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

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Overview

Timeline

- Start – May 2017
- End – December 2019
- Budget Period I will be completed in May 2018

Barriers / Challenges

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

Budget

- Total project funding
  - DOE share – $1.95M
  - Cost share from partners – $712K
- Funding received in FY17: $750k
- Funding for FY18: $750K

Partners

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

Project Objective and Relevance

- **Overall Objective**
  - **Design, model, simulate, build, integrate, and test a bidirectional wireless power transfer (BWPT) system for medium duty delivery trucks**
    - A vehicle integrated >20 kW wireless power transfer system with bidirectional operation
    - High-efficiency (85%) with a nominal magnetic airgap of 11 inches
    - Vehicle-to-grid mode 6.6 kW wireless power transfer to building or grid loads (grid support or ancillary services)
    - Integration of the WPT system into the vehicle
    - Modeling and analysis of BWPT systems
- **FY18 Objective**
  - Design, model, simulate, and analyze grid interface converter
  - Design, model, simulate, and analyze primary side high-frequency inverter/rectifier
  - Design, model, simulate, and analyze vehicle side rectifier/inverter
  - Design, model, simulate, and analyze electromagnetic coupling coils and resonant stage

Milestones

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

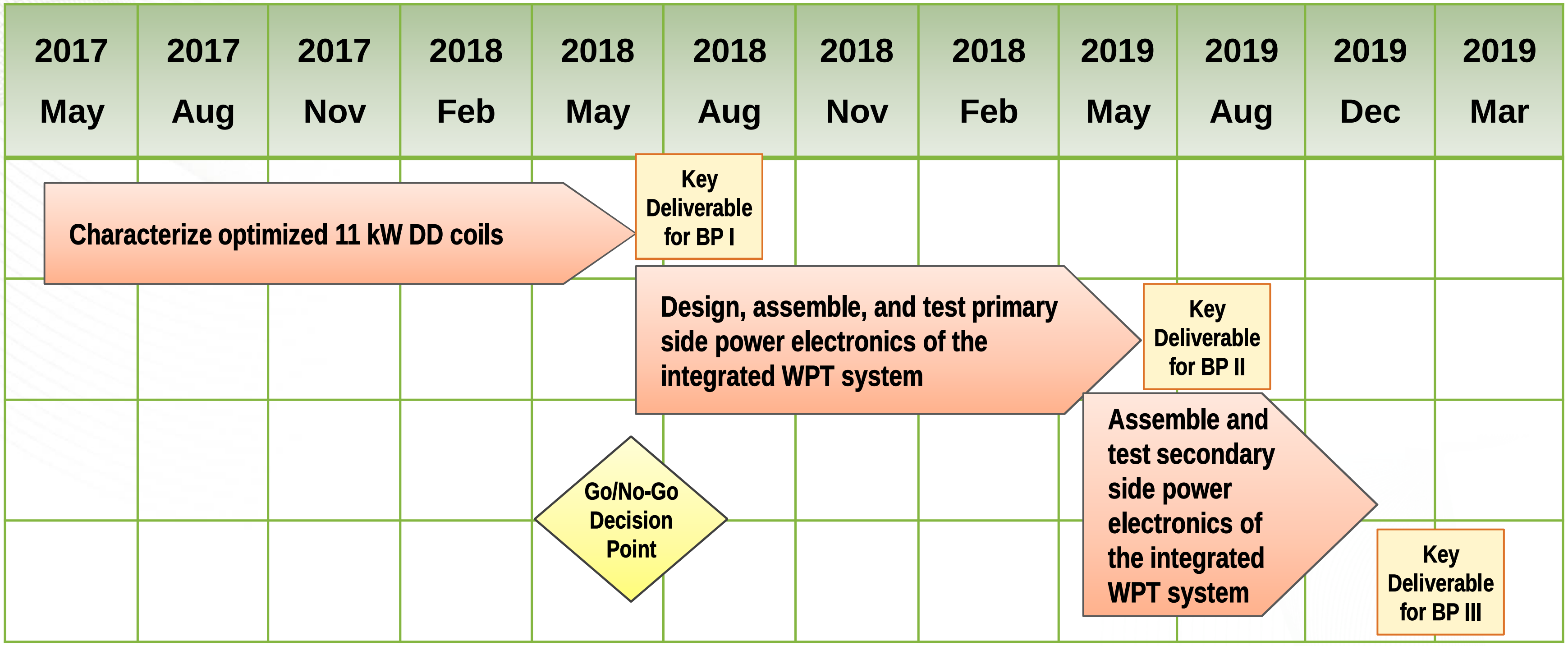
Any proposed future work is subject to change based on funding levels

Approach/Strategy

- Team identified baseline performance metrics and system specifications that the system must deliver once in operation.
- A comprehensive review, modeling, design, and simulation phase allowed the selection of the best power electronics architecture.
- Iterative design and the use of finite element analysis based modeling for the design optimization of the electromagnetic coupling coils.
- Vehicle charging load and the power level to be sent to the grid allowed the proper system design and cascaded down to the appropriate subsystems and components.
- During Budget Period II, system power conversion stages will be built in an integrated approach for an optimal system design in terms of complexity and compactness.
- All the power conversion stages will be independently tested for functionality and validation of the performance.
- Entire system will be tested using grid and battery emulators before vehicle integration.

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

Project Timeline with Three Budget Periods



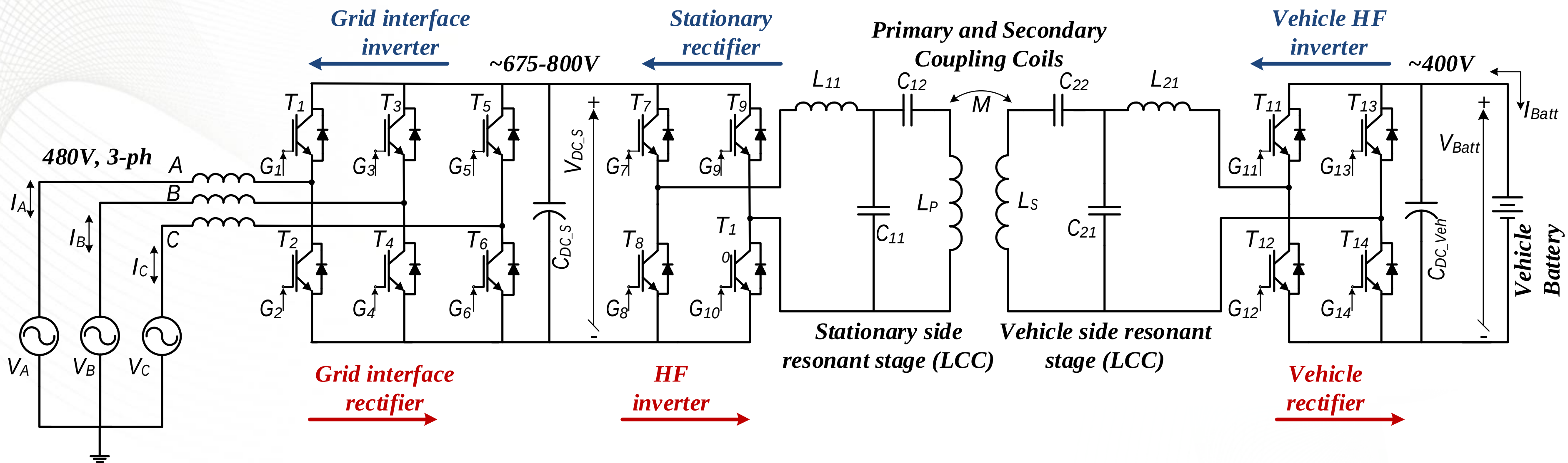
Go/No-Go Decision Point: Weather the system design, models, and simulations indicate the feasibility of 20 kW wireless charging operation over 11 inches magnetic airgap with at least 85% efficiency

