EVs@Scale
U.S. Department of Energy

EVs@Scale High-Power Charging (HPC) Pillar Deep-Dive Technical Meeting

John Kisacikoglu, NREL

April 23, 2024

U.S. DEPARTMENT OF ENERGY | Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

NREL/PR-5400-89760

Introduction and Overview of High-Power Charging Pillar

EVs@Scale Lab Consortium addressing challenges, developing solutions and enabling technologies for transportation electrification ecosystem

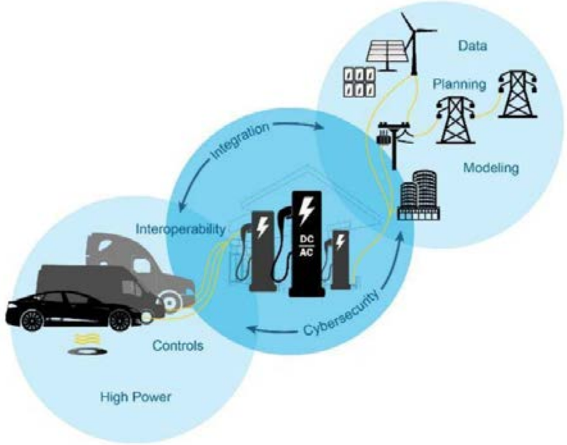
High-Power Charging: Bring together hardware and software expertise, capabilities, and facilities related to high power EV charging, charge management and grid integration

Deep-dive technical meetings providing opportunity for more industry engagement and technical feedback

Industry partnership is key for success.

High-Power Charging Pillar has two projects:

- Next-Gen Profiles (NGP)
- High-Power Electric Vehicle Charging Hub Integration Platform (eCHIP)



The EVs @ Scale Lab Consortium will consider these key components of the transportation electrification ecosystem

Agenda for Today

Time (EST)	Session	Presentation
11:00AM-11:10AM	Introductions and Overview	Executive Summary and Overview of Progress, **John Kisacikoglu (NREL)**
11:10AM-12:20PM	**Session 1:** Modeling and Analysis of High-Power Charging	• Next-Gen Profiles: Grid Modeling Using EV Profiles (20 min), **Sadam Ratrout (Argonne)** QandA and Discussion (15min) • Comparison of AC and DC Distribution Architectures for HPC Facilities (20 min), **Derek Jackson (NREL)** QandA (15min)
5-min Break		
12:25PM-1:45PM	**Session 2:** High Power DC Distribution System Operation and DC/DC Charger Integration	• DC-DC Universal Power Electronics Regulator (UPER) Testing and Integration (25 min), **Prasad Kandula (ORNL)** QandA (15min) • Commercial-off-the-shelf DC-DC Converter and SpeC Module Integration (20 min), **Akram Ali (Argonne)** QandA (20min)
Closing Remarks		

Next-Gen Profiles – Project Overview

Objective: Assess a portfolio of **EVs**, **EVSEs**, and **Fleets** that are expected to utilize High Power Charging (>200kW) to understand **charging rates**, **time**, **grid impacts**, and **asset utilization.** Provide DOE, project partners, stakeholders, and the public with insight into the capability of HPC and performance of today's charging infrastructure.

Outcomes:

- Assessment of assets under Nominal & Off-nominal conditions
- Assessment of conductive vs non-conductive systems
- Assessment of EV/EVSE fleet utilization & performance
- System responses to grid disturbances & charging management
- Unique & thoughtful methods of performance characterization
- Collaboration with OEMs & industry for:
    - Procedures development
    - Testing Assets
    - Report feedback

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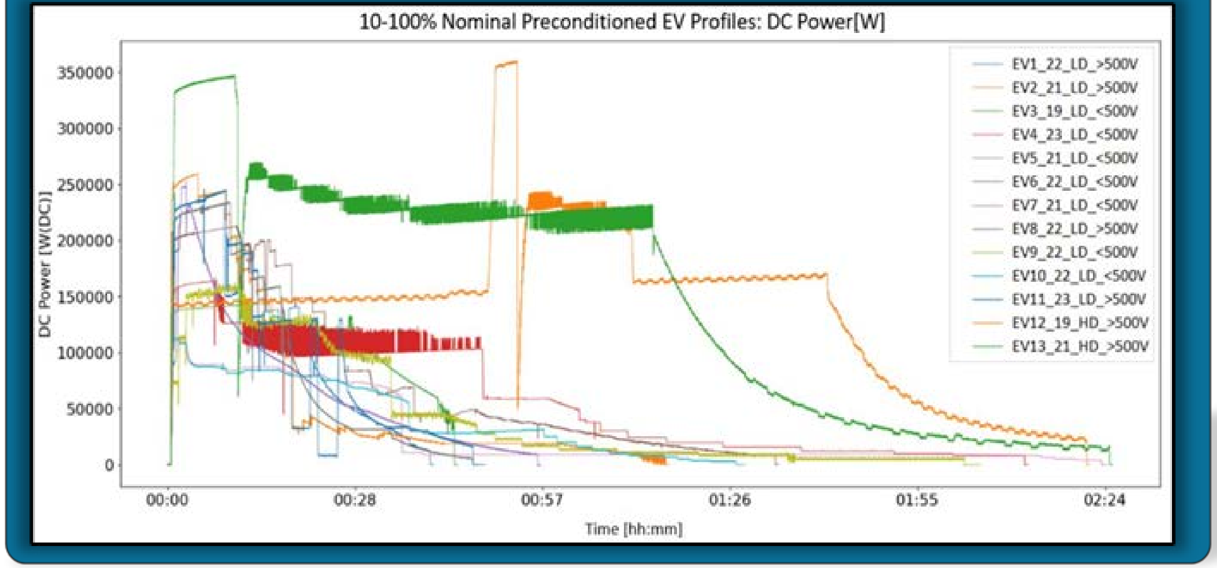
EV Profile Capture: 10-100% Nominal Preconditioned DC Power[W]



Next-Gen Profiles – Three Pillar Approach

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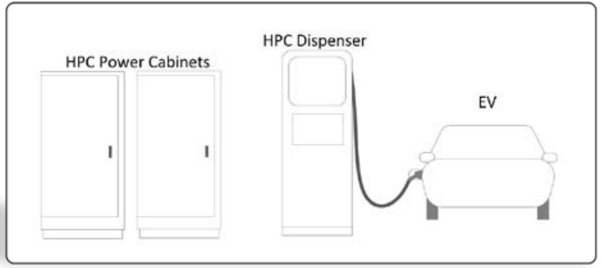
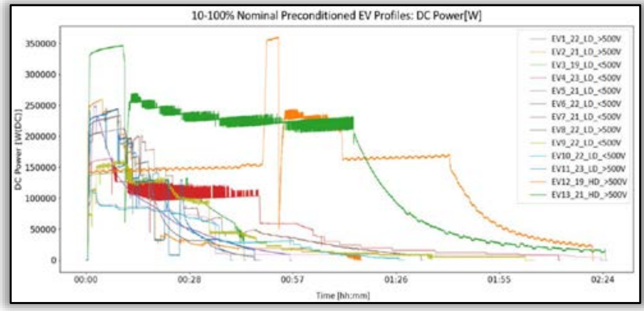
1. EV Profile Capture

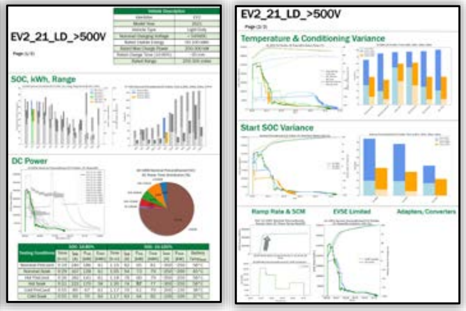


- **Assets**: Production EVSEs, Production EVs
- **Conditions:** SOC, Batt Temp, Vehicle Cond
- **Edge Cases:** Power/voltage limited, SCM, Adapters, WPT
- **Cadence:** 10Hz data, lab collected & processed

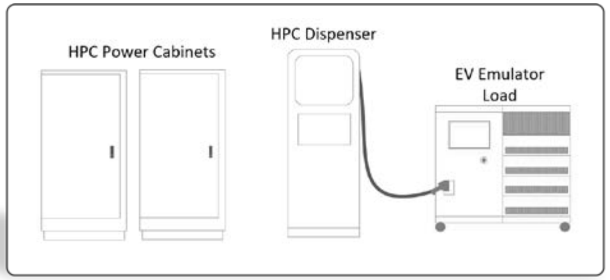
EVs Charge Profile Comparison



EV Boundary Condition Analysis

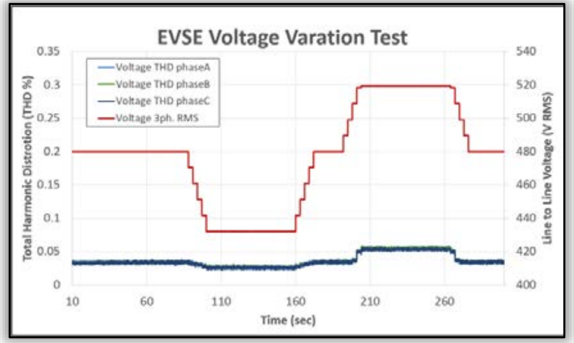


2. EVSE Characterization

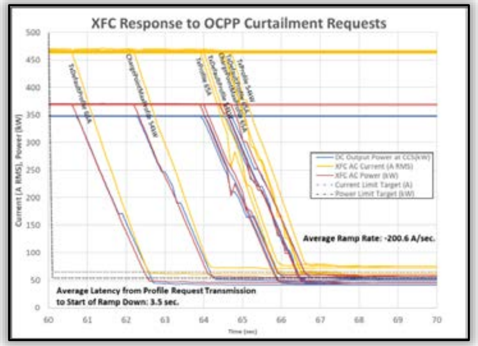


- **Assets**: Production EVSEs, Emulated EVs
- **Conditions**: Voltage, Current, Ambient temperature, Grid supply
- **Edge Cases:** Voltage deviation, Frequency deviation, Harmonics injection, High utilization, V2X, SCM
- **Cadence:** 10Hz data, lab collected & processed

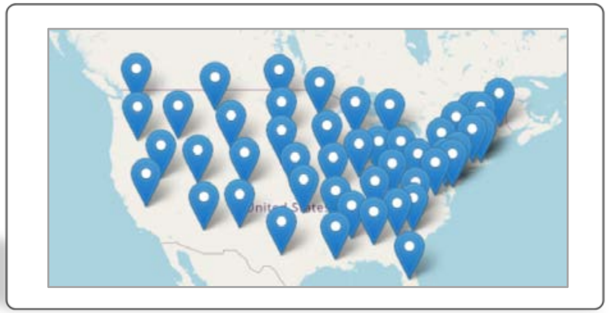
Grid Disturbance Analysis



Charge Management Analysis

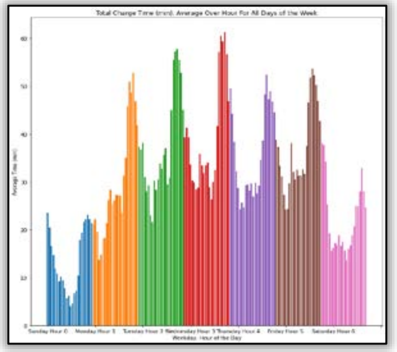


3. Fleet Utilization Analysis

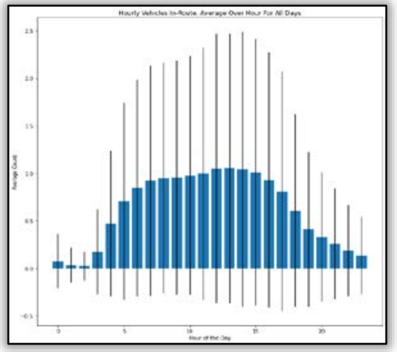


- **Assets**: Production EV and/or EVSE Fleet
- **Analysis**: Fleet description, Meta-data,
- **Time-series Categories:** Charging, Routing, Other
- **Cadence:** 1-minute data, fleet collected & lab processed in post
- **Analysis Types:** Hourly, Daily, Weekly, yearly, Totals and Averages

Weekly Charge Time Average



Daily In-Route Time Average



eCHIP – Project Overview

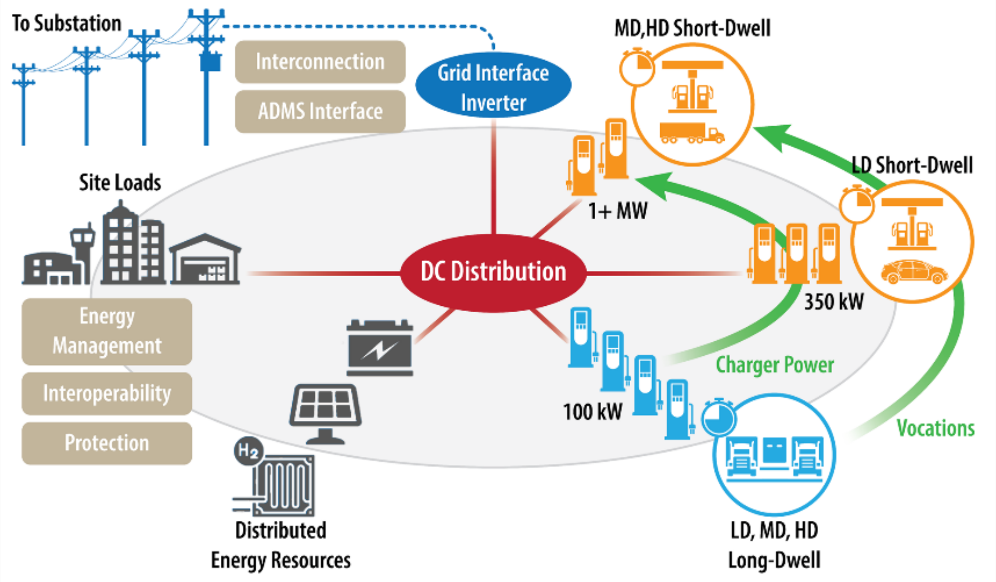
High-Power Electric Vehicle Charging Hub Integration Platform (eCHIP)

Objective: Develop plug-and-play solution allowing charging site to organically grow with additional chargers and DERs through predefined compatibility with standards that will ensure interoperability

Outcomes:

- Determine interoperable and scalable hardware, communication, and control architectures for high-power charging facilities
- Broadly identify limitations and gaps in DC distribution and protection systems that allow for modular HPC systems
- Develop and demonstrate solutions for efficient, low-cost, and high-power-density DC-DC for kW- and MW-scale charging

Argonne National Laboratory
NREL
Oak Ridge National Laboratory



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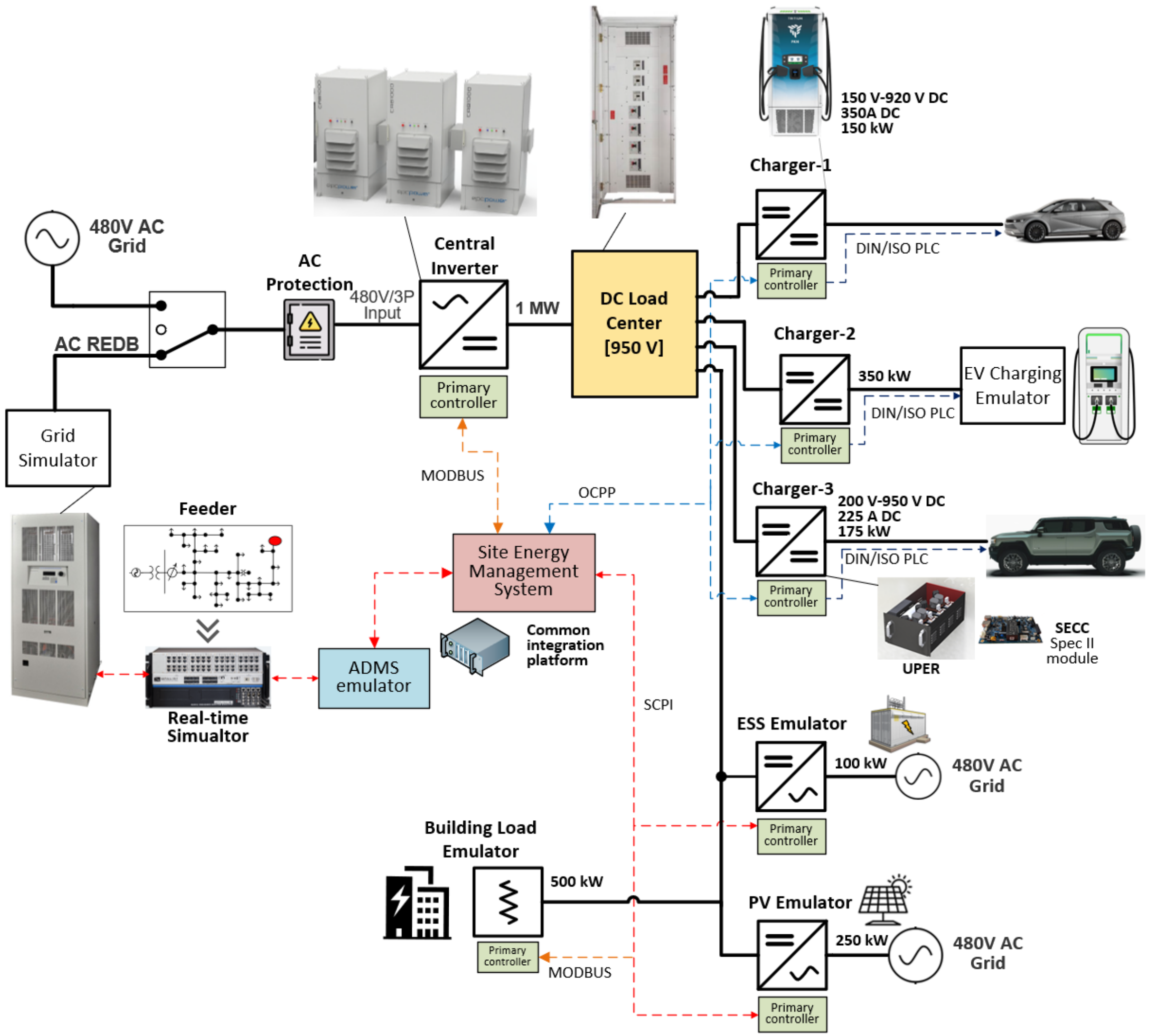
Proof of Concept DC Charging Hub Platform Overview

- Proof of concept test platform components
  - Grid-tie inverter
  - DC-distribution system
  - DC-DC charger
  - Real and emulated EVs
  - Battery ESS
  - PV emulation
  - Building load emulation
  - Open-source site energy management system (SEMS) platform
- DC hub platform explores:
  - <u>**SEMS control strategies**</u>
  - <u>**Communications and interoperability**</u>
  - <u>**Bidirectional grid integration operation**</u>



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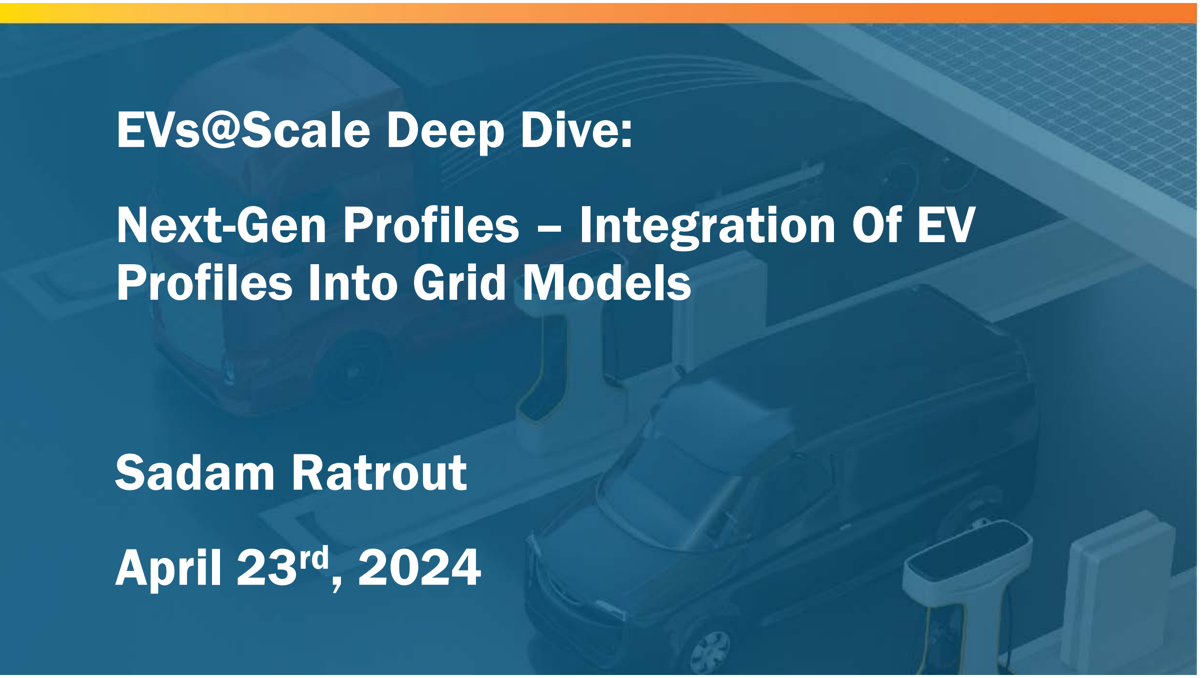

EVs@Scale Deep Dive:

Next-Gen Profiles – Integration Of EV Profiles Into Grid Models

Sadam Ratrout

April 23rd, 2024

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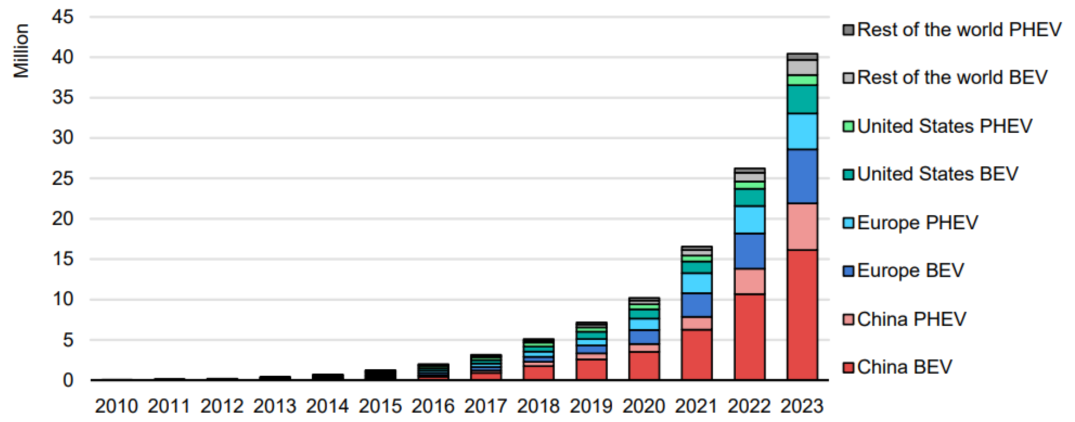
Introduction: Exponential Growth of EV Adoption

- Globally, around 14 million EVs were sold in 2023 (18% of all new cars sold).
- Q1 of 2024 showed a 25% increase in sales compared to the same period of 2023.
- It is estimated by the end of 2024 the total EV sales will reach 17 million, accounting for more than one in five cars sold worldwide. 13% increase compared to 2023.
- In the US By the end of 2022 there were 49,383 publicly accessible EVSEs.
- 6409 (13%) are DCFC stations with 24,932 ports, that mostly can deliver 150 kW or less. Some of these stations can deliver up to 350 kW.
- The number of DCFC ports has increased by 50.7% and reached 37,572 by the end of 2023.



