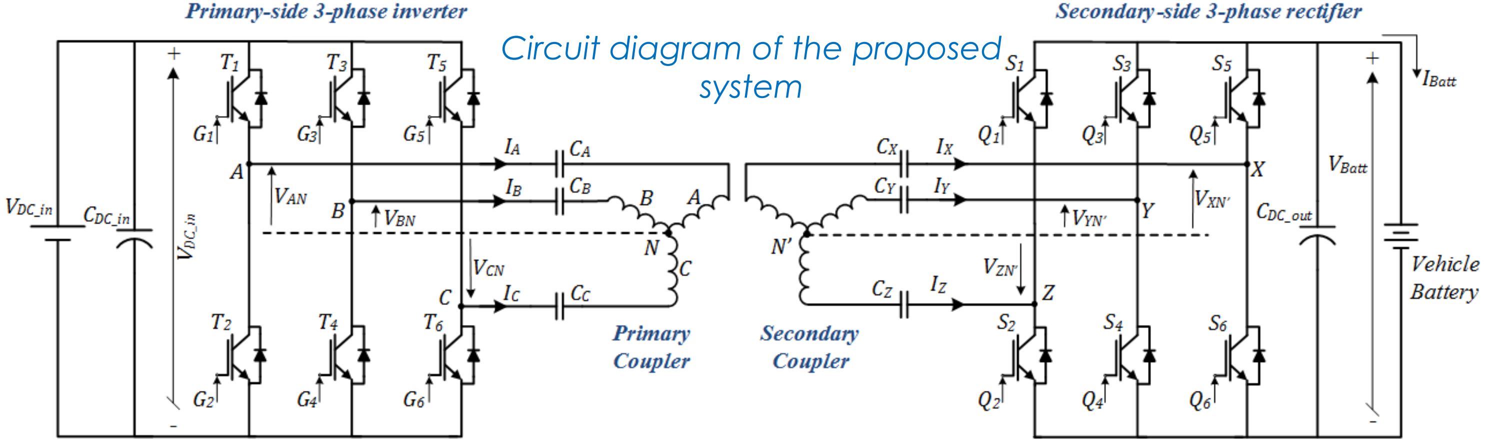
Design and hardware realization of 3-phase polyphase electromagnetic couplers

	Aligned		Δφ=30°		Δx=Δy=100 mm	
	Sim.	Exp.	Sim.	Exp.	Sim.	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

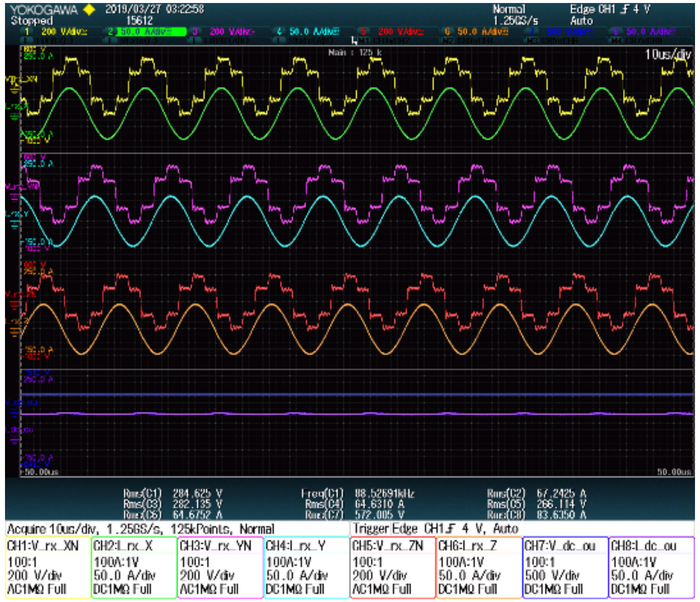
Technical Accomplishments – BP I

Developed a laboratory benchtop test setup to validate the concepts

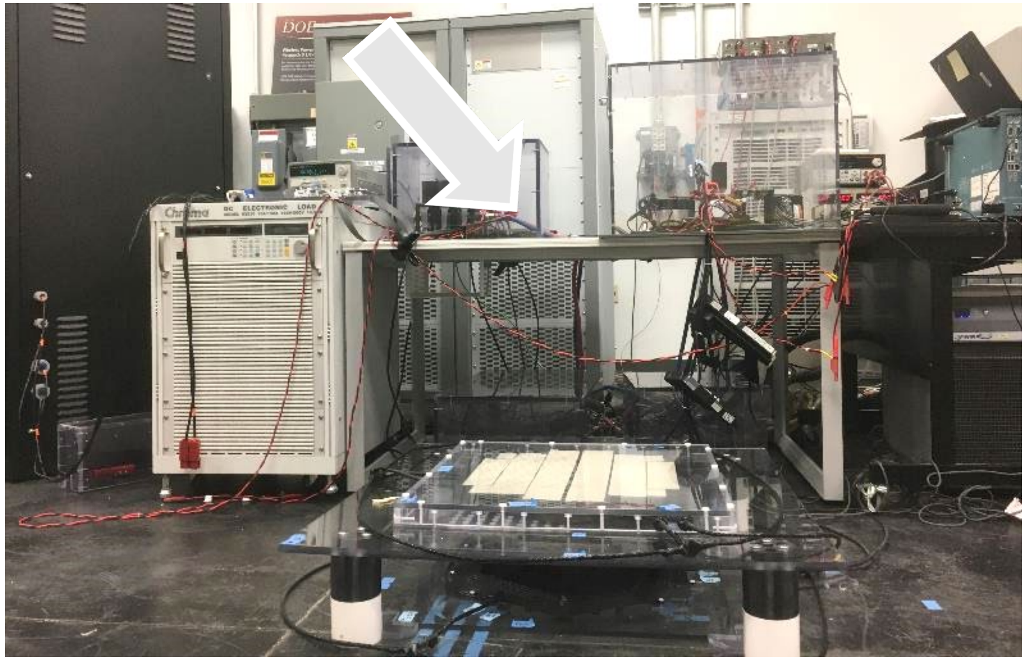
- Hardware development and experimental test results



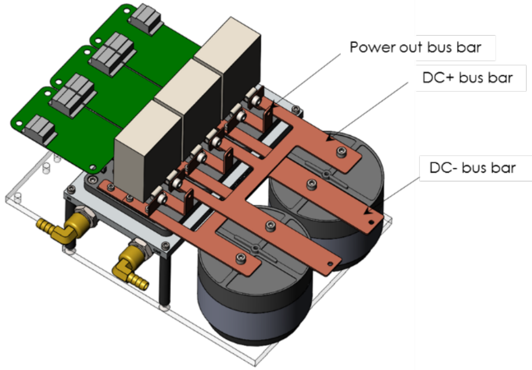
Circuit diagram of the proposed system



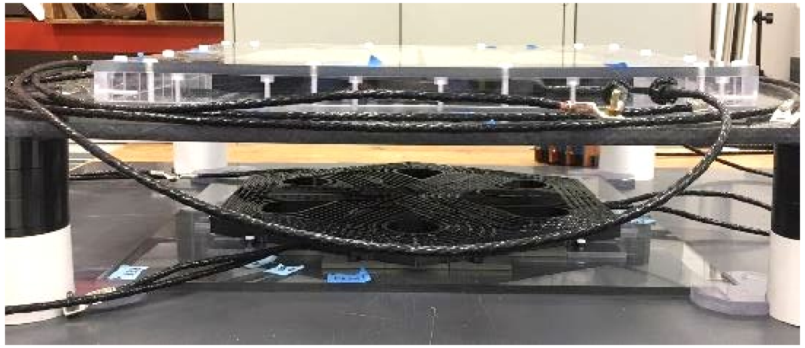
Secondary-side voltages and currents



Experimental hardware of the proposed system



3-phase inverter design rendered image

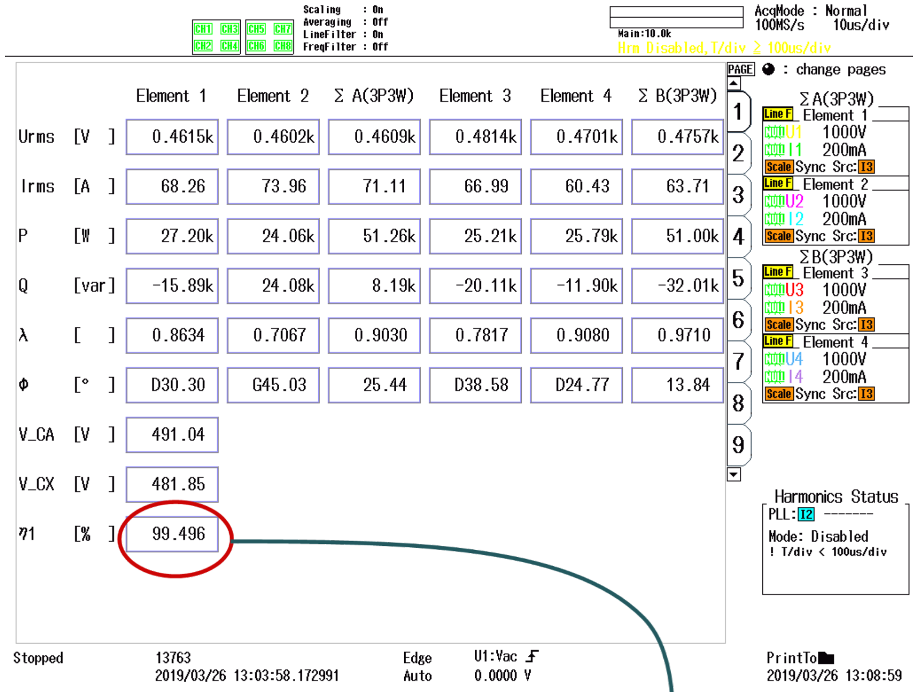


Design and hardware realization of 3-phase polyphase electromagnetic couplers

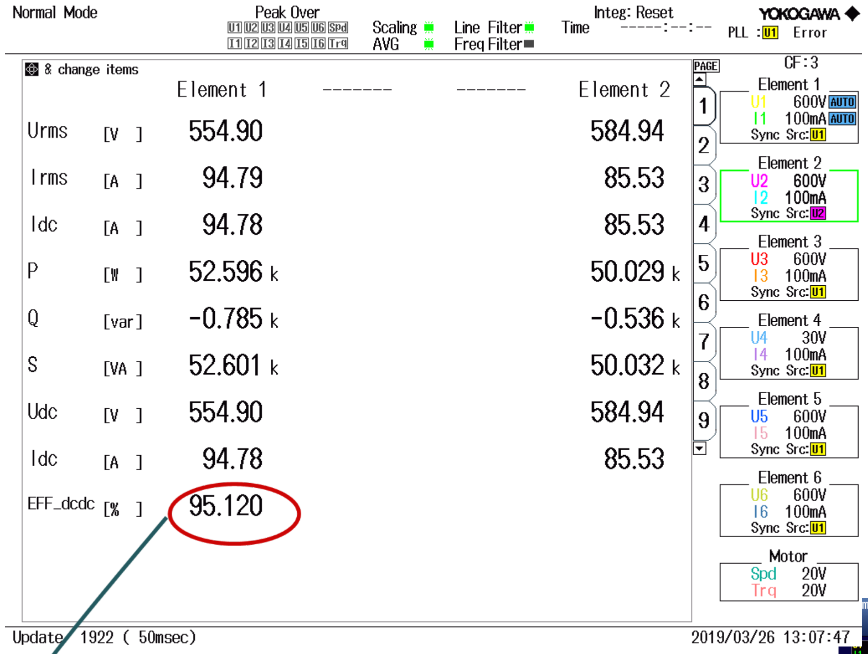
Technical Accomplishments – BP I

Developed a laboratory benchtop test setup to validate the concepts

- Hardware development and experimental test results: 99.49% coil-to-coil efficiency
- Closely matches the simulation results – validating the model