Key Deliverable for BP I: Annual report detailing the design process, system modeling, expected performance, and discussion on simulation results at the end of the budget period I.

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

Technical Accomplishments – Budget Period I

System Level Diagram with Symmetric Double Sided LCC Resonant Tuning



System architecture determined and designed for all power conversion stages

- Grid interface power converter with active rectification and power factor correction (rectifier/inverter)
- High-frequency inverter / rectifier
- Resonant tuning configuration (LCC) for primary and secondary
- Electromagnetic coupling coils
- Vehicle side rectifier / inverter
- Overall control system

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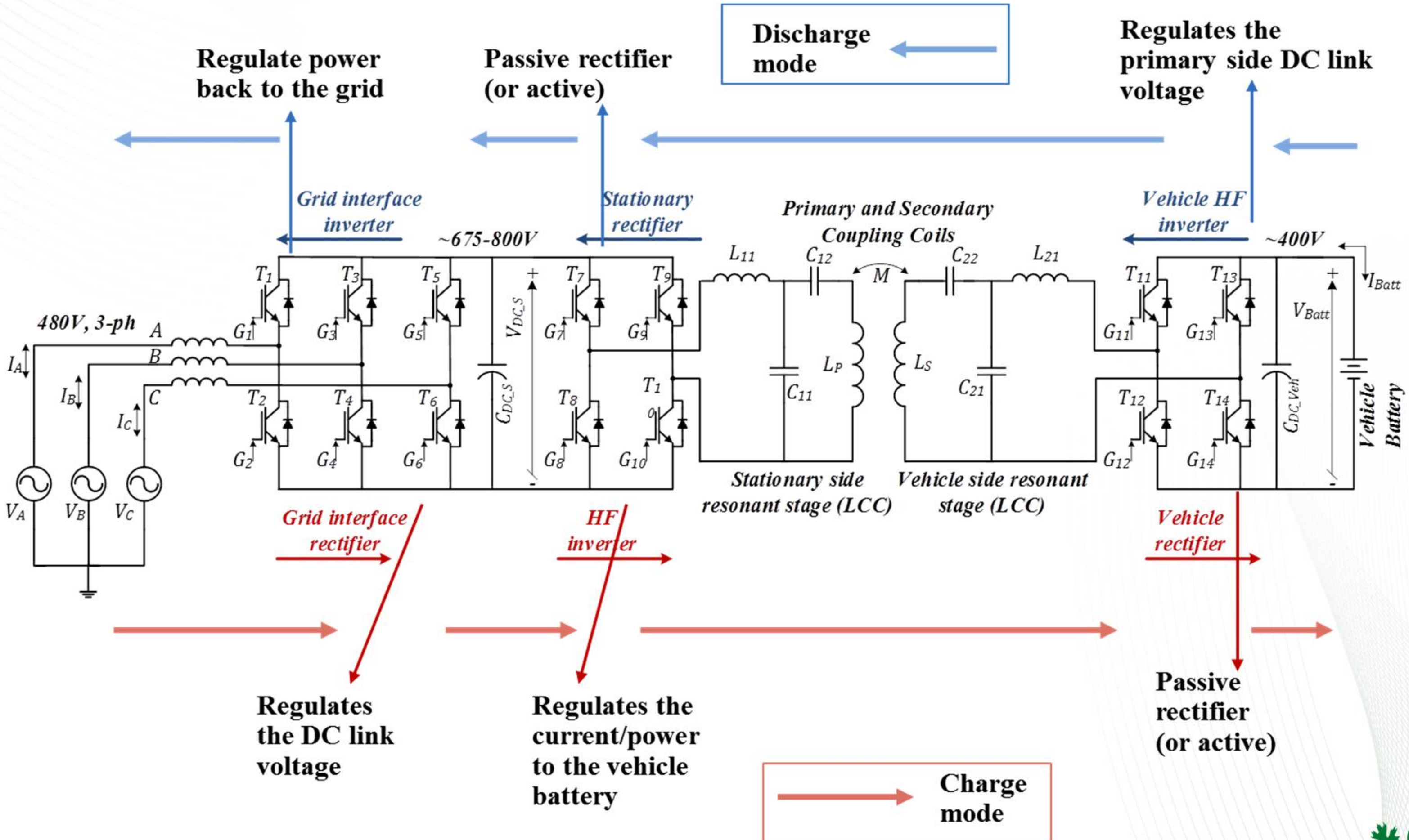
Technical Accomplishments – Budget Period I
Power Flow Control Modes