IEA. CC BY 4.0.

Notes: BEV = battery electric vehicle; PHEV = plug-in hybrid vehicle. Includes passenger cars only.
Sources: IEA analysis based on country submissions and data from ACEA, EAFO, EV Volumes and Marklines.

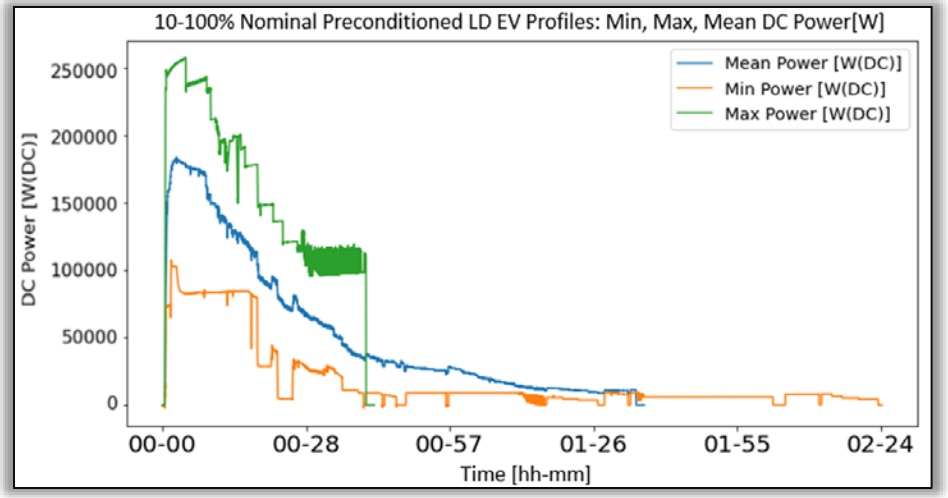
Global electric car stock trends, 2010-2023 [GEVO2024-IEA]

Introduction: Next-Gen Profiles (NGP) Project Overview

- EVs@Scale Consortium > HPC Pillar > Next-Gen Profiles

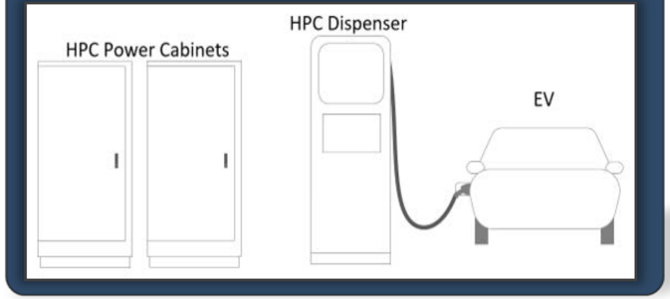
  "To further understand the most recent technological capabilities of the electric mobility industry related to charging performance."

- What to consider when assessing high-power charging (> 200 kW):
  - ➢ Nominal vs Off-Nominal conditions.
  - ➢ Conductive & Non-Conductive Equipment.
  - ➢ System responses to grid disturbances & charging management.
  - ➢ Unique & thoughtful methods of performance characterization.

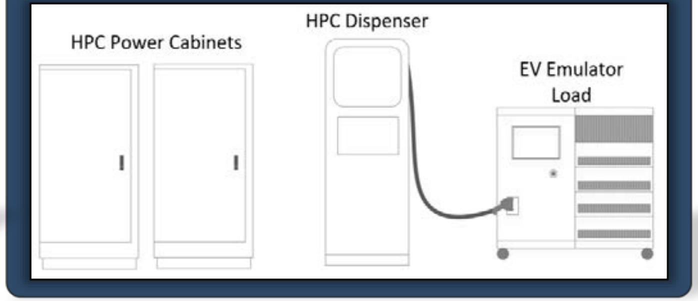


- Three categories of HPC under investigation in Next-Gen Profiles:

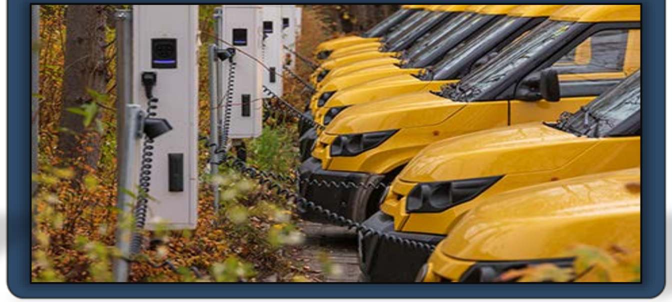
1. EV Profile Capture



2. EVSE Characterization

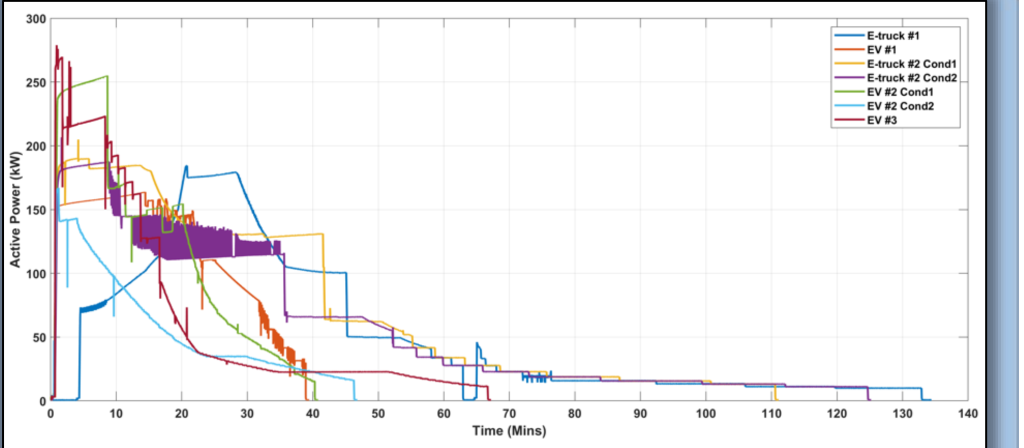


3. Fleet Utilization



EV Profile Capturing: Testing Assets & Conditions

- Previous developed study relied on theoretical charging profiles. This study uses real-world charging load profiles for E-trucks and EVs. The behavior and grid impact would be closer to reality.
- These charging profiles have been captured at ANL, ORNL, and NREL.
- EV Assets: Production EVs, rated 150-400kW DC charging
- EVSE Assets: Production DCFC (500A, 1000VDC), typically dual cabinet topology, multiple handle types
- Nominal test conditions:
  - 10-100% EV state of charge (SOC)
  - Nominal (23°C/75°F) ambient temperature
  - EV pre-driven/preconditioned for 30-40min prior to plug-in
- Off-nominal test conditions:
  - 25-100%, 50-100% EV state of charge
  - Hot (40°C/100°F), Cold (-7°C/20°F) ambient temperature
  - EV temperature soaked for 4-hours, or pre-driven 30-40min

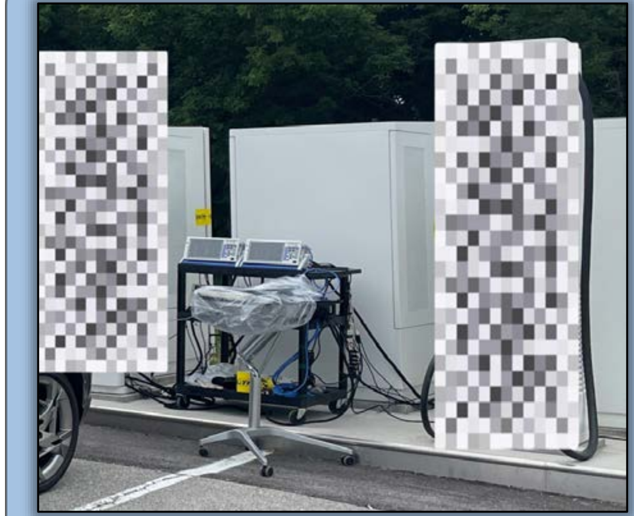


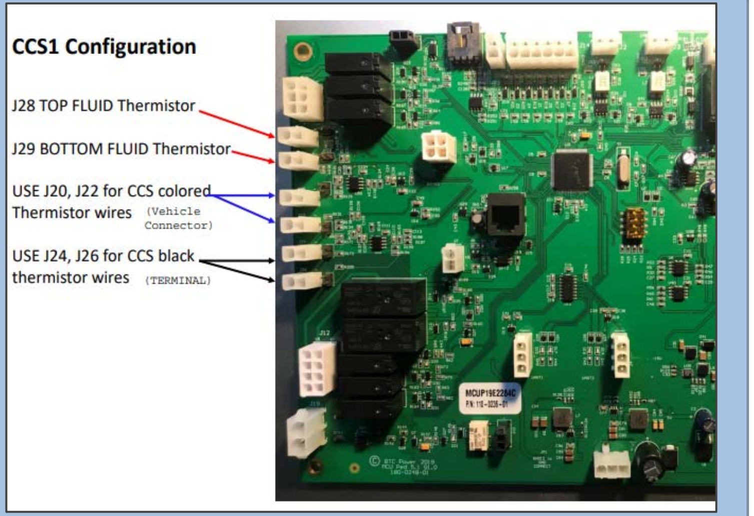
Sample of Real-world HPC Profiles for EVs and E-trucks

EVSE Condition Categories		Condition Metric Requirement	Tolerance
EVSE Power Limited		No Limit, Dual Tower (Nominal)	--
		Limited, Single Tower	--
Boost Converters		Not Utilized (Nominal)	--
		Utilized	--
Outside Ambient Temperature		23°C (Nominal)	± 2°C
		40°C (Hot)	± 2°C
		-7°C (Cold)	± 2°C
Smart Charge Management Scheduled	Request	FALSE (Nominal)	--
		TxProfile	--
	Duration	No Limit (Nominal)	--
		2 Minutes	--
	Scheduling	No Request (Nominal)	--
		2 (min) After Charge Session Start	± 1 (min)
	Value	No Limit (Nominal)	--
		65A (AC Input Current)	--
WPT Alignment	X-Direction	<5% coil length offset (Nominal)	± 2%
		10% coil length offset	± 2%
		25% coil length offset	± 2%
		40% coil length offset	± 2%
	Y-Direction	<5% coil length offset (Nominal)	± 2%
		10% coil length offset	± 2%
		25% coil length offset	± 2%
		40% coil length offset	± 2%
	Z-Direction	Unloaded (Nominal)	± 2%

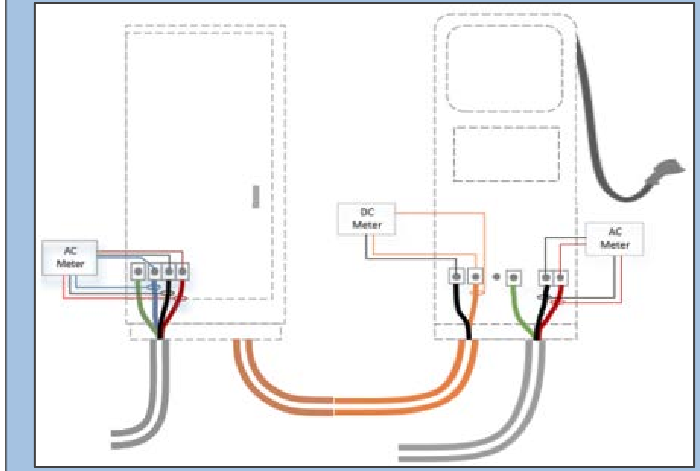
EV Profile Capturing: Measurement Locations & Signals

- **EVSE DAQ:**
  - AC grid input:
    - 3-phase current, voltage, and frequency
    - Real power, reactive power, power factor
    - Current THD, Harmonics (3rd, 5th, 7th, 9th)
  - DC output from power cabinets:
    - DC current, voltage, power, energy charged
  - Auxiliary loads:
    - Ancillary loads power (120VAC)
  - Component temperatures:
    - Liquid-cooled CCS cable & connector temperature at positive and negative
    - Power cabinet internal air temperature
- **EV DAQ:**
  - OBD-II Vehicle CAN data:
    - Display SOC, Actual SOC, Estimated range (based on SOC)
    - Battery avg/min/max temperature
    - Battery DC current, voltage, power


EVSE and DAQ equipment at ANL



EVSE Dispenser Temperature Sensors

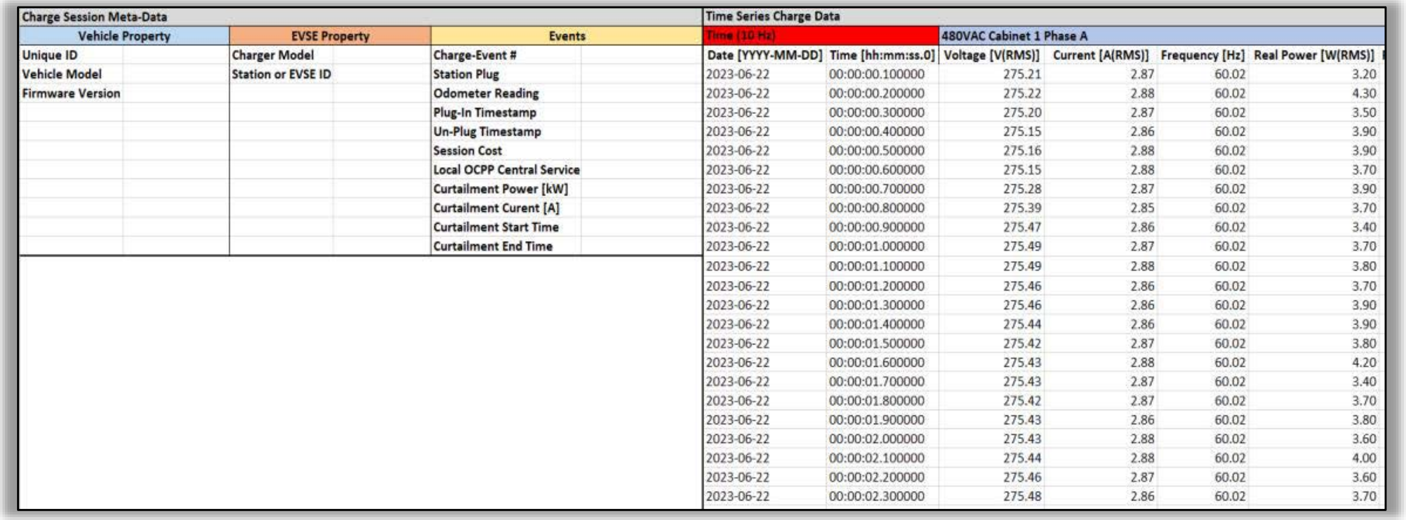


EVSE Cabinet & Dispenser Metering Locations


Vehicle data logging through OBD

Next-Gen Profiles: Data, Reports, & Procedures

- (x4) *Next-Gen Profiles* reports posted publicly to the OSTI portal from CY2023.
- (x1) Procedures Revision underway.
- (x4) NEW *Next-Gen Profiles* technical reports to be completed at the end of CY2024.
- Specific report on captured profiles can be found here:
  - https://www.osti.gov/biblio/2293478
- Anonymized 10 Hz and lowered cadence time-series data will be available soon.

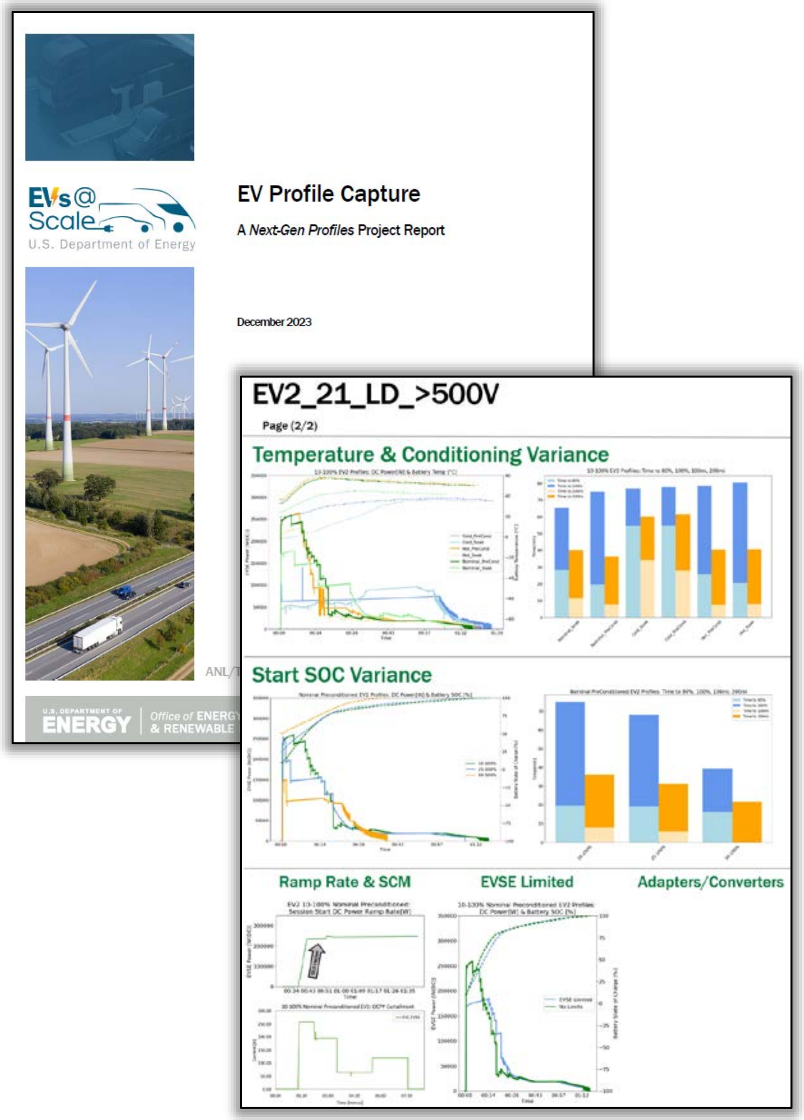


Charge Session Meta-Data

Vehicle Property	EVSE Property	Events
Unique ID	Charger Model	Charge-Event #
Vehicle Model	Station or EVSE ID	Station Plug
Firmware Version		Odometer Reading
		Plug-In Timestamp
		Un-Plug Timestamp
		Session Cost
		Local OCPP Central Service
		Curtailment Power [kW]
		Curtailment Curent [A]
		Curtailment Start Time
		Curtailment End Time

Time Series Charge Data

Time (10 Hz)		480VAC Cabinet 1 Phase A			
Date [YYYY-MM-DD]	Time [hh:mm:ss.0]	Voltage [V(RMS)]	Current [A(RMS)]	Frequency [Hz]	Real Power [W(RMS)]
2023-06-22	00:00:00.100000	275.21	2.87	60.02	3.20
2023-06-22	00:00:00.200000	275.22	2.88	60.02	4.30
2023-06-22	00:00:00.300000	275.20	2.87	60.02	3.50
2023-06-22	00:00:00.400000	275.15	2.86	60.02	3.90
2023-06-22	00:00:00.500000	275.16	2.88	60.02	3.90
2023-06-22	00:00:00.600000	275.15	2.88	60.02	3.70
2023-06-22	00:00:00.700000	275.28	2.87	60.02	3.90
2023-06-22	00:00:00.800000	275.39	2.85	60.02	3.70
2023-06-22	00:00:00.900000	275.47	2.86	60.02	3.40
2023-06-22	00:00:01.000000	275.49	2.87	60.02	3.70
2023-06-22	00:00:01.100000	275.49	2.88	60.02	3.80
2023-06-22	00:00:01.200000	275.46	2.86	60.02	3.70
2023-06-22	00:00:01.300000	275.46	2.86	60.02	3.90
2023-06-22	00:00:01.400000	275.44	2.86	60.02	3.90
2023-06-22	00:00:01.500000	275.42	2.87	60.02	3.80
2023-06-22	00:00:01.600000	275.43	2.88	60.02	4.20
2023-06-22	00:00:01.700000	275.43	2.87	60.02	3.40
2023-06-22	00:00:01.800000	275.42	2.87	60.02	3.70
2023-06-22	00:00:01.900000	275.43	2.86	60.02	3.80
2023-06-22	00:00:02.000000	275.43	2.88	60.02	3.60
2023-06-22	00:00:02.100000	275.44	2.88	60.02	4.00
2023-06-22	00:00:02.200000	275.46	2.87	60.02	3.60
2023-06-22	00:00:02.300000	275.48	2.86	60.02	3.70



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EV Profile Capture

A *Next-Gen Profiles* Project Report

December 2023

ANL/T

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Page (2/2)

Temperature & Conditioning Variance

Start SOC Variance

Ramp Rate & SCM

EVSE Limited

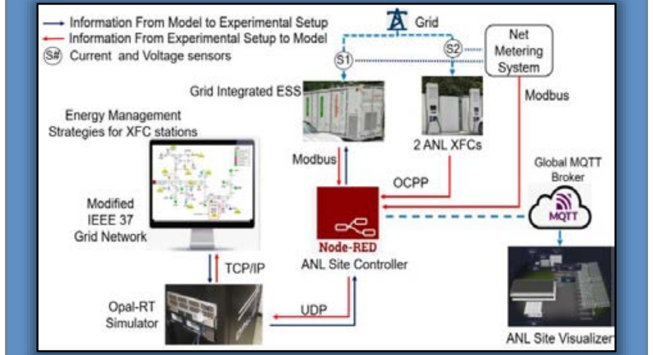
Adapters/Converters

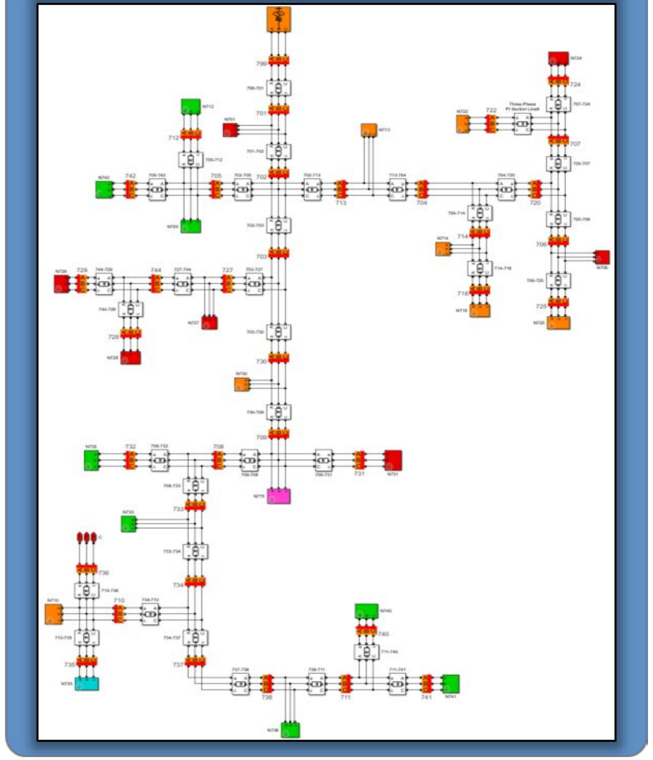
Next-Gen Profiles: Grid Utilization

- A project milestone is to integrate captured EV profiles into advanced grid modeling for utilization analysis.