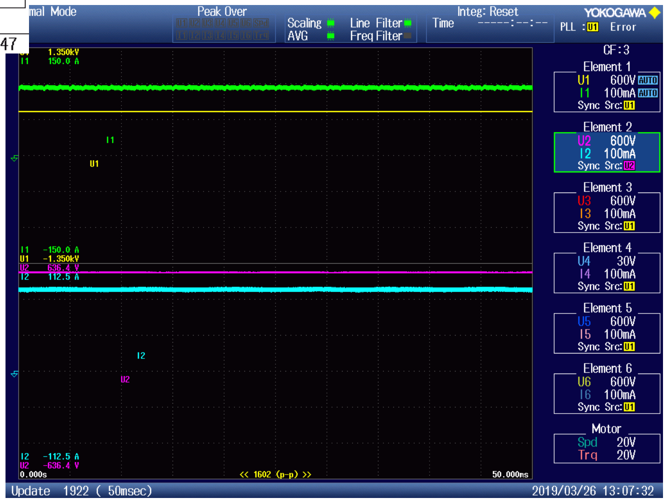


3-phase couplers transmitter to receiver efficiency analysis with 2-wattmeter method



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

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

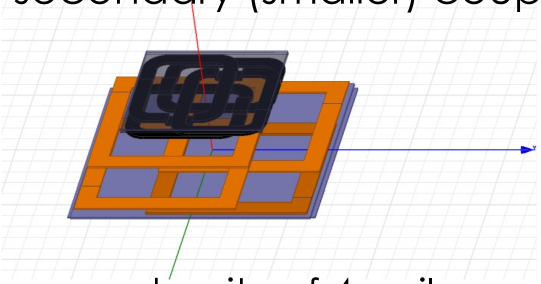


- 97.5% inverter efficiency
- 98.1% rectifier efficiency
- 99.49% coil-to-coil efficiency
- 95.12% overall efficiency

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



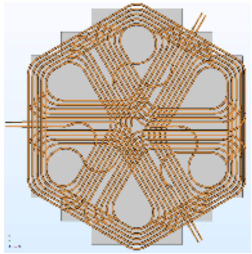
- Surface power density of 4-coil coupler:

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

- 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

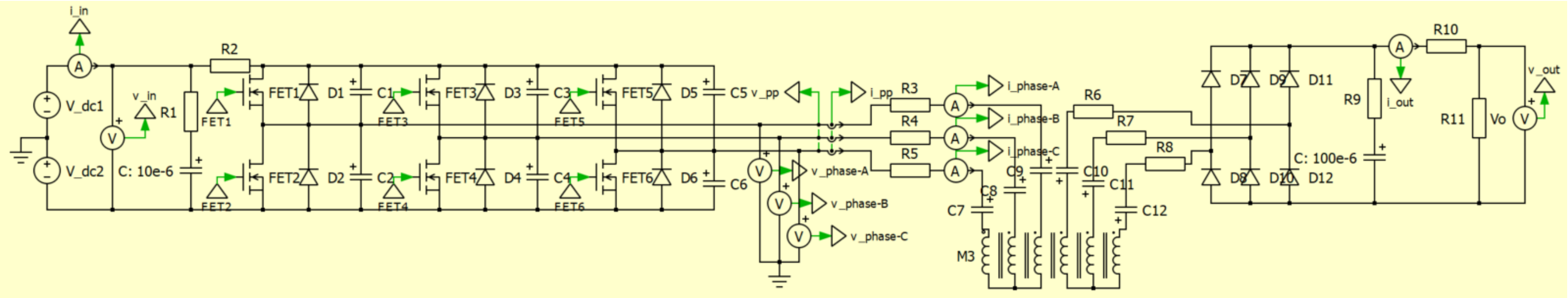
$$d_{vp\_ORNL} = \frac{55kW}{406.53\ in^3} = 135\ W/in^3$$

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

Technical Accomplishments – BP II

Developed Simulations and Detailed Loss Models for Power Stage Development Considerations

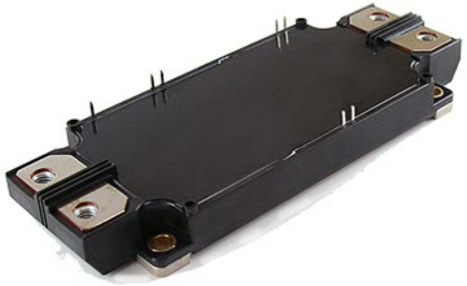
- Created a simulation model using the designed polyphase coupler parameters for comparisons of the inverter power modules (CREE and ROHM SiC modules).
- Evaluated a single 3-phase inverter for up to 300 kW in simulations.



Simulation model of the power stage for power device evaluations.

CREE SiC Module

CAS325M12HM2 (1200V/356A)



ROHM SiC Module

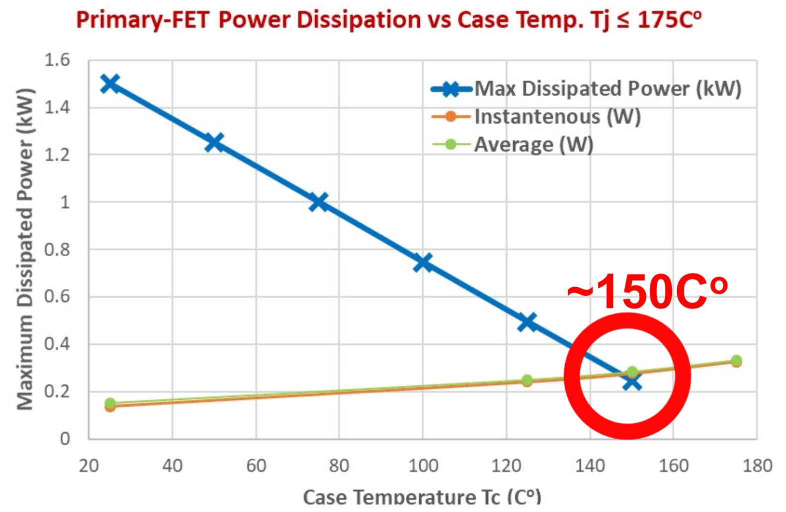
BSM600D12P3G001 (1200V/600A)

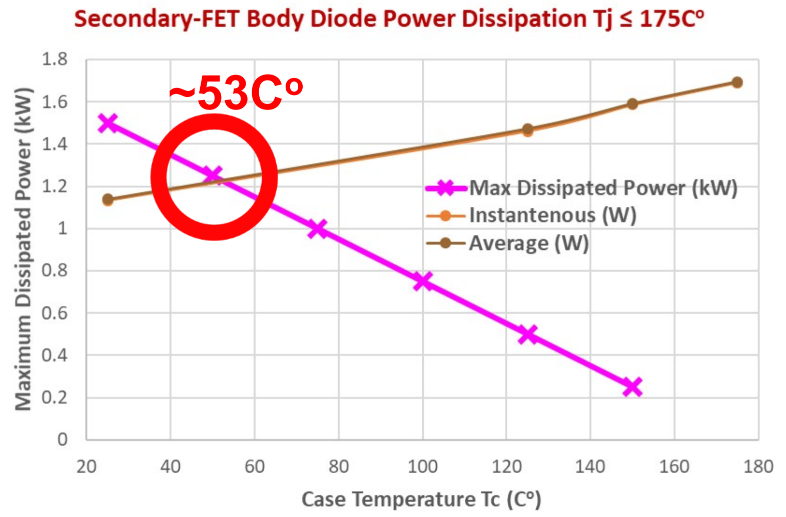
- Determined the voltage and current required for 300 kW.
- Developed detailed loss models based on the device characteristics considering the turn-on time, turn-off time, dead-time, and diode reverse recovery time.
- Analyzed thermal performance to evaluate these devices in a 3-phase inverter arrangement.

Technical Accomplishments – BP II

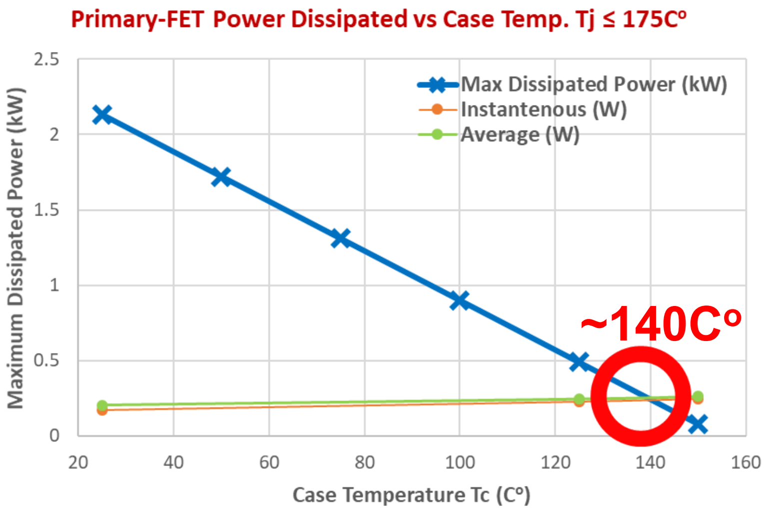
Completed the Thermal Analysis for Power Modules for the Feasibility of 3-Phase Inverter at 300 kW