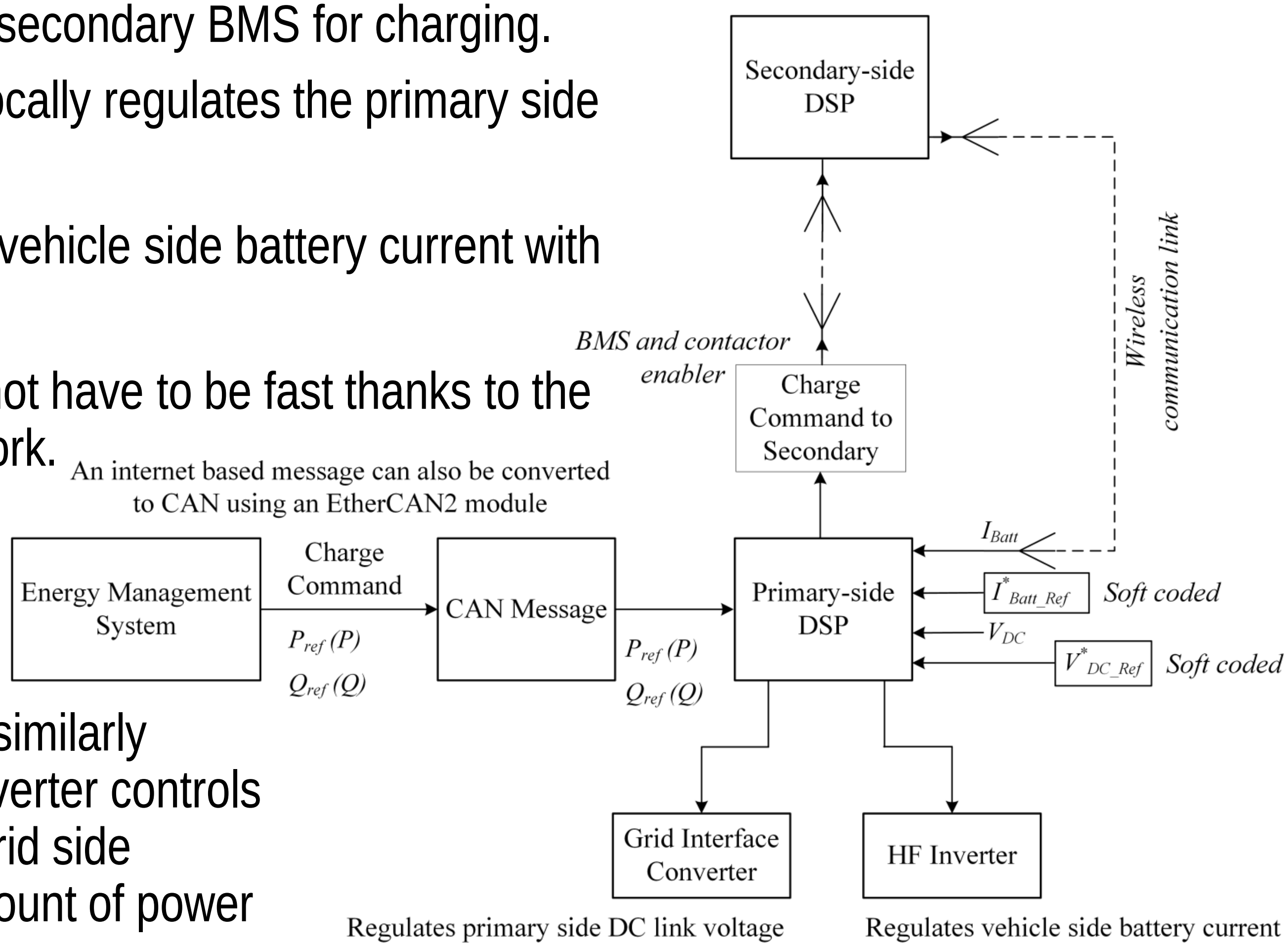
Designed the control system for each power conversion stages for different scenarios

- Vehicle battery power can be regulated from primary or secondary side
- Grid power can be regulated from grid side



Technical Accomplishments – Budget Period I
Power Flow Control Design

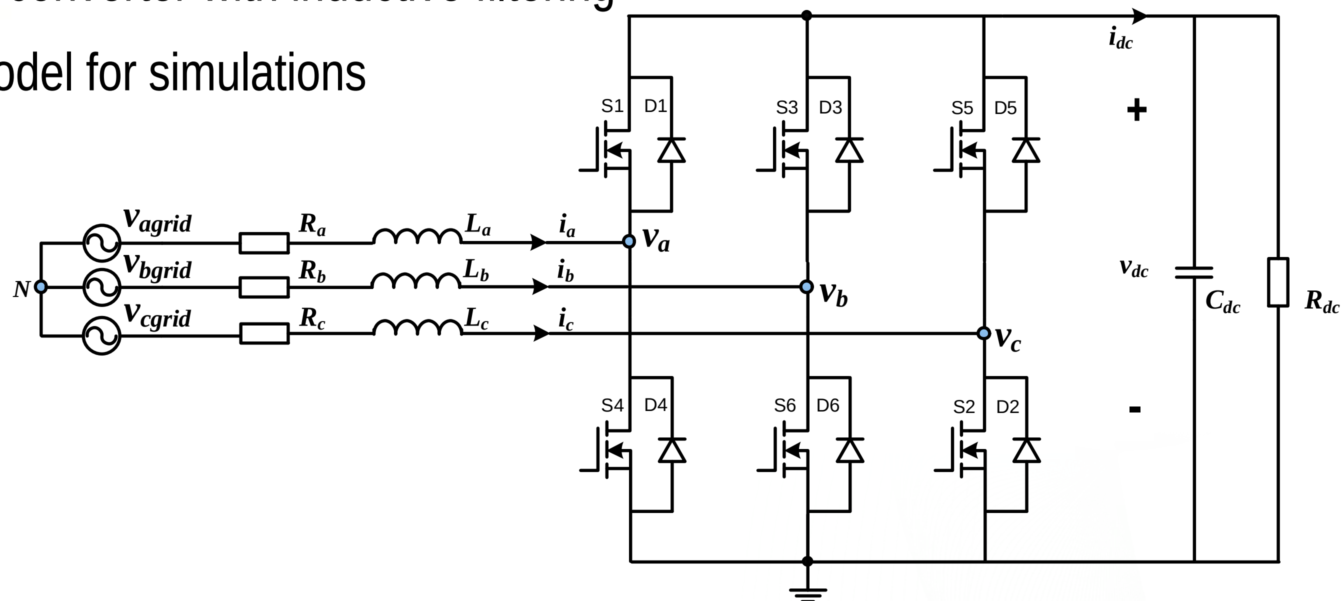
- Energy manager (or charge/discharge coordinator) sends the charge command to primary DSP (via CAN or Ethernet).
- Primary side enables the secondary BMS for charging.
- Grid interface converter locally regulates the primary side DC link voltage.
- HF Inverter regulates the vehicle side battery current with wireless feedback loop.
- Wireless feedback does not have to be fast thanks to the LCL tuned resonant network.



- Discharging event works similarly except the vehicle side inverter controls the primary DC link and grid side converter controls the amount of power being pushed back.

