NREL
Transforming ENERGY

Project ID# ELT204

Charging Infrastructure Technologies: Development of a Multiport, >1 MW Charging System for Medium- and Heavy-Duty Electric Vehicles

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June 24, 2021

DOE Vehicle Technologies Program
2021 Annual Merit Review and Peer Evaluation Meeting

Overview

Timeline

• Project start date:	October 2018
• Project end date:	December 2021
• Percent complete:	83%

Budget

• Total project funding:	$ 7.0 M
• DOE Share:	$ 7.0 M
• Contractor Share:	$ 0
• Fiscal Year 2020 Funding:	$ 2.0 M
• Fiscal Year 2021 Funding:	$ 2.0 M

Barriers Addressed

- Integration of Medium Duty (MD) and Heavy Duty (HD) vehicle charging loads consistent with smart grid operation
- Power conversion topologies, electronics, and connectors for megawatt charging.
- A need to develop and enable reduced costs for electric charging infrastructure.
- Developing new control analytics for MD/HD vehicle charge control

Partners

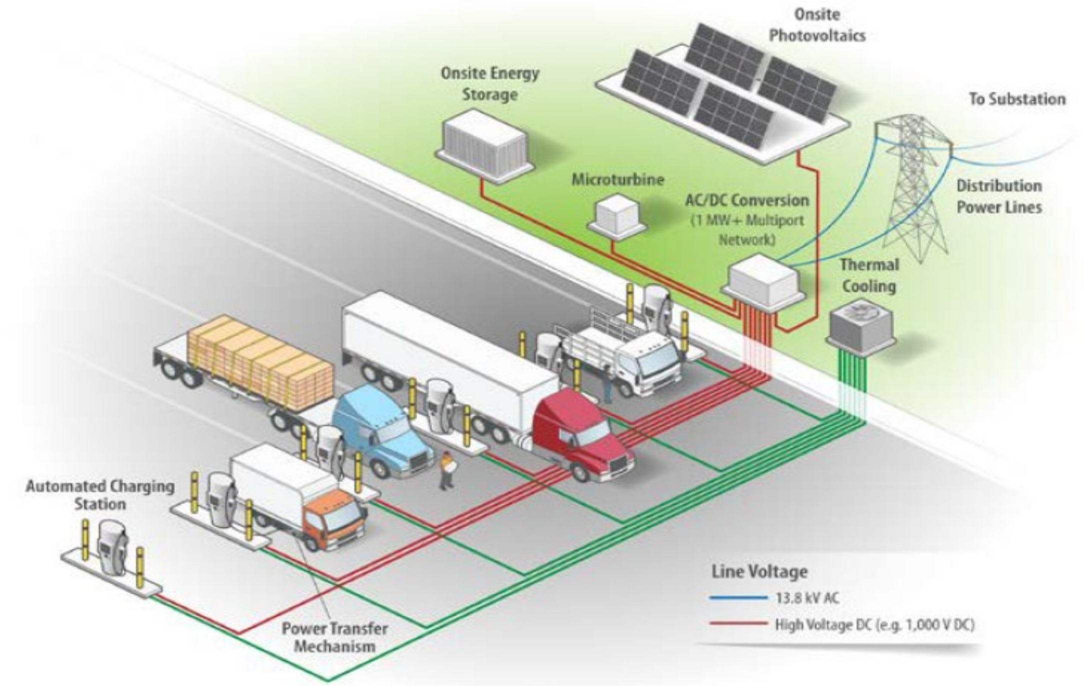
- Oak Ridge National Laboratory (ORNL)
- Argonne National Laboratory (ANL)
- National Renewable Energy Lab (NREL)

Relevance

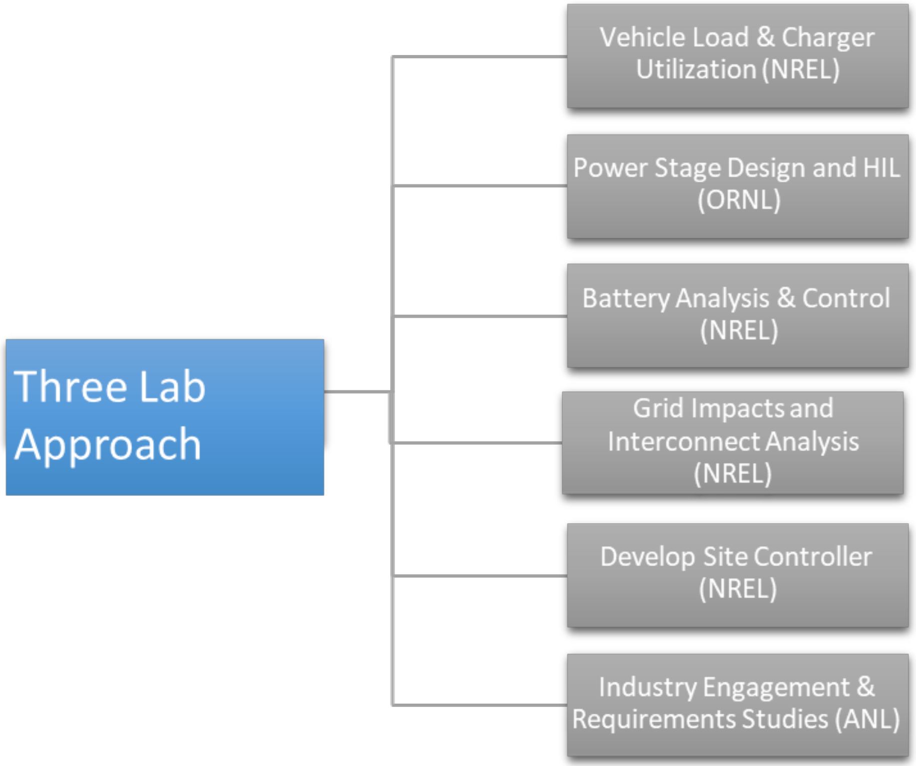
This project will: develop research tools for a framework to design, optimize, and demonstrate key components of a multi-port 1+ MW medium-voltage connected charging system.

Objective(s): Develop strategies and technologies for multi-port 1+ MW grid-connected stations to recharge MD/HD electric vehicles at fast-charging travel plazas or at fleet depots; through:

- Industry Engagement
- Charging station utilization and load analysis
- Grid impacts and interconnection analysis
- Detailed power electronics component design and controller demonstration
- Site and battery charge control design and controller demonstration
- Charging connector design



Resources



HIL: hardware-in-the-loop

NREL Team:
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ORNL Team:
Michael Starke
Brian Rowden
Madhu Chinthavali
Rafal Wojda
Shilpa Marti
Aswad Adib

Total Funding:
$7M over 3 years

NREL: $3M ($1M/yr)
ORNL: $3M ($1M/yr)
ANL: $1M ($0.3M/yr)

Milestones: All Labs

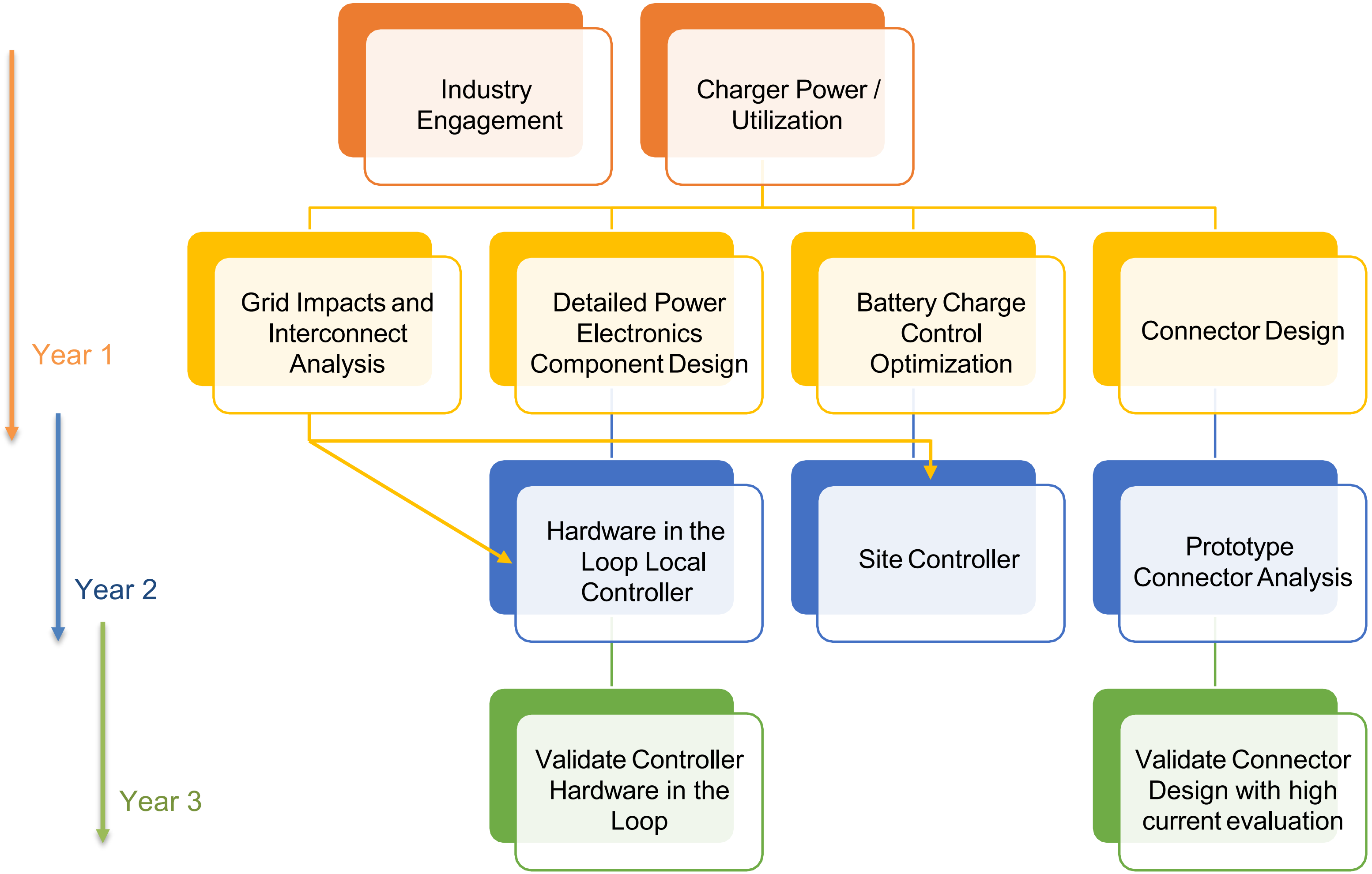
Milestone Name/Description	Deadline	Milestone Type
Quarterly reports on progress of year 1 activities (include tasks 1, 2, 6, 7, 8, 12)	End of Q1, Q2, Q3 FY 19	Quarterly Progress Measures
Complete the simulation and performance analysis of at least one power conversion topology	9/30/2019	Go/No-Go Milestone
Provide Draft Summary Report on Industry Engagement and Charging Requirements for MDHD, EV Transit Bus and DC-as-a-Service	9/30/2019	Annual Milestone
Quarterly reports on progress of year 2 activities (include tasks 3, 4, 5, 8, 9, 10, 12)	End of Q1, Q2, Q3 FY20	Quarterly Progress Measures
Battery modeling grid interface control architecture prototype design for power stage; prototype design for power mechanism	9/29/2020	Go/No-Go Milestone
Quarterly reports on progress of year 3 activities (include tasks 10, 11, 12)	End of Q1, Q2, Q3 FY21	Quarterly Progress Measures
Complete integration of the overall control architecture and virtual 1 MW evaluation platform; verify through control HIL simulation; evaluate power transfer mechanism using prototype hardware	9/29/2021	Quarterly Progress Measures
Prepare journal quality papers to document outcomes	12/31/2021	Annual Milestone

Year 3 Milestones will show:

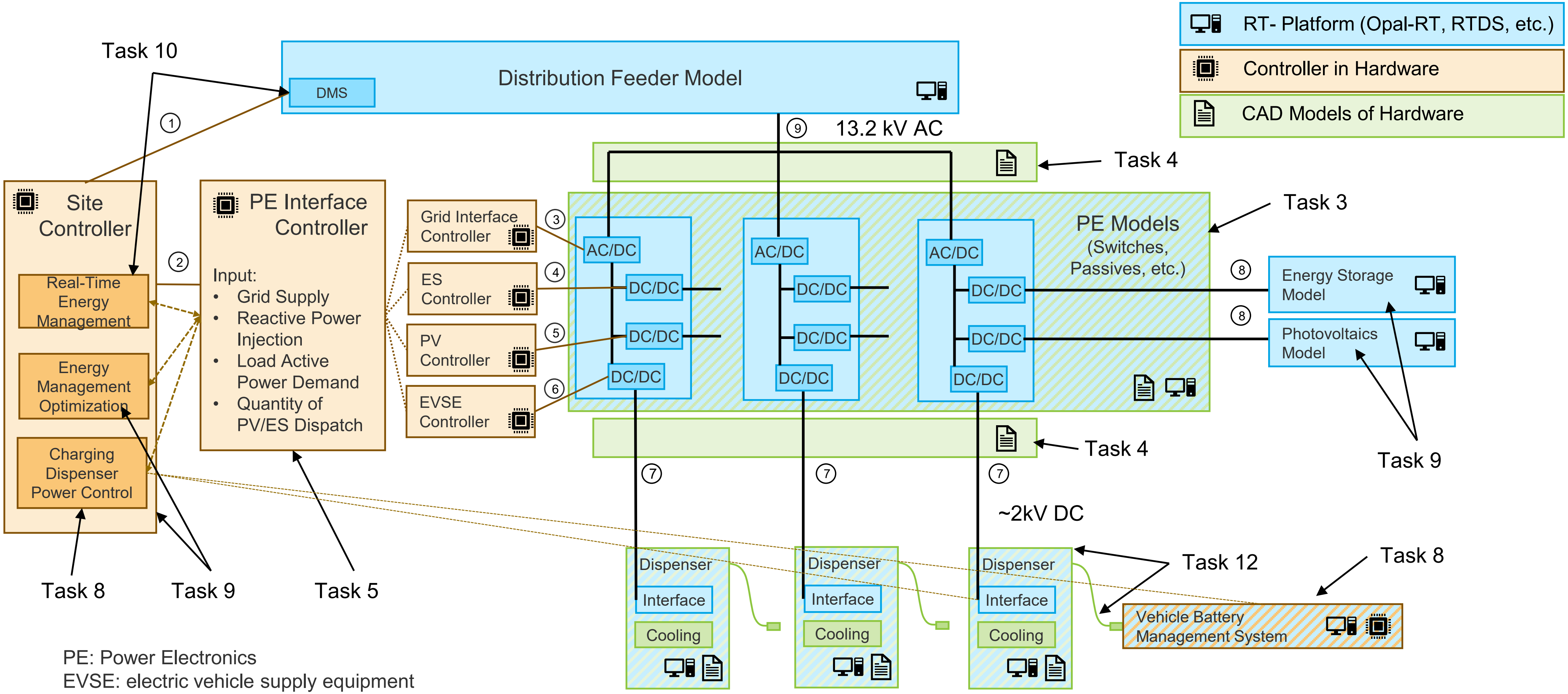
1) Evaluation of vehicle charge connectors
2) Development of optimized battery charging algorithms for multi-port charge control
3) Site controller development for grid interface and distributed energy resources
4) Complete switch-level control and detailed physics-based models for power conversion
5) Complete full system controller hardware-in-the-loop evaluation

EV: electric vehicle
DC: direct current
DCaaS: DC as a Service
PE: power electronics
FMEA: Failure Modes and Effects Analysis

Approach: Multi-Task, Multi-Year



Approach: Multi-Task, Multi-Year



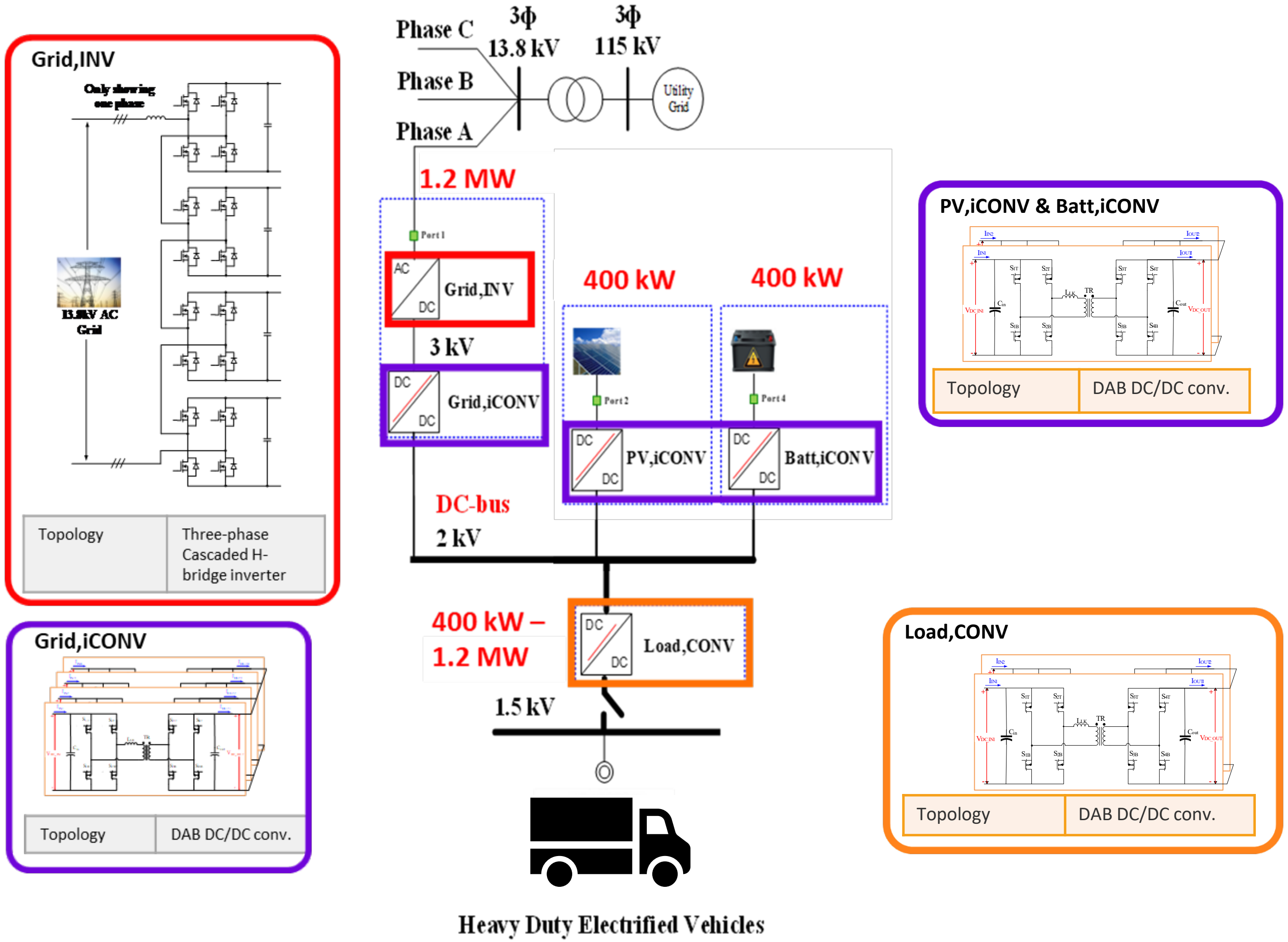
PE: Power Electronics
EVSE: electric vehicle supply equipment
ES: energy storage
PV: photovoltaics
CAD: Computer aided design

Technical Accomplishments and Progress:

Task 1 / 2 / 3 – PE Topology Review, Simulation, and Selection

PE Models (Switches, Passives, etc.)

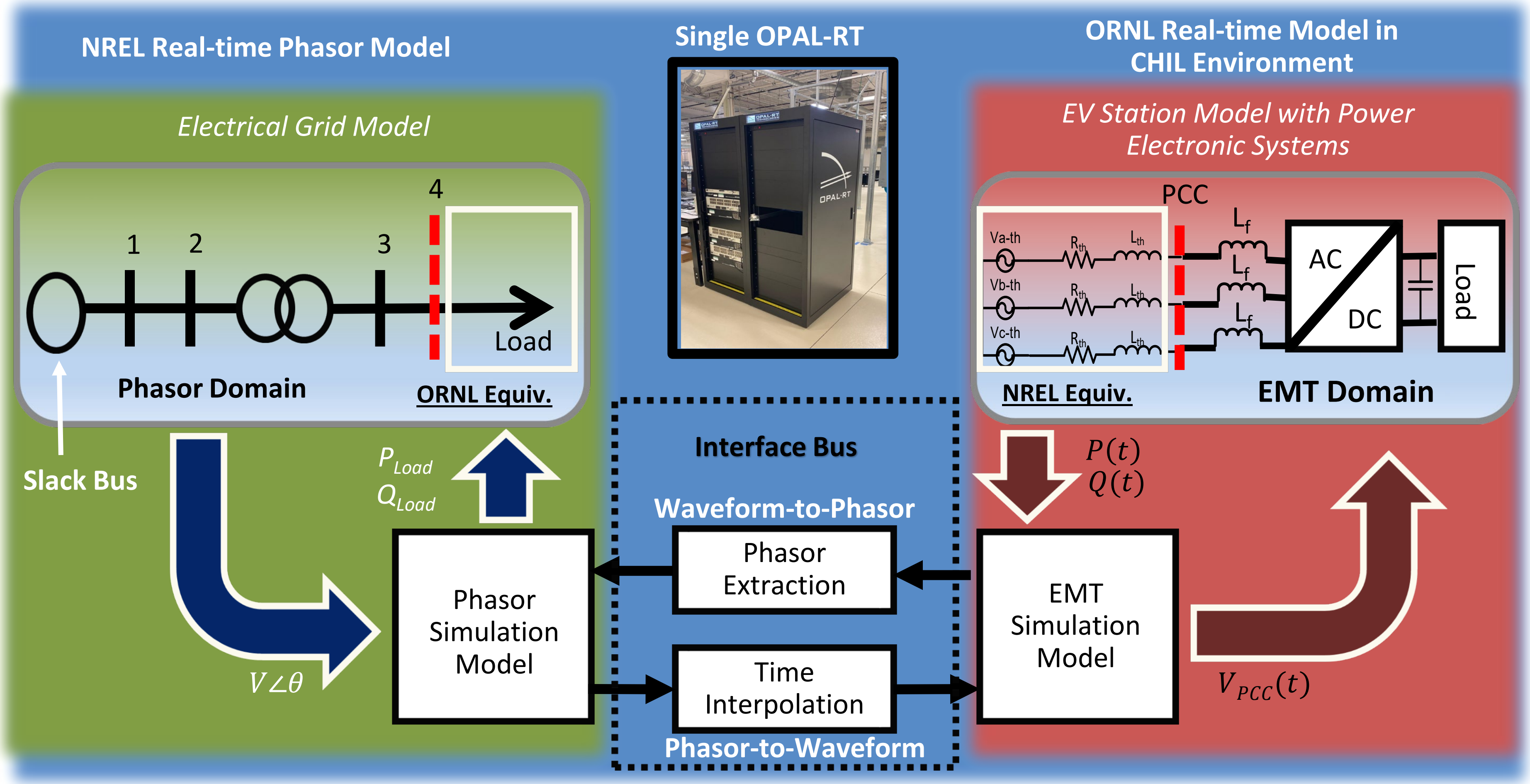
- Detailed MV Architecture investigation
  - **Detailed loss values including passives, protection, and interconnects**
  - Translation to thermal management requirements
  - **Final device selection**
- MV Gate Drive Test Hardware
  - **MV Si/SiC Device level testing providing detailed PE model input**
- Thermal Management
  - Strategy, sizing, and ancillary impact
- Cabinet level AC Grid Connection and Protection
- Cabinet level DC interconnects (DER/Load)
- DC interface to Charge connector



Technical Accomplishments and Progress:

Task 11 – Grid Model Linkage to Real-time Simulation

PE Models (Switches, Passives, etc.)