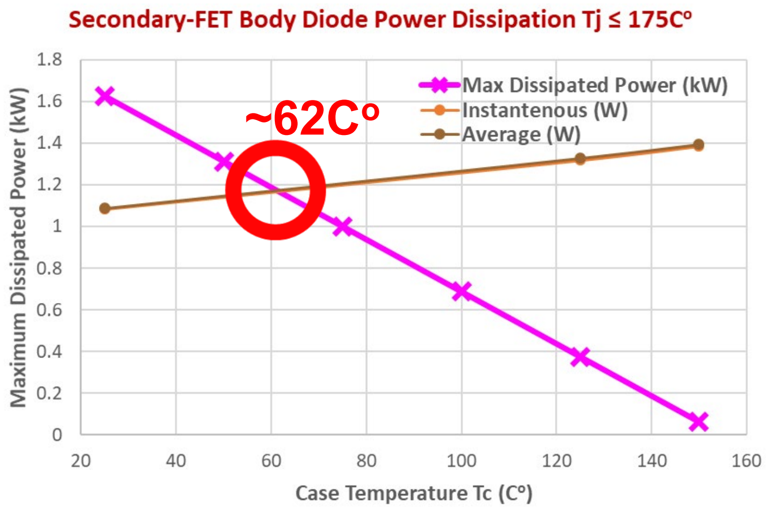
CREE SiC Module CAS325M12HM2





ROHM SiC Module BSM600D12P3G001



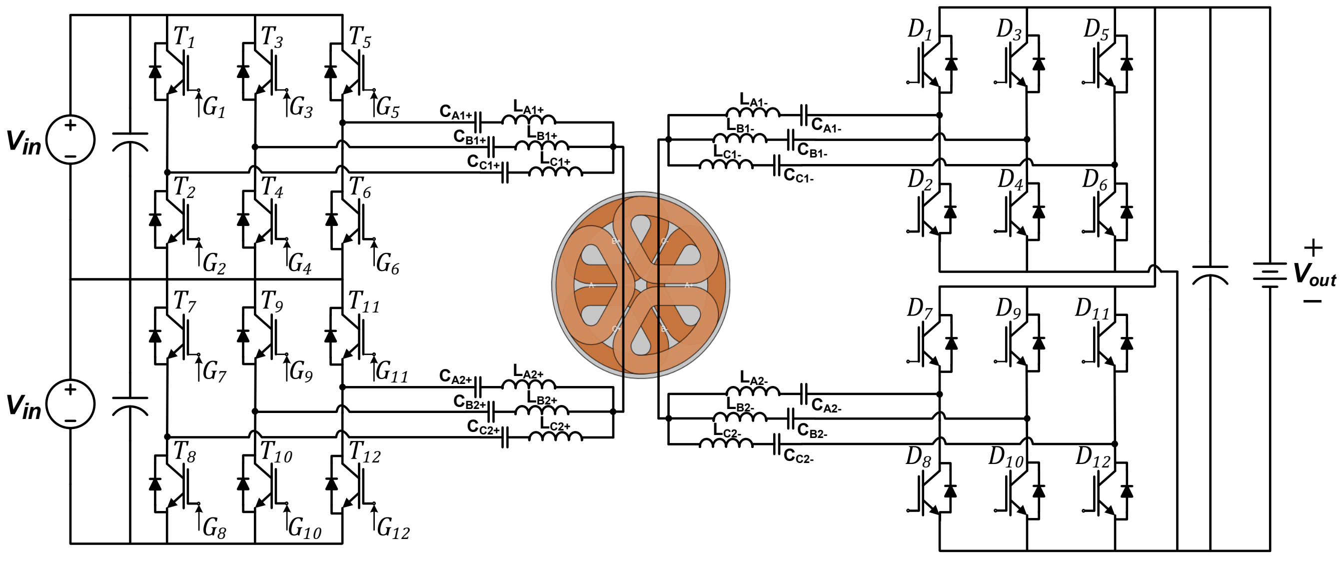


- Both power modules can be used to form a single 3-phase inverter for up to 300 kW operation but they will operate very close to their thermal limits.
- Long-duration operation may not be guaranteed.
- Lifetime may be an issue for long-term if operated at these points.
- These modules could be safely used on the vehicle side rectifier but it would be a very expensive solution for the vehicle side.
- 2 parallel inverters or more advanced designs would be needed for reasonable thermal conditions.

Technical Accomplishments – BP II

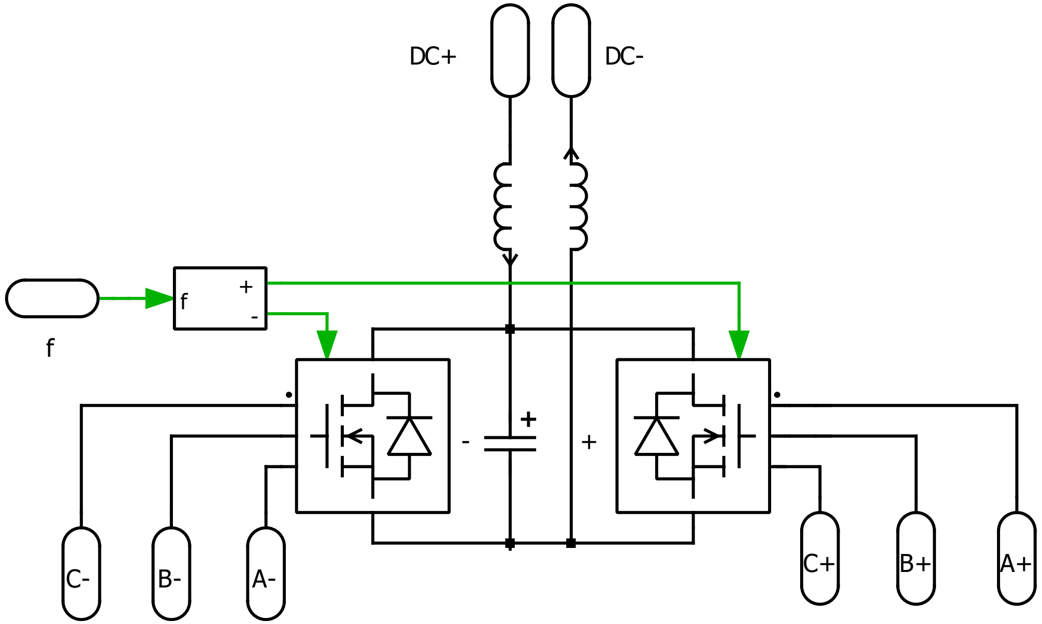
Analyzed Advanced Inverter Architectures for the Primary-Side

Series Cascaded Inverter (Multilevel inverter)



- Would require dividing the input power blocks into two and synchronizing them
- Would also require two high-precision input capacitors and a more complicated dc bus bar design
- More complicated controls
- More relaxed voltage limitations, higher efficiency

Open-ended winding dual inverter topology



- Open-ended winding/six-phase design
- Each inverter sees the same dc bus voltage
- Two three-phase inverters with shared dc-Link capacitors
- Doubles effective output voltage while maintaining dc-link capacitor size reduction compared to 3 single-phase H-bridges

Technical Accomplishments – BP II

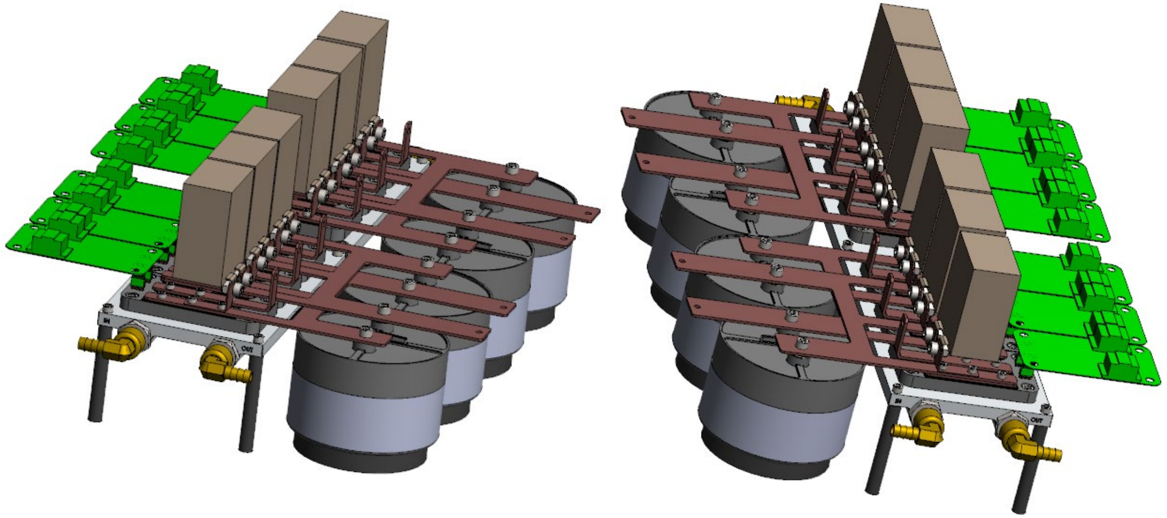
Compared the Power Stage Architectures and Determined the Inverter Design

- Open-ended dual inverter, 6-phase parallel (two 3-phase inverters simply paralleled), and 3-phase multi-level converter topologies reduce the primary current in the SiC FET switches.
- Primary coil current is reduced half in 6-phase parallel connection and almost four times less in open-ended dual inverter and 3-phase multi-level inverter options.
- Also, secondary coil currents and secondary rectifier current RMS values are half for both 6-phase parallel and multi-level connection compared to the 3-phase connection. For open-ended dual inverter option, it is almost 5 times less considering 3-phase inverter.
- Considering the secondary side current reduction performance, 9-phase coil design and open-ended dual inverter option is selected.

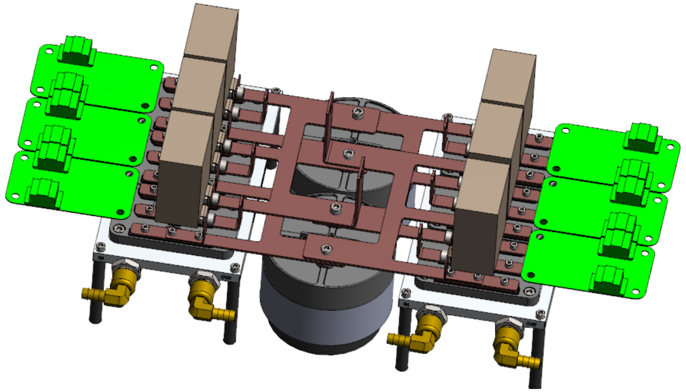
Inverter type	Phase-A current [A_{rms}]	FET current [A_{rms}]	Primary coil current [A_{rms}]	Secondary coil current [A_{rms}]	Secondary diode voltage [V_{rms}]	Secondary diode current [A_{rms}]
Single 3-phase inverter	291.4	204.8	289.3	553.6	288.24	394.6
6-phase conventional parallel inverter	144.3	100.4	144.2	277.6	285.6	196.2
Series cascaded multilevel inverter	71.8	101.4	71.7	277.7	285.4	197.1
Open-ended winding dual inverter	155.2	109.9	63.1	108.2	255.8	72.1

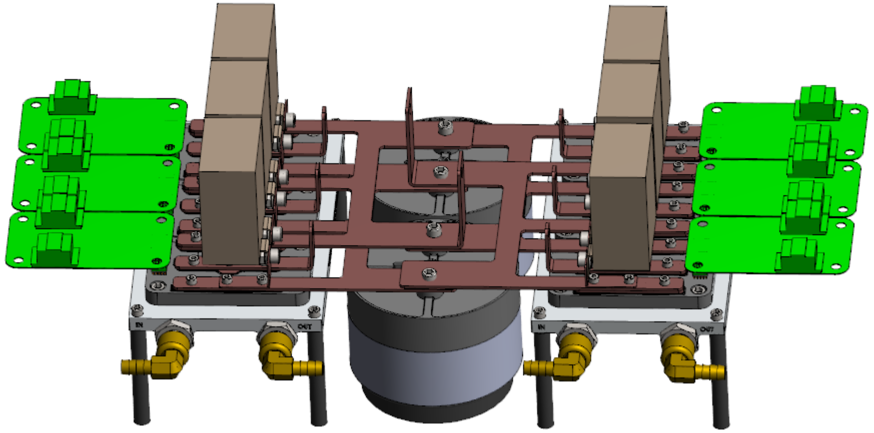
Technical Accomplishments – BP II

Analyzed Power Stage Design Alternatives for the Open-Ended Dual Inverter Configuration