Technical Accomplishments – Budget Period I
Completed the Bidirectional Grid Interface Converter Design

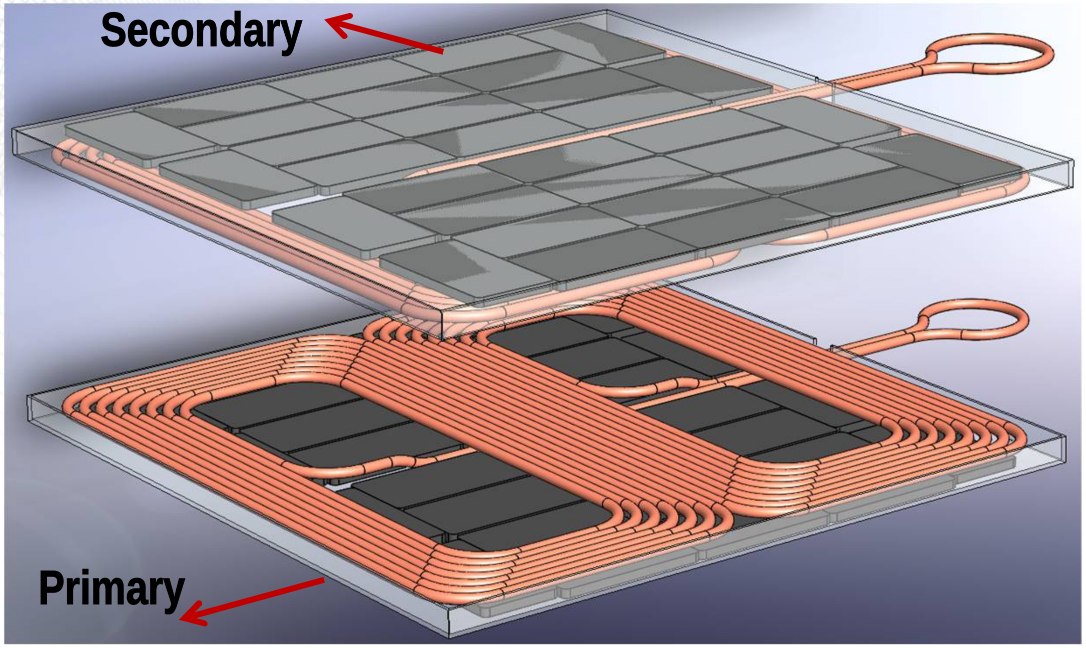
- Two-level three-phase converter with inductive filtering
- Created the system model for simulations and analysis
- Created a double-loop voltage and current control system



Parameter	Description	Value
R_a=R_b=R_c=R	Three-phase AC line resistance	5 mΩ
L_a=L_b=L_c=L	Three-phase AC line inductance	750-780 µH
V_{agrid}=V_{bgrid}=V_{cgrid}	Three-phase nominal grid voltage (phase-to-neutral RMS)	277 V
f	Nominal grid frequency	60 Hz
P_n	Nominal power	20 kW
V_{dc}	Nominal dc bus voltage	800 V (for 480V±5%)
C_{dc}	Dc bus capacitor	1 mF
S for pf_min=0.6	Apparent power rating	40 kVA for pf_min=0.6

Technical Accomplishments – Budget Period I

Completed the Design and Optimization of Coupling Coils

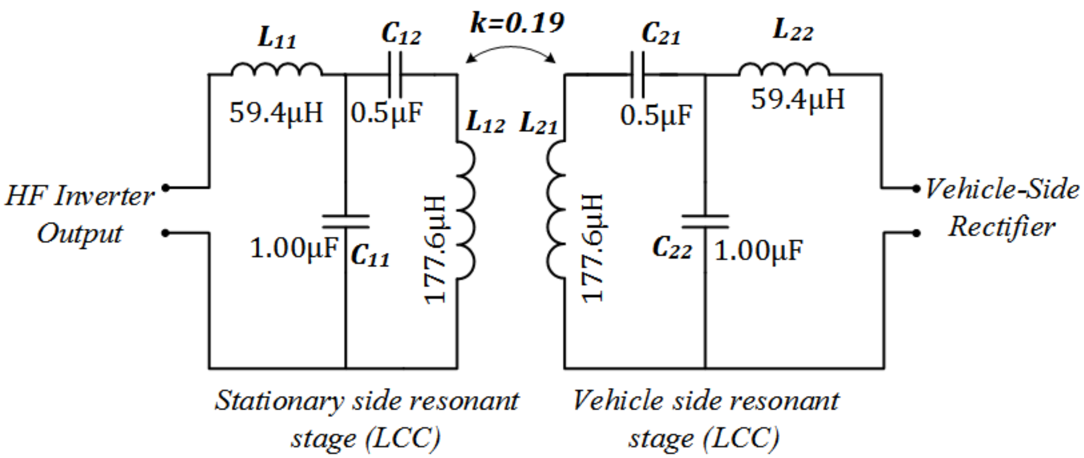


Coupling coils designed for full power and 11 inches airgap

- Designed for two cases including a 420V vehicle battery (plug-in hybrid truck) and 650V vehicle battery (all-electric truck)

P_{in}	31.9	kW
P_{out}	31.1	kW
η (expected efficiency)	97.4	%
Primary V_{dc}	800	V
Secondary V_{dc}	400	V
V_{dc}	720	Vrms
I_{dc}	44.4	Arms
I_p	93.5	Arms
V_{bt}	360	Vrms
I_{bt}	86.4	Arms
I_s	93.5	Arms
f	20.65	kHz
ω	130	kRad/s

Coupling	M	27.5	uH	@11 inches airgap
	k	0.19		

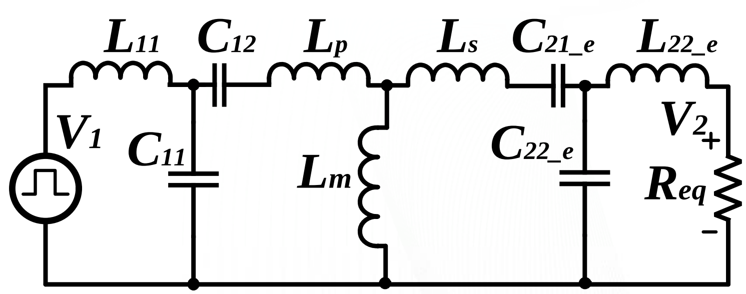


- Designed the resonant tuning circuit topology
- Identified resonant stage parameters based on power levels, component stresses, and coil parameters

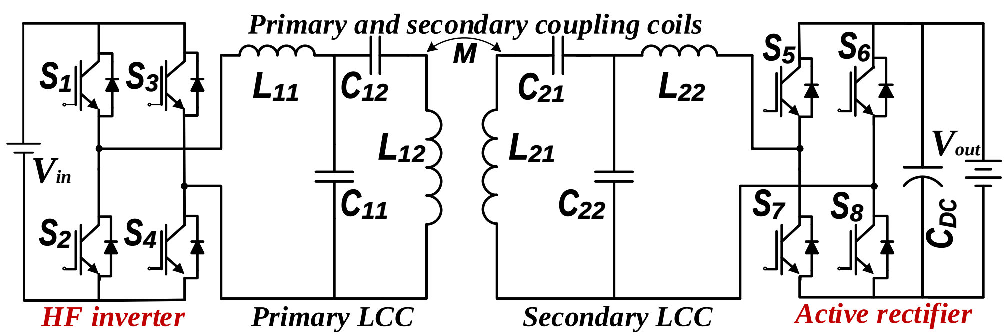
Technical Accomplishments – Budget Period I
Resonant Stage Analysis

Completed the design, modeling, and analysis of the double-sided LCC resonant tuning configuration that will be used in the resonant stage of the power architecture.