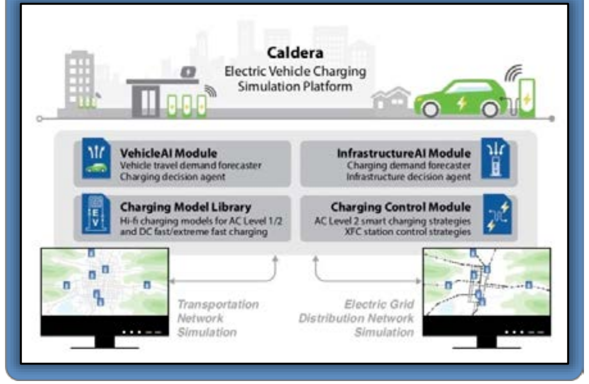
- Lab Models:
  - ANL: IEEE 37-bus HIL Grid Model.
  - INL: Caldera Simulation Platform.
  - NREL: EVI-X Modelling Suite.

ANL: IEEE HIL Grid Model





INL: Caldera Models



NREL: EVI-X Simulations

Three Types of Tools

Network Planning ›

Use these tools to quantify charging infrastructure needs such as:

- Number, type, and location of charging ports
- Recommended power levels and grid impacts
- Accessible and affordable charging
- Optimized charging for fleets and ride-hailing services
- Long-distance travel along highway corridors
- Utility partners for infrastructure installation.

Site Design ›

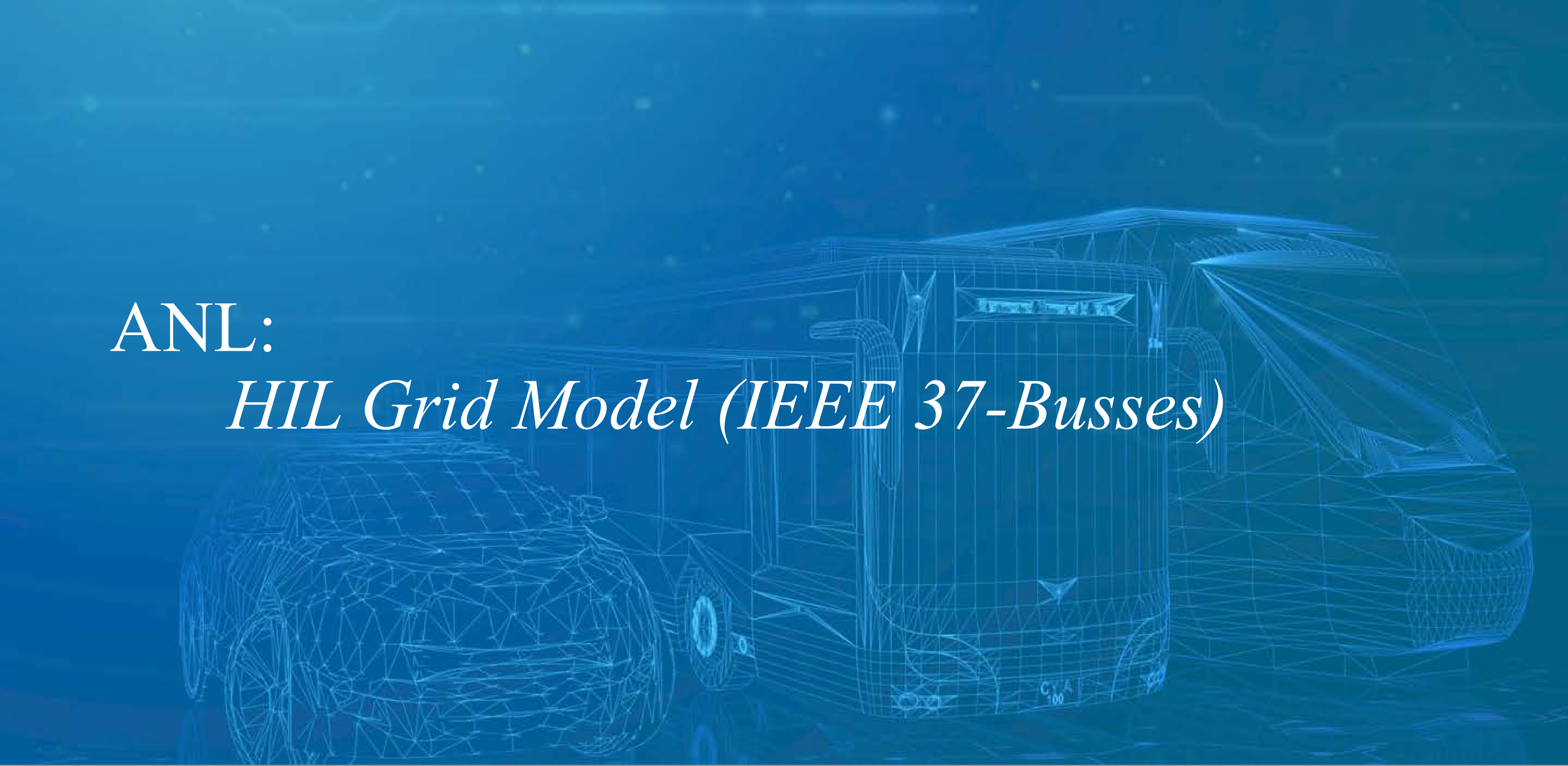
Use these tools to inform charging station design for:

- Dynamic roadway charging feasibility
- Energy estimation and site optimization
- Optimal sizing and control of behind-the-meter storage
- Composition and size of EV fleets
- Optimal placement of charging station equipment.

Financial Analysis ›

Use these tools to assess costs associated with charging infrastructure such as:

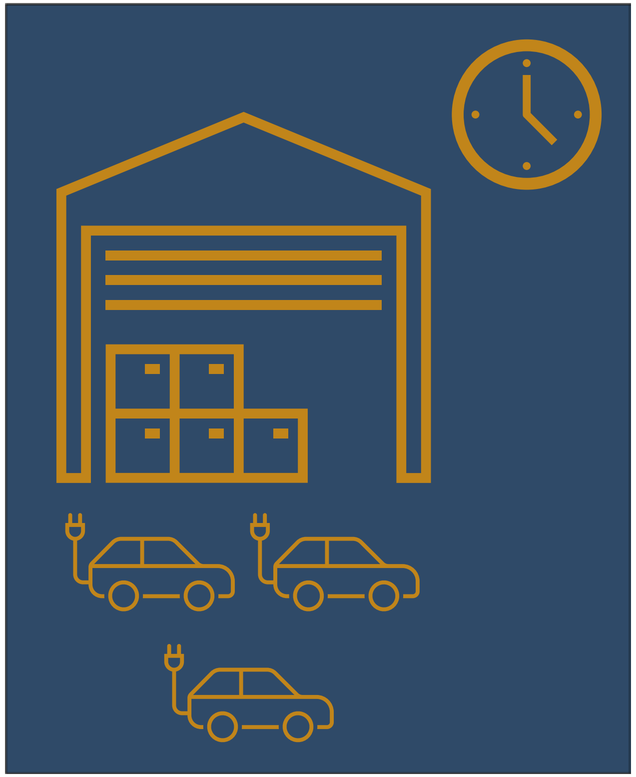
- Station and network economics
- Levelized cost of charging
- Investor payback period and risk analysis.



ANL:
HIL Grid Model (IEEE 37-Busses)

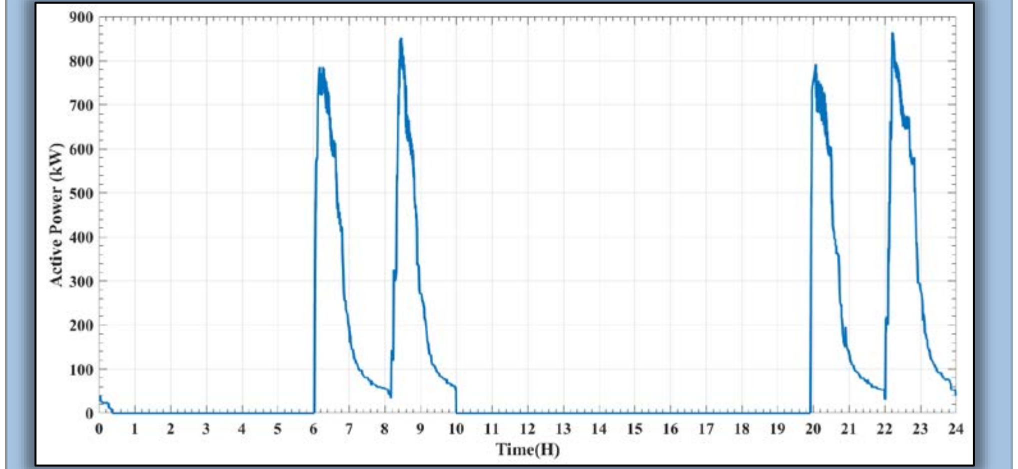
ANL Grid Model: Scenario Description

- “Mega-Watt Charging Site Model”
- ANL’s HIL Grid Model utilizes Smart Electric Power Alliance (SEPA)’s mixed usage fleet and public charging business depot sites (Site EVSEs & Fleet EVs) that opened for public usage (Public EVs)
- Site EVSEs:
  - ➢ Close to a medium-sized residential zone
  - ➢ (x5) 350 kW XFC ports.
  - ➢ Utilization rate of a charger will increase from 14% to 22% (by 8%)
  - ➢ 15-minute demand (at nameplate capacity) will increase by 10%.
- Fleet EVs:
  - ➢ This fleet has a controlled charging process.
  - ➢ (x20) light-duty electric trucks/pick-ups with a battery size of 150 kWh.
  - ➢ (x2) Charging intervals: 8pm-12am, 6am-10am.
  - ➢ (x2) Charge sessions per Charging interval (20 charges/week)
- Public EVs:
  - ➢ (x1) Single-family housing: top-off of only once a week.
  - ➢ (x1) Multi-family housing: charge at least twice a week with 50% or lower starting SoC.
  - ➢ (x5) chargers: available 10am-2pm
  - ➢ (x3) chargers: available 2pm-5pm
- During weekends, the site will be closed and neither fleet nor public charging will occur.

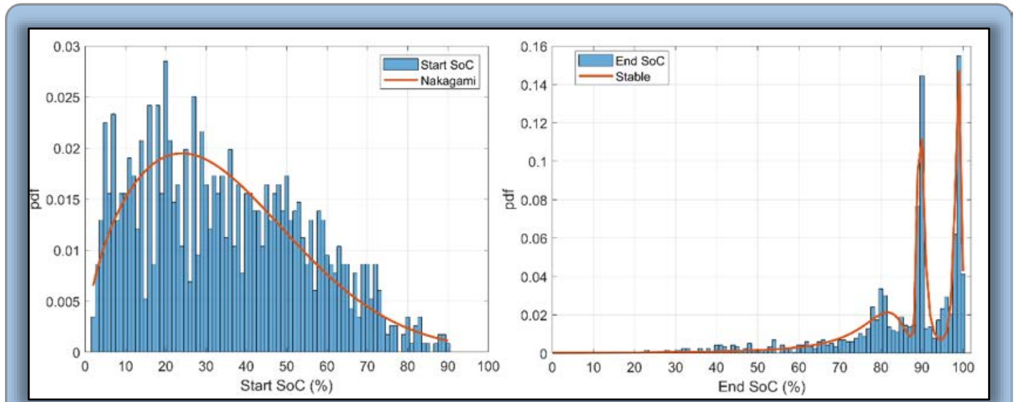


ANL Grid Model: Modeling and Construction of MW Charging Site

- Fleet EVs charge profiles:
  - Controlled charging process.
  - 0 to 5 minutes of uncertainty for both the start and stop times.
  - 10am is the cutoff time for charging.
  - 10pm-12am charging session does not have this hard limit.
  - NGP EV Profiles used to construct (x2) charge curves per charging interval
- Public EVs charging profiles:
  - Variable start and end SoCs.
  - This important factor determines site utilization, i.e. how long the charging session usually lasts and how many vehicles charge daily.
  - charging sessions arrangement.
  - Determine the Start and End SoC for the Charging Profile:
    - ✓ A statistical study on 1446 DCFC and XFC charging sessions was conducted.
    - ✓ Start SoC: Nakagami distribution.
    - ✓ End SoC: Cascaded Alpha Stable distribution .



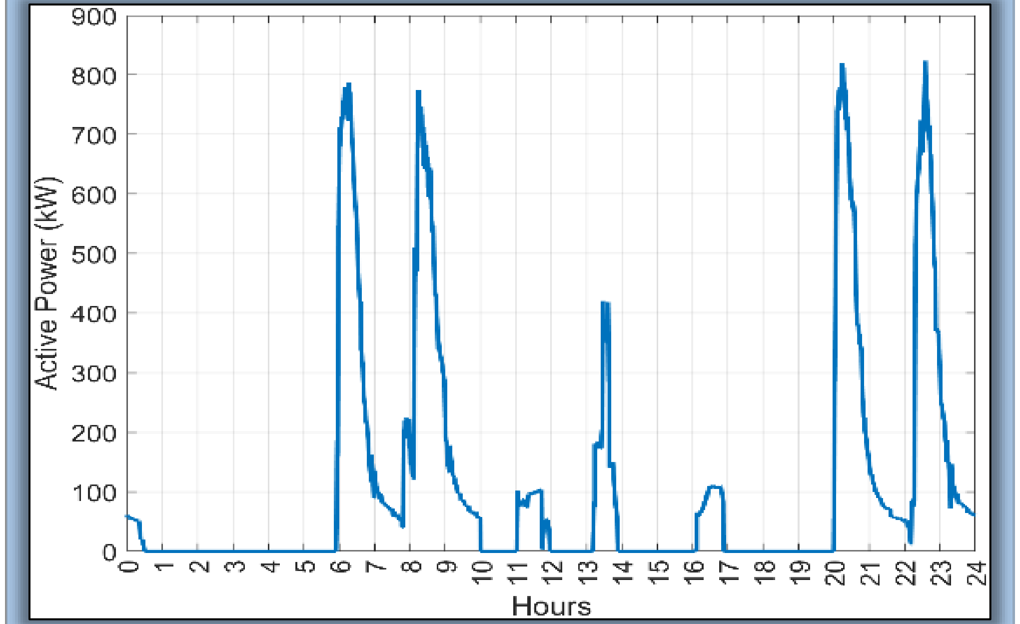
EV Fleet: E-trucks/fleet load profiles



EV Public: Modeled Start and End SoC

ANL Grid Model: Resulting 24-hour Profile

- Quantile data were calculated and used to obtain charging profile loads.
- A uniform distribution was used to obtain the probability to get the SoC value from the start SoC quantile data.
- The end SoC value should be at least 10% higher than the start SoC to have a reasonable charging session.
- Based on the corresponding SoC range, active and reactive power load profiles were trimmed from the real-world captured full profiles.
- Public charging profiles were chosen randomly from 73 available profiles. E-truck profiles were randomly chosen from 20 available profiles
- Result:
  - 24-hour MW-site modelled load (in kW)



Resulting MW-site load over 24 hours

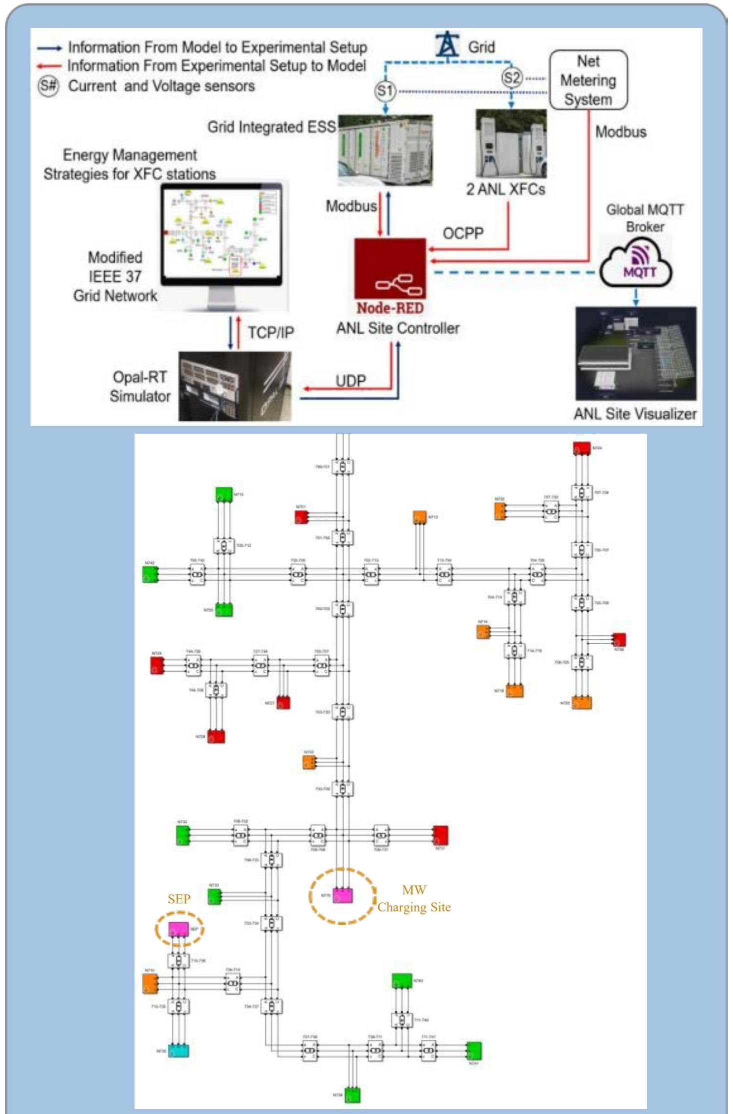
ANL Grid Model: Current Progress & Future Work

Current Progress:

- The developed model is used to study the impact of HPC profiles on the electric grid.
- Multiple studies to address the grid impacts using this model can be conducted.
- The model could be expanded to include more scenarios or to work with bigger grids.
- As for now; the model used to conduct a study on the effect of HPC loads on grid frequency.

Future Work:

- The results will be presented in:
  - ➢ Conference: 2024 IEEE Transportation Electrification Conference & Expo (iTEC)
  - ➢ Titled: *P-HIL Model Development for MW Charging Sites Incorporating Real-World XFC Load Profiles.*
  - ➢ When: June 19-21, 2024.
  - ➢ Where: Rosemont, IL, USA,
- Contact sratrout@anl.gov for more info

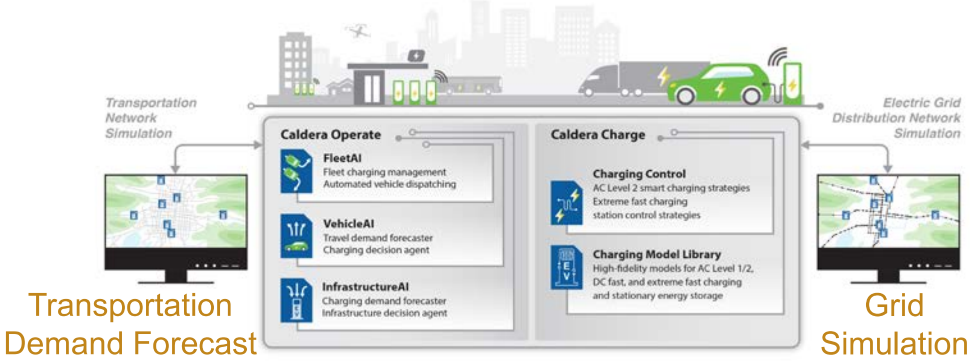


HIL system overview

INL:
Caldera

INL: Caldera, Electric Vehicle & Infrastructure Decision Management Simulation Platform

- Caldera is an agent-based modeling platform for predicting detailed system impacts and demonstrating intelligent management strategies.