- Extended dc bus to connect two three-phase inverters
- Two three-phase inverters
- Simple but difficult to reduce volume by eliminating the capacitors
- Dimensions: 556mm (L) × 196 mm (H) × 341 mm (D)
- Volume: 37.16 liters
- Power density: 13.45 kW/liter

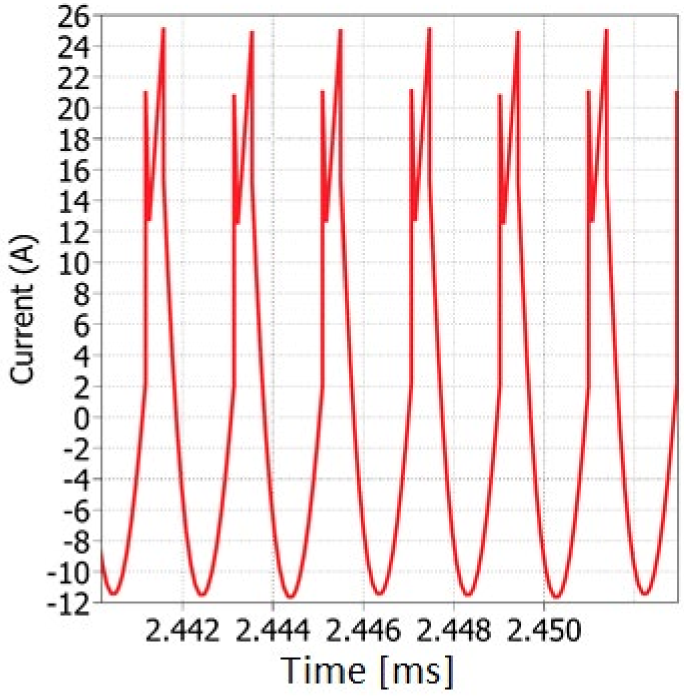


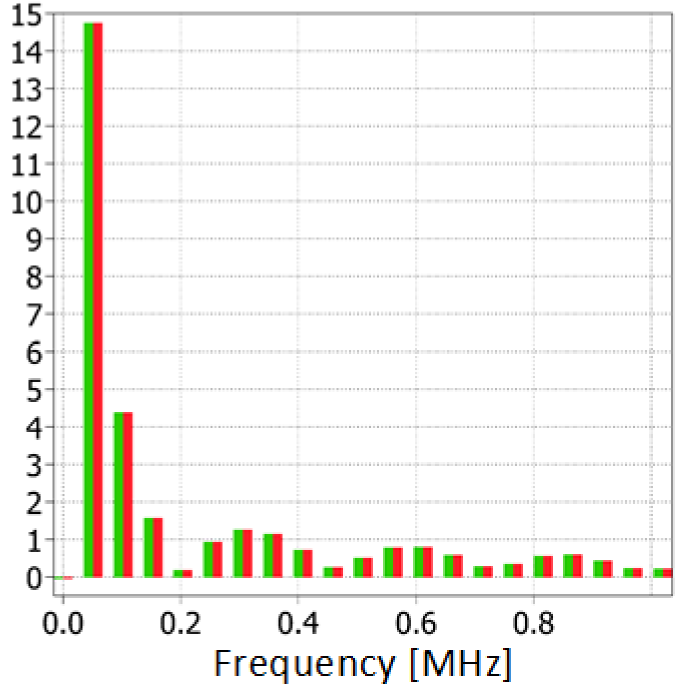


- Modified dc bus for connecting two three-phase inverters
- Reduced capacitors by half, more volume reductions possible
- Dimensions: 567mm (L) × 196 mm (H) × 276 mm (D)
- Volume: 30.67 liters
- Power density: 16.30 kW/liter

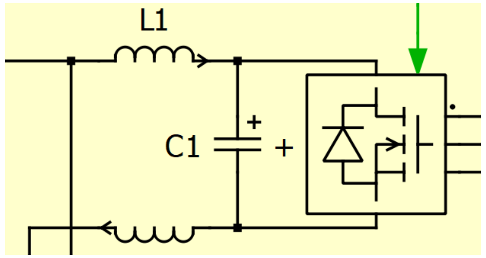
Technical Accomplishments – BP II

Analyzed Ripple Current Characteristics for Capacitor Sizing for 300 kW Output Power





Inverter dc-bus capacitor ripple current and its harmonic spectrum



- Harmonics at 6nth resonant frequency ()
- Ripple rms – 11.2 A for each of the 3-phase inverter
- Ripple frequency 510 kHz
- Results indicate very low current ripple harmonics and significant reductions in capacitance is possible
- Higher frequency capable capacitors are needed.

FFT Results for Current Requirement

Frequency	510kHz	1.02MHz	1.53MHz	2.04MHz	2.55 MHz	3.06MHz	3.57 MHz
Current amplitude	14.8	4.4	1.57	0.19	0.93	1.25	1.14

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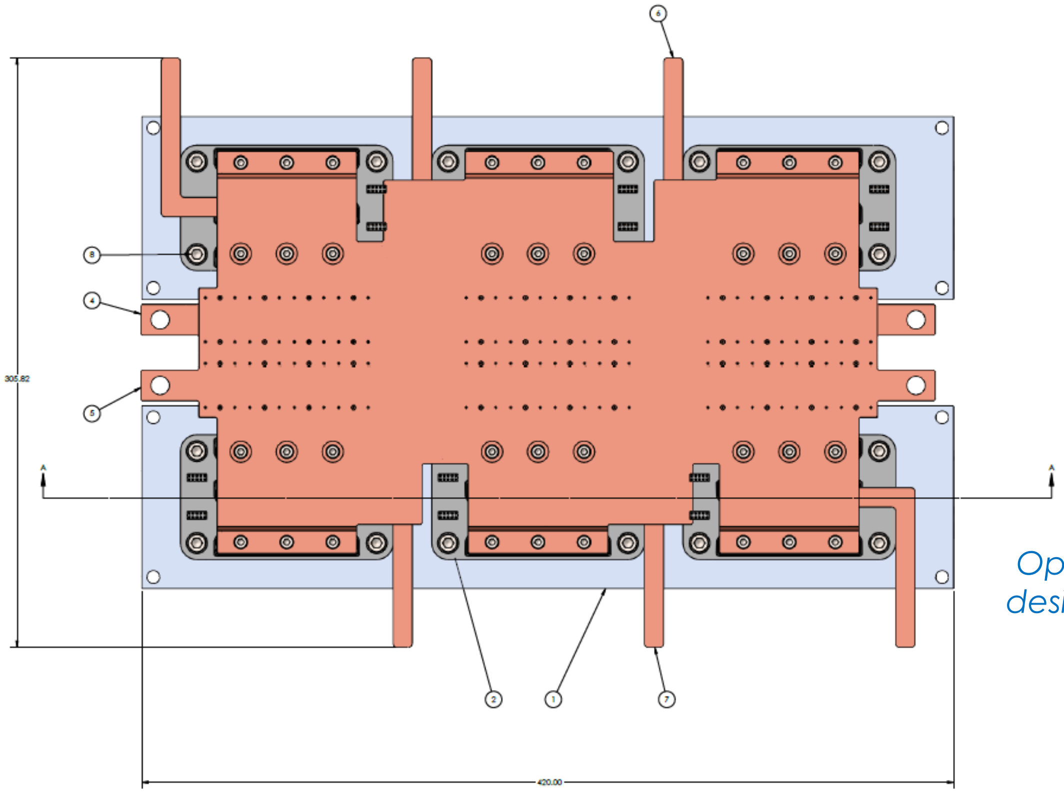
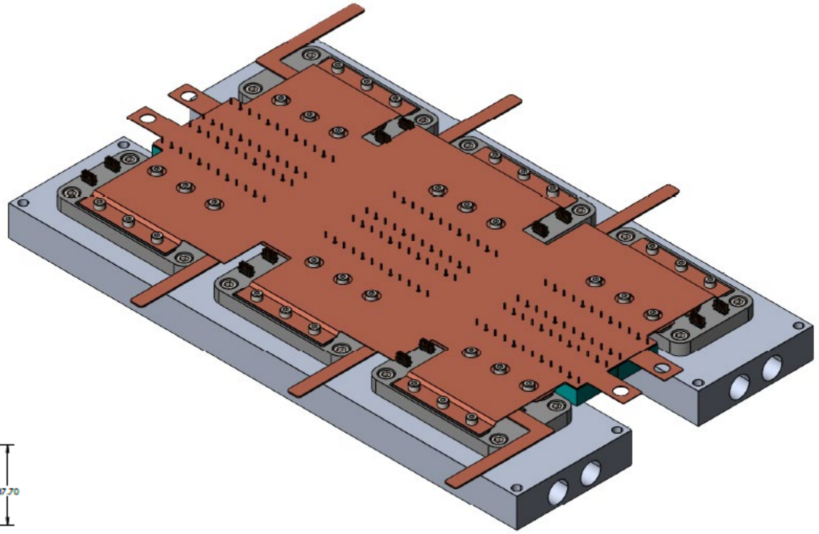
Technical Accomplishments – BP II

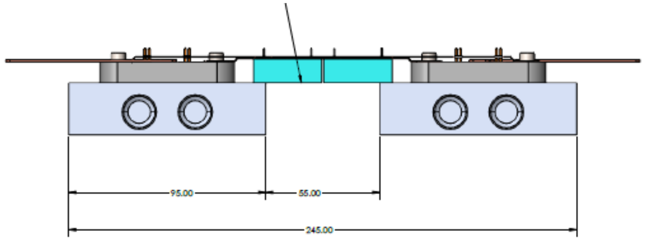
Completed the Design of the Open-Ended Dual Inverter with two 3-phase Inverters with Custom Design Heatsink, Custom Design Bus Bars, and TDK Ceralink™ High-Frequency and High-Temperature Capacitors

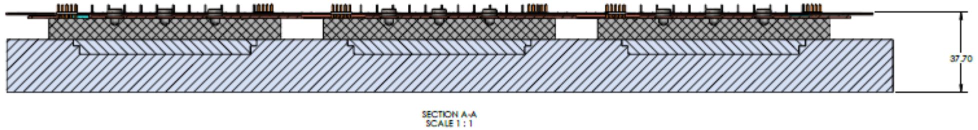


- Dimensions: 305.82mm (L) × 70 mm (H) × 420 mm (D)
- Volume: 8.99 liters
- Power density: 55.61 kW/liter
- Bus bars can be fabricated easily but assembly of capacitors is very complicated and difficult - due to the thermal inertia of the copper bus bars

Open-ended winding dual inverter design with copper dc bus bars with Ceralink capacitors