- Derived linear models for double-sided LCC tuned architecture based on
  - Replacing WPT coils by loosely coupled model of the transformer
  - Approximating the output of the inverter by the fundamental frequency component
- Analyzed sensitivity of the system to
  - Misalignment of coils along the x and y axis
  - Variation of coil-to-coil distance
  - Variation of load power



Equivalent circuit of the resonant stage.



System modeling for double-sided LCC resonant stage

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Technical Accomplishments – Budget Period I

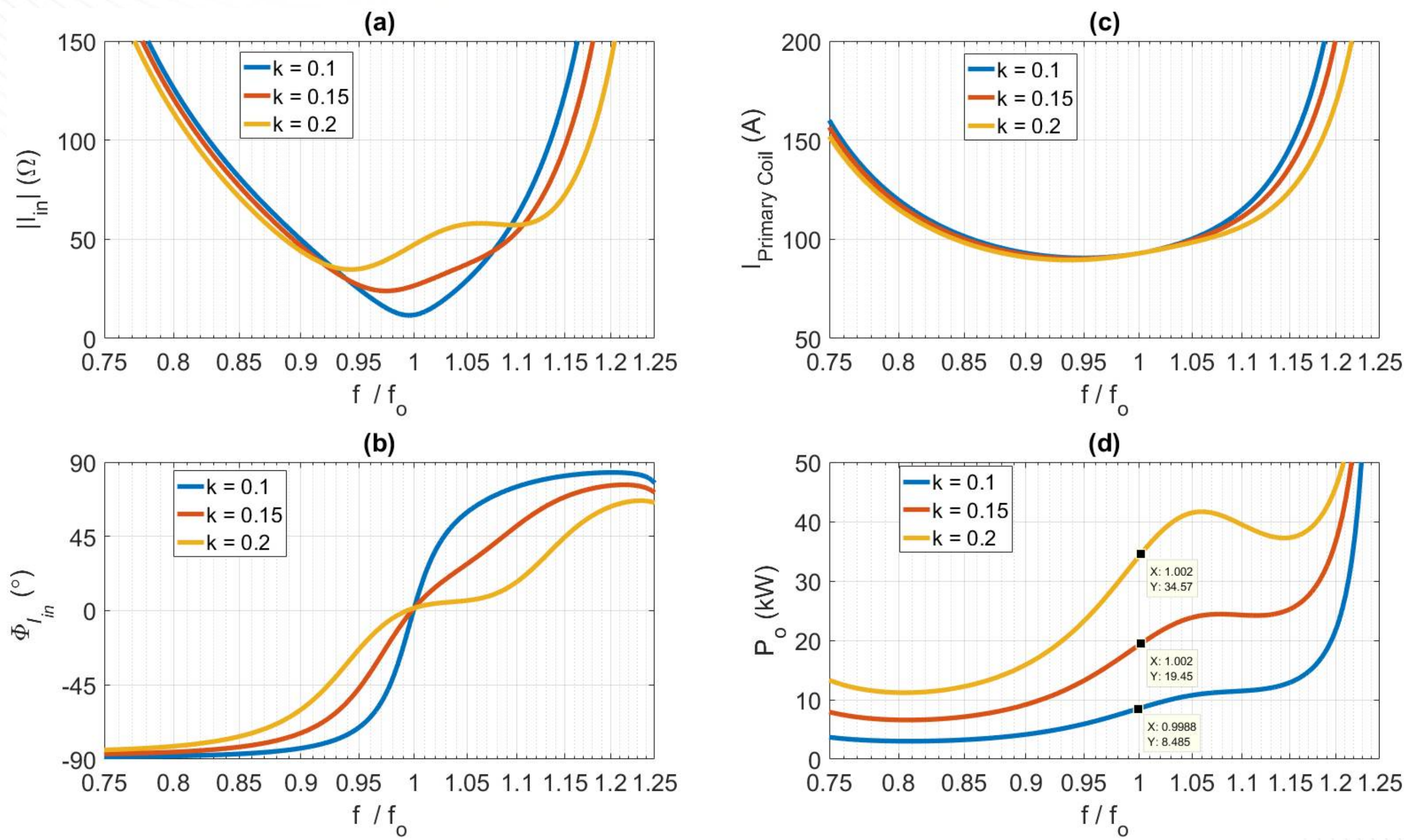
Performed Sensitivity Analysis

1. Inverter current has near zero phase angle independent of load resistance
2. Inverter current has near zero phase angle independent of the coupling between the WPT coils

Leads to high efficiency operation and the inverter does not need to be oversized

3. Primary coil current is constant independent of load resistance
4. Primary coil current is constant independent of coupling between the coils