Caldera Operate

FleetAI
Fleet charging management
Automated vehicle dispatching

VehicleAI
Travel demand forecaster
Charging decision agent

InfrastructureAI
Charging demand forecaster
Infrastructure decision agent

Caldera Charge

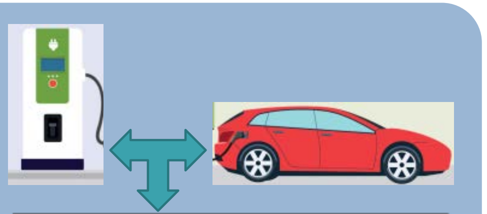
Charging Control
AC Level 2 smart charging strategies
Extreme fast charging
station control strategies

Charging Model Library
High-fidelity models for AC Level 1/2, DC fast, and extreme fast charging and stationary energy storage

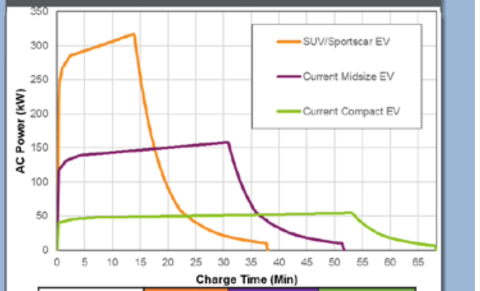
Transportation Demand Forecast

Grid Simulation

1



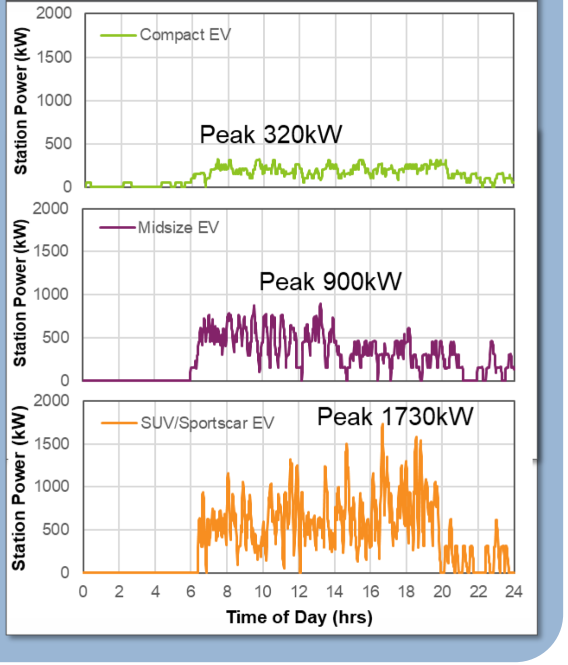
XFC Charge Profiles for Hypothetical Vehicles



	SUV/ Sportscar EV	Current Midsize EV	Current Compact EV
Max Charge Rate (kW)	300	150	50
Vehicle Range (Miles)	250	275	150
Vehicle Resembles	Porsche Taycan	Tesla Model 3	Nissan Leaf

2

XFC Site Power



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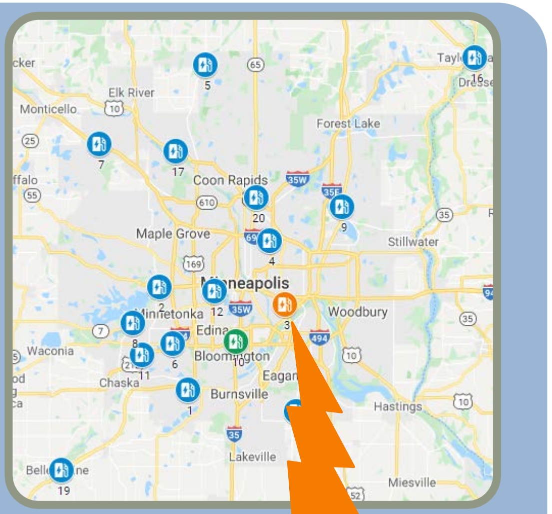
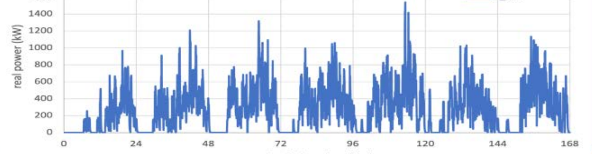
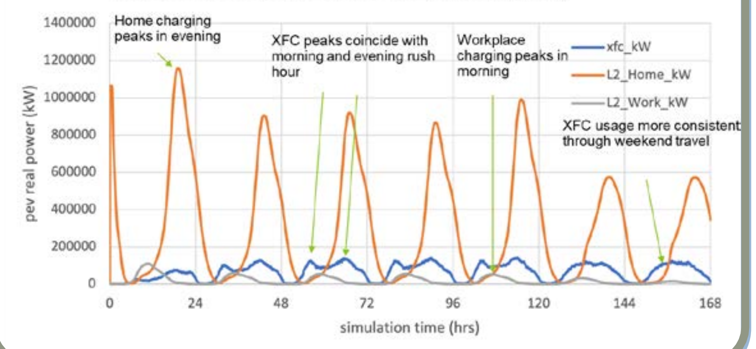


Power Profile of Single XFC Station



Aggregate Power Load Profile (All Charging)



Home charging peaks in evening

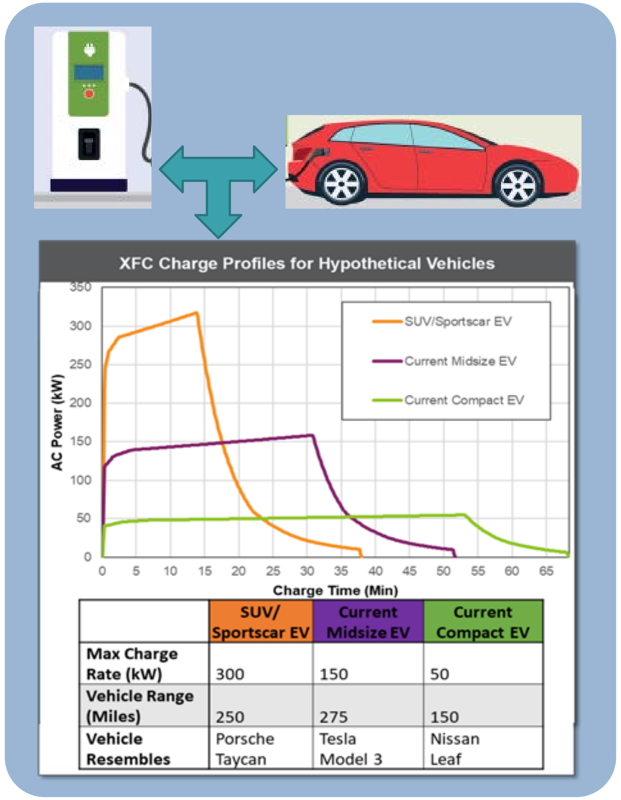
XFC peaks coincide with morning and evening rush hour

Workplace charging peaks in morning

XFC usage more consistent through weekend travel

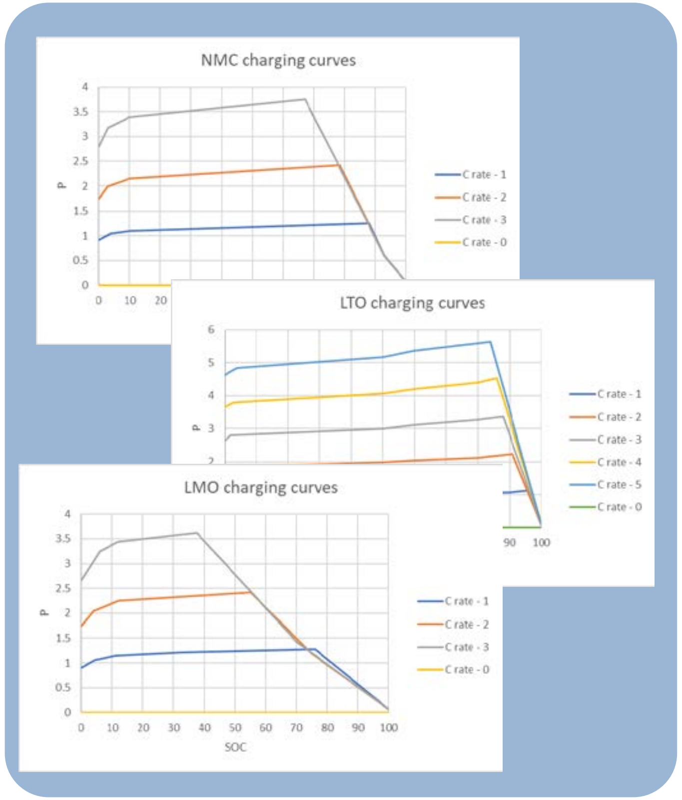
INL: Caldera Model Improvements with Next Gen Profiles

Caldera's foundation as an agent-based model is in the charging profile for each EV/EVSE pair



	SUV/ Sportscar EV	Current Midsize EV	Current Compact EV
Max Charge Rate (kW)	300	150	50
Vehicle Range (Miles)	250	275	150
Vehicle Resembles	Porsche Taycan	Tesla Model 3	Nissan Leaf

These unique profiles are built by an algorithm that utilizes electro-chemical battery models



- Contact Timothy.Pennington@inl.gov for more info

Steps in this validation and improvement task:

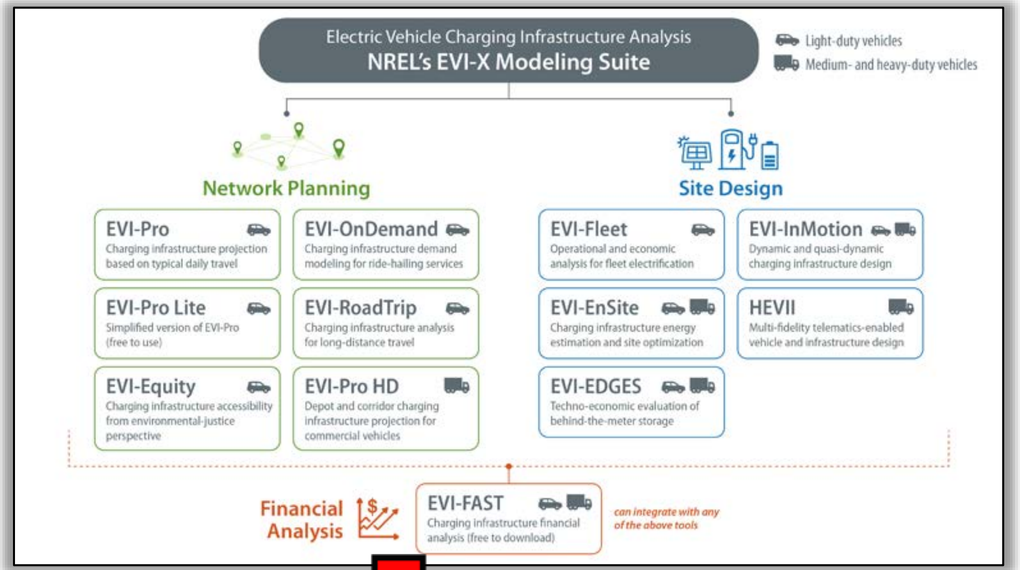
1. Use Caldera's existing tools to build battery curves based on the battery characteristics for NGP-tested EVs.
2. Compare the generated Caldera curves to the NGP test data.
3. Adjust Caldera curve generation as appropriate to improve accuracy.
4. Assess chemistries in Caldera and work with battery experts to add new baseline curves to increase coverage
5. Consider how Caldera might be enhanced to include non-standard, non-electrochemical based, BMS controls impacts on charging profiles.

NREL:

EVI-X Modelling Suite

NREL: EVI-X Modeling Suite

- EVI-X Categories
  - ➢ Network Planning
  - ➢ Site Design
  - ➢ Financial Analysis
- Integrating EV profiles from *Next-Gen Profiles* into:
  - ➢ EVI-Pro
  - ➢ EVI-RoadTrip
  - ➢ EVI-EnSite (soon)
- Model integration estimates charging needs of those without residential access, long-distance travel, and ride hailing electrification.



Electric Vehicle Charging Infrastructure Analysis
NREL's EVI-X Modeling Suite

Light-duty vehicles
Medium- and heavy-duty vehicles

Network Planning

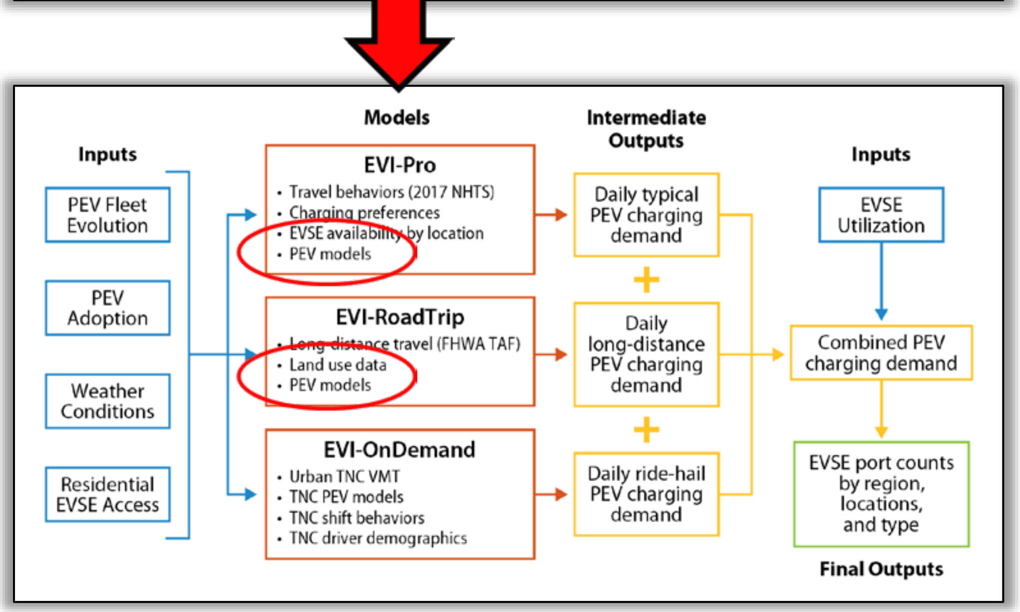
EVI-Pro Charging infrastructure projection based on typical daily travel
EVI-OnDemand Charging infrastructure demand modeling for ride-hailing services
EVI-Pro Lite Simplified version of EVI-Pro (free to use)
EVI-RoadTrip Charging infrastructure analysis for long-distance travel
EVI-Equity Charging infrastructure accessibility from environmental-justice perspective
EVI-Pro HD Depot and corridor charging infrastructure projection for commercial vehicles

Site Design

EVI-Fleet Operational and economic analysis for fleet electrification
EVI-InMotion Dynamic and quasi-dynamic charging infrastructure design
EVI-EnSite Charging infrastructure energy estimation and site optimization
HEVII Multi-fidelity telematics-enabled vehicle and infrastructure design
EVI-EDGES Techno-economic evaluation of behind-the-meter storage

Financial Analysis

EVI-FAST Charging infrastructure financial analysis (free to download)
can integrate with any of the above tools



Inputs
PEV Fleet Evolution
PEV Adoption
Weather Conditions
Residential EVSE Access

Models

EVI-Pro
- Travel behaviors (2017 NHTS)
- Charging preferences
- EVSE availability by location
- PEV models

EVI-RoadTrip
- Long-distance travel (FHWA TAF)
- Land use data
- PEV models

EVI-OnDemand
- Urban TNC VMT
- TNC PEV models
- TNC shift behaviors
- TNC driver demographics

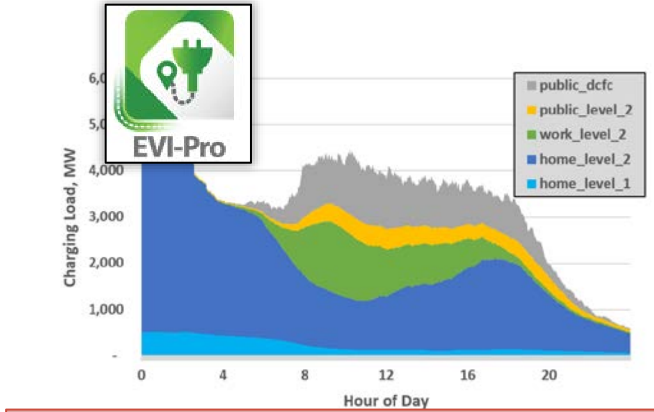
Intermediate Outputs
Daily typical PEV charging demand
+
Daily long-distance PEV charging demand
+
Daily ride-hail PEV charging demand

Inputs
EVSE Utilization

Combined PEV charging demand

EVSE port counts by region, locations, and type

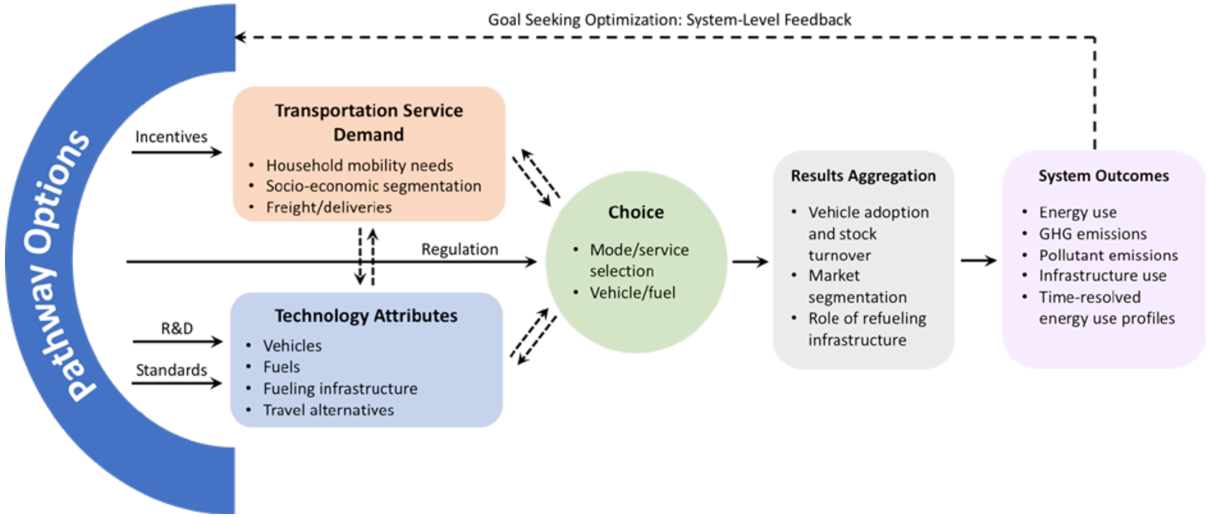
Final Outputs



2030 California Statewide Charging Load (simulated)

NREL: EVI-X Modeling Suite

- TEMPO simulates **pathways to achieve decarbonization goals** based on travel demand, mode choice, technology adoption, and associated energy use of household passenger and freight movements.



Pathway Options

Goal Seeking Optimization: System-Level Feedback

Incentives

Regulation

R&D

Standards

Transportation Service Demand

- Household mobility needs
- Socio-economic segmentation
- Freight/deliveries

Technology Attributes

- Vehicles
- Fuels
- Fueling infrastructure
- Travel alternatives

Choice

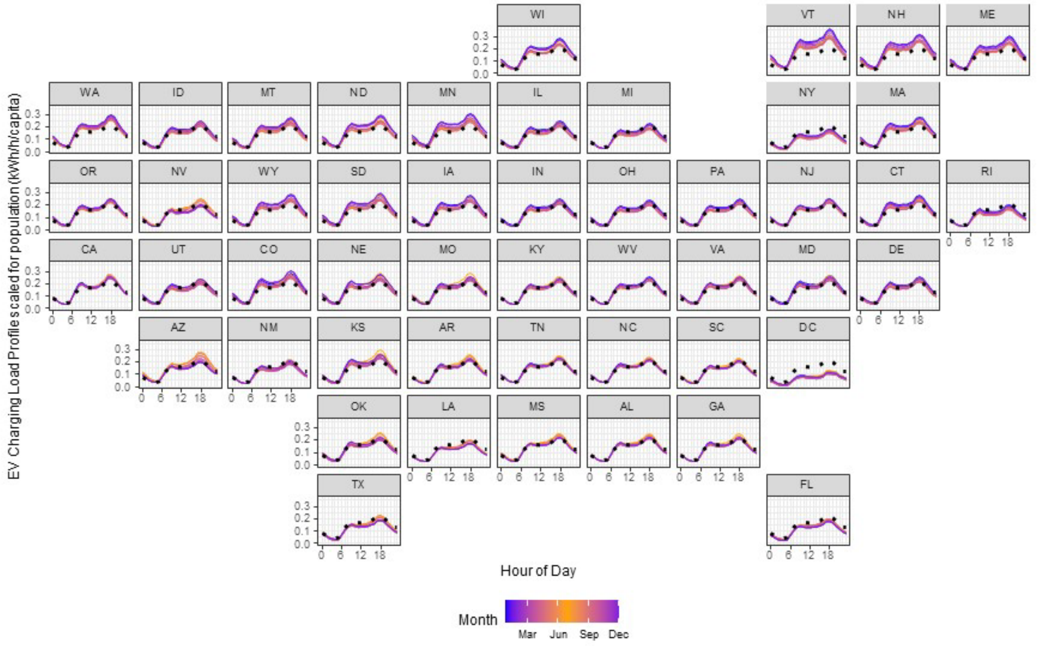
- Mode/service selection
- Vehicle/fuel

Results Aggregation

- Vehicle adoption and stock turnover
- Market segmentation
- Role of refueling infrastructure

System Outcomes

- Energy use
- GHG emissions
- Pollutant emissions
- Infrastructure use
- Time-resolved energy use profiles



- **NGP collaboration with TEMPO to update charging profiles and efficiencies based on vehicle type and environmental factors like temperature.**

- **Link:** https://www.nrel.gov/docs/fy23osti/83916.pdf

- Contact Namrata.Kogalur@nrel.gov for more info

Figure: State-level per-capita EV charging load profiles for an average weekday for the All EV Sales by 2035 scenario for projected year 2036 under the immediate and ubiquitous charging strategy, for the contiguous United States, with seasonal variation shown by line color (blue for winter, orange for summer) and U.S. annual average in black dashes.