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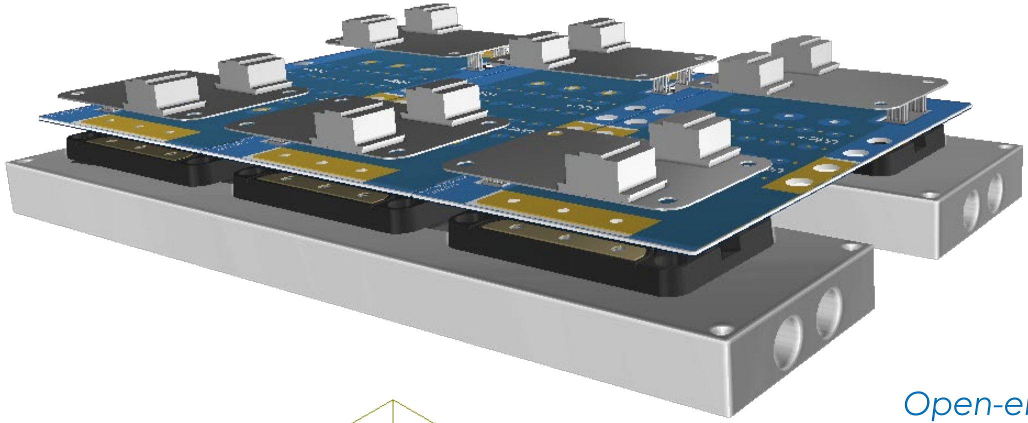
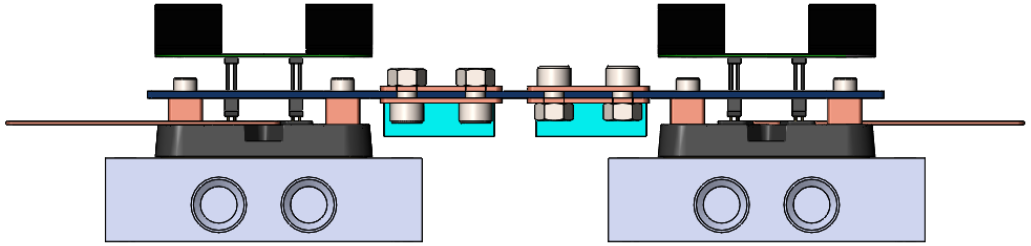
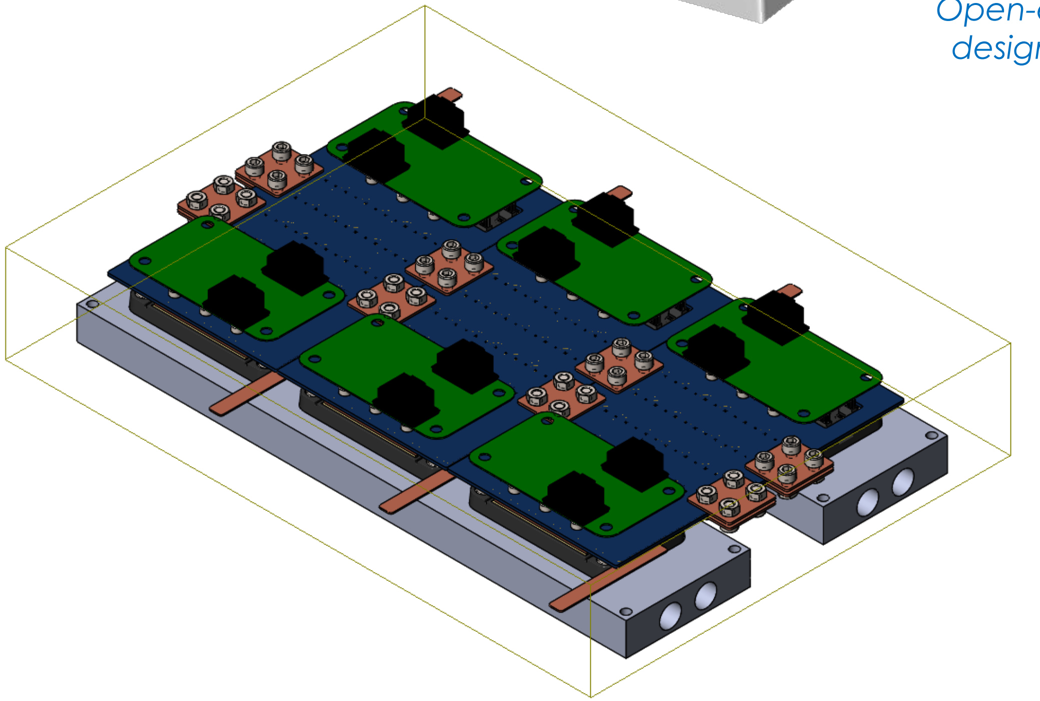
Technical Accomplishments – BP II

Completed the Open-Ended Dual Inverter Design with Two 3-Phase inverters with Custom Design Heatsink, Custom Design PCBs with TDK Ceralink® Capacitor Assembly with Wave Soldering





Open-ended winding dual inverter design with PCB dc bus bars with Ceralink capacitors

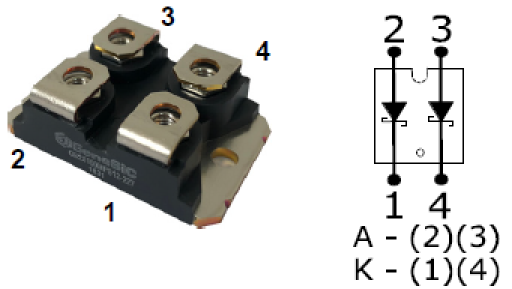


- Dimensions: 305.62mm (L) × 70.86 mm (H) × 423.22 mm (D)
- Volume: 9.16 liters
- Power density: **54.58 kW/liter**
- PCB bus bars are in the process of fabrication.

Technical Accomplishments – BP II

Completed the Design and Development of Vehicle-Side Rectifier

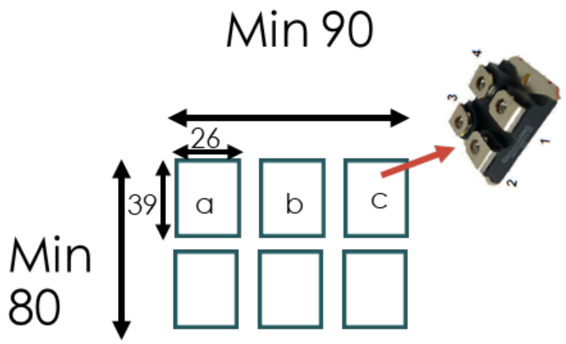
- GB2X100MPS12-227 Manufacturer Genesic Semiconductor
- 1200 V, 152A continuous forward current each diode @100 °C



SOT-227 (Isolated Base)

- Safe to parallel multiple modules
- Maximum allowable junction temperature 175°C
- Propose to use 1 such module (total of 2 diodes) in parallel for 1 equivalent diode for the rectifier.
- A total of 6 rectifiers, 3 for positive and 3 for negative in parallel
- Total number of modules needed = 36

- Considering 300 kW output power with 320 V at the minimum battery voltage the following values are obtained from simulations
- Average current per module = 50.7A (to be divided among the 2 diodes in parallel)
- Average current per diode = 25.35A
- Rms current per diode = 40.5A
- Min area of each rectifier: 6084 mm2 = 9.43 sq in
- Min area of all 6 rectifiers: 43200 mm2 = 66.96 sq in

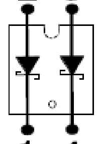


6 Heat sinks required (or a liquid cooled option): Fischer LA7/150, 12 V Fan (150x125x74)
https://www.newark.com/fischer-elektronik/la-17-150-24v/fan-force-cooled-heat-sink-0-07/dp/58M7921

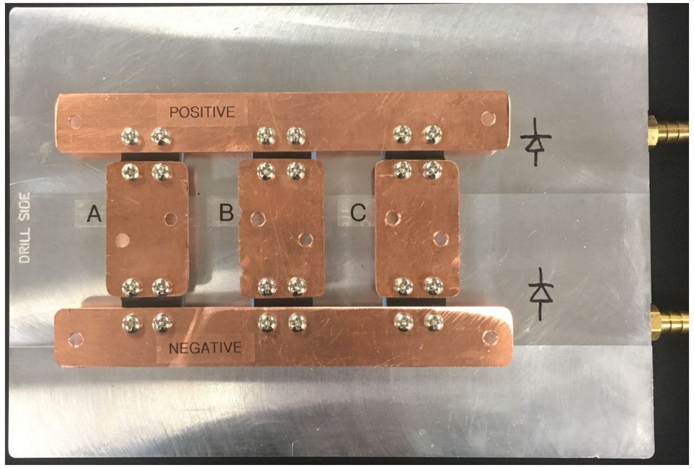
Technical Accomplishments – BP II

Analyzed the Vehicle-side Rectifier Design Considerations and Development

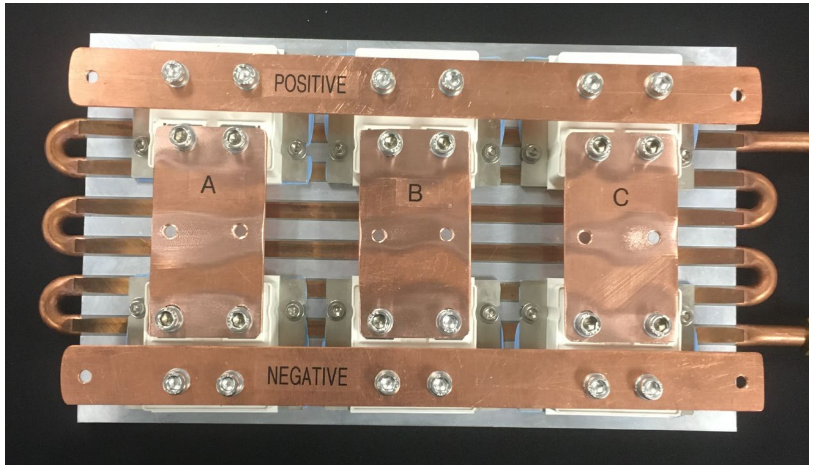
	GB2X100MPS12-227 SiC Schottky diode module T_j at 125°C	APTDF400U120G Si p-n junction module T_j at 100°C
Quantity	36	12
Total area of rectifiers	66.96 sq. in	284.76 sq. in
Losses	2686 W (0.89% of Pout)	3060 W (1.02% of Pout)
Cold plate requirements	< 0.032 C/W for all 8 modules on 1 single cold plate	= 0.0156 C/W for all 4 modules on 1 single cold plate
Price	$135 /module	$65 /module



SOT-227 (Isolated Base)