Primary side is decoupled from the secondary side disturbances



(a) Primary coil current as a function of load resistance

(b) Inverter voltage and current phase angle as a function of load resistance

(c) Primary coil current as a function of coupling coefficient

(d) Power transfer as a function of the coupling factor and frequency

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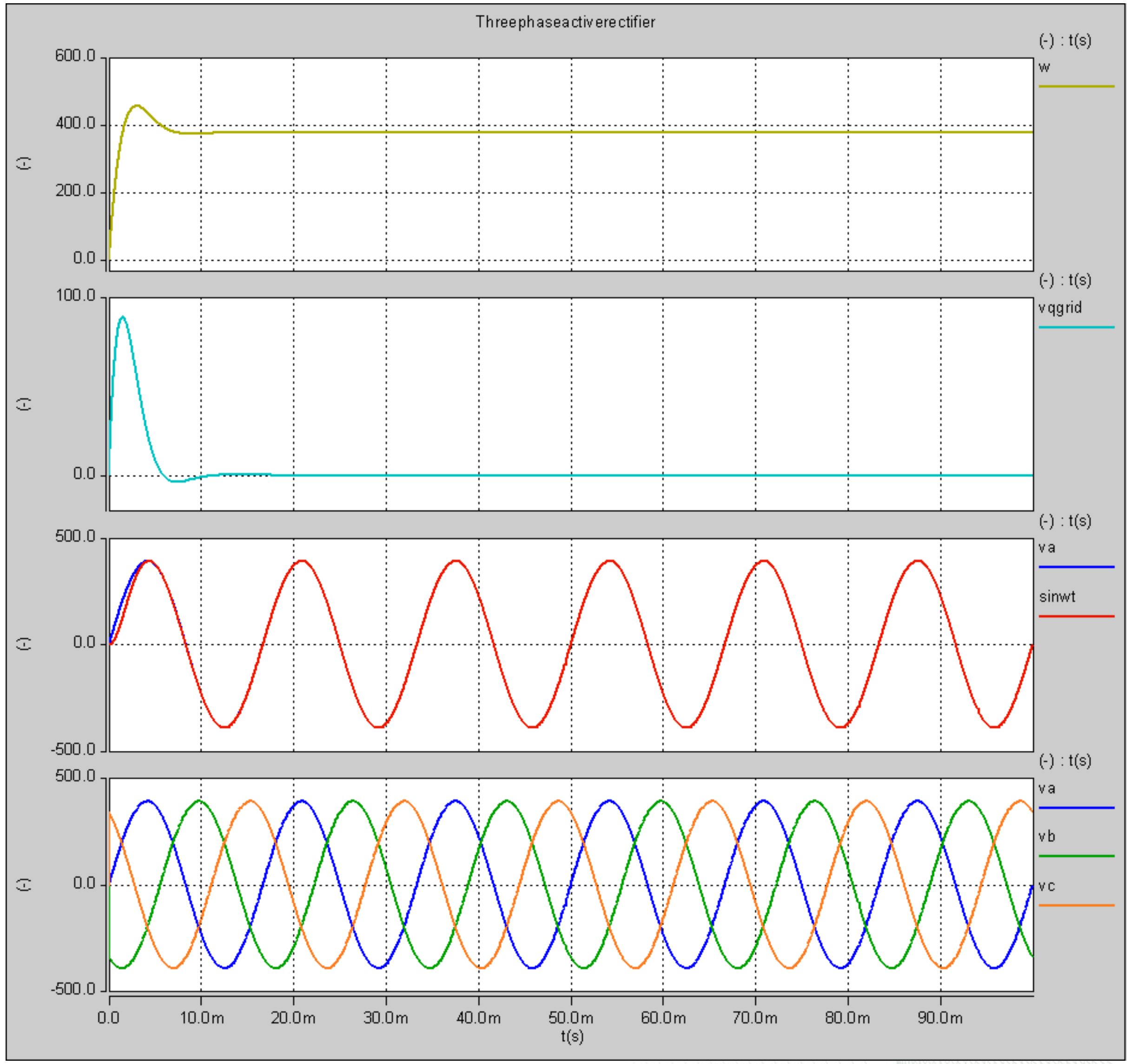
Technical Accomplishments – Budget Period I
Completed the Phase-Locked-Loop Design and Performance Analysis

- PLL provides the synchronization with the grid phase angle
- Phase-angle detection is extremely important for fast and accurate reactive power supply, voltage regulation, and other grid services.
- Phase angle is immediately detected here (blue and red line overlap)



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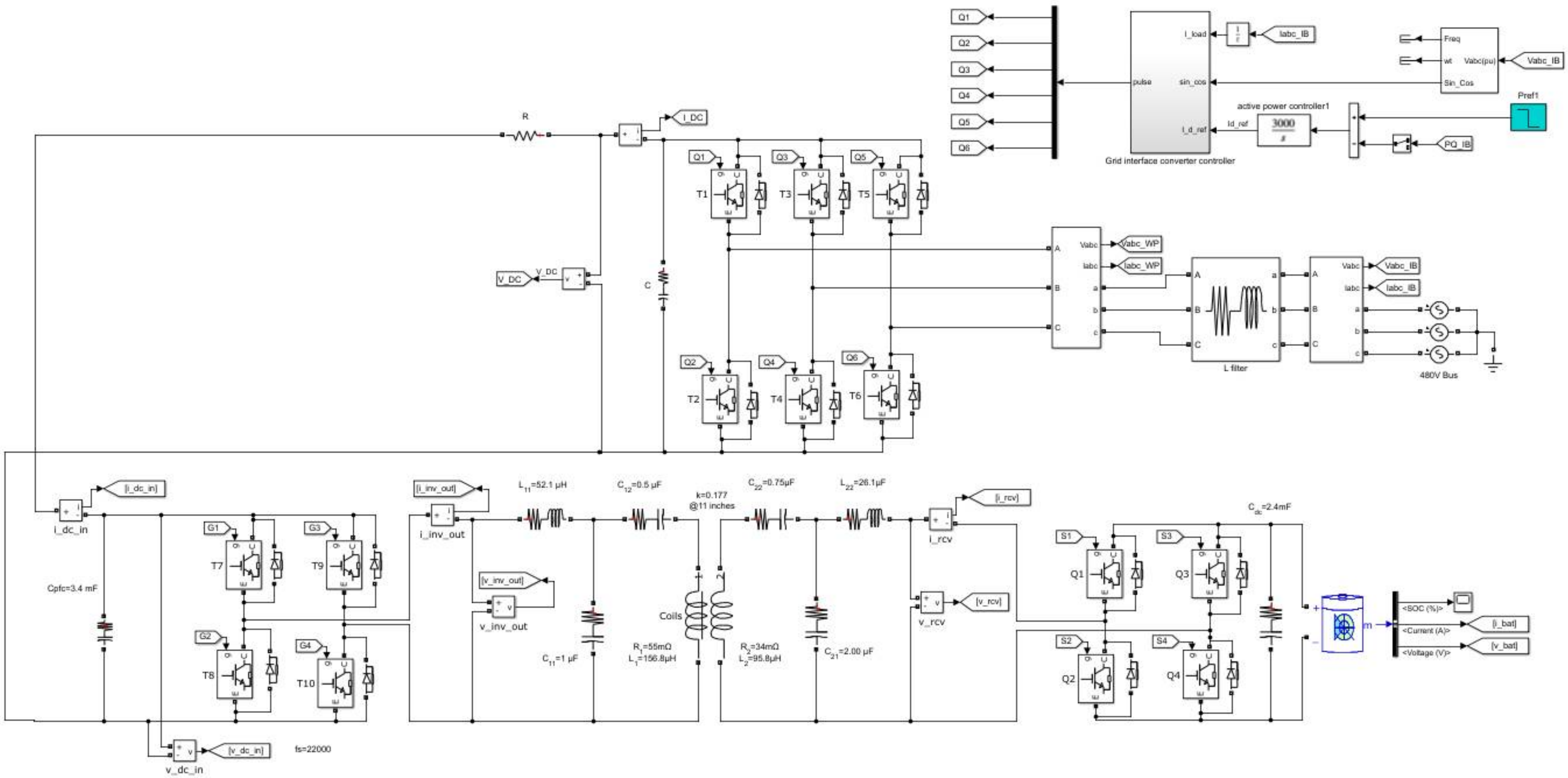
Technical Accomplishments – Budget Period I
Completed the Entire System Model and Obtained Simulation Results