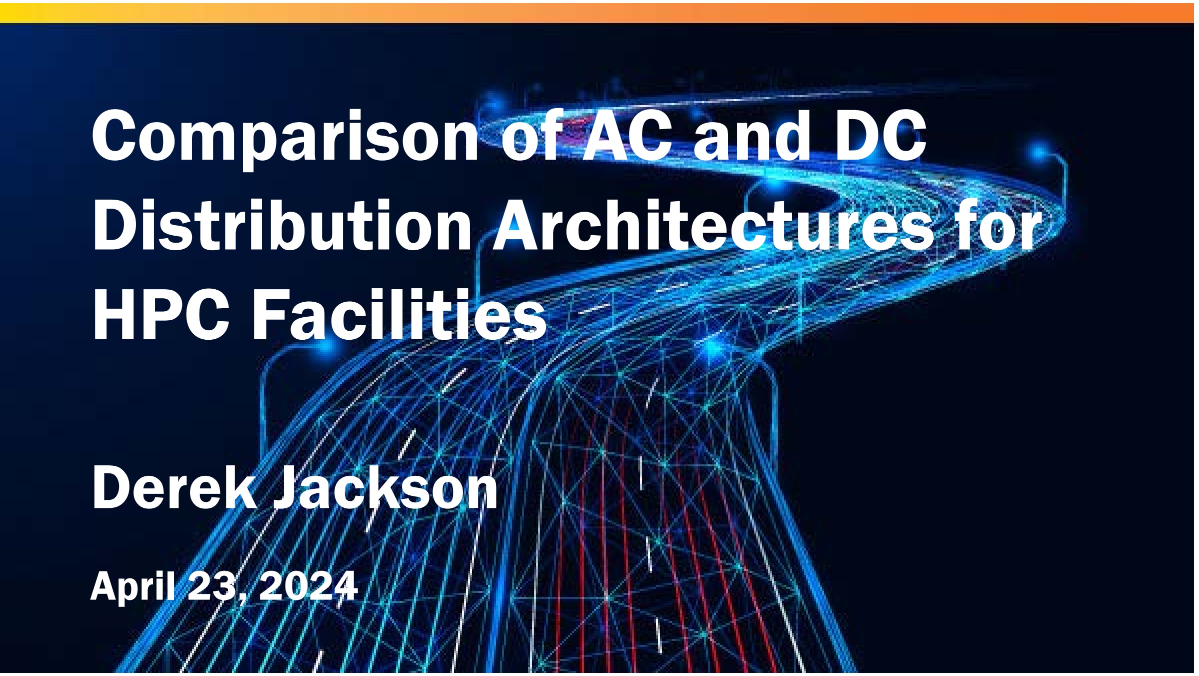
Thank You!

Q&A

EVs @ Scale

U.S. Department of Energy

EVs@Scale
U.S. Department of Energy



Comparison of AC and DC Distribution Architectures for HPC Facilities

Derek Jackson

April 23, 2024

U.S. DEPARTMENT OF ENERGY | Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

Outline

- AC vs. DC Common Comparison Points & This Comparison Approach Overview
- Leveraging EV Charging Profiles To Limit Charging Capacity
- Energy Loss Comparison
- A Case Study: 20 EVSE Charging Facility
- Conclusion

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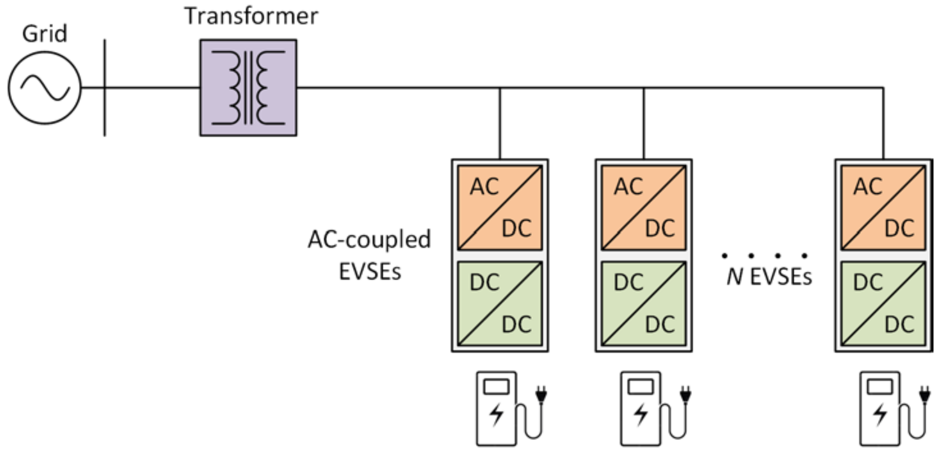
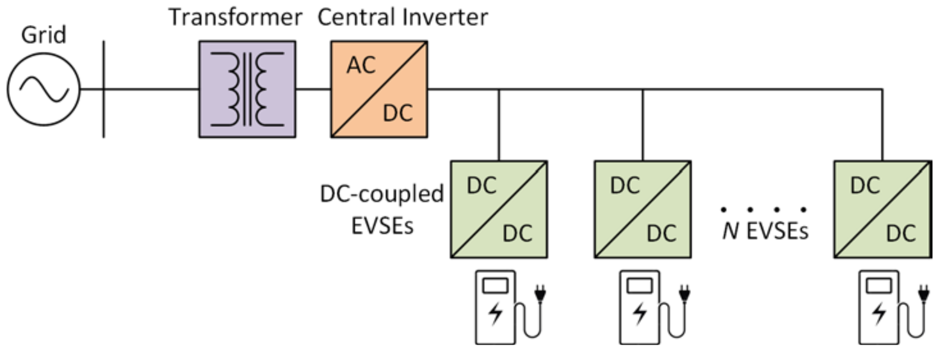
AC vs. DC Common Comparison Points

AC Distribution Architecture



- ✗ **Many power conversion stages**
  - More stages for power loss
- ✗ **Larger cable sizes**
- ✗ **Complex controls as each EVSE interacts with the grid**
- ✓ **Mature technology and standards**
- ✓ **Simple protection**

DC Distribution Architecture



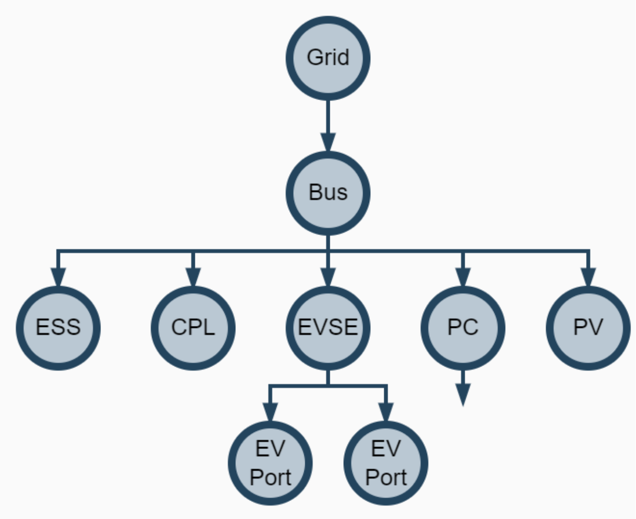
- ✓ **Less power conversion stages**
  - Improved efficiency
  - Reduced upfront equipment cost
- ✓ **Reduced cable sizes**
  - Permitted by higher distribution voltage
- ✓ **Simplified controls**
- ✗ **Lack of standardization and equipment availability**
- ✗ **Complex protection**

This Comparison Approach

- **Challenges** for AC vs. DC HPC facility comparison**:**
  - Converter efficiency and pricing varies between manufacturer, topology, and quality
  - Benefits are largely dependent on a specific scenario and level of demand
  - Onsite ESS convolutes comparison with many control strategy options
- Approach: a **simplified and relative comparison**
  - Set aside nuances in system architecture, converter topologies, and controls
  - **Problem simplification** through defining a baseline scenario:
    - ESS and DERs not included
    - Generalized and modularize power electronic conversion stages (e.g., inverter, EVSEs)
    - Equipment costs are relatively quantified
    - Location and time dependent demand avoided by assuming constant occupancy levels
- Even with this simplification, it is shown that **DC architectures still have energy and equipment investment savings**

AC vs. DC Comparison Simulation Tool: EVI-EnSite

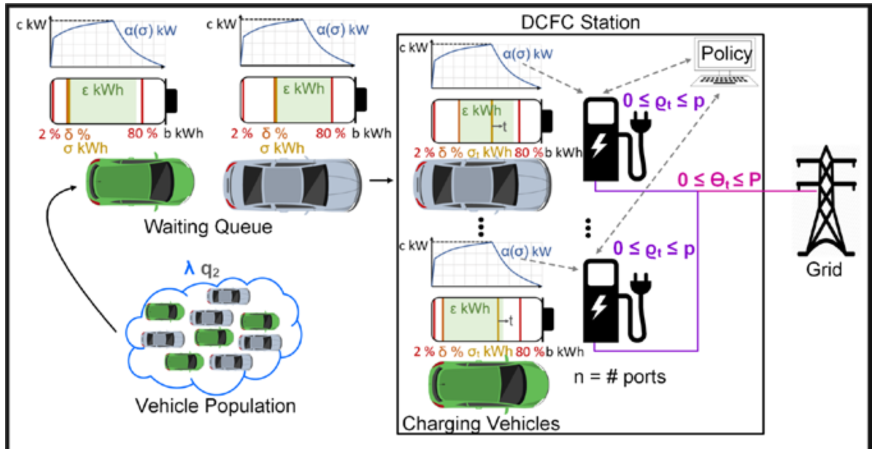
- **E**lectric **V**ehicle **I**nfrastructure – **En**ergy Estimation and **Site** Optimization Tool
  - Part of the NREL developed EVI-X modeling suite of EV charging infrastructure analysis tools: https://www.nrel.gov/transportation/evi-x.html
- A charging station design, modeling, and analysis tool
  - Can analyze a wide array of station architectures through flexible node tree site construction
- Performs agent-based, discrete time-domain simulations
  - Vehicle agents: defined by arrival time, initial SOC, battery capacity, and charge-acceptance curves
  - Equipment agents: defined by equipment type, power capacity, and power efficiency curves



EVI-EnSite

Input

- EV arrival and demand information
- Station architecture and equipment specifications
- Simulation parameters



Source: R. Buckreus, *et al*. (2021)

Output

- Equipment and EV power profiles
- Station performance statistics (e.g., energy loss, utilization rates, EV throughput, etc.)

Outline

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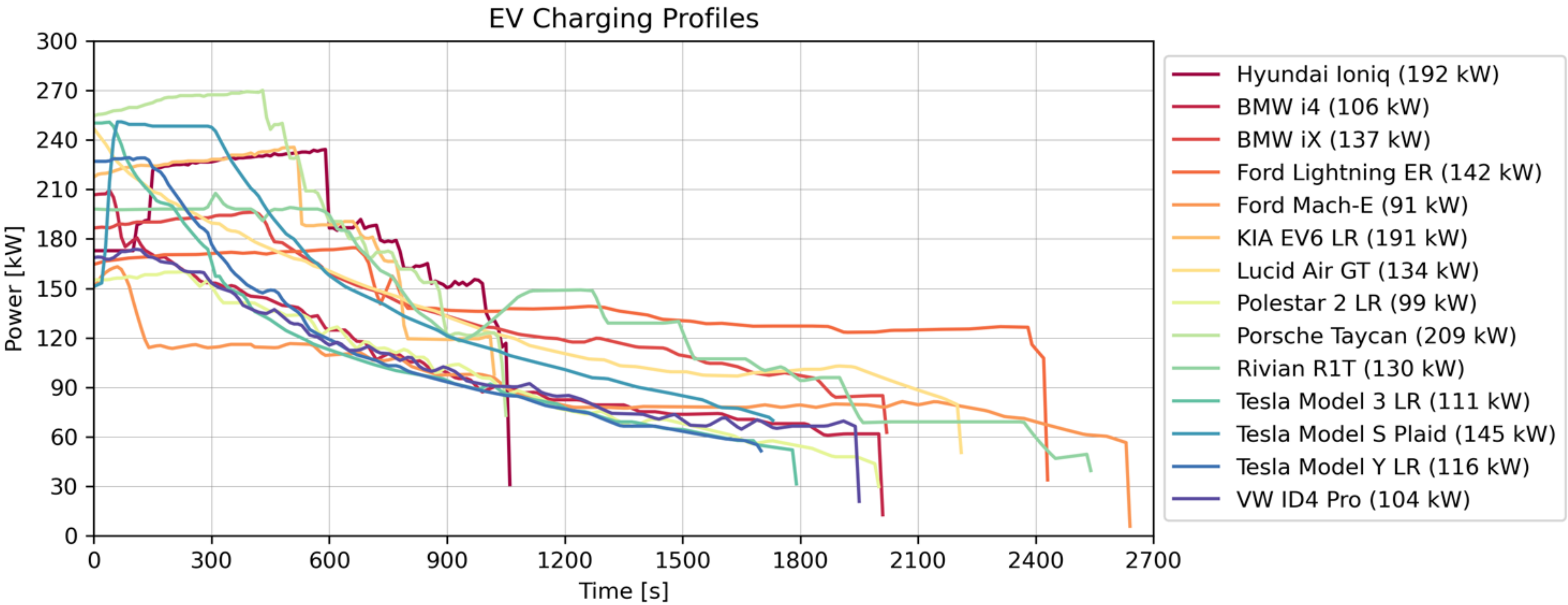
EV Charging Profile Characteristics

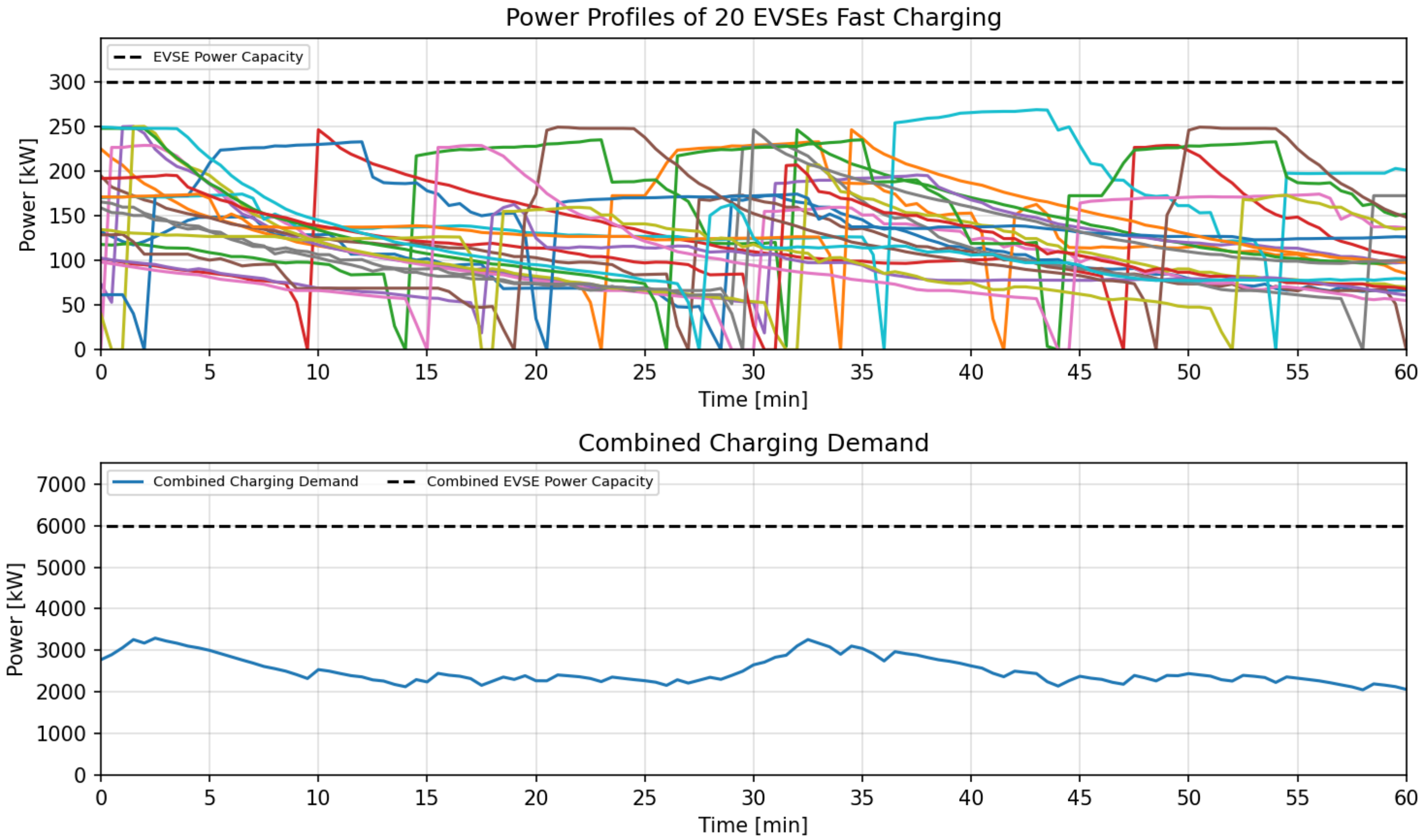
- Power profiles shown for fast charging from 10-80% SOC
- Average vs. peak power ratio ranges from 44-82%, averaging 136 kW
- Outcome: **average EVSE power capacity utilization is low**



*Profiles synthesized using charge acceptance data from “P3 charging index - US: Comparison of the fast-charging capability of electric vehicles,” P3 Group, Tech. Rep., 2023

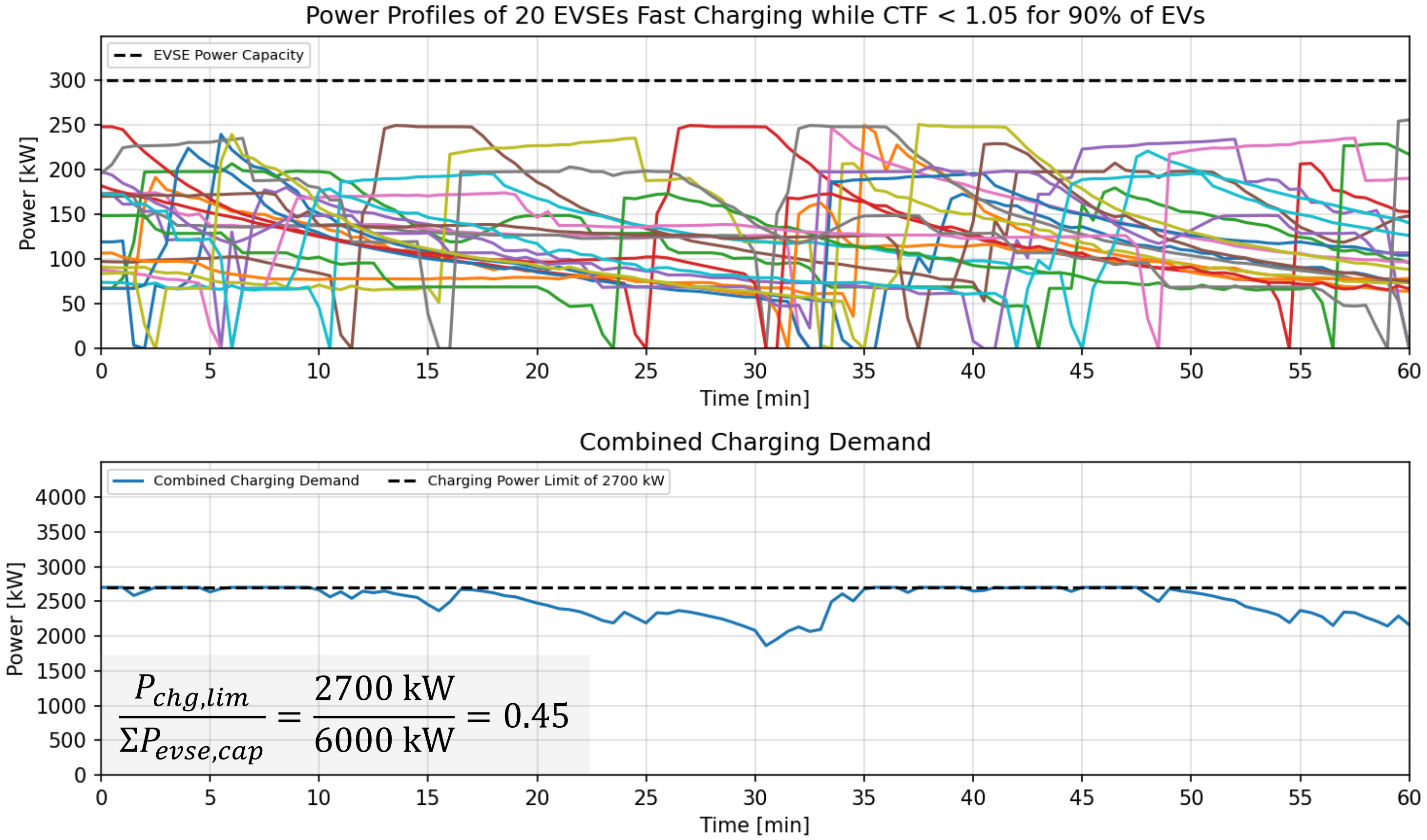
EV Charging Profile’s Impact on Peak Demand

- EV arrivals are staggered in practice
  - Each EV will be at different points in their charging session
  - Results in a combined charging demand much lower than the combined EVSE power capacity
- This suggests that **centralized equipment can be derated** to lower than the combined EVSE power capacity



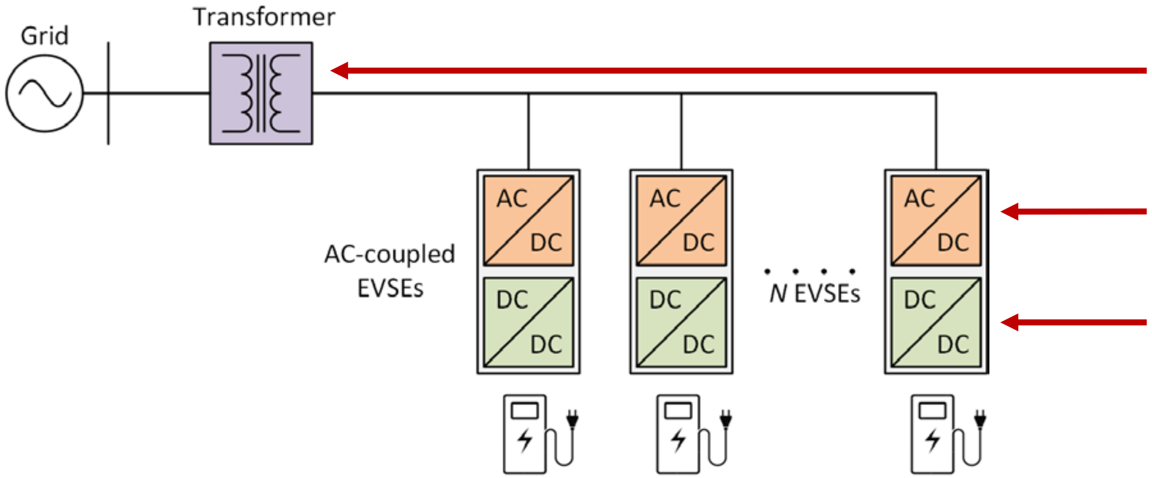
Leveraging EV Charging Profiles to Limit Charging Capacity