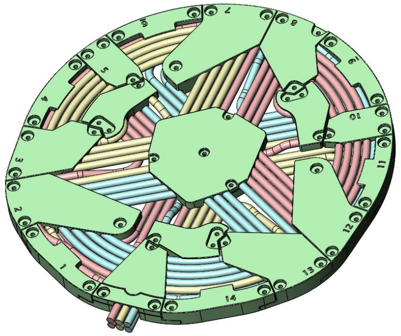
Genesic SiC rectifier

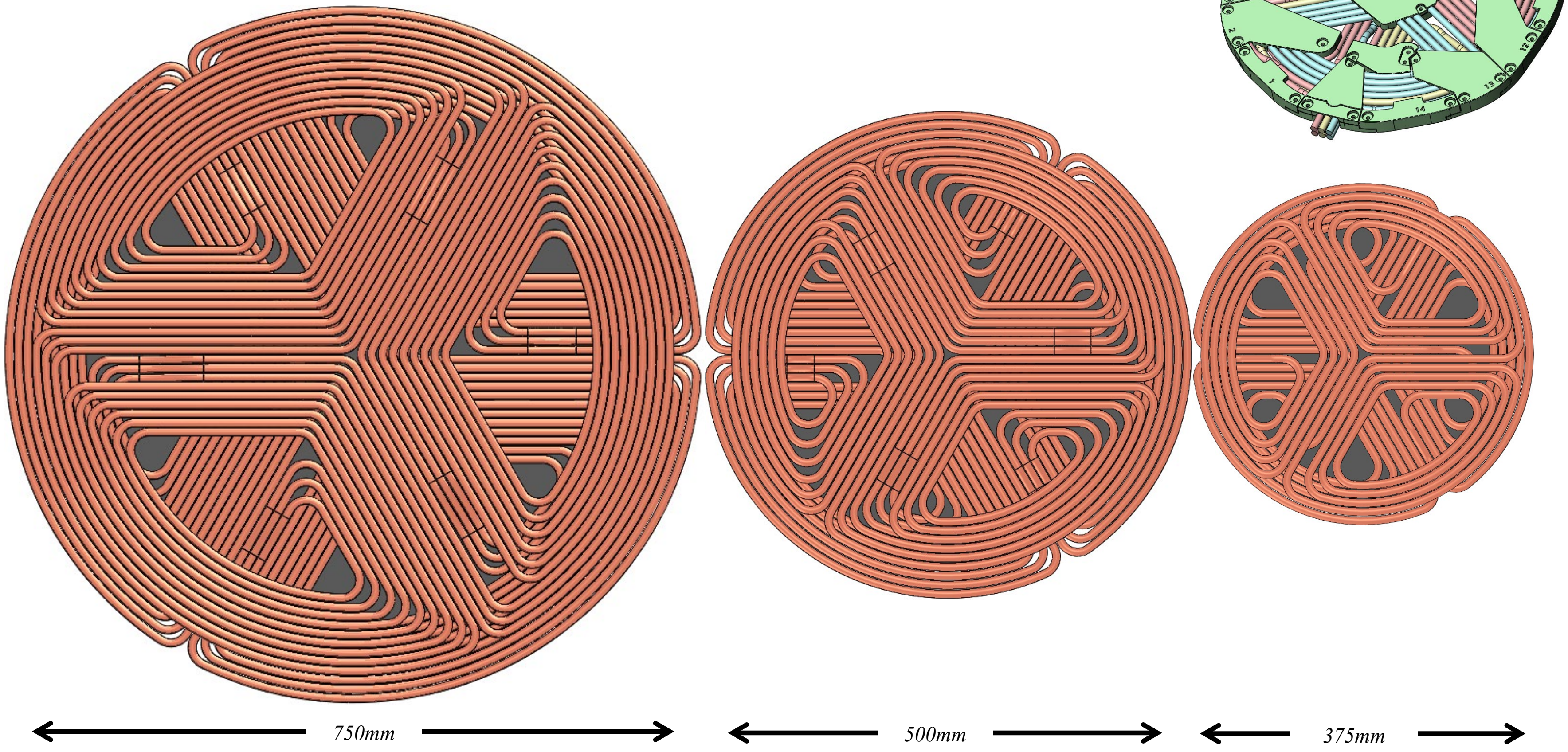


Microsemi rectifier

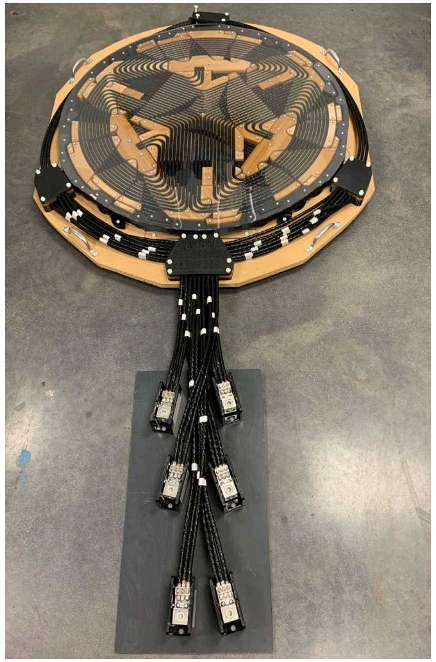
Technical Accomplishments – BP II

Completed the Ground and Vehicle Coupler Designs and Developments

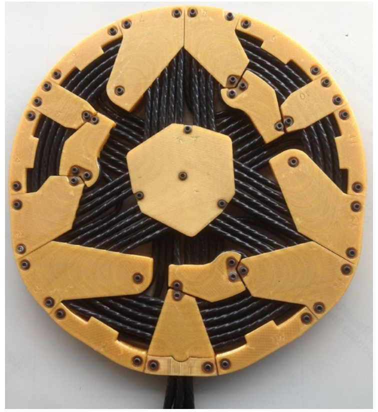




100kW/300kW Ground Coupler	*300kW Vehicle Coupler*	*100kW Vehicle Coupler*
$0.44\ m^2$	$0.196\ m^2$	$0.11\ m^2$
$0.68\ MW/m^2$	$1.53\ MW/m^2$	$0.905.4\ MW/m^2$



Completed laboratory development of the 300 kW ground coupler



Completed laboratory development of the 100 kW ground coupler

Technical Accomplishments – BP II

Finalized Coupler Specifications

	Interoperable GA	100kW VA	300kW VA
Diameter	750 mm	375 mm	500 mm
Litz Wire	3×4AWG/phase	1×4AWG/phase	3×4AWG/phase
Litz + Ferrite Thickness	33.6 mm (18.6 + 15)*	28.6 mm (18.6 + 10)*	33.6 mm (18.6 + 15)*
Litz + Ferrite Mass	42.2 kg (9.9 + 32.3)*	8.8 kg (2.4 + 6.4)*	19.4 kg (4.7 + 14.7)*
Worst Case Losses	2362 W (697 + 1665)*	596 W (169 + 311)*	1343 W (331 + 1012)*
Surface area	0.44 m^2	0.196 m^2	0.11m^2
Surface power density	0.68 MW/m^2	1.53 MW/m^2	0.905.4 MW/m^2
Coil to Coil Efficiency		97.4%	98.8%

- Also considered 12 and 18 winding options for balance among phases and parallel wires within each phase
- Misalignment tolerance up to 125 mm in any direction

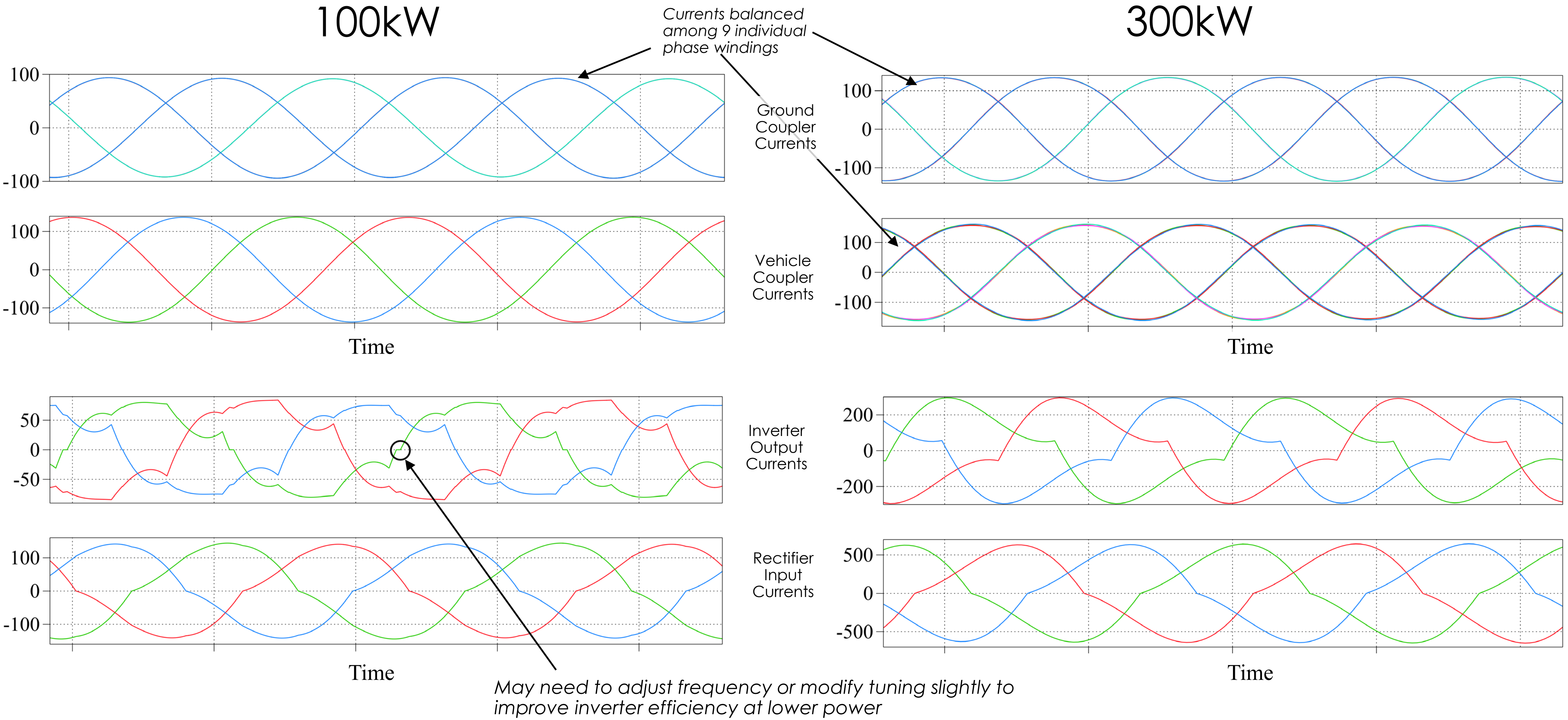
Technical Accomplishments – BP II

Analyzed the Component Stresses for Series and LCC Tuned Secondary-Side

Comparison	Secondary Tuning	Series	LCC
dc-link ripple current	Capacitor Size (<10 V_{pp} ripple)	39 μF	15 μF
	Current ripple	155 A_{rms}	79 A_{rms}
Inverter output current [A]	Current rating	183 A_{rms}, 171 A_{avg}	159 A_{rms}, 140 A_{avg}
	Turn-off current	129 A_{rms}, 229 A_{avg}	18 A_{rms}, 110 A_{avg}
Primary coupler current [A]	Current rating	86 A_{rms}	88 A_{rms}
Secondary coupler current [A]	Current rating	142 A_{rms}	110 A_{rms}
Rectifier input current [A]	Current rating	381 A_{rms}, 344 A_{avg}	402 A_{rms}, 351 A_{avg}
Rectifier output current [A]	Capacitor Size (<3.6 V_{pp} ripple)	175 μF	74 μF
	Current ripple	240 A_{rms}	100 A_{rms}

Technical Accomplishments – BP II

Completed Interoperability Simulations with Inverter, Resonant Network, and Transmitting Coil are Fixed for the Two Different Receivers