EMT- Electromagnetic Transient

Technical Accomplishments and Progress:

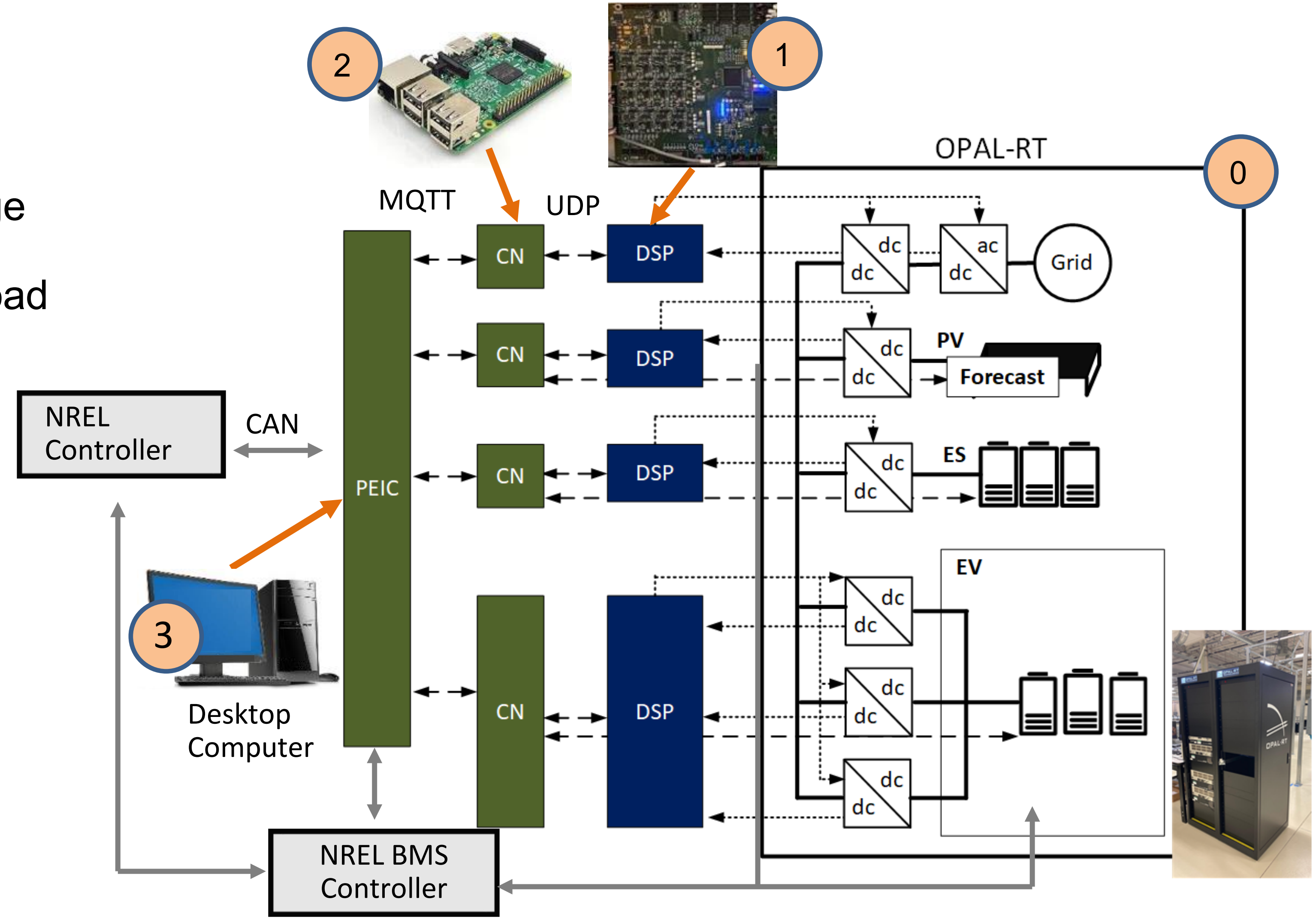
Task 11 – CHIL Demonstration: Controller Hardware Architecture

PE Interface Controller | Grid Interface, ES, PV, EVSE Controllers

0 Simulation:
- DAB+CHB
(3 phase x 4 Converters), 12 converters with DC bus voltage control
- 2kV DC bus controllable load

1 2 Controllers:
- 1 x ORNL DSP
Closed loop control of 12 converters avg model
- 1 x Raspberry Pi
Full agent systems running

3 Central System:
- Desktop Computer
Autointegration and CAN communications



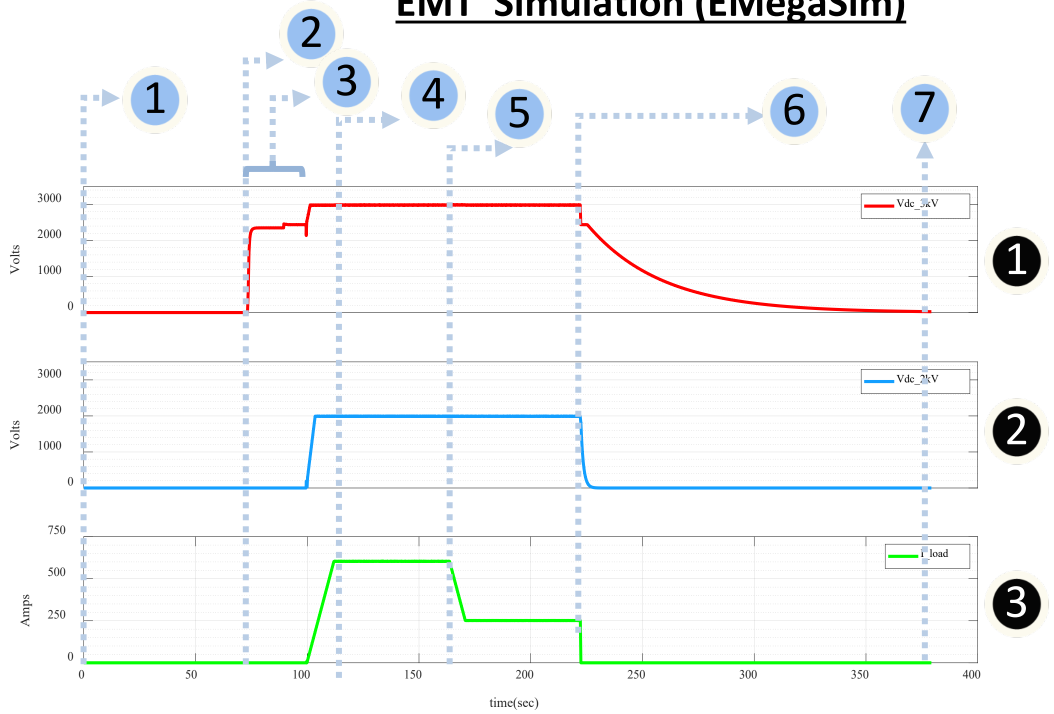
CN - Controller Node

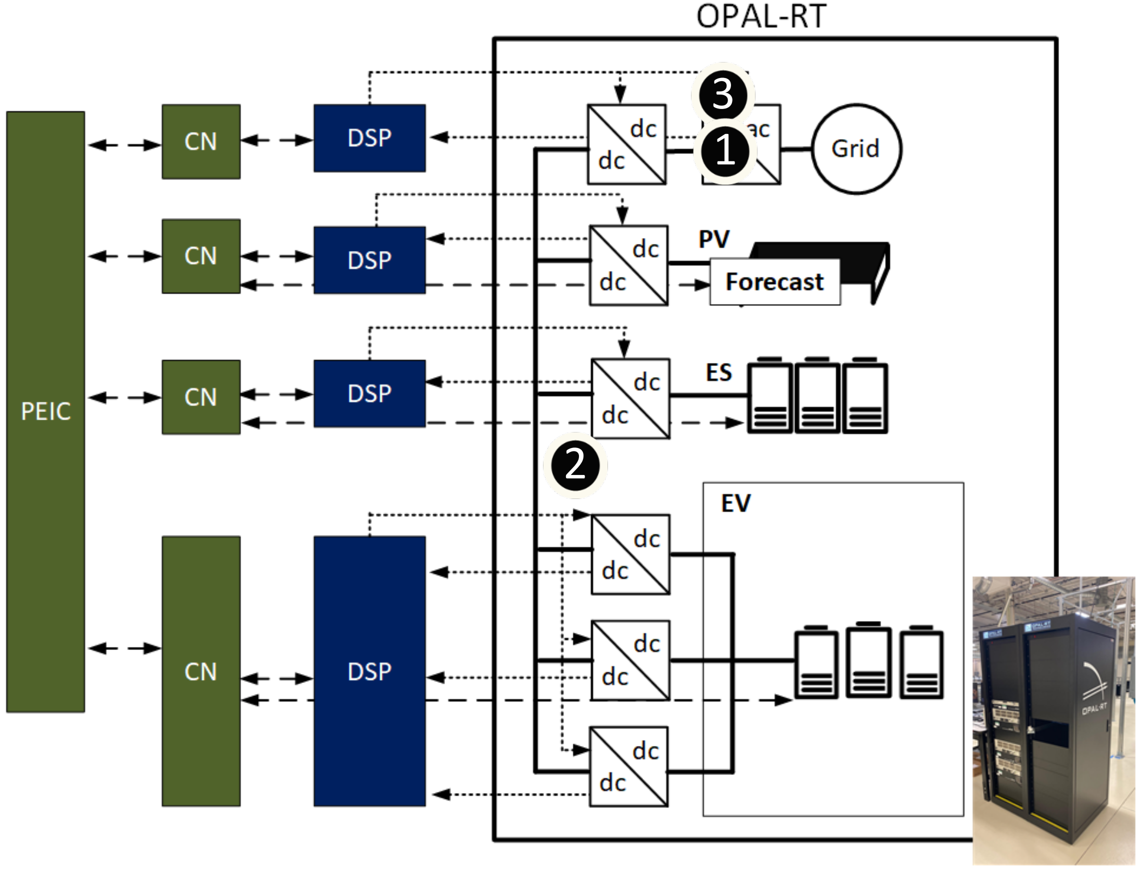
Technical Accomplishments and Progress:

Task 11 – Startup and Shutdown of Resources in Simulation

PE Interface Controller | Grid Interface, ES, PV, EVSE Controllers

Model of a single 1+MW port
EMT Simulation (EMegaSim)





1) Start of HIL Simulation
2) Start-up Sequence Commenced
3) Pre-chargeing sequence
4) Converter start-up complete
5) Load Change from 1.2MW to 500kW
6) Shut-down sequence commenced
7) HIL Simulation Complete

Technical Accomplishments and Progress:

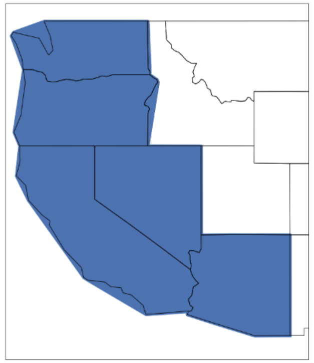
Task 6 – Site Utilization and Load Profile

21st CENTURY TRUCK PARTNERSHIP℠

- Supporting the 21st Century Truck Partnership to identify charging infrastructure technology targets.
  - Cost of charging from site utilization and equipment requirements
- Linear programming used to define usage vs charge needs in Western Region
- Dataset is from telematics of conventional CL 8 vehicles

Class 8 Tractor Dataset Description

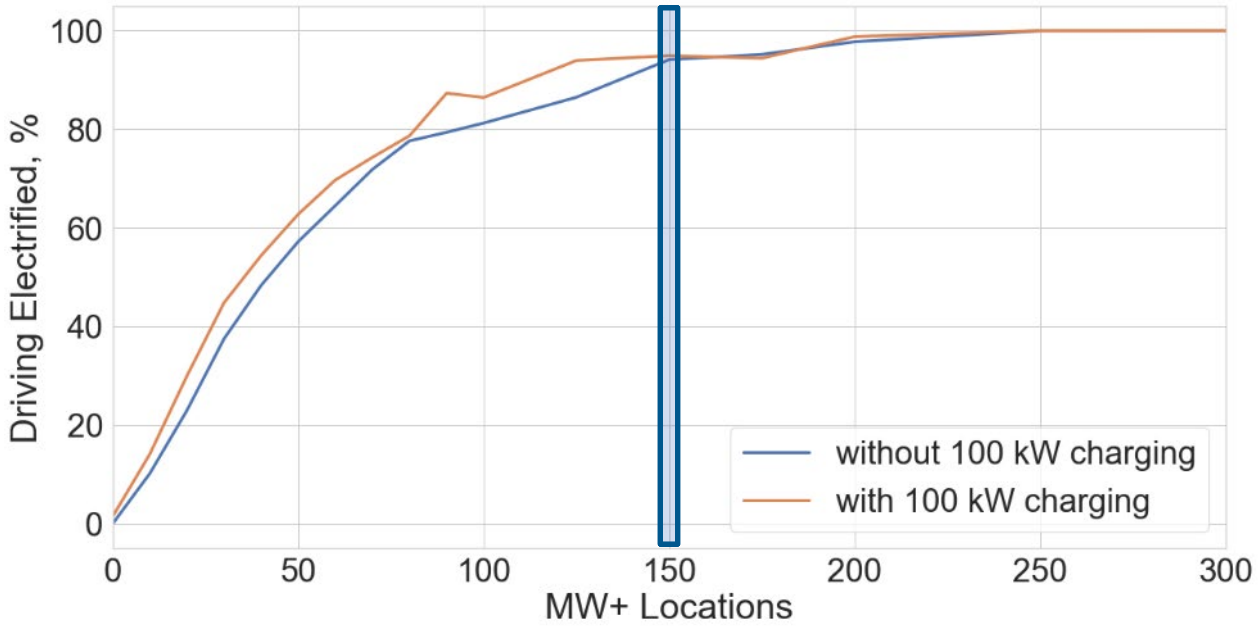
	FAF VMT/day	Dataset VMT/day
All of USA	290M	17.23M
5-state region	31.35M	2.16M
5-state exclusive	-	0.716M