- Simulations performed using MATLAB Simulink/SimPowerSystems, SABER, and PCIM
- Magnetic simulations use COMSOL and JMAG



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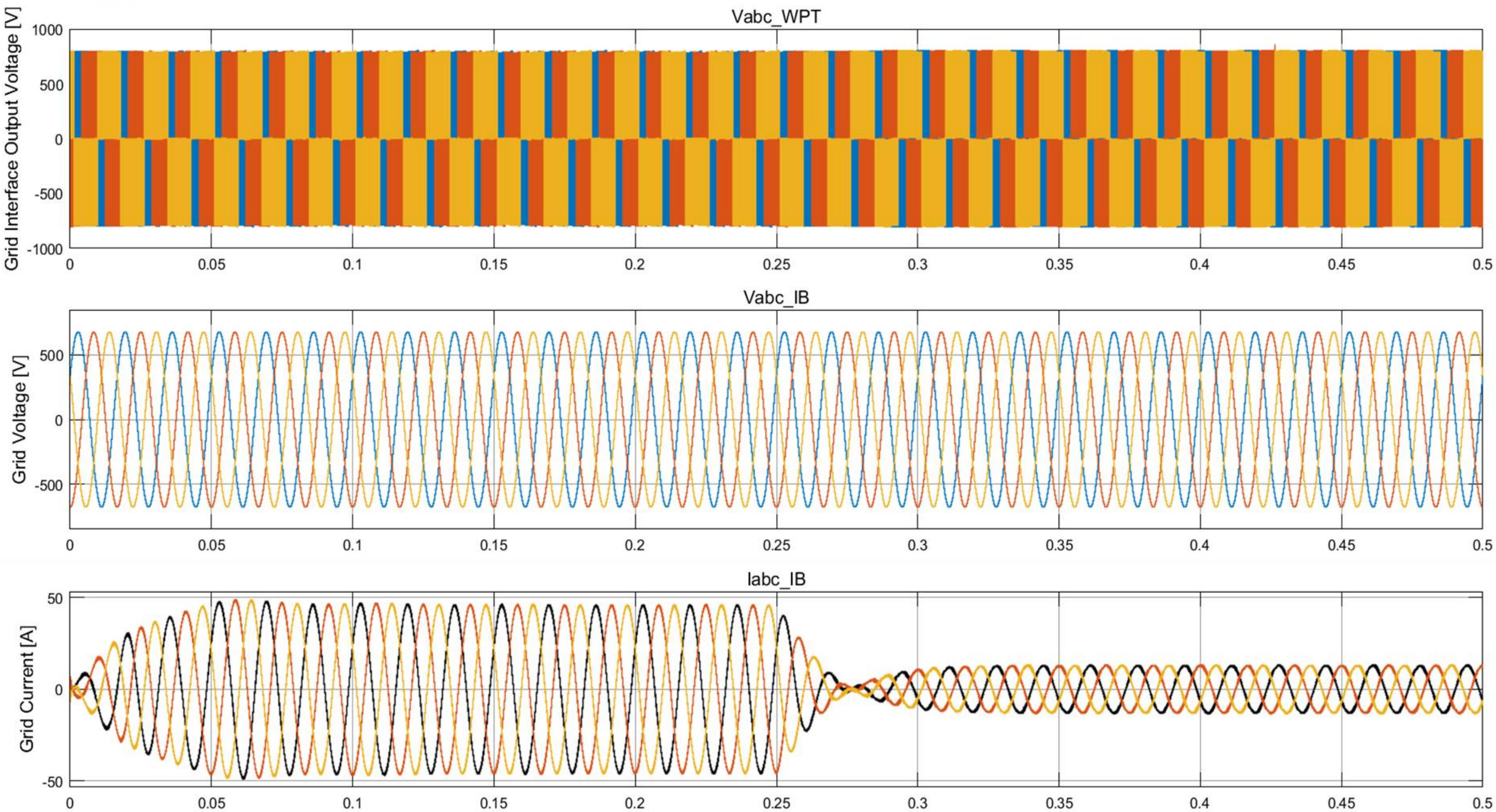
Technical Accomplishments – Budget Period I
Entire System Model Simulation Results

- Grid interface converter operation
- Ability to transition the power flow direction (t=0.25, discharge command sent)
- Can operate in reactive power injection / absorption modes (capacitive or inductive reactive)