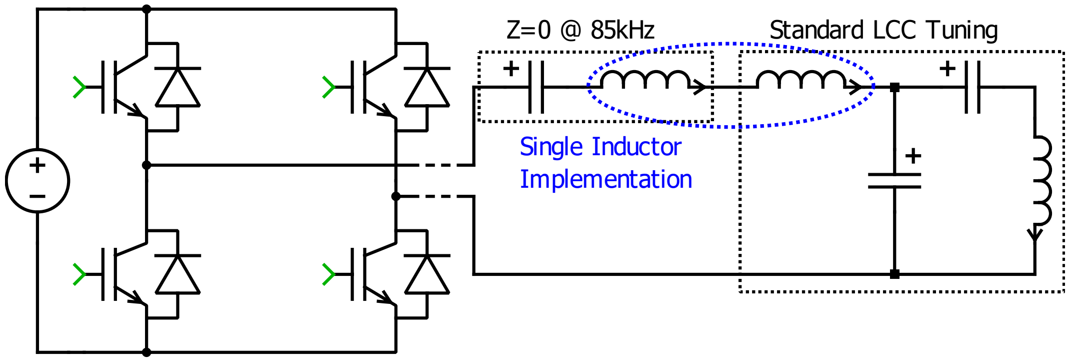


Simulation results for two different receivers

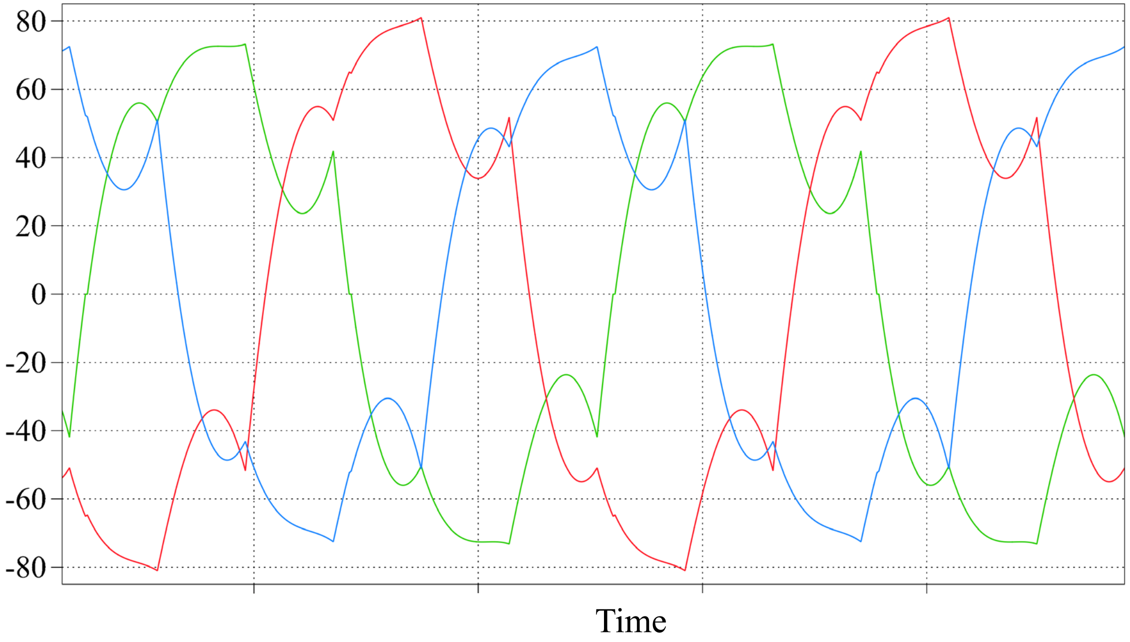
Technical Accomplishments – BP II

Modeled and Simulated LC-LCC resonant tuning configuration

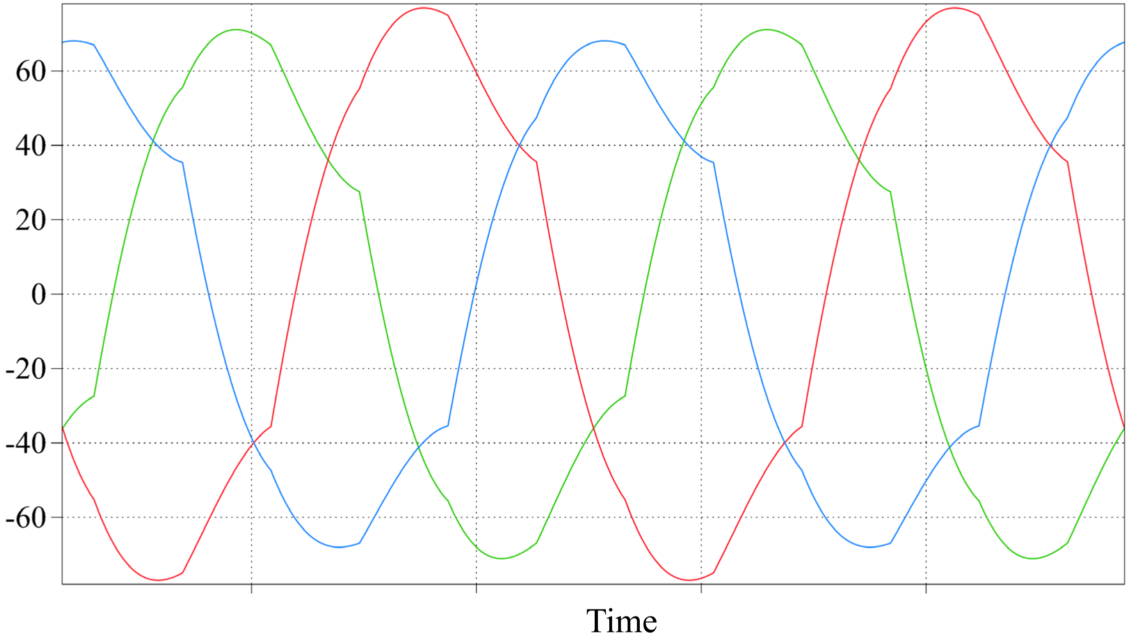
- Improves inverter efficiency at low power,
- Reduces harmonic content,
- Provides more sensitive reactive impedance control



100kW, Conventional Tuning



100kW, Modified Tuning

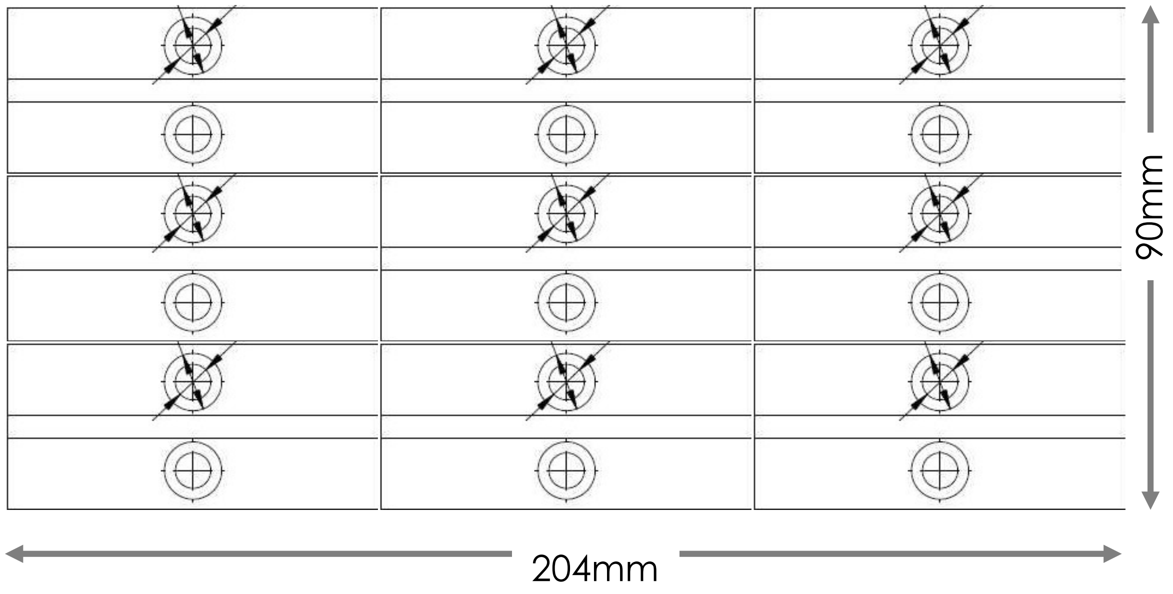


Investigating balance between inverter loss decrease and inductor size/loss increase

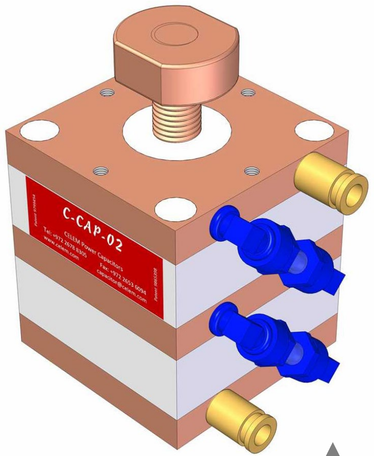
Technical Accomplishments – BP II

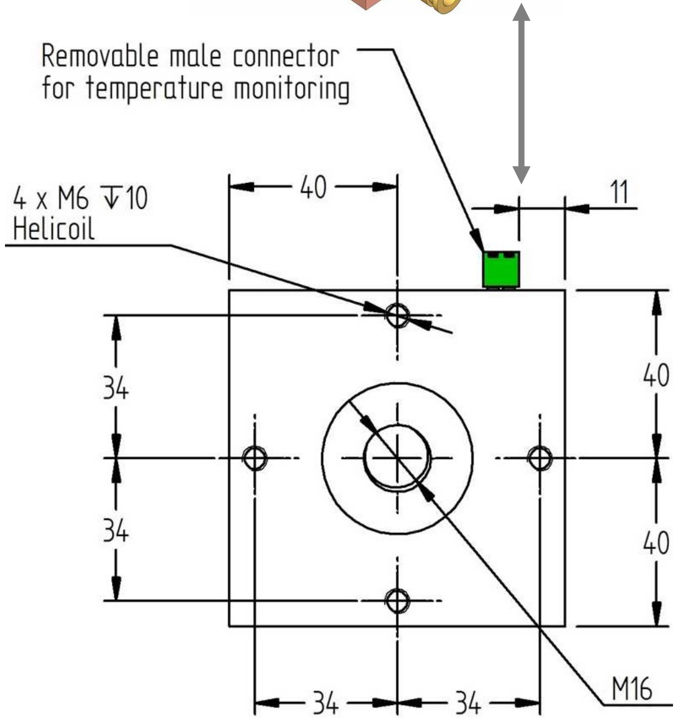
Determined the Resonant Tuning Capacitors

- Integrated cooling
- Reduced footprint by 65%
- No high frequency bus bars for series/parallel combinations



Conventional tuning capacitor and dimensions





Tuning capacitor with integrated cooling and dimensions

Technical Accomplishments – BP II

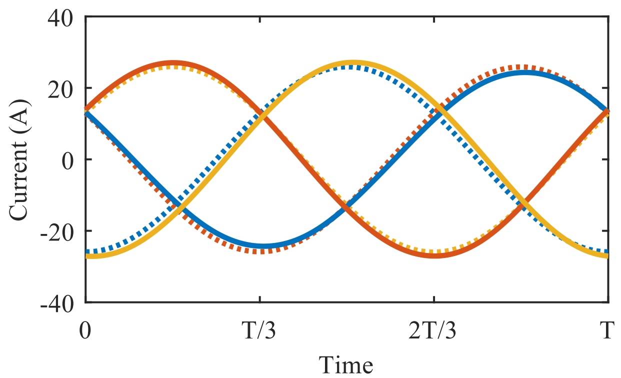
Analyzed Control Requirements for Three-Phase Inverter Control Under Misalignment