- Total charging capacity can be further limited at the cost of increased EV charging time
- **Charging Time Factor (CTF)**
  - Quantifies the increase in charging time for a given charging limit
  - The ratio between actual charging session duration T_{actual} and shortest possible charging session T_{best}:
    $$CTF = \frac{T_{actual}}{T_{best}}$$
  - A $CTF = 1.05$ means the EV took 5% longer to charge than its fastest possible time
- Can determine the minimum charging power limit $P_{chg,lim}$ for a given CTF limit



$$\frac{P_{chg,lim}}{\Sigma P_{evse,cap}} = \frac{2700\ \text{kW}}{6000\ \text{kW}} = 0.45$$

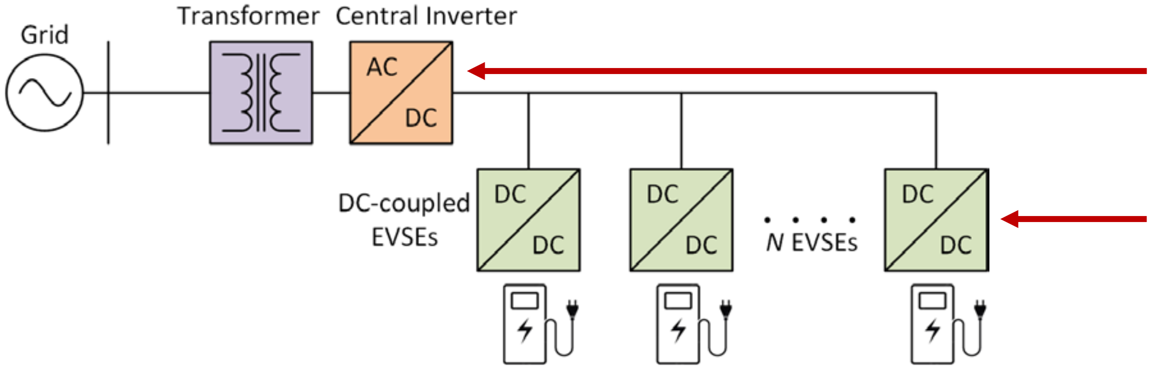
Leveraging EV Charging Profiles to Limit Charging Capacity



Derated transformer to $\sim 0.45 \cdot \Sigma P_{evse,cap}$

Fully rated AC/DC converters

Fully rated DC/DC converters

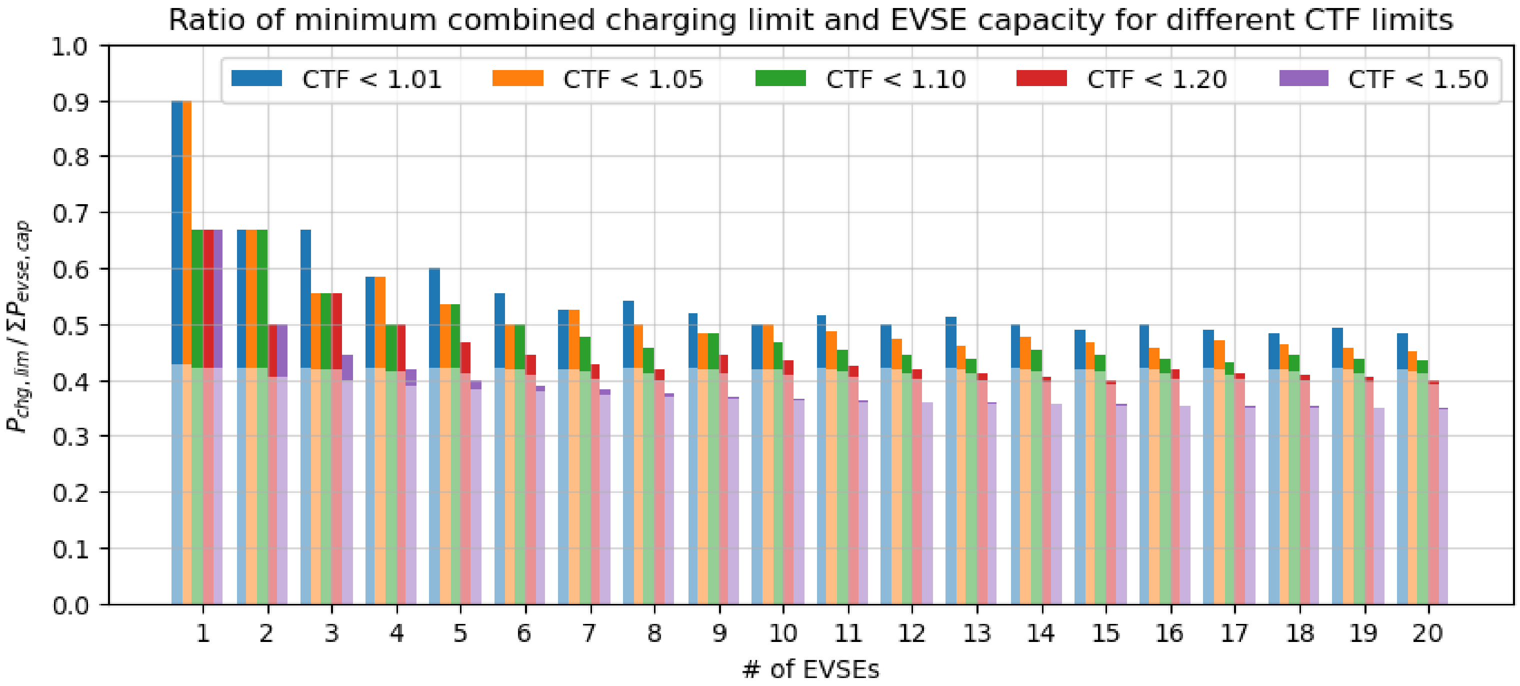


Derated transformer **and AC/DC converter** to $\sim 0.45 \cdot \Sigma P_{evse,cap}$

Fully rated DC/DC converters

Leveraging EV Charging Profiles to Limit Charging Capacity

- Fifty, day-long Monte Carlo simulations ran for each charging hub size, uniform distribution of EV arrivals, all charging sessions from 10-80% SOC
- The size of the charging hub impacts how much the charging power limit can be reduced
  - Approaches limit $\frac{P_{chg,lim}}{\Sigma P_{evse,cap}} \approx 0.42$ for $CTF < 1.10$ for 90% of all EV charging sessions
  - $\frac{P_{chg,lim}}{\Sigma P_{evse,cap}}$ can be further reduced by relaxing CTF constraint



*The average, combined charging power during the simulations are represented by the lighter colored bottom half of each bar

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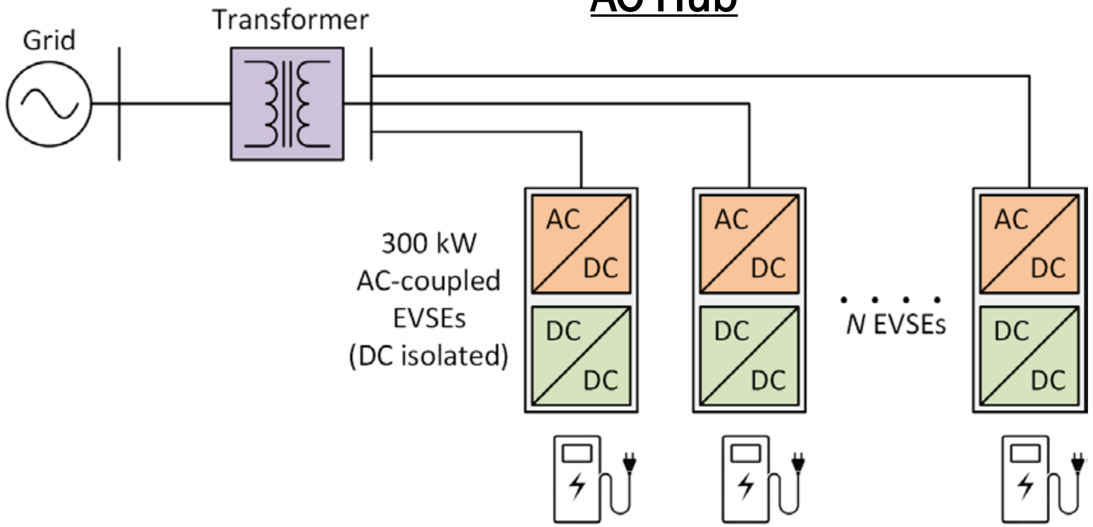
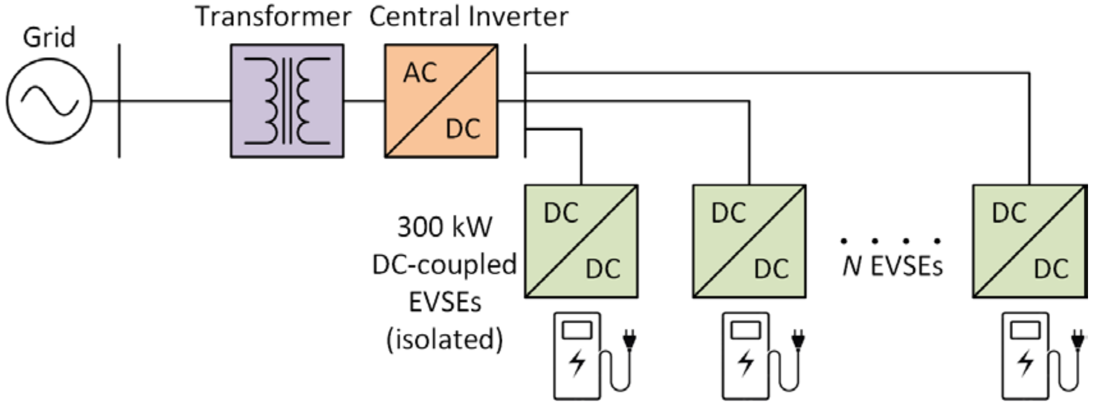
HPC Facility Architecture and Equipment for Comparison

- Both AC and DC distribution architectures use the same equipment modules
  - DC isolation used in both architectures
  - All power converters consist of 300 kW power modules
- The same AC/DC modules are used in both EVSEs (AC arch.) and centralized inverter (DC arch.)
- EVSEs consist of a single module per conversion stage
- EVSEs individually wired to centralized equipment

AC Hub

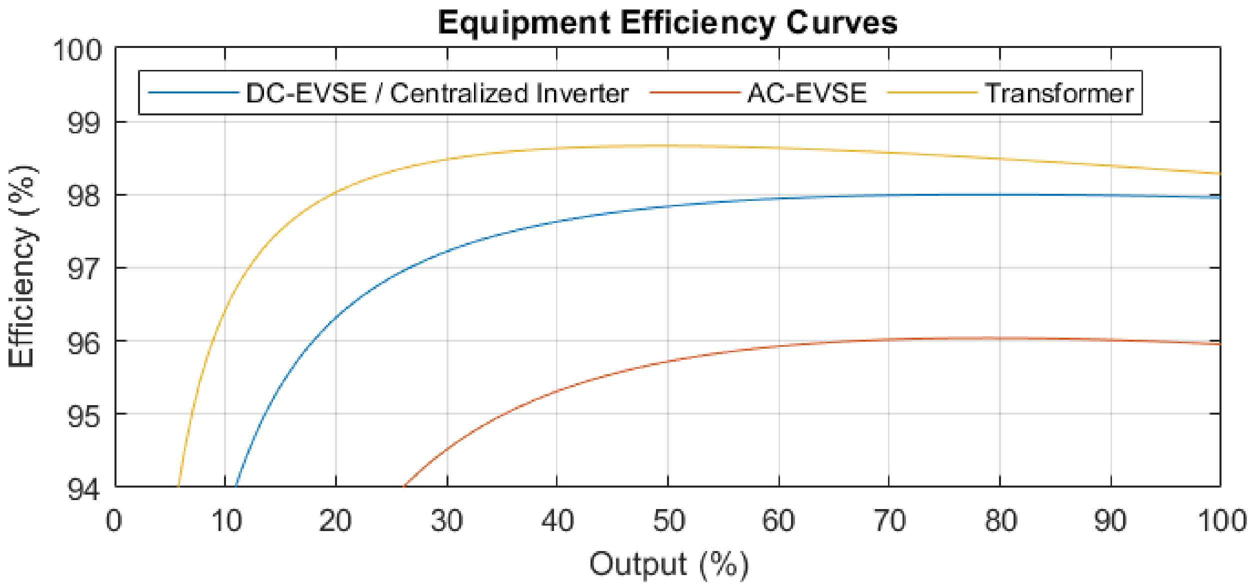


DC Hub



HPC Facility Architecture and Equipment for Comparison

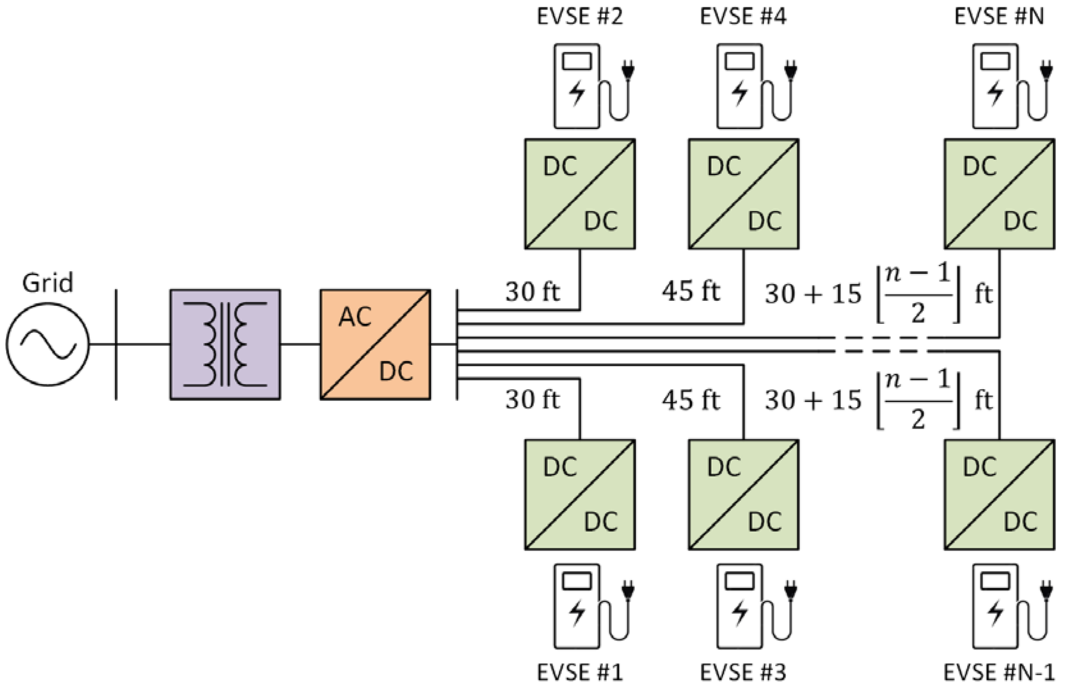
- General converter and transformer efficiency curves are constructed using data from a literature survey
  - Each converter efficiency curve from literature is normalized and scaled to have a max efficiency of 98%
  - Same efficiency curve used for both AC/DC and DC/DC modules
- AC-input EVSE has efficiency of combined AC/DC and DC/DC modules
- The centralized inverter (DC arch.) optimally splits power among AC/DC modules to improve efficiency, a benefit of centralization



HPC Facility Architecture and Equipment for Comparison

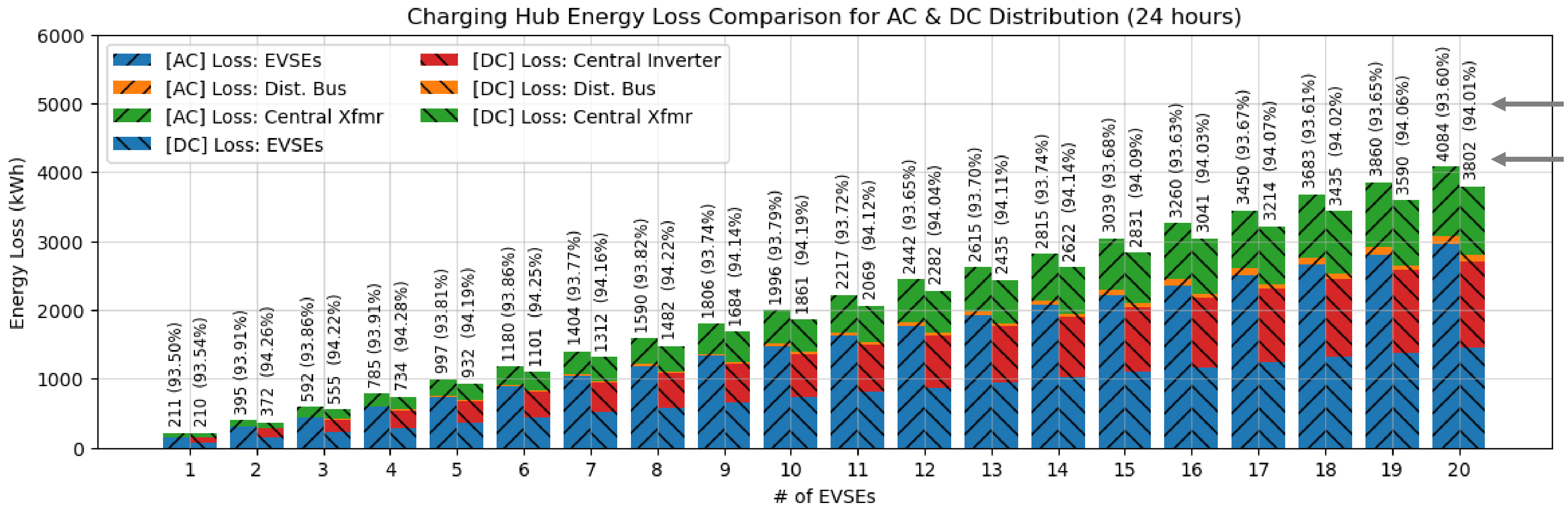
- Distribution cables independently selected for each architecture
  - The smallest wire gauge is selected that can supply current for the 300 kW EVSE output power
    - i.e., (AC) $I_{rms} = 361\ A$ and (DC) $I_{dc} = 300\ A$
- Each EVSE individually wired to centralized equipment
- Cable lengths identical in both architectures
- Based on selected wire gauges and voltages, **AC requires 150% more copper while incurring 139% more power loss compared to DC**

	Bus Voltage [V]	Cable Size [kcmil]	Cable Resistance @ $90^\circ C$ [mΩ/ft]	Copper mass [lbs./ft]	Cable Count
AC	480	500	0.029	1.544	3
DC	1000	300	0.045	0.926	2



AC vs. DC HPC Facility Energy Loss Comparison

- Comparison details:
  - Fifty, day-long Monte Carlo simulations ran for each charging hub size, uniform distribution of EV arrivals, all charging sessions from 10-80% SOC
  - Lowest $P_{chg,lim}$ selected for a $CTF < 1.05$ for 90% of all EV charging sessions
- Comparison results:
  - For any number of EVSEs, a DC-coupled distribution facility is just as or more efficient than AC-coupled
  - Energy loss difference primarily caused by the more efficient centralized inverter and higher voltage distribution
  - Difference in losses scale with facility size, with up to 282 kWh of energy saved per day with DC for a 20 EVSE hub



Average Efficiency

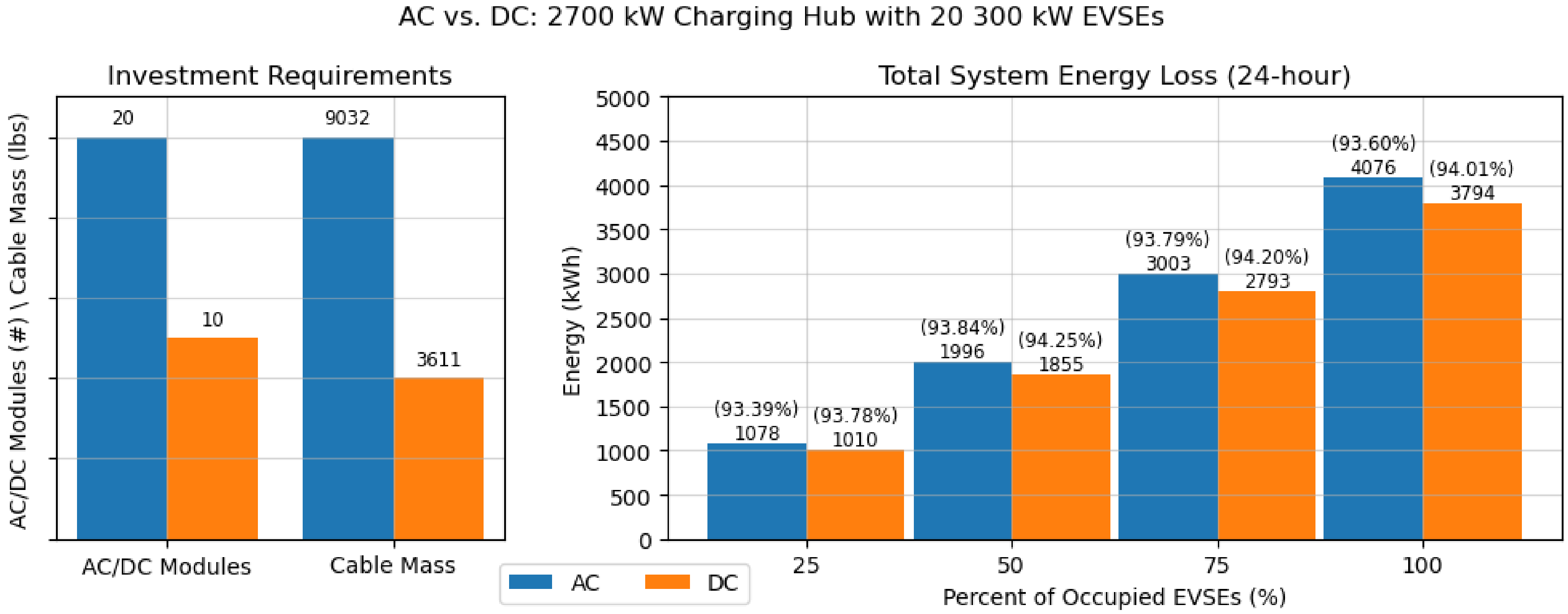
Total Energy Loss

Outline

- AC vs. DC Common Comparison Points & This Comparison Approach Overview
- Leveraging EV Charging Profiles To Limit Charging Capacity
- Energy Loss Comparison
- A Case Study: 20 EVSE Charging Facility
- Conclusion