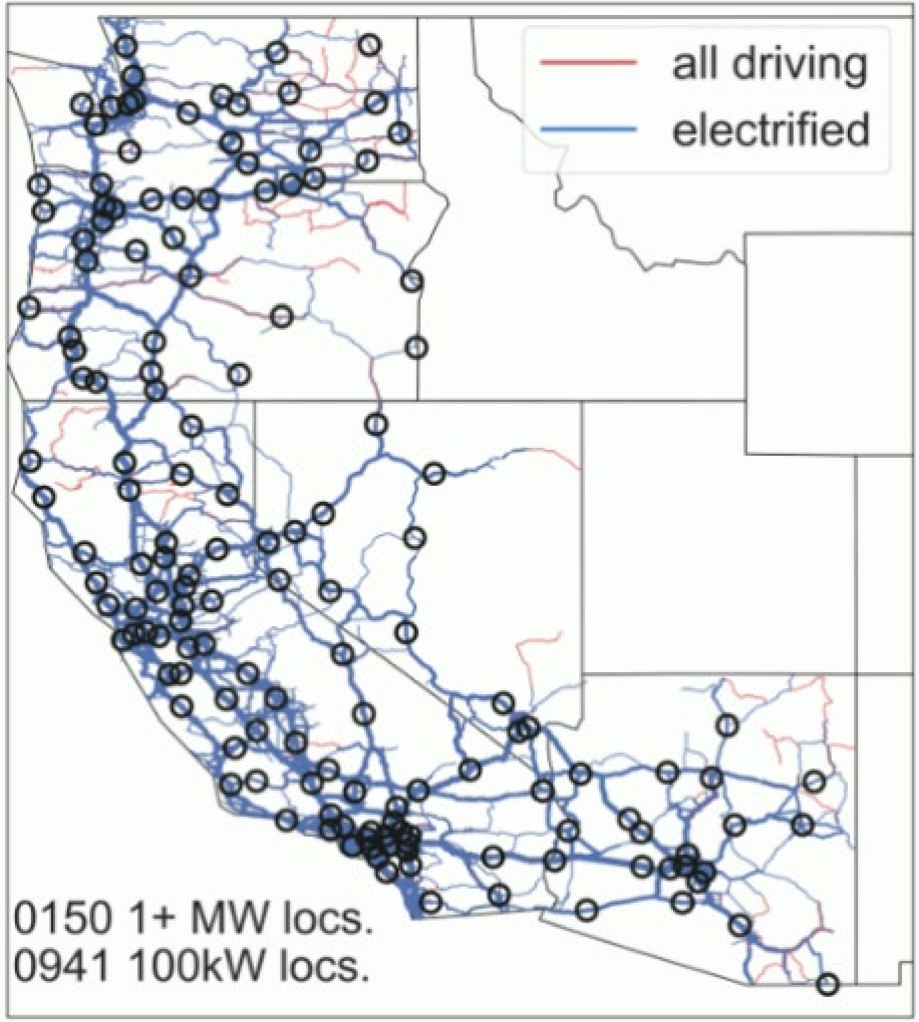


5-state exclusive uses data from trucks which did 100% of their driving in AZ, CA, NV, OR, and WA.
10 to 12 M VMT/day estimated for FAF in 5-state exclusive zone.

Technical Accomplishments and Progress:

Task 6 –Site Utilization and Load Profile





- 1+MW Charging Infrastructure is the primary driver of vehicle electrification.
- California's major cities and shipping corridors are electrified first due to traffic density.

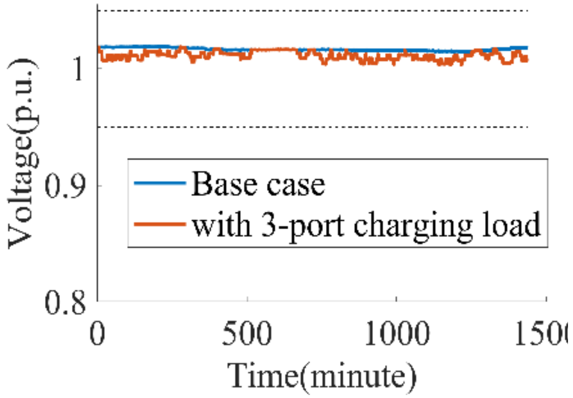
Technical Accomplishments and Progress:

Task 7 – Grid Impacts Analysis

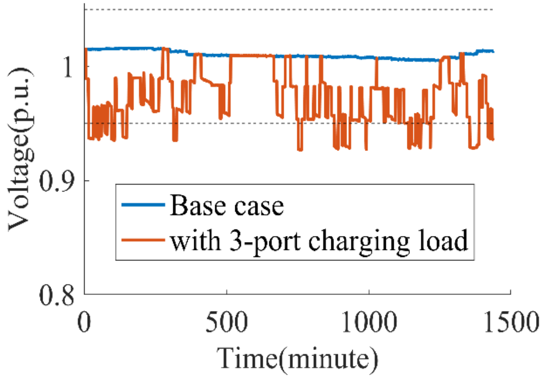
Site Controller

Distribution Feeder Model

One day voltage profile on selected best location

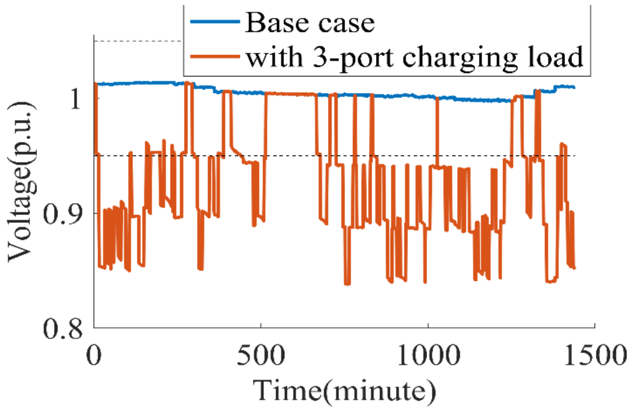


One day voltage profile on selected good location



- ✓ Voltage sensitivity analysis [1] to determine best- and worst-case areas for HD charging stations
- ✓ Four representative distribution systems including different single-feeder cases and multi-feeder cases have been selected for grid impact analysis
- ✓ Impact mitigation solutions have been developed using onsite PV and ES and reactive power support from charger

One day voltage profile on selected worst location



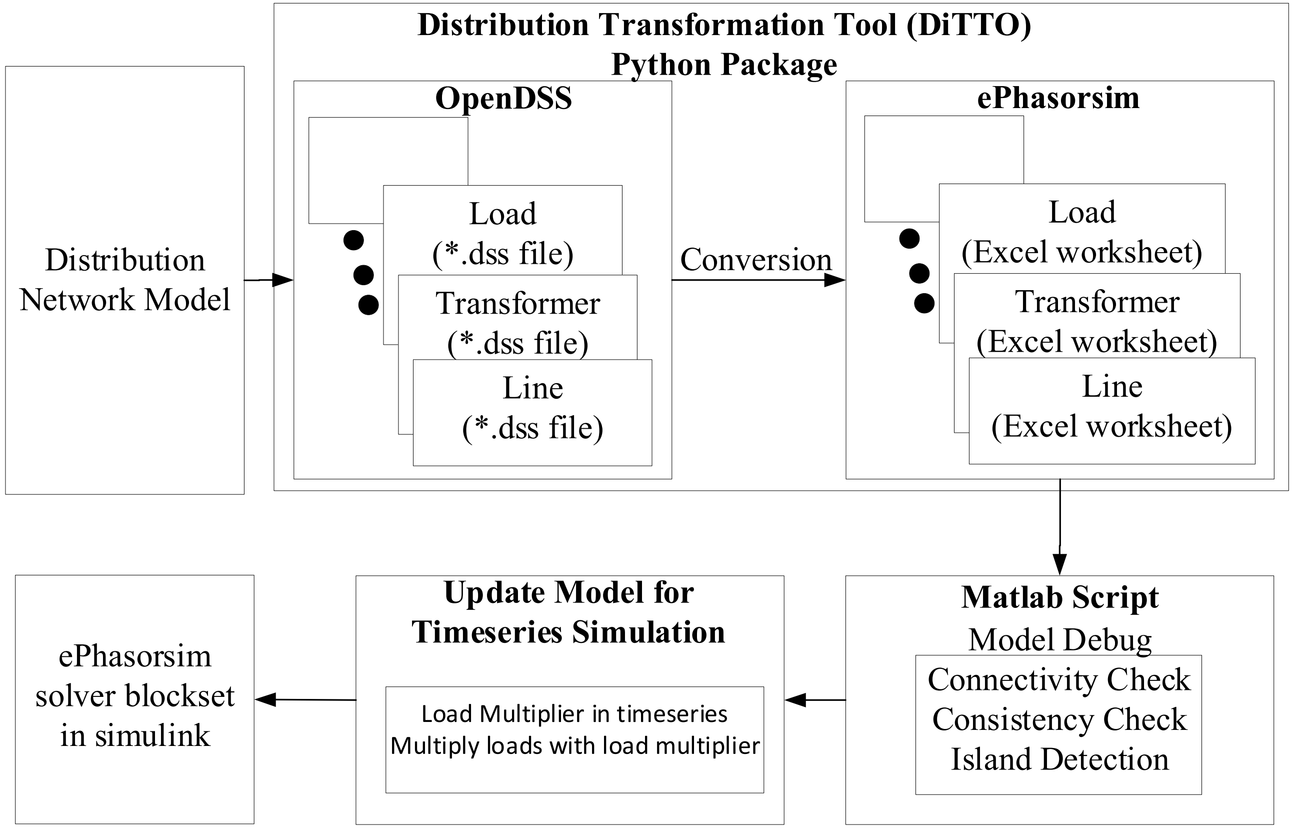
[1] Xiangqi Zhu, Barry Mather and Partha Mishra, "Grid Impact Analysis of Heavy-Duty Electric Vehicle Charging Stations", Proc. of 2020 Conference on Innovative Smart Grid Technologies (ISGT), 2020 IEEE

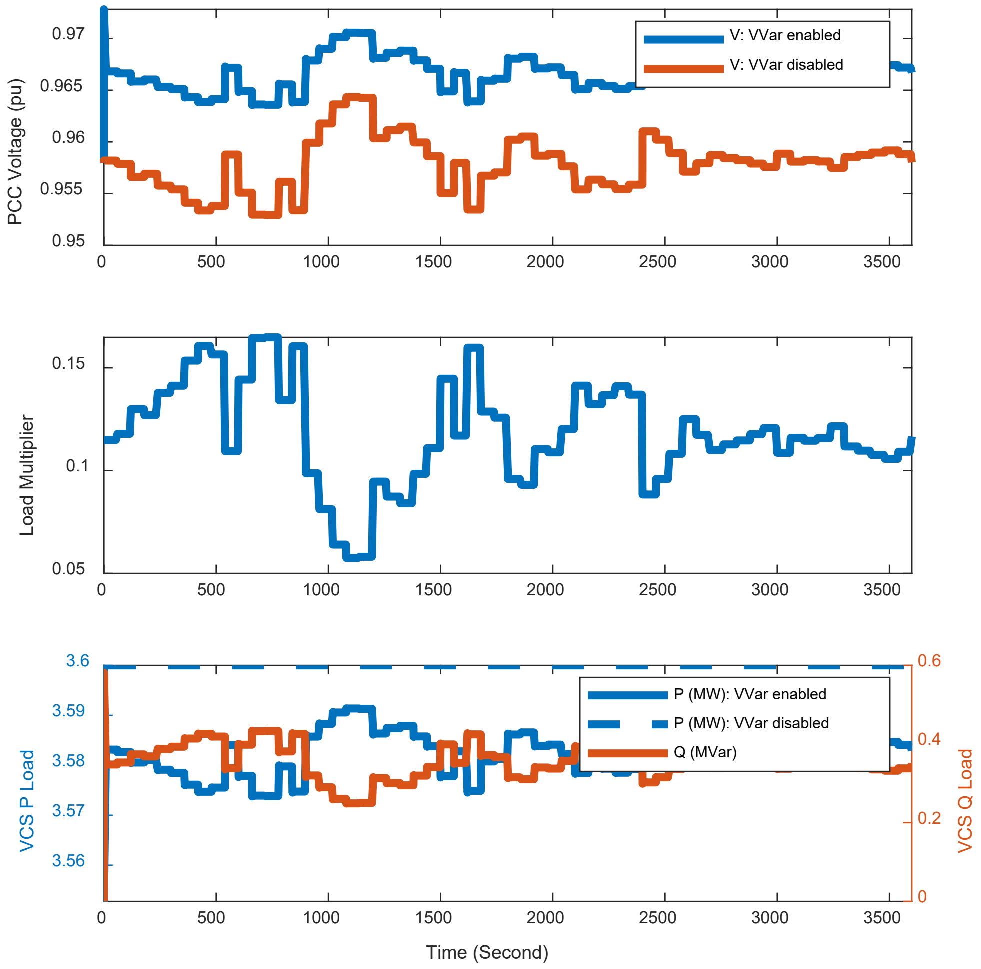
Technical Accomplishments and Progress:

Task 7/10 – RT-EMS and Dist. Network Real-Time Simulation

Distribution Feeder Model

A Model conversion process, from OpenDSS to ePhasorSim, for real-time simulation



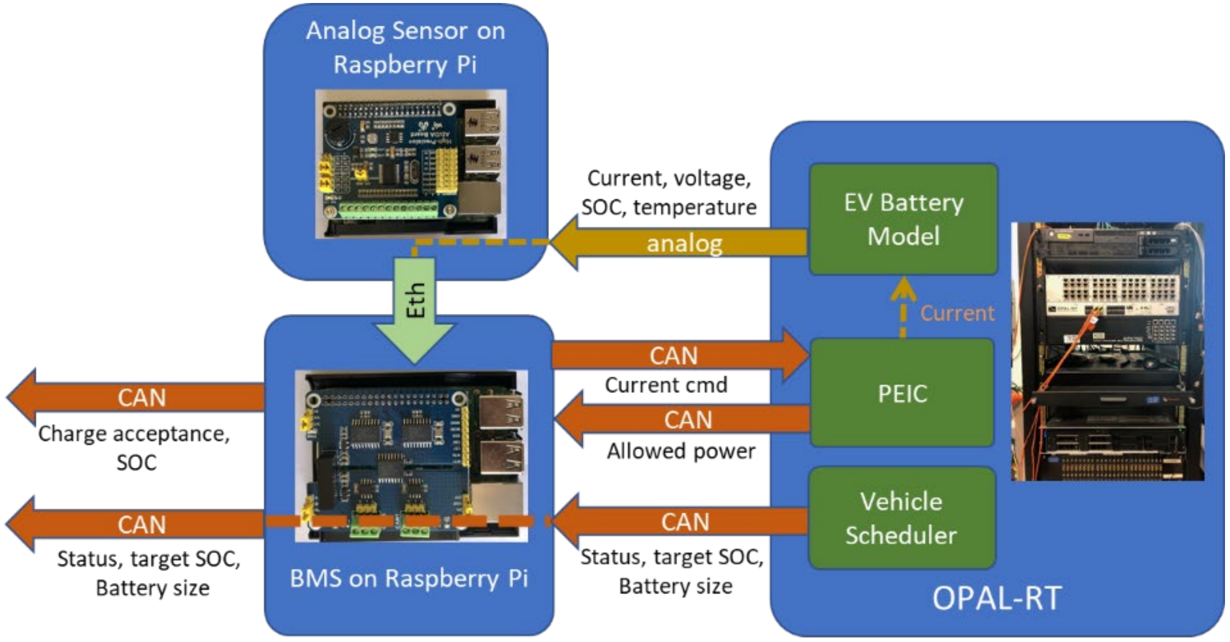


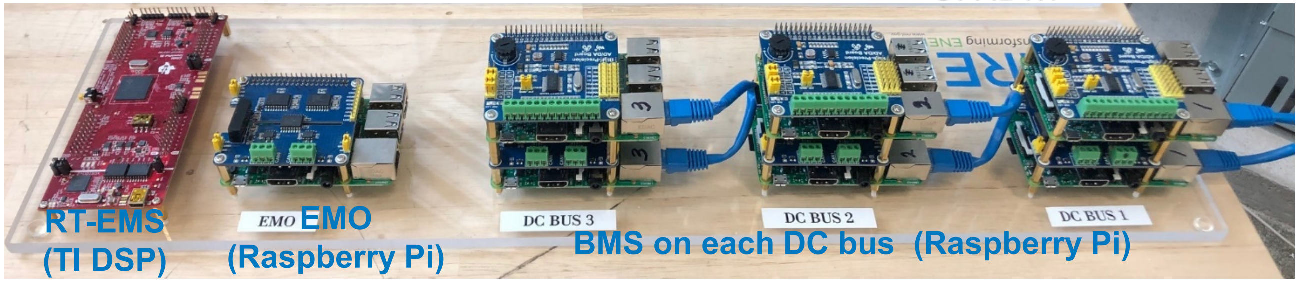
Technical Accomplishments and Progress:

Task 8 – Battery Load Profile and Optimal Charge Control

Vehicle Battery Management System

- **Objective** of Battery Charging emulation:
  - (a) Implement battery management system's (BMS) charging algorithm using real-time hardware,
  - (b) Demonstrate adaptivity of BMS charging algorithm in response to change of reference setpoint from site controller
- **Algorithm**: Model predictive control (MPC) framework using electrochemical-thermal models of Lithium-ion battery
- **Real-time hardware**: algorithm resides on a raspberry pi, acting as the BMS





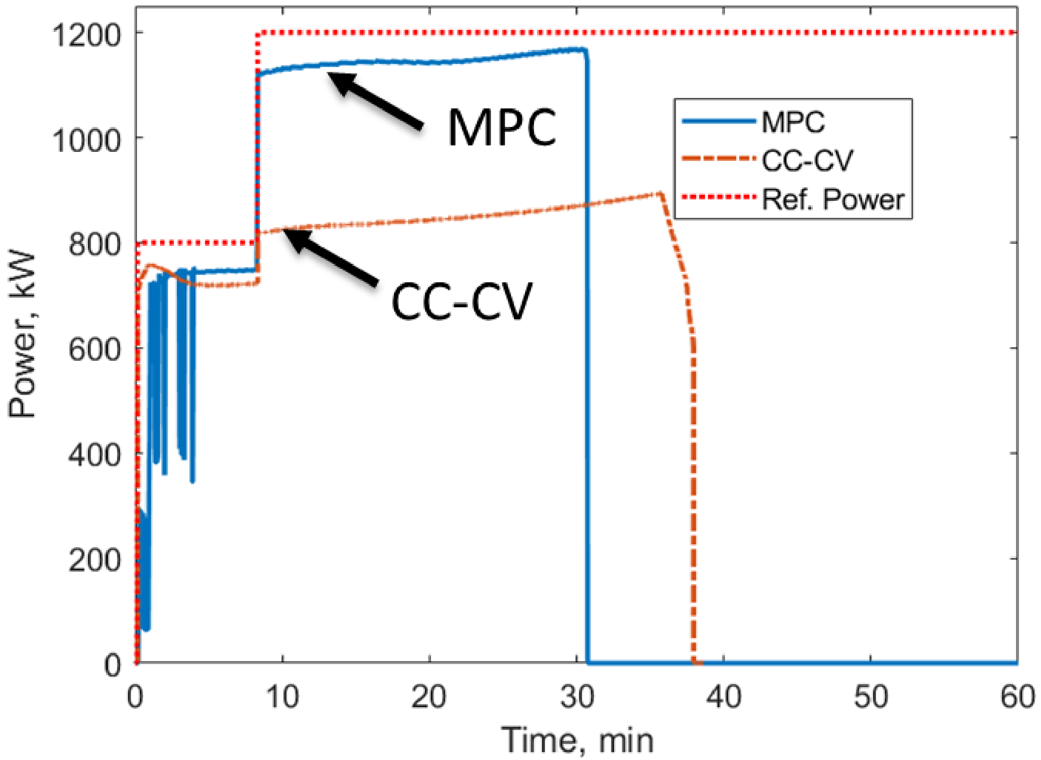
Embedded Controllers for Site Controller and Vehicle BMSs

Technical Accomplishments and Progress:

Task 8 – Battery Load Profile and Optimal Charge Control

Coordination between the Site Controller (EMO, RT-EMS) and the BMS of each vehicle

- **EMO optimizes the allotment of power setpoints** for every controllable load and energy source for the station
    - A critical input to the EMO is the battery's forecasted charging power outlook over a time horizon
    - This horizon is used to plan the charging across multiple charging ports, and DER at the site
- **BMS optimizes the charging current** using an MPC-based control algorithm such that the vehicle is charged as fast as possible while satisfying all operational constraint
- These results show that the BMS adjusts battery charge current command based on EMO reference power setpoints
- When compared with a conservatively designed CC-CV algorithm for the same power curtailment the MPC takes advantage of increased charging power allocation

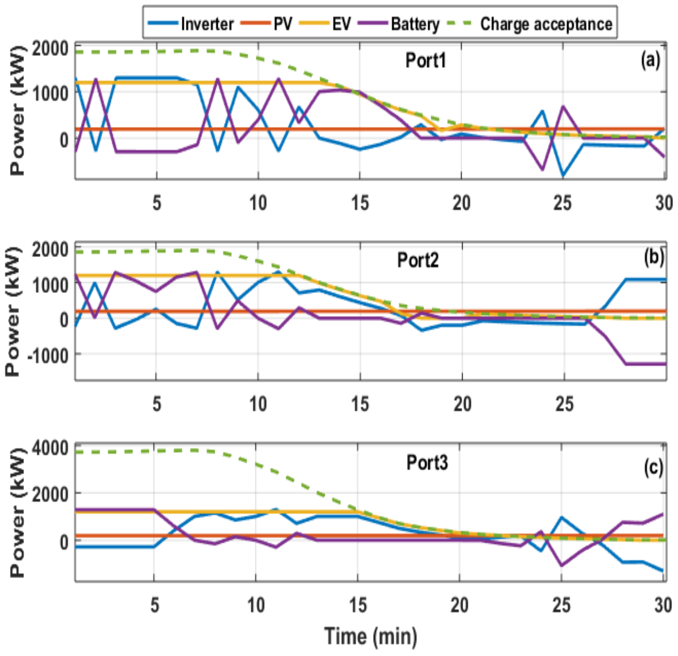


Comparison of CC-CV and MPC BMS response to EMO load curtailment

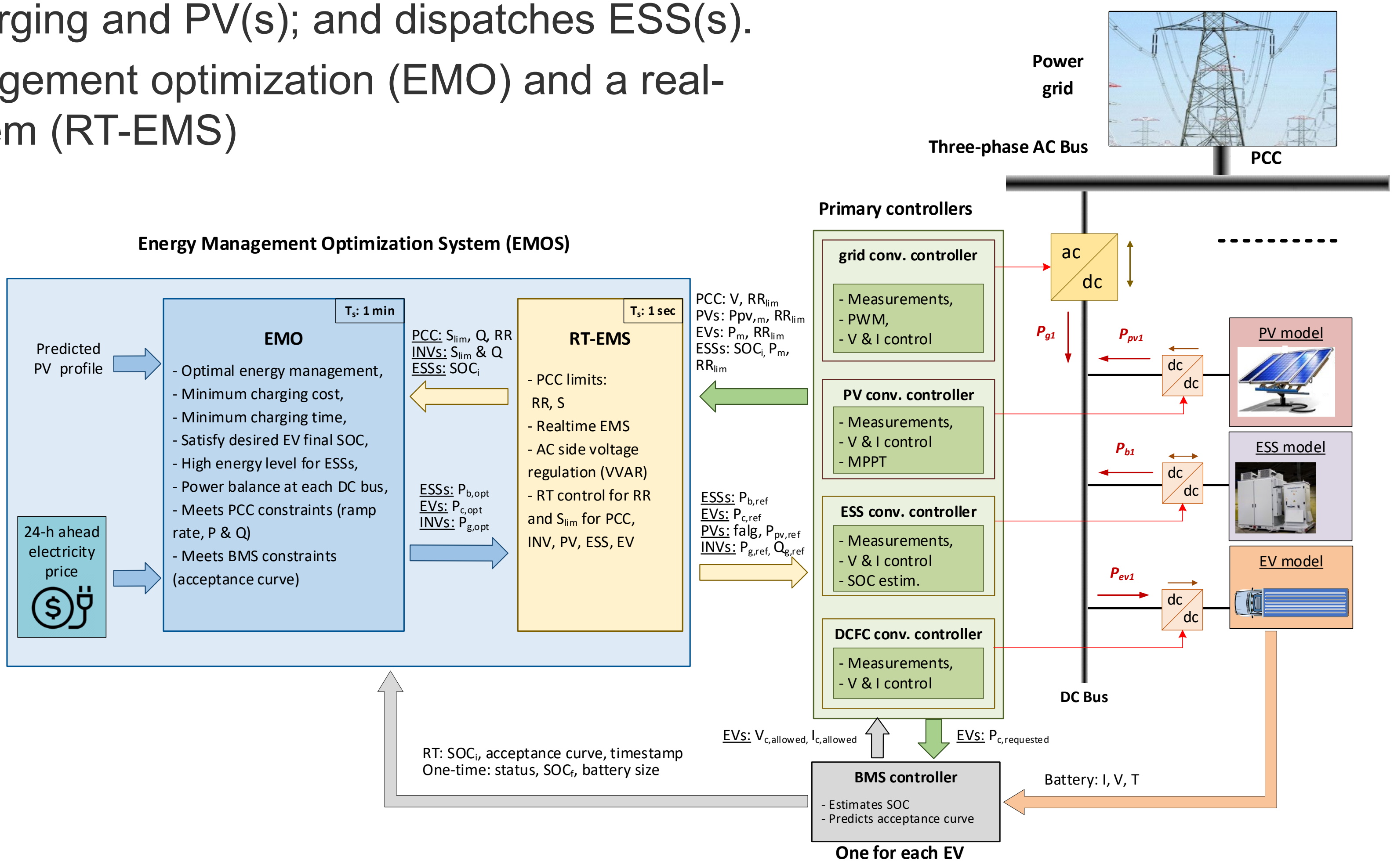
Technical Accomplishments and Progress:

Task 10 – Energy Management Optimization

- Site controller is a **bi-level real-time energy management system that manages operation** of EV charging and PV(s); and dispatches ESS(s).
- It incorporates an energy management optimization (EMO) and a real-time energy management system (RT-EMS)



30-minute EMO results for three-port station

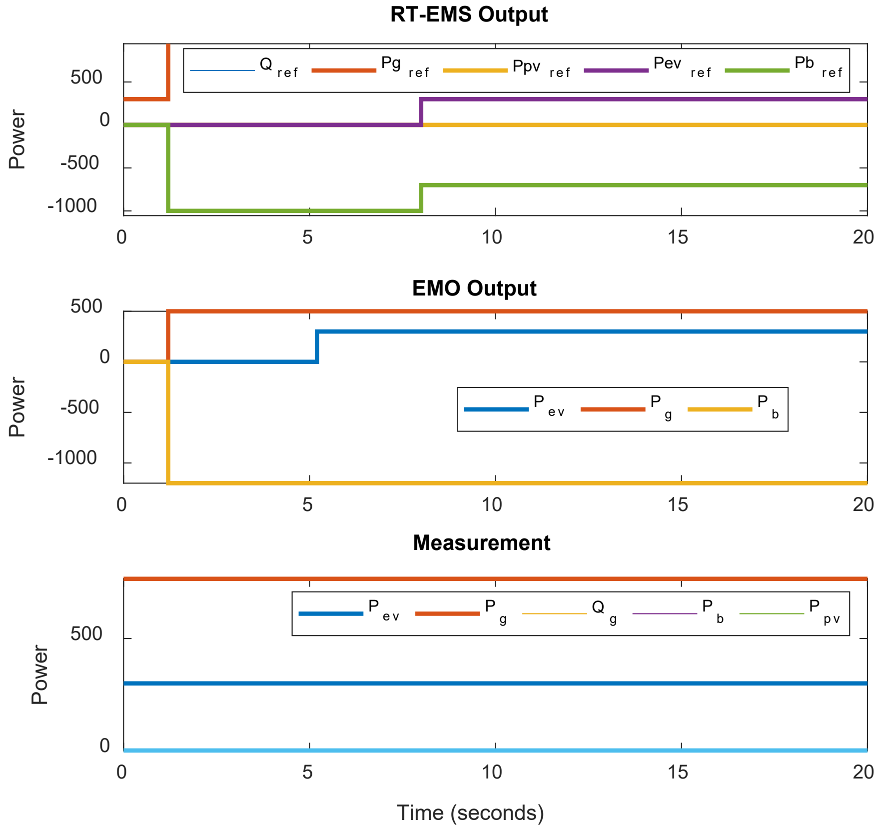


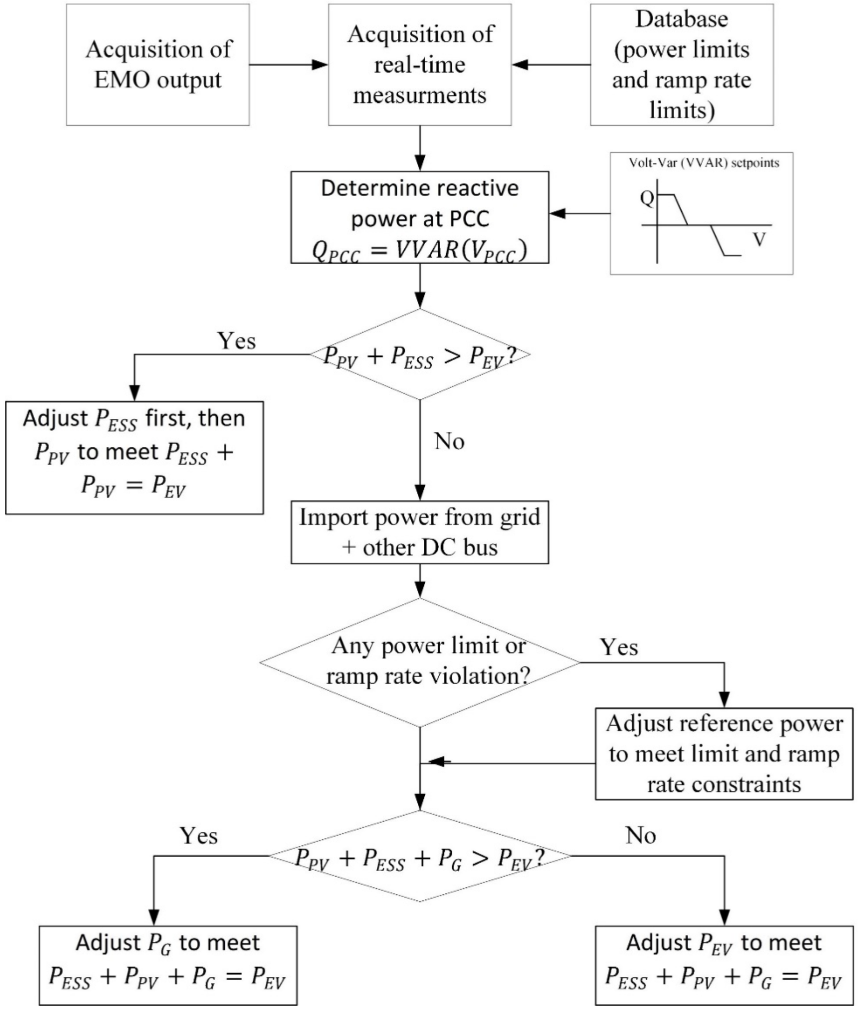
Technical Accomplishments and Progress:

Task 10 – RT-EMS

Site Controller | Real-Time Energy Management

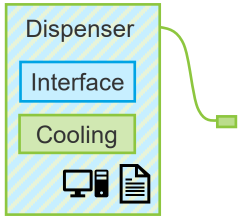
- RT-EMS adjusts the optimum control actions to compensate for fast disturbances:
  - Supports AC voltage using Volt-VAR method
  - Regulates site power within ramp-rate limits





Technical Accomplishments and Progress:

Task 12 – Design and Thermal Management of 1+MW Connector



- Supporting the CharIN Megawatt Charging System (MCS) Task Force to evaluate performance of prototype connector hardware from industry partners
  - Developed approach to support four levels of evaluations
    - Level 0: Unpowered fit and ergonomics / mechanical strength
    - Level 1: Powered without cooling up to 350 A
    - Level 2: Powered with connector cooling up to 1000 A
    - Level 3: Powered with connector and inlet cooling up to 3000A
  - Developed draft hardware specification setup and shared with MCS task force members and industry partners
  - Developed experiment hardware designs for each evaluation level
- The first evaluation event was completed in Fall 2020 and results disseminated to the taskforce
- A second event planned for Summer 2021 (June/July) will support mechanical and further fit and thermal evaluation to support design results to support a standardization effort.

Thermal Evaluation

Fit and Ergonomics Evaluation

Technical Accomplishments and Progress:

Task 13 / 14 / 15 – Industry Engagement and Recommendations


Released Draft- December 2020

Metering for multiport DC charging systems could require many measurement points with communication between each subsystem. Figure 22 shows typical communication standards for function blocks. These include Open Charge Point Protocol (OCPP, charger to system host), ISO15118 (vehicle to charger), Sunspec (P2030.5, PV inverter), MESA (storage control), and OpenADR/DNP3 to the SCADA-site controller.

Current sensors for DC distribution at MW+ power levels will require accurate, rugged, and modestly priced solutions. Figure 23 shows a differential fluxgate magnetometer-based magnetic field sensor that needs no flux concentrating core. This sensor is based on the Texas Instruments DRV425 5mm square surface mount IC. The geometry of the differentially mounted flux sensing IC in the center of the bus bar leverages the sum of magnetic fields due to current flowing in each half of the bus bar on either side of the sensor to infer current in the bus bar. Also shown is the GMW Hall type CP series bus bar current sensor that fits in tight spaces and has good stray field rejection from adjacent conductors.

FIGURE 23 TI DRV425 bus bar current sensor (left), GMW Hall type CP bus bar current sensor (center), Riedon 250A-1000A isolated active 'smart shunt'(1.25v output), MagnaPower 4000A bench power supply for testing connectors and current sensors (right). {T. Bohn photos}

This sensor has been bench tested at better than 0.5% accuracy up to 1000A with a component cost under $10, using a single 5v power supply. Embedding the sensor in the bus bar also reduces required space for metering in crowded high power/high current distribution equipment. Isolated amplified shunt type current sensors can achieve better than 1% tolerance across full temperature range for under $100. The Riedon SSA smart shunt is shown in figure 23 (250A, 500A, 1000A versions) with the exposed signal conditioning circuits (Texas Instrument AMC1302). The ANL Magnapower 4000A power supply used to test high current sensors and meter accuracy for DC distribution systems (DCaaS, DC charging) is shown on the right in figure 23.

The **ANL-developed 40x60mm DC meter**, shown in Figure 24 (left), has 4500vdc of isolation and mounts directly to low cost (.1% accuracy) manganin temperature stabilized shunt sensor (500A shunt shown here; matching CCS couplers, optional OLED display not shown). Another version with a $0.50 pot box enclosure on an sub-$100 smart-shunt, up to 1000A range in a compact footprint is also shown. The LEM DCMB meter is shown on the right (1000v-

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Released Draft- December 2020

600A), purpose built for DC charging systems with sensor module and remote display/metering head. The array on the lower row include the Porsche Engineering DCEM-1000, Isabellenhuette IEM-DCC-500-1000, Tritium proprietary designed DC meter, AcuDC 243, and Measurlogic DTS-DC meters. Lower left is the Isabellenhuette IVT-S-500-U3 voltage/current transducer with three voltage inputs and CAN data output. It is the foundation of the Isabellenhuette, LEM and Porsche meter solutions.

FIGURE 24 Example DC meters for EV charging, 1000vdc up to 5000A; {Photos by T. Bohn}

5.5 REGULATORY STATUS- COMMERCIAL TRANSACTIONS OF ELECTRICITY AS A FUEL

California will enforce NIST Handbook 44-3.40/5.55 for commercial sale of electricity as a fuel in January 2021. Other states will follow in the coming years with different phase-in schedules, California also requires compliance by 2033 all DC charging systems installed before 2023. Most EVSE manufacturers and EV charging network operators are preparing existing EV charging products to meet these requirements. Acknowledging the limited selection of DC meters for EV charging (in section 5.4), the only known gap in the state of readiness is test equipment for type evaluation of DC charging systems at these higher power levels. ANL has

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ANL/ES-20/6 report

- MD/HD truck-bus charging and DC as a Service distribution Topics:
  - Year 1: collect requirements from industry input; generate summary
  - Year 2: discuss case studies, develop use cases/test cases, test bed capabilities
  - Year 3: perform 3000A cable testing, communication signal testing, monthly meetings

- Sept. 2020 workshop hosted with mini-panel discussion by stakeholders from the ~450 member industry engagement group covering sub-transmission utility inter-connection to battery terminal charging pathway in megawatt level multiport charging systems.