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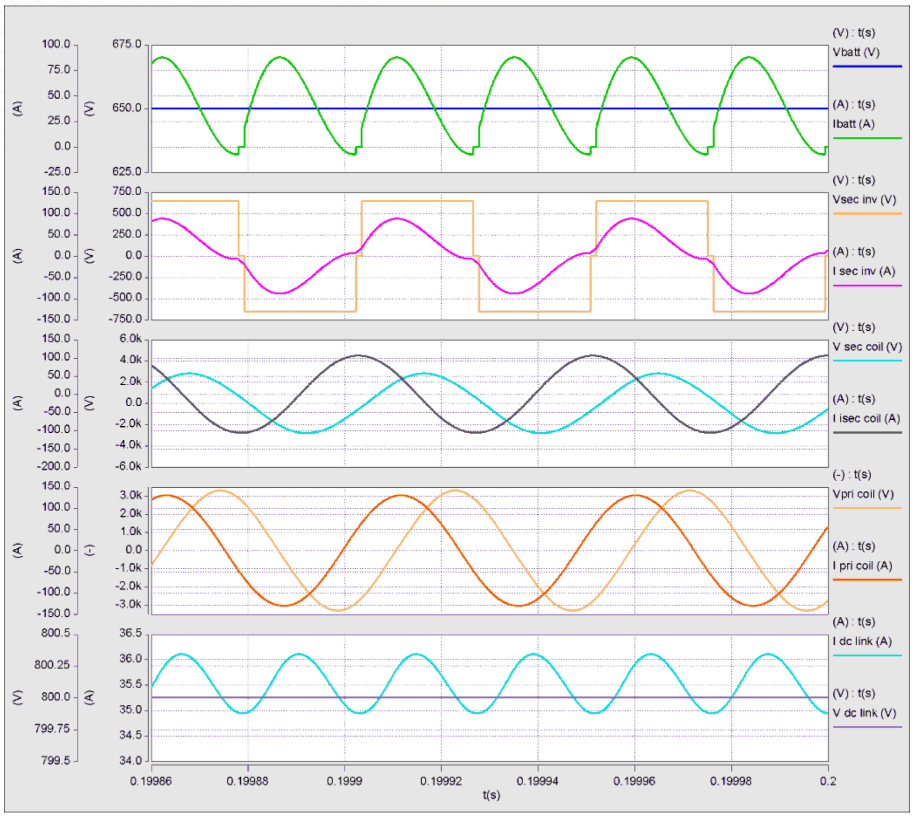
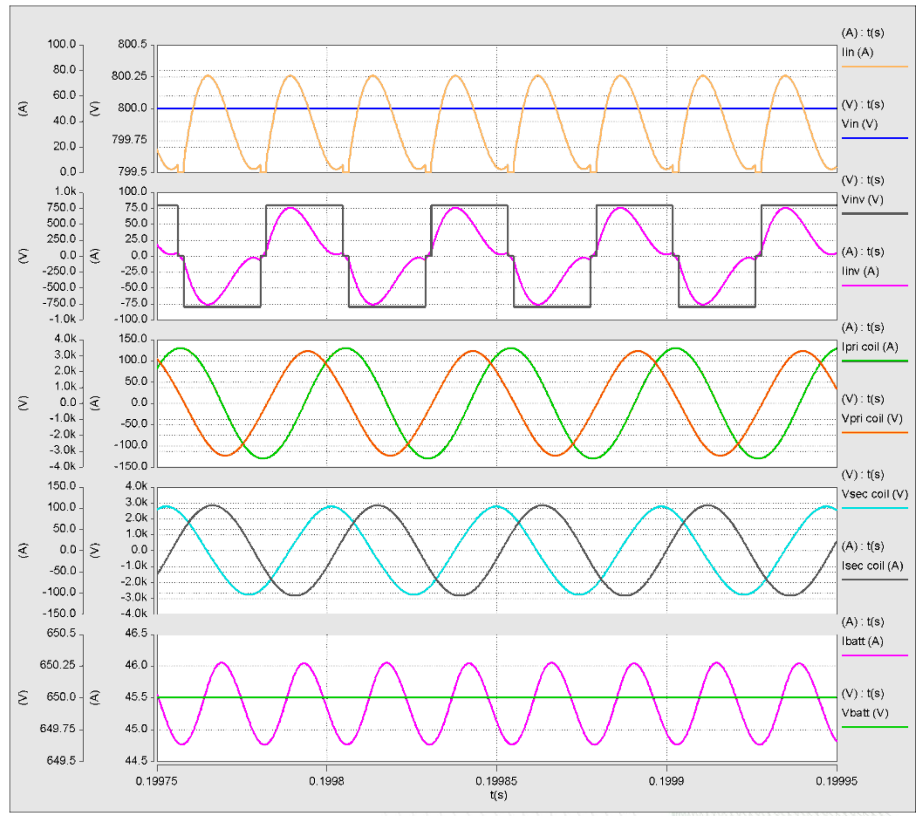
Technical Accomplishments – Budget Period I

Entire System Model Simulation Results

- High-frequency inverter / rectifier and resonant stage simulations
- Vehicle charging mode (a) and vehicle discharging mode of operations
- Minimal current ripple on battery and primary side DC link
- Zero voltage and zero current switching by the converters for reduced switching losses



(a)



(b)

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Technical Accomplishments – Budget Period I
Entire System Loss Analysis and Breakdown

- Loss models created to evaluate system efficiency performance to confirm the design

Loss analysis in 20kW charge mode

PFC stage		Comments
PFC inductor core loss	32.1	includes switching ripple and ferrite loss
PFC conduction loss	241.3	includes Switches and winding, wires
PFC switching loss	85.8	turn-on/turn-off; gate loss; junction cap charge loss
PFC output cap loss	6.8	line-freq voltage ripple
PFC total loss	**366**	**0.9817**
Double LCC		
Inverter loss	129.4	conduction loss+switching loss, assuming ZVS
Coil loss	574.2	
LCC primary inductor loss	73.9	winding+core loss
LCC secondary inductor loss	47.8	winding+core loss
LCC res caps loss	227.8	Depends on ESR, set as 0.006
Rectifier loss	193.6	turn-on/turn-off; gate loss; junction cap charge loss
Circulating energy loss	127.1	Assume 0.15 duty cycle for PWM
Output DC cap loss	6.7	5A current, ESR=0.006
LCC total loss	**1380.5**	**0.929688296**
System total efficiency	**0.912675**	**91.26% Overall Efficiency**

Technical Accomplishments – Budget Period I

Entire System Loss Analysis and Breakdown

- Loss models created to evaluate system efficiency performance to confirm the design

Loss analysis in 6.6kW discharge mode

PFC stage		
PFC inductor core loss	**31.5**	includes switching ripple and ferrite loss
PFC conduction loss	**26.3**	includes Switches and winding, wires
PFC switching loss	**47.6**	turn-on/turn-off; gate loss; junction cap charge loss
PFC output cap loss	**0.8**	line-freq voltage ripple
PFC total loss	**106.2**	**0.983909091**
Double LCC		
Inverter loss	**84.8**	conduction loss+switching loss, assuming ZVS
Coil loss	**167.4**	
LCC primary inductor loss	**24.7**	winding+core loss
LCC secondary inductor loss	**16**	winding+core loss
LCC res caps loss	**61.3**	Depends on ESR, set as 0.006
Rectifier loss	**100.3**	turn-on/turn-off; gate loss; junction cap charge loss
Circulating energy loss	**39.9**	Assume 0.15 duty cycle for PWM
Output DC cap loss	**0.08**	5A current, ESR=0.006
LCC total loss	**494.48**	**0.923853522**
System total efficiency	**0.908988**	**90.89% overall efficiency**

Responses to Previous Year Reviewers' Comments

None. New Start (this project started in May 2017).

Collaboration and Coordination with Other Institutions

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

Remaining Challenges and Barriers for Budget Period I

- None at this point.

Proposed Future Work

- **Budget Period II**
  – Complete the hardware development, validation, testing, and vehicle integration.
- **Budget Period III**
  – System deployment, control system fine tuning, validation, data collection.

Summary

- **Relevance:** Increasing the benefits and reduce the barriers in vehicle electrification, wireless charging, and vehicle to grid integration.
- **Approach:** Proposed an bidirectional wireless power transfer system that operates at a high airgap for medium duty delivery trucks with high-efficiency and functionality through advanced power electronics and magnetics design, vehicle systems integration, and control system design.
- **Collaborations:** CALSTART, ORNL, UPS, Workhorse, and Cisco
- **Technical Accomplishments:**
  - Completed the design, modeling, simulations, and analysis for the 20 kW bidirectional wireless power transfer system including the grid interface converter, high-frequency inverter and rectifier, coupling coils, resonant stage, and the control systems.
- **Future Work:**
  - Develop and test the hardware, complete vehicle integration, testing, and data collection.