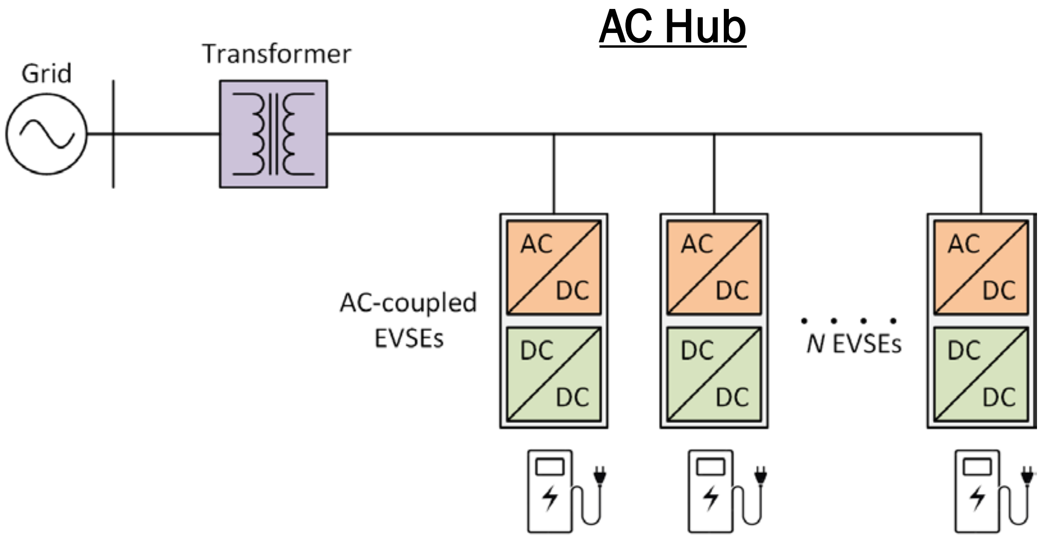
Case Study: Charging Facility with 20 EVSEs

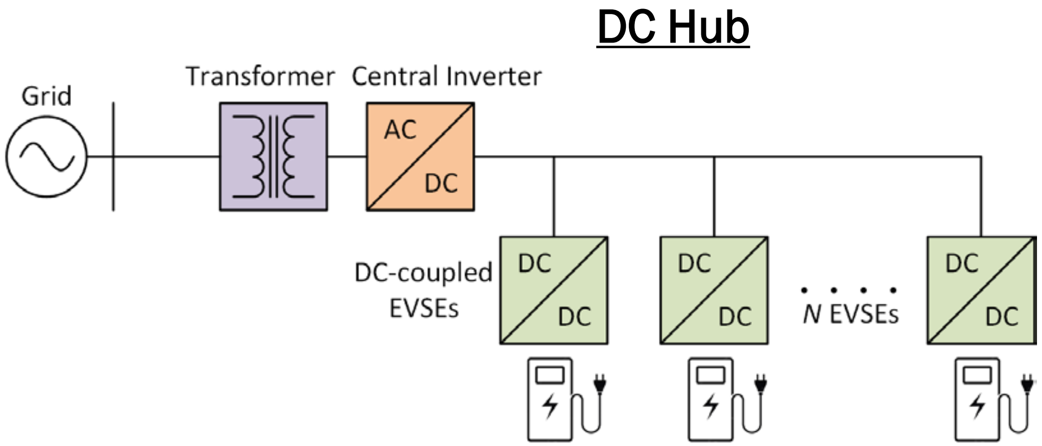
- In practice, a hub will not often be at maximum occupancy. How does this impact the comparison?
  - No impact on equipment investment. Dependent on the facility's desired maximum capacity
    - Number of AC/DC modules halved for DC architecture
    - 2/5 of the cable mass required for DC architecture
  - DC architecture cost savings from energy loss diminish at low occupancy levels*
    - *Percent savings of energy remains relatively constant throughout occupancy levels



Conclusion

- DC Distribution Advantages
  - **Higher equipment utilization**
    - 2X AC/DC converter modules required for AC
  - **Less power distribution cable mass**
    - 2.5X cable mass required for AC
  - **Higher efficiency operation**
    - ~70-200 kWh of daily energy savings for 20 EVSE HPC facility possible with DC
  - **Above advantages increase when ESS and DERs integrated**
- DC Distribution Disadvantages
  - **More complex protection**
  - **Product immaturity**
  - **Lack of standardization for DC**





Pending publication of this work:
D. Jackson, E. Ucer, J. Kisacikoglu, and A. Thurlbeck, “A comparison of AC and DC distribution architectures for EV high power charging facilities,” submitted to ECCE 2024

Thank You

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Design of Universal Power Electronics Regulator as a Charger Module in eCHIP

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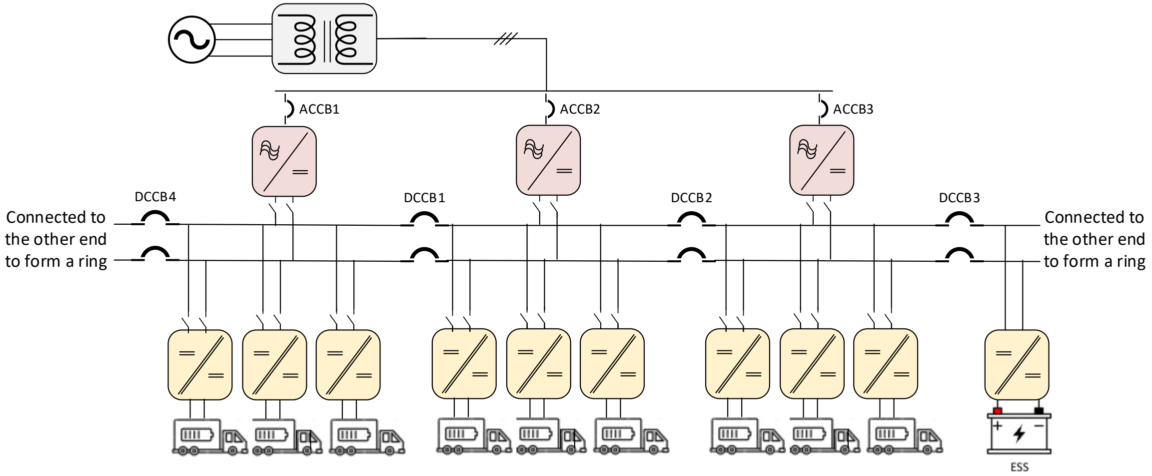
April 23rd, 2024

Objective

- Develop universal power electronics regulator (UPER) for DC distribution to interface
  - LD/MD/HD charging
  - Renewables
  - Grid interface converter
  - Local loads

Conceptual realization of DC Hub Architecture



***Data derived from actual installations**

$$\frac{\sum(VA\ rating\ of\ DC/DC\ converters)}{\sum(VA\ rating\ of\ AC/DC\ converters)} = 3\ to\ 20$$

Factors affecting the ratio

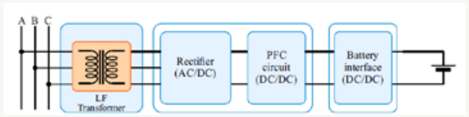
- Load diversity
- Storage capacity
- Grid strength
- Available capacity
- Cost of AC grid infrastructure
- Peak Demand charges
- Grid services
- Storage costs

Bi-directional Isolated DC/DC module: a critical element to realize a DC hub

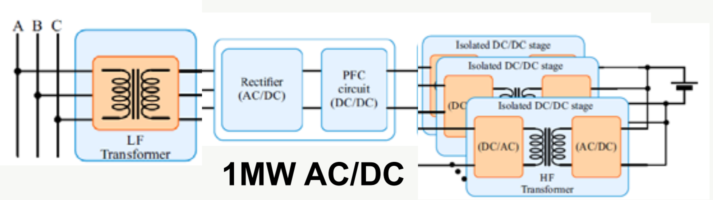
Design Specification development: Gaps in EV charger

- **EVSE DC/DC building block limited in size**
  - Commercial DC/DC converters are typically 25-100 kW
  - High-power building block (350 kW) to meet heavy duty (1 MW+) charging requirements is required
- **Bi-directionality is lacking**
- **Limited peak charging voltage**
  - Current SOA is <1000 V for the DC bus and charging
  - Off-road vehicles like the battery-locomotives, eVTOLs may transition to 1500 V
    - Battery locomotives driven by high power
    - eVTOLs driven by need for extreme fast charging
  - DER integration will require 1500 V class DC/DC converters

Vendor	Voltage class	Bi-directionality	HF Isolation	Power rating Block/full unit	Efficiency	Power density	Thermal Management
A	500 V DC	Claim-Not implemented	Yes	125/375 kW DC-DC 70 kW AC-DC			liquid
B	950 V DC	None	Yes	60/360 kW DC-DC	98% (AC-DC) 98.5 % (DC-DC)	92"x24"x40" (AC-DC) 79"x 22.5"x15.5" (DC-DC)	Air Cooled
C	920 V DC	None	No	175 kW/350 kW	94% (Grid - Car)	46"x 30"x 30"	Air Cooled
D	920 V DC	None	Yes	100 kW/1 MW	94% (Grid - Car)		Air cooled

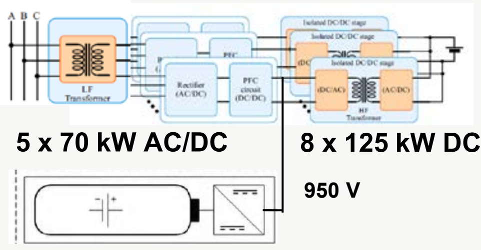


1 x 175 kW AC/DC



1MW AC/DC

10 x 100 kW DC/DC

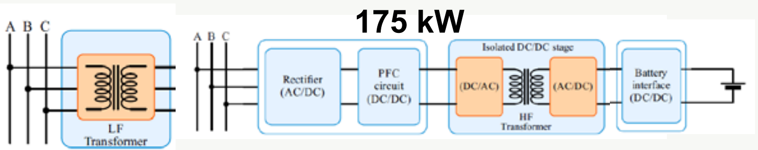


5 x 70 kW AC/DC

8 x 125 kW DC/DC

950 V

175 kW



1 x 360 kW AC/DC

6 x 25/60 kW DC/DC

Proposed UPER Development

Proposed development of a 2000 V class 350 kW and a 1000 V class 175/350 kW isolated DC/DC converter

Multi-Dimensional Improvement v/s SOA

High power Building block
Enable MW+ Charging
350 KW instead of 50-100 kW

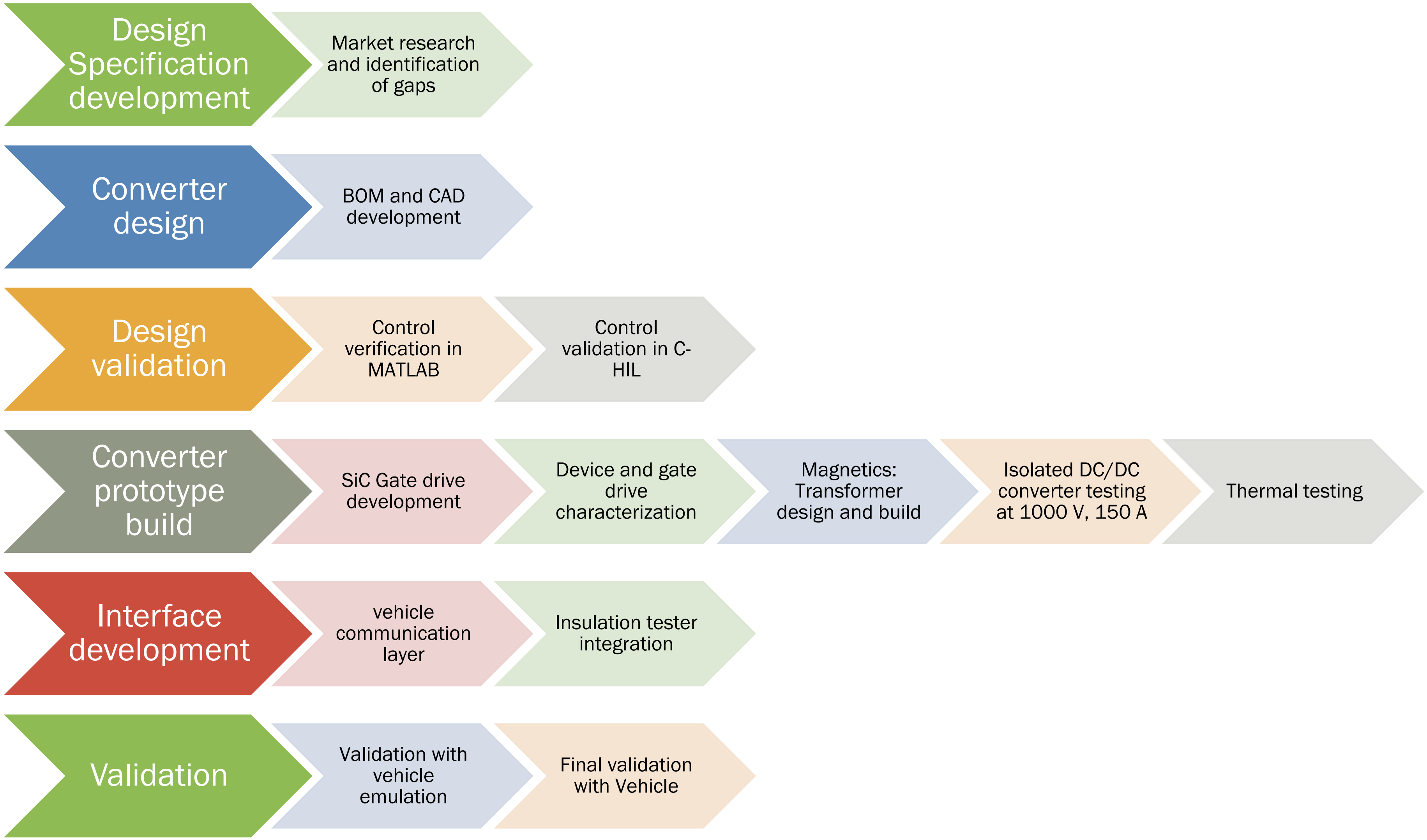
Power density
Frequency > 20 kHz, η > 99%, > 0.7 W/cm3
air cooled, > 2 W/cm3 water cooled
Enable Two men carry < 80 Lbs

Higher Working voltages
DC Distribution increased to 2 kV from 950 V
Vehicle voltage increased from 900 V to 1500 V

Bidirectional Power (V2X)
Controls to enable bidirectional power
transfer while maintaining low loss

Each of these goals are a challenge in itself

UPER Development Steps

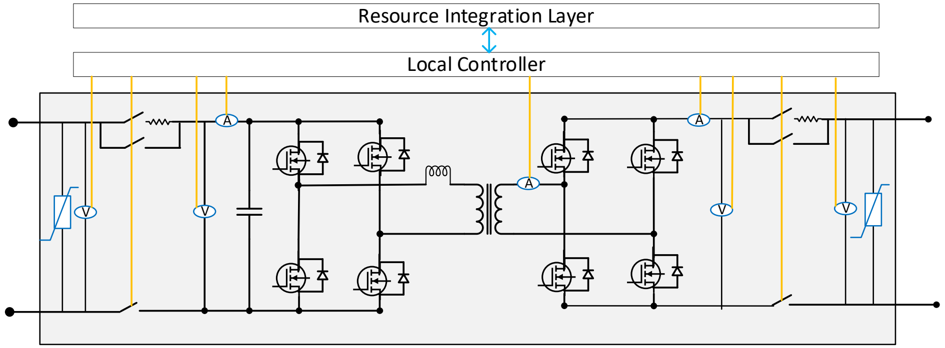


- Design Specification development
  - Market research and identification of gaps
- Converter design
  - BOM and CAD development
- Design validation
  - Control verification in MATLAB
  - Control validation in C-HIL
- Converter prototype build
  - SiC Gate drive development
  - Device and gate drive characterization
  - Magnetics: Transformer design and build
  - Isolated DC/DC converter testing at 1000 V, 150 A
  - Thermal testing
- Interface development
  - vehicle communication layer
  - Insulation tester integration
- Validation
  - Validation with vehicle emulation
  - Final validation with Vehicle

UPER Design

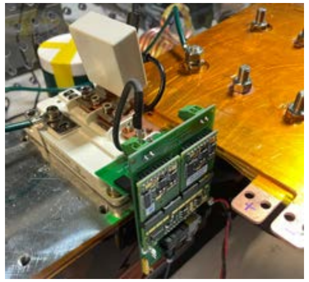
- Multiple isolated DC/DC converter topologies/implementations have been compared
- Dual Active Bridge (DAB) has been selected to meet bi-directionality and control range requirements.
- Galvanic isolation with compact 20 kHz transformer
- Taps provided to select between 400 V and 800 V class charging
- 1700 V SiC MOSFETS, 20 kHz switching
- Innovative modulation for achieving zero voltage switching (ZVS) over entire operating range
- Small input/output capacitances (< 150 uF)
- Air cooling for ease of maintenance
- Integrated vehicle comms and isolation monitoring

Schematic of the DAB based DC/DC charger

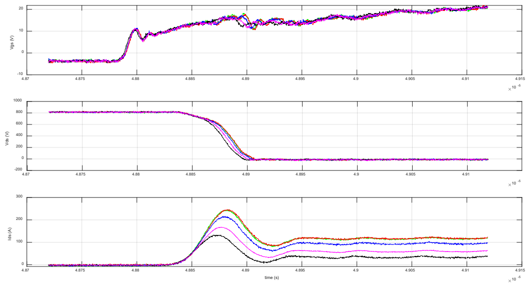


Design Cycle

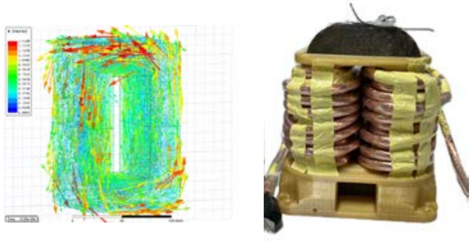
Gate drive compatible with Microsemi 1.7 kV MOSFET



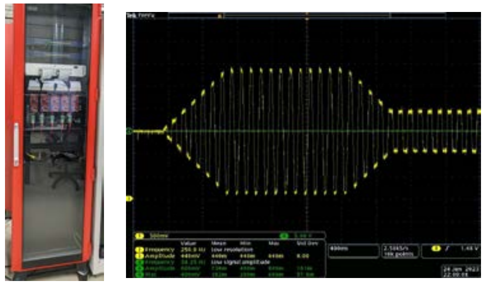
Device characterization
Turn On Results at 800 V, Rg_ext = 2 Ω



175 kW, 20 kHz Nanocrystalline Transformer 8”x 7” x 7”



CHIL results for the charger at 1000 V and 200 A



Transformer Challenge: High Current Design

- Design of 20 kHz transformer while handling currents in the range of 200 A is identified as a challenge
- Litz wire, selected for winding is supposed to reduce AC losses (proximity effect) but is not ideal

Transformer designed to achieve high efficiency, high power density and low parasitics

- Winding pattern selected to reduce the proximity effect
- Number of layers selected to improve cooling (forced air)
- Nanocrystalline core selected for 20 kHz operation
- Efficiency at 900 V 150 A is 99.75%
  - Core loss @900 V : 200 Watts
  - Copper loss @150 A: 150 Watts

Prototypes developed at ORNL

1 kV Class 200 A, 20 kHz Nanocrystalline Transformer

V1: 11”x 7” x 7”

V2: 8”x 7” x 6”

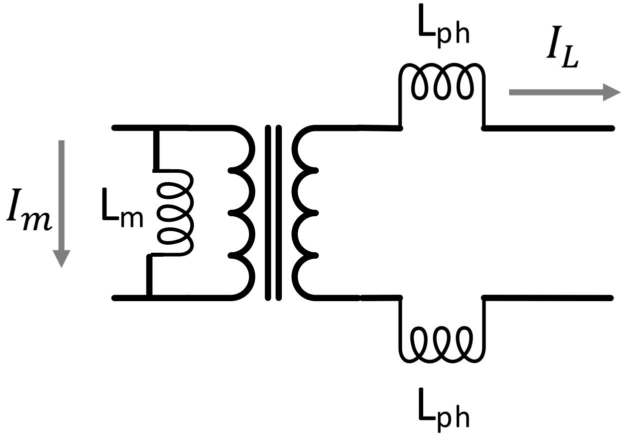
$$N1:N2 = 13:10\ (5)$$

$$L_m = 1.7\ mH, L_{lkg} = 3.5\ \mu H, C_{ps} = 572\ pF$$

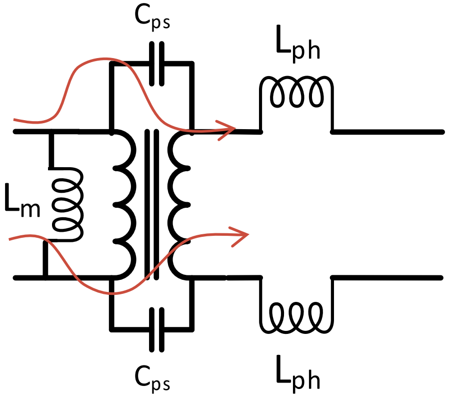
Transformer Challenge: DC Saturation

- Transformer saturation caused by DC current is a major issue, caused by PWM dead times, transients, or modulation issues
- DC offset can be either in the magnetizing current (I_m) or the inductor current (I_L)
- To address DC offset issues following methods are required: Prevention, Protection, Detection and Compensation.
- Major challenge is to detect whether the DC offset is in $I_m or I_L$
- Typically, transformer leakage inductance is used as energy transfer inductance (L_{ph})
- In this design, transformer is designed with low leakage inductance and two physical inductors are chosen to implement L_{ph}
- Selected implementation decouples parameters controlling I_m & I_L and simplifies DC offset detection and compensation logics.
- Selected design also gives additional freedom to reduce common mode currents through transformer inter-winding capacitance