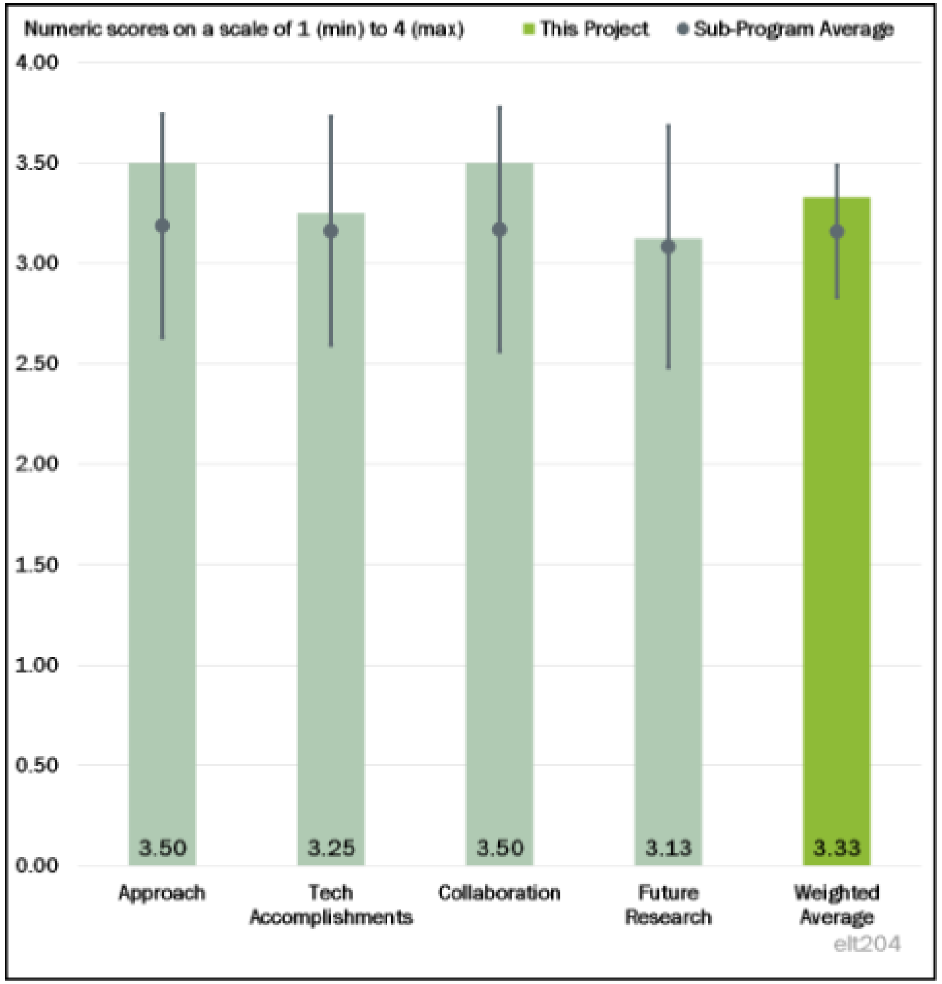
- FY19-20 version of **gap analysis report *"Industry Engagement Insights into MD/HD EV MW+ Charging systems"*** updated in FY21 with case studies and subsystem benchmark testing examples in support of the CharIN Megawatt Charging Standard (MCS).

- Successfully tested 3000A liquid cooled charging cables (without coupler) for losses and stability in tandem with physical layer communication interference testing. This testing is in support of interoperability within the weekly CharIN MCS safety and communication subcommittee meetings with industry subject matter experts.

Reponses to Previous Year Reviewer's Comments

Two concerns raised at the last AMR:

- *... how much scale can actually be achieved in what is being proposed… [as] scaling up to accommodate several vehicles at one time would need to be accounted for while attempting to dispense that much energy. How resilient would that be in the middle of the summer, especially for an air-cooled converter?*
  - <u>Response:</u> We are analyzing a 3-port system to show power balance; however, the grid analysis has shown locations on our feeders with up to 5-ports though this is location dependent. The thermal analysis for the analyzed system is capable up to a 50C environment
- *There should be more discussion regarding which parts of the project will be demonstrated in hardware and how the PI plans to execute the demonstration and evaluate and benchmark the results*
  - <u>Response:</u> The teams evaluation work will be in the controller hardware space with detailed models of the power electronics and the grid. Hardware evaluation of the charging connector is part of the CharIN MCS work.



Collaboration and Coordination

Multi-Lab Approach with Multiple Industry Partners

Three Lab Approach
- Vehicle Load & Charger Utilization (NREL)
- Power Stage Design and HIL (ORNL)
- Battery Analysis & Control (NREL)
- Grid Impacts and Interconnect Analysis (NREL)
- Develop Site Controller (NREL)
- Industry Engagement & Requirements Studies (ANL)

NREL Team:
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Shilpa Marti
Aswad Adib

1 Coordination across three labs

2 Key industry partner engagement through monthly webinars

3 Direct support of CharIN HPCCV Taskforce for connector development activities

- **Utilities, planning services, site operators**
  Black & Veatch, Burns & McDonnel, CTE, AEP-Ohio, Duke Energy, EPRI, MG&E, PG&E, Seattle City Light, Southern Company, CTA-Chicago, Electrify America, EVgo, Loves/Trillium, TA Petro
- **EVSE, power electronics, couplers/cable systems**
  ABB, BTCPower, Chargepoint, Delta Products, Eaton, Efacec, Heliox, Siemens, Tritium, Marquette Univ., JMM Consulting, Huber+Suhner, ITT, Phoenix Contact, Power Hydrant, Rema, Schunk, Staubli, TE Connectivity,
- **Vehicle OEM, end users/customers**
  Autocar Truck, BYD, Cummins, DTNA/Daimler, FCA , Ford, Gillig, MAN/VW Group, Navistar, New Flyer, Nova Bus, PACCAR/Peterbuilt, Proterra, Tesla, Thor, Transpower, Penske Leasing, Ruan Transportation
- **DOE Funded/Lab coordination**
  ANL, NREL, ORNL, U-Del, ThinkSmartGrid, EPRI

Remaining Challenges and Barriers

- Definition and refinement of 1+MW charging site scenario (distribution feeder and charger utilization) that will drive understanding and R&D
- 1+MW Charging System Emulation Platform
  - Availability and additional characterization of wide-bandgap medium-voltage industrial modules
  - Deployment of site controller optimization algorithm that balances grid interface requirements, onsite energy resources, and battery charging while maintaining real-time performance.

Proposed Future Research

- FY21:
  - Integration of the overall control and virtual 1+ MW multi-port charging system evaluation platform;
  - Verify through control HIL simulation the charging system response to grid disturbances, effectiveness of site control, and grid interface control capability to mitigating grid impact
  - Evaluation of power transfer mechanism using prototype hardware

	Description
Task 10	Evaluate smart control for overall site management in controller HIL environment using plant models for system components to include appropriate response and control
Task 11	Function validation of single multiport MW charging system through controller HIL simulation
Task 12	Perform analysis and modeling to evaluate power transfer mechanisms and develop prototype design for technology validation
Task 13 - 15	Identify standards gaps, perform interoperability testing; collect data for standards

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

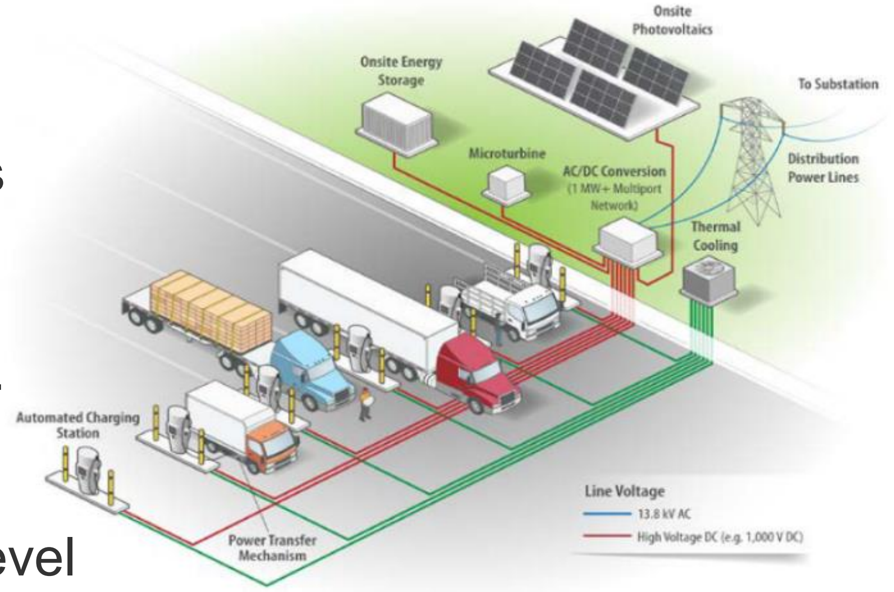
Challenges for Future Research

- Challenges to scaling-up for MW charging
  - Availability of high-voltage, high-current devices for power electronics
  - Switchgear, grid interface devices, interconnection requirements are needed for these multi-MW charging sites to support commonality
  - Circuit protection devices for very fast devices at high current DC for charging system fault protection.
  - There is a need to understand modularity across sites to support the correct balance
  - A common standard for MW charging connectors
- Standards for grid integration for charging systems to address the reactive power support and ramping requirements for non-export.
- Transitioning to the power-hardware-in-the-loop environment for validation of control approaches
- Charging profiles and battery design to support greater than 3-C charging rates for en-route charging

Summary

This project will:

1) Address challenges and develop solutions for **1+ MW systems through a national laboratory and industry collaboration**
2) Overcome barriers to deployment of a 1+ MW-scale integrated charging station and provide answers to fundamental questions associated with the feasibility of the system
   - Identify hardware component needs
   - **Develop and test hardware and system** designs
   - Develop design guidelines and performance metrics
   - Assess potential **grid impacts and grid services**
3) Develop safe systems and smart energy management techniques, including on-site resource sizing and control.
4) Demonstrate through controller hardware-in-the-loop the **real-time operation of a 1+MW charging system** to analyze grid integration, power electronics control, site-level energy control, and system communication requirements.



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Thank You !
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Technical Back-Up Slides

Technical Back-Up Slides:

Task 1 / 2 / 3 – PE Topology Review, Simulation, and Selection

Attribute	Metric	Architecture		
		DC Coupled Arch.	AC Coupled Arch.	MV-CHB Arch.
Efficiency	Semiconductor Losses	Lowest in pure-DER mode	Lowest during pure-grid mode	Balanced
	Overall System Efficiency	94-98%	92-95%	95-98% Minimize number of parallel stages
	Standby Efficiency	Good	Good	Good
Performance	Transient DC Voltage Stability	Better	Good	Best
	Grid-side voltage stability	Best	Poor	Good
	Advanced Grid Support	Comparable	Comparable	Comparable
	Output current ripple control	Good	Good	Best
System Ratings	Active device ratings	Good	Good	Best, Low due to Modular converter structure
	Low Frequency Stepdown Transformer	Required	Required	Not Required
	AC-side breaker and switchgear requirements	High-current AC interface	High-current AC interface	Low-current AC interface
Scalability	Modularity	Good	Good	Best
	System Scalability	Good – Parallel systems required in BOS	Poor – Parallel systems required in BOS, stages for DER inclusion	Best – minimum BOS for multi-MW installation

CHB: Cascaded H-Bridge
DER: Distributed Energy Resource
MV: medium voltage
BOS: Balance of System

Best Overall Performance and Balance of System Utilization

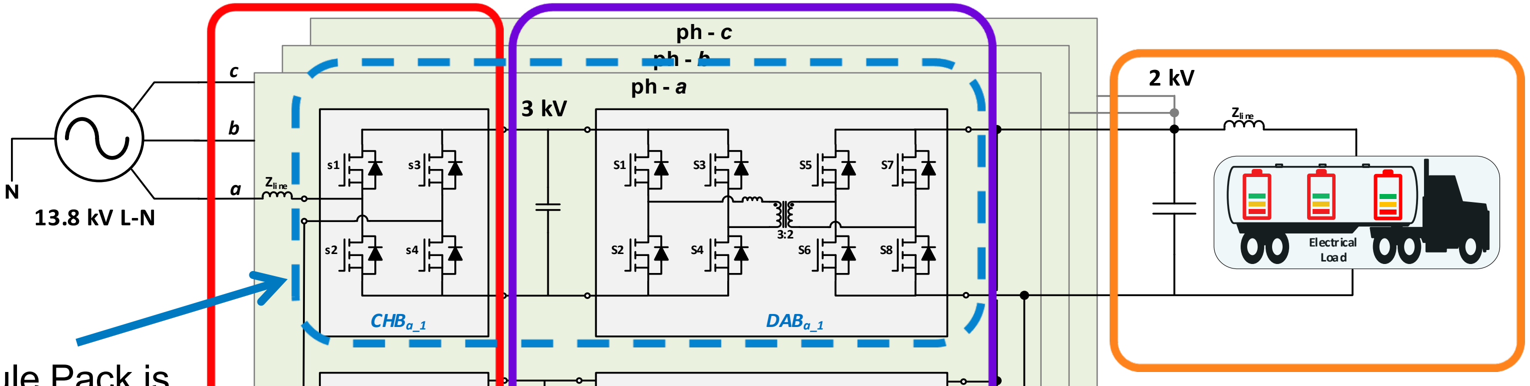
1. Efficiency: initial evaluation based on semiconductor losses and refined with passive element losses
2. AC and DC Coupled based on 480V class which limits switch utilization
   - Optimization for wide-bandgap (WBG) introduction for increased switching frequency and higher voltage consideration
3. Complexity of adding DER to system