- 72% reduction in RMS output current ripple
- 90% reduction in 2nd output second harmonic
- Marginal impact on inverter input current ripple

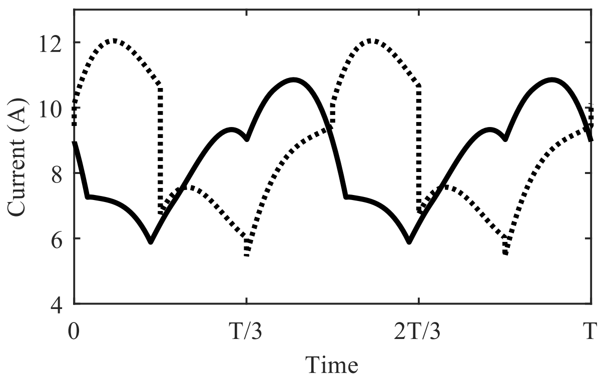
Secondary Phase Current & Rectifier Output Current (solid line)

Primary Phase Current & Inverter Input Current (dashed line)

120 Degree Phase Shift

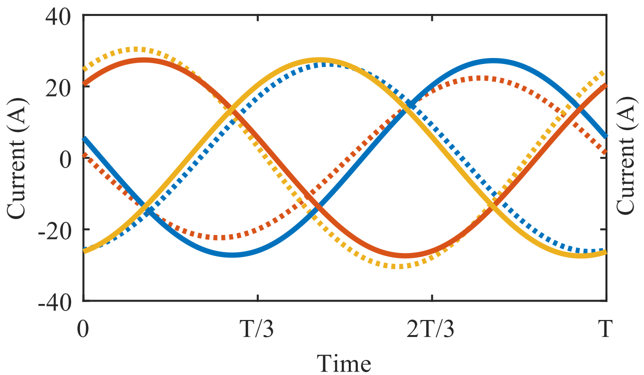


Primary and secondary coupler currents

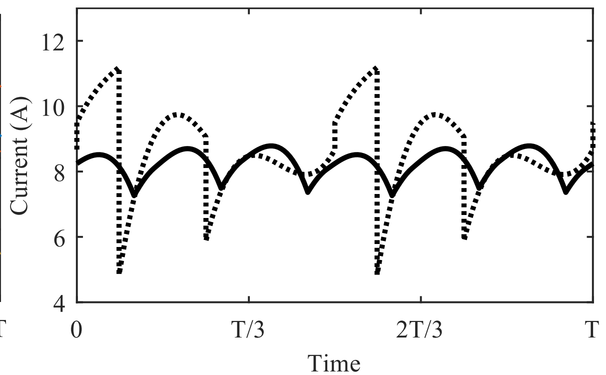


Inverter input and rectifier output currents

Phase Shift for Low Output Ripple



Primary and secondary coupler currents



Inverter input and rectifier output currents

Mathematical Model:

$$\vec{I}_g = \frac{1}{j\omega}\mathbf{T}'_{\alpha\beta}\left(\mathbf{T}_{\alpha\beta}\mathbf{D}_{ll}\mathbf{M}\mathbf{T}'_{\alpha\beta}\right)^{-1}\mathbf{T}_{\alpha\beta}\vec{V}_v$$

$$\vec{V}_g = \mathbf{D}_{ll}\left(j\omega\mathbf{L}_g + \frac{1}{j\omega C_{g,s}}\mathbf{I}\right)\vec{I}_g$$

$$\bar{V} = \frac{V^g_{bc}}{V^g_{ab}} = \frac{e^{j\phi_b} - e^{j\phi_c}}{1 - e^{j\phi_b}} = e^{j\frac{\phi_c}{2}}\frac{\sin\left(\phi_c/2 - \phi_b/2\right)}{\sin\phi_b/2}$$

$$\phi_c = 2\angle\bar{V},$$

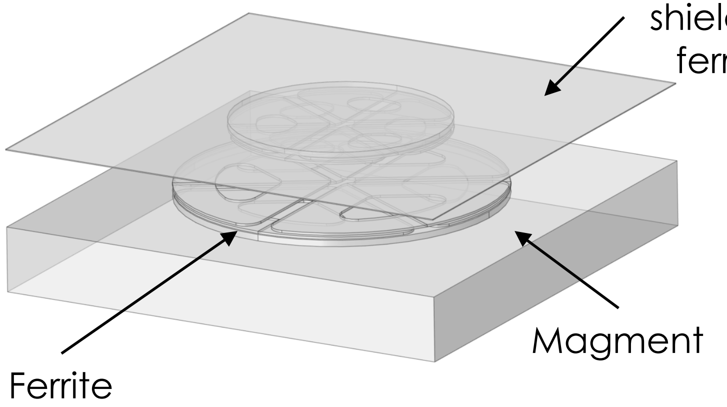
$$\phi_b = 2\arctan\left(\frac{\sin\left(\phi_c/2\right)}{|\bar{V}| + \cos\left(\phi_c/2\right)}\right)$$

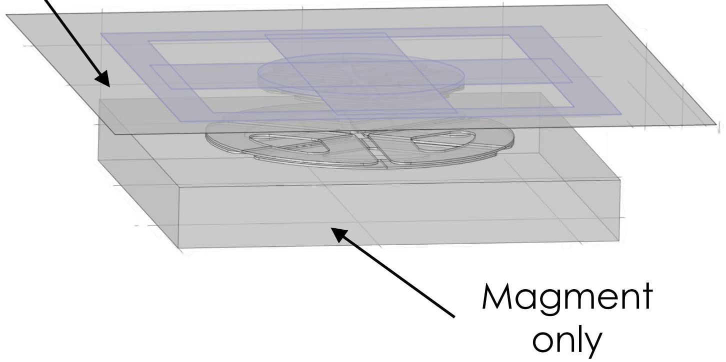
Technical Accomplishments – BP II

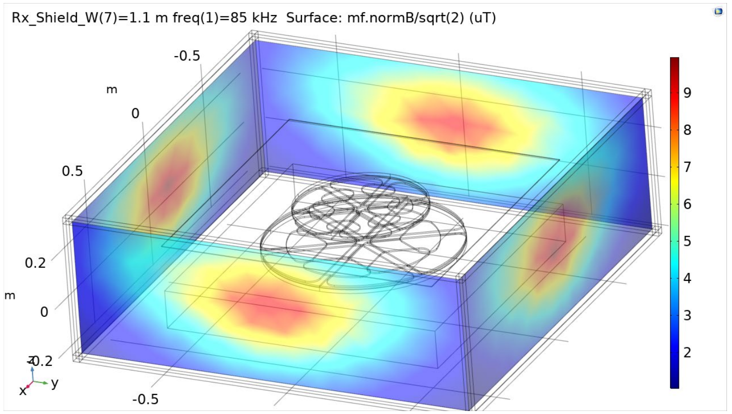
Analyzed Electromagnetic Field Emissions at 800 mm Away from the Center and Evaluated Shield Designs

- Several passive shielding options using magnetizable concrete appear viable for reducing electromagnetic field emissions to acceptable levels

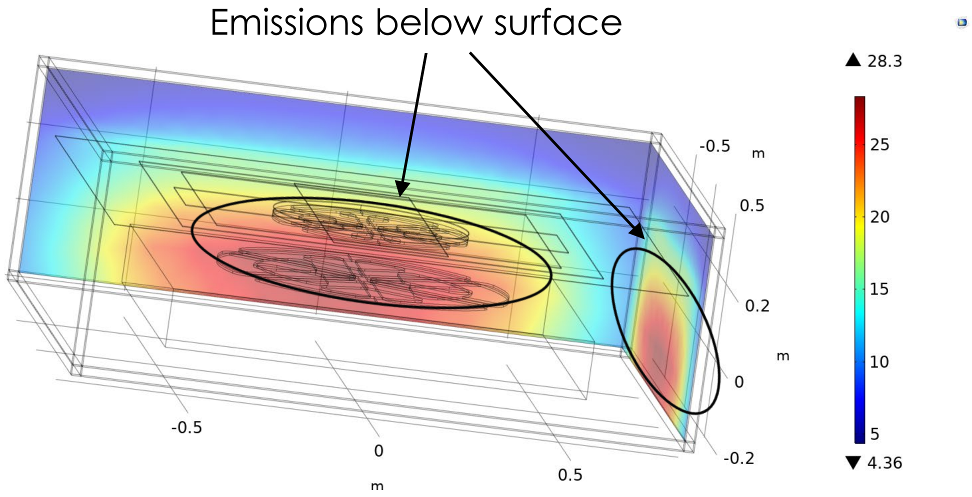
- Use of large volume of low permeability material such as Magment can be beneficial for electromagnetic field emissions in high-power wireless systems







Thin ferrite shield on vehicle and low permeability embedded magnetic brings emissions into compliance in alignment



Magment completely replaces ferrite; peak emissions move below the surface; hybrid shield reduces additional shield ferrite mass

Response to Previous Year Reviewers' Comments

- Project team would like to thank all of the reviewers for the feedback and the comments. All of the comments were positive and encouraging.
- Some of the comments:
  - *The reviewer said the approach is solid, well thought out, methodical, and incremental.*
  - *The reviewer said the project appeared to show significant improvements over existing baseline designs, as well as demonstrate a working proof of concept for the initial design. The measured DC-DC efficiency shows a sensible check of the analytical efficiency prediction.*
  - *Results indicate that the project is well underway to meet the performance indicators for this budget period.*
  - *The reviewer noted that this the first budget period, and the team has accomplished a lot, modeled and analyzed and more importantly, designed and prototyped a 3-phase 2-layer polyphase coupler with 95.6% efficiency. This is amazing.*
  - *The project collaboration appears well defined among partners.*
  - *This reviewer stated that the project collaborators are leaders in the field and their roles are clearly defined. Each collaborator has a specific contribution to the success of the program as a whole.*
  - *The reviewer remarked that the proposed future work seems like a good progression of showing technology readiness.*
  - *The reviewer stated that the future work seems appropriate given the accomplishments to date.*
  - *This reviewer stated that fast wireless charging is extremely important for vehicle electrification. This work directly and solidly addressed the overall DOE goal on reducing the barriers in vehicle electrification, wireless charging, and vehicle to grid integrations.*

Response to Previous Year Reviewers' Comments

- One reviewer stated that the *funding looks like sufficient but is not sure how the cost share of $3 million is planned*.

  - This cost share from partners is in-kind cost share with ChargePoint providing the power blocks (grid-interface converter), Hyundai providing a research vehicle with engineering support and guidance on vehicle integration and vehicle CAN and BMS controls and communications and access to the battery and vehicle-side thermal management systems, and SERES providing another research vehicle with the same level of engineering support and collaboration on vehicle integration, testing, and validation of the proposed technology. The total of this level of support from all three partners will be equal to the cost share identified in the project.

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.
- **SERES**: Vehicle manufacturer; providing the research vehicle along with engineering and integration support, support on BMS, battery thermal management, and technical specifications for the 300kW 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 2020**
  - Integrate the final design to a Hyundai-Kia vehicle (Kona) with 100kW power transfer demonstration
- **FY 2021**
  - Integrate the final design to an SERES 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.
  - **SERES Automotive**: 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