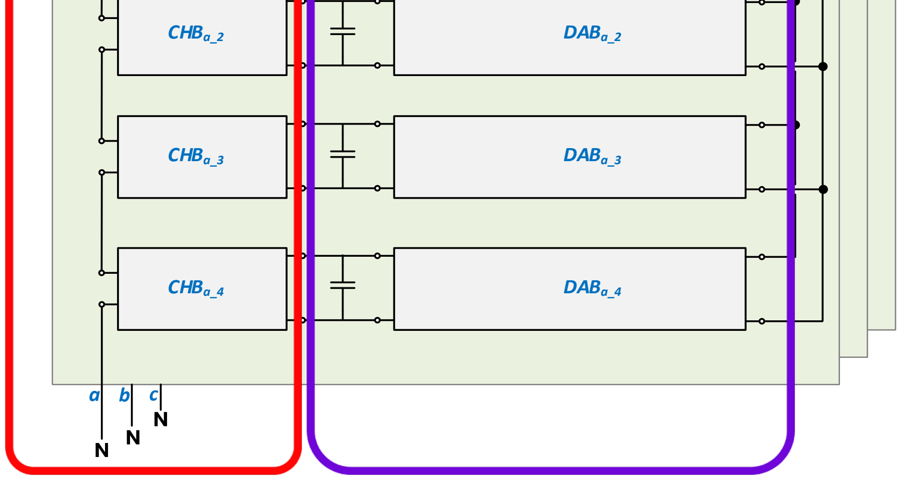
Technical Back-Up Slides:

Task 1 / 2 / 3 – PE Topology Review, Simulation, and Selection

CAD Models of PE Hardware

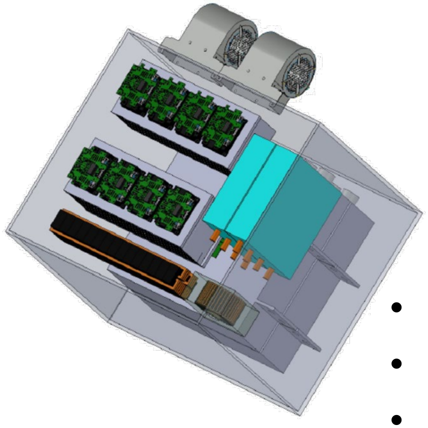
UPDATE



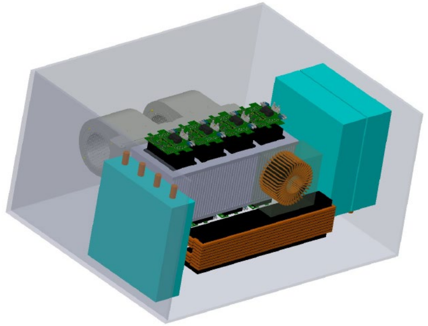


Each Module Pack is 300 kW

- 4 Module Packs Per Phase (1.2 MW)
- 12 Module Packs Total (3.6 MW)



- CHB-DAB 300kW Module Pack (AC-DC, DC/DC isolated)
- Air Cooled
- Max Output Power: 300 kW
- Output Voltage: 2000V DC



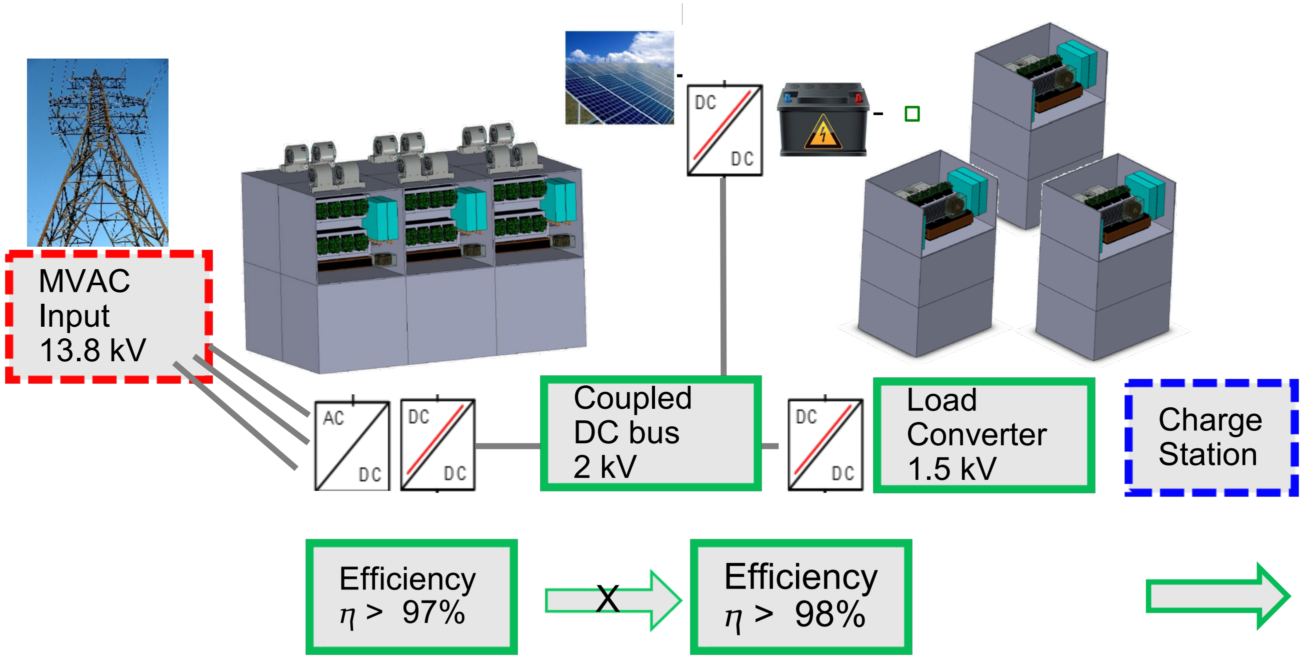
- Load Converter Module Pack (Isolated DC/DC)
- Air Cooled
- Max Output Power: 400 kW
- Output Voltage: 1500V DC

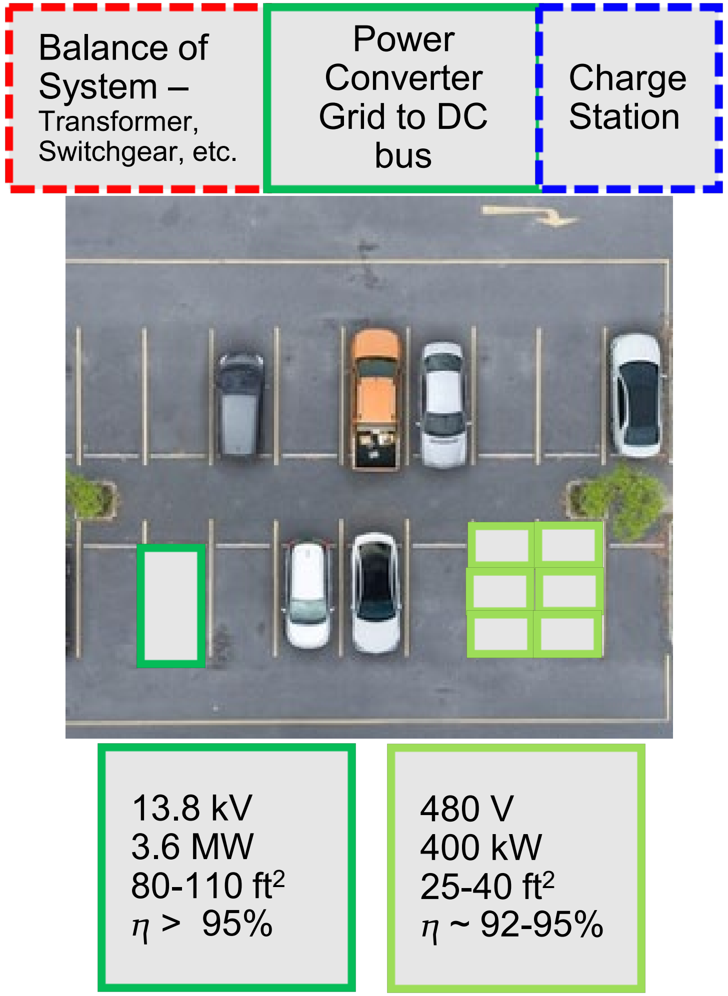
Technical Back-Up Slides:

Task 4 / 5 – MW+ Charging Equipment and Module Control

CAD Models of Hardware

- Estimate 2X improvement in Power Density in MV architecture
- Expect BOS comparison to improve the Power Density further
- Potential for increased efficiency both at PE and BOS





Technical Back-Up Slides

Task 7 – Grid Impacts Analysis

Site Controller

Distribution Feeder Model

Distribution Systems: Best Location	Feeder Requirements						Note
		Ramp Rate		Peak Charging Load		**Smart Charger Capacity (Reactive Power support) Requirement ****	
		Without mitigation (MW/min)	With mitigation (MW/min)	Without mitigation (MW)	With mitigation (MW)		
IEEE standardized test case: IEEE 34-bus system	Nominal	2.00	5.00	3.50	6.50	Total Capacity: 8.23 MVA Q Capacity: 5.05 MVAR	
	Maximum	2.50	5.50	4.00	7.00		
Single feeder case: California feeder	Nominal	1.80	2.50	**1.80**	**30.00 ***	Total Capacity: 33.71 MVA Q Capacity: 15.37 MVAR	Voltage goes out of upper bound if use lower PF
	Maximum	2.00	3.00	2.00	31.50 *		
Two feeder case: Hawaii feeder M1&M2	Nominal	2.16	6.50	5.50	70.00 *	Total Capacity : 78.65 MVA Q Capacity: 35.86 MVAR	Voltage goes out of upper bound if use lower PF
	Maximum	2.20	7.00	6.50	75.00 *		
Dedicated feeder case: derived from California feeder	Nominal	2.17	5.22	19.50	47.00 *	Total Capacity : 52809kVA Q Capacity: 24079kvar	
	Maximum	2.22	5.33	20.00	48.00 *		

* Analysis for four representative distribution systems.
* This **shows best location**, the max load feeders can hold will be lower at other locations.
* Considering substation cap (e.g. 10MVA), with smart charger support, max **charge load can reach 5 times of that without any mitigation strategies** (e.g., 10MW V.S. 1.8 MW for single feeder case)
* If equipped with PV and energy storage, the feeders can handle higher charging load

* Total capacity will be limited by substation transformer and sub-transmission limitations

** Smart charger capacity calculated from nominal charging load with mitigation

Technical Back-Up Slides

Task 7 – Grid Impacts Analysis

Distribution Systems: Mediocre Location	Feeder Requirements						Note
		Ramp Rate		Peak Charging Load		Smart Charger Capacity (Reactive Power support) Requirement **	
		Without mitigation (MW/min)	With mitigation (MW/min)	Without mitigation (MW)	With mitigation (MW)		
IEEE standardized test case: IEEE 34-bus system	Nominal	0.06	0.15	0.06	0.15	Total Capacity: 0.19 MVA Q Capacity: 0.12 MVAR	
	Maximum	0.08	0.20	0.08	0.20		
Single feeder case: California feeder	Nominal	0.30	2.50	0.30	2.50	Total Capacity: 3.16 MVA Q Capacity: 1.94 MVAR	
	Maximum	0.35	3.00	0.35	3.00		
Two feeder case: Hawaii feeder M1&M2	Nominal	0.40	1.50	0.40	1.50	Total Capacity: 1.90 MVA Q Capacity: 1.16 MVAR	
	Maximum	0.50	1.70	0.50	1.70		
Dedicated feeder case: derived from California feeder	Nominal	n/a	n/a	n/a	n/a	n/a	
	Maximum	n/a	n/a	n/a	n/a		

** Smart charger capacity calculated from nominal charging load with mitigation