Energy transfer inductance/phase inductance implementation



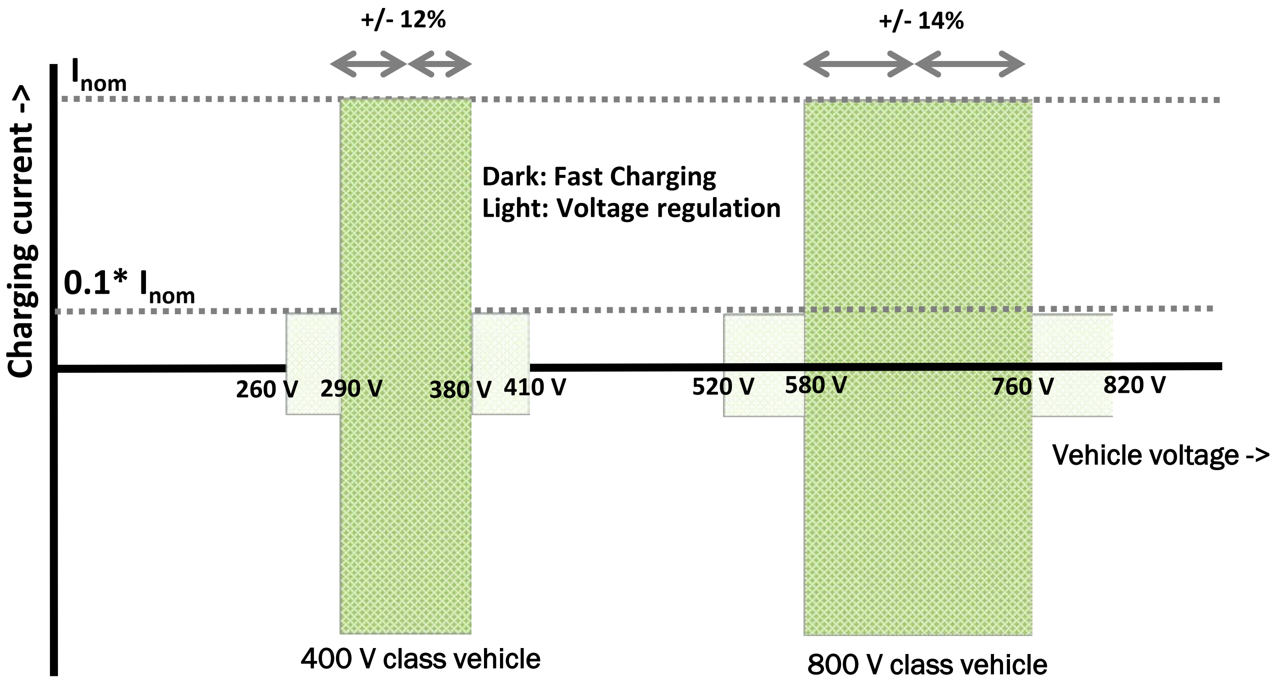
Common mode currents through Transformer inter-winding capacitance



Control Challenge: Required Operating Range

- Typical fast charging range of Li based batteries is about +/- 14% around nominal voltage
  - Selected range of operation is based on data obtained from literature and partner battery manufacturers.
  - Even for flow batteries the maximum range is +/- 22%
- Special case of consumer vehicle
  - Requirement to charge both 400 V and 800 V class vehicles will increase the required range
  - However, the required range is not dynamic and is limited (+/- 14%) once connected to the vehicle

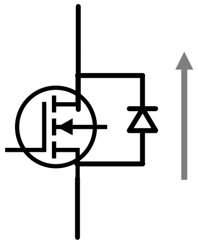
Typical operating range of 400 V and 800 V class vehicles



The objective is to achieve controllability in this region, and additionally, ZVS

Control Challenge: Need for ZVS

What is ZVS?



ZVS: Switching the device when the voltage across it is zero
ZVS mechanism in DAB: Turn on the switch when the current is in the corresponding diode

ZVS reduces switching loss

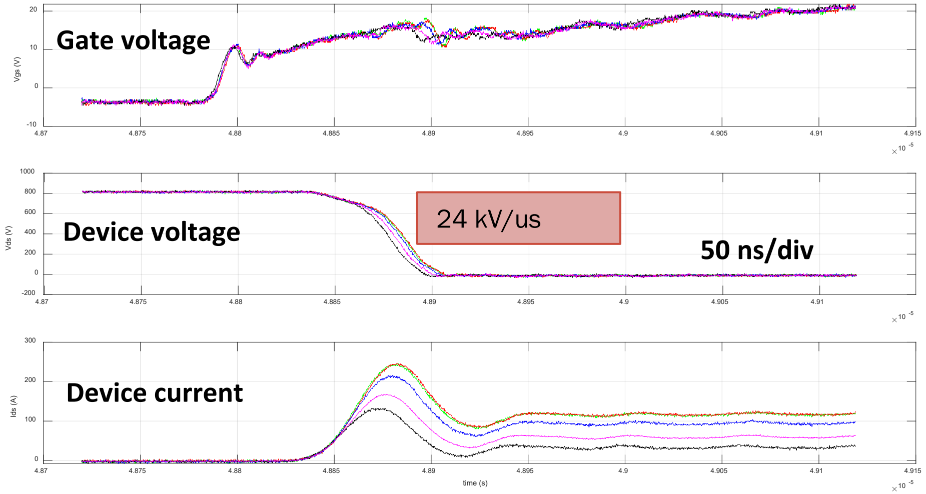
- In the selected MOSFET turn-on loss is 3x turn-off loss
- With ZVS turn-on, all the turn-on loss can be eliminated

Switching loss of 1.7 kV SiC MOSFET

E_{on}	Turn-on energy	V_{GS} = –5 V/20 V V_{Bus} = 900 V I_D = 300 A R_G = 0.5 Ω	T_J = 150 °C	—	9.4	—	mJ
E_{off}	Turn-off energy		T_J = 150 °C	—	3.1	—	

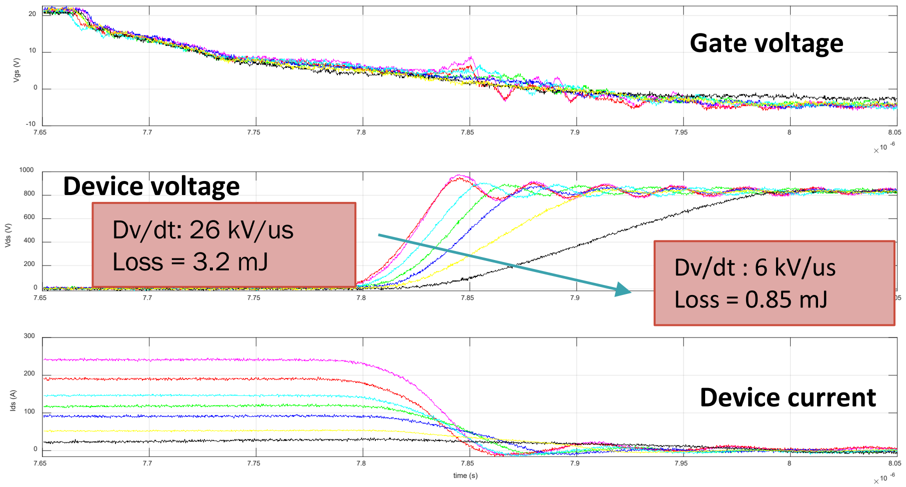
ZVS reduces *dv/dt*

Turn On Results of 1.7 kV SiC MOSFET at 800 V, Rg_ext = 2 Ω



During turn-on dv/dt is almost independent of current

Turn Off Results of 1.7 kV SiC MOSFET at 800 V, Rg_ext = 2 Ω

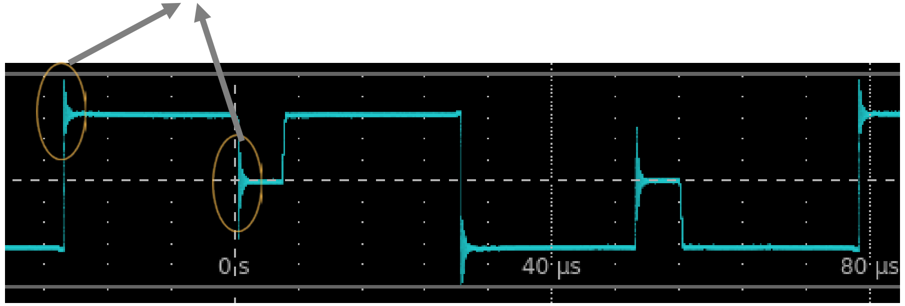


During turn-off dv/dt is proportional to currents

Control Challenge: Need for ZVS

High dv/dt causes conducted and radiated noise – ZVS reduces *dv/dt and hence noise*

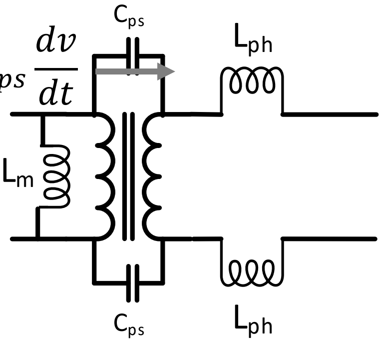
High dv/dt causes both conducted and radiated noise



DAB Transformer voltage under hard switching (high dv/dt) conditions

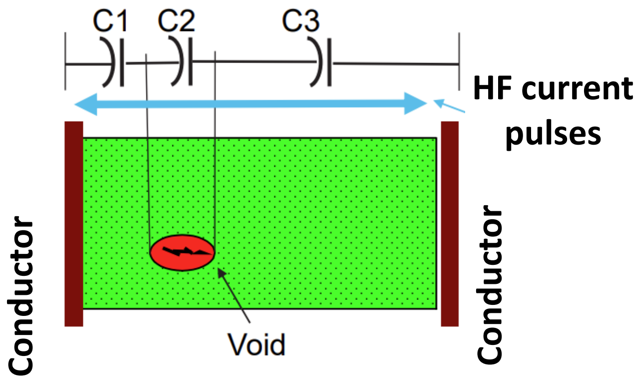
dv/dt causes high frequency currents in the transformer - ZVS reduces dv/dt improves insulation life

$$i = C_{ps}\frac{dv}{dt}$$



ZVS reduces dv/dt and partial discharge and hence improves transformer life

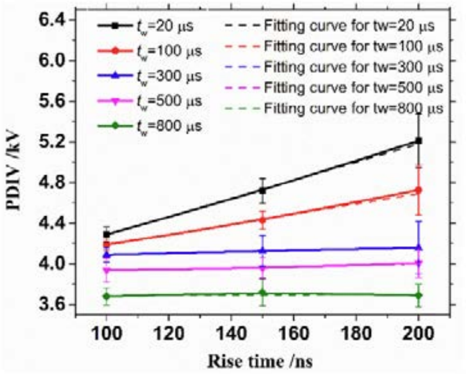
Phenomenon of partial discharge



Example of surface partial discharge

https://site.ieee.org/sas-pesias/files/2020/05/IEEE-Alberta_Partial-Discharge.pdf

Small rise time (increased dv/dt) reduces votlage (PDIV) at which PD occurs

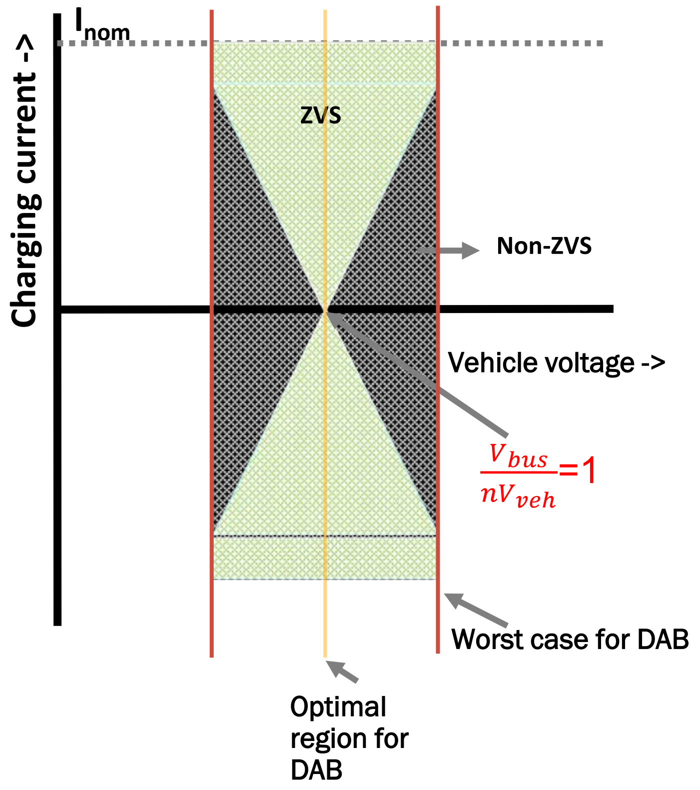


H. You, et.al, "Partial Discharge Behaviors in Power Modules Under Square Pulses With Ultrafast dv/dt," in *IEEE Transactions on Power Electronics*, vol. 36, no. 3, pp. 2611-2620, March 2021

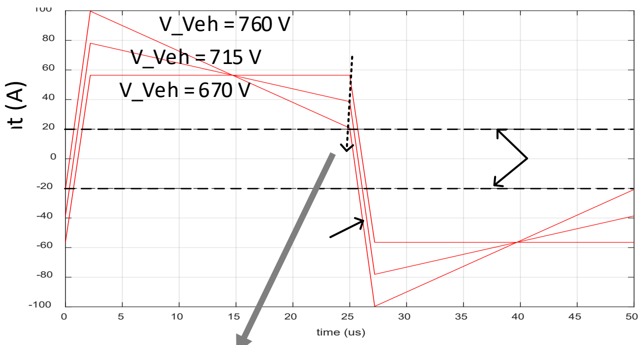
Control Challenge: DAB ZVS Operating Range

- DAB can achieve the desired operating range of the charging application
- However, if zero-voltage-switching (ZVS) is desired then the operating region is limited
- DAB looses ZVS at non unity operation ($\frac{V_1}{nV_2}$) and at lower currents

ZVS Range of DAB with Standard Modulation

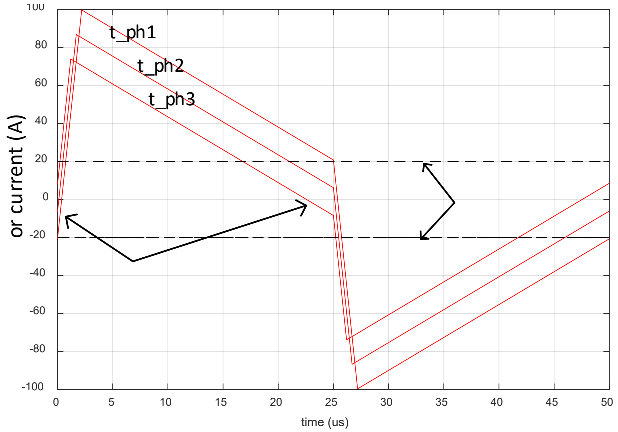


ZVS failing with increase in Vehicle voltage



For the positive half, any switching below I_{min} implies ZVS fail

ZVS failing with decrease in current

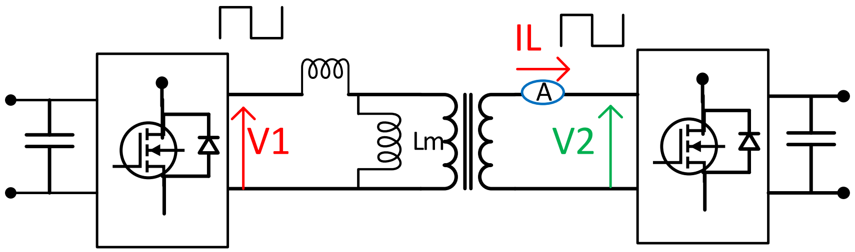


Standard DAB modulation techniques cannot achieve ZVS over the desired operating range

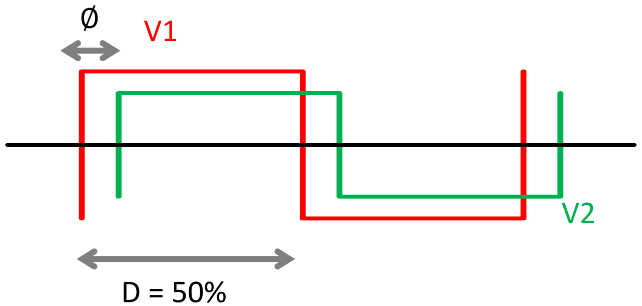
Novel Modulation: Zero State Modulation (ZSM)

- Novel modulation called as zero-state modulation (ZSM) is introduced to increase the ZVS operating range
- In standard modulation phase shift is controlled to increase/decrease current and duty cycle is fixed at 50%
- In ZSM, duty cycle is controlled to increase/decrease the current
- The method ensures ZVS even as low as 1 A and across the whole voltage range

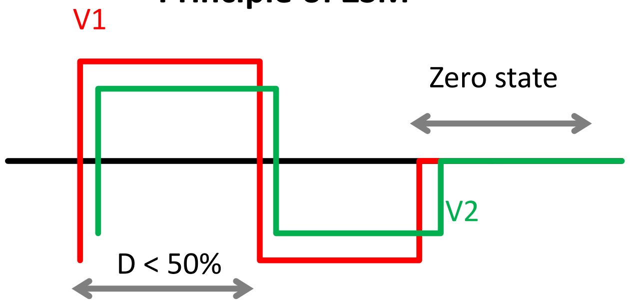
DAB Simplified Schematic



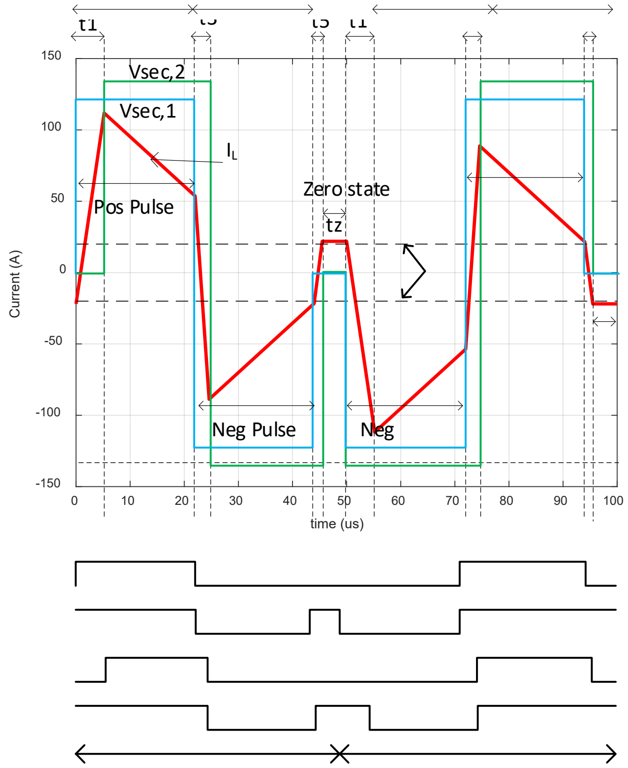
Standard Modulation



Principle of ZSM



Detailed switching scheme of the proposed ZSM technique



Prasad K, et.al, "1 kV 150 A Bidirectional Isolated DC/DC Converter With Full Range ZVS For Charger Application" ITEC 20204

The proposed method is universal in the sense that it achieves ZVS for any bus/vehicle voltages and for any currents

ZSM Technique Implementation

- **Model based control is used to derive the timings (phase shifts) and duty cycle**
- **Two different methods are proposed**
  - Optimal ZSM technique
  - Simplified technique
- **In optimal technique, timings (phase shifts) and duty cycle are derived every switching cycle. In addition to ZVS, RMS current is also optimized.**
- **In simplified technique, timings (phase shifts) are pre-calculated for worst case and only duty cycle is varied to control current.**
  - Advantage: single parameter control (duty cycle)
  - Disadvantage: Increased RMS currents

Model to derive timings (phase shifts)

Boost Mode

$$t_1 = \frac{(V_{veh} - V_{bus})DT_s}{V_{veh}} + \frac{2I_{min}L_{ph}}{V_{veh}} \tag{1}$$

$$t_2 = DT_s - t_1 \tag{2}$$

$$t_3 = \frac{(V_{veh} - V_{bus})DT_s}{2V_{veh}} + \frac{I_{min}L_{ph}}{V_{veh}} \tag{3}$$

$$t_4 = DT_s - t_3 \tag{4}$$

$$t_5 = \frac{2I_{min}L_{ph}}{V_{veh}} \tag{5}$$

$$t_z = T_s(1 - 2D) - t_5 \tag{6}$$

$$D < 0.5(T_s - t_z - t_5)/T_s, V_{veh} \geq V_{bus} \tag{7}$$

Buck Mode

$$t_1 = \frac{2I_{min}L_{ph}}{V_{bus}} \tag{8}$$

$$t_2 = DT_s - t_1 \tag{9}$$

$$t_3 = \frac{(V_{bus} - V_{veh})(DT_{s-}t_1)}{(V_{veh} + V_{bus})} + \frac{I_{min}L_{ph}}{(V_{veh} + V_{bus})} \tag{10}$$

$$t_4 = DT_s - t_3 \tag{11}$$

$$t_5 = \frac{(V_{bus} - V_{veh})t_4}{V_{veh}} + \frac{2I_{min}L_{ph}}{V_{veh}} \tag{12}$$

$$t_z = T_s(1 - 2D) - t_5 \tag{13}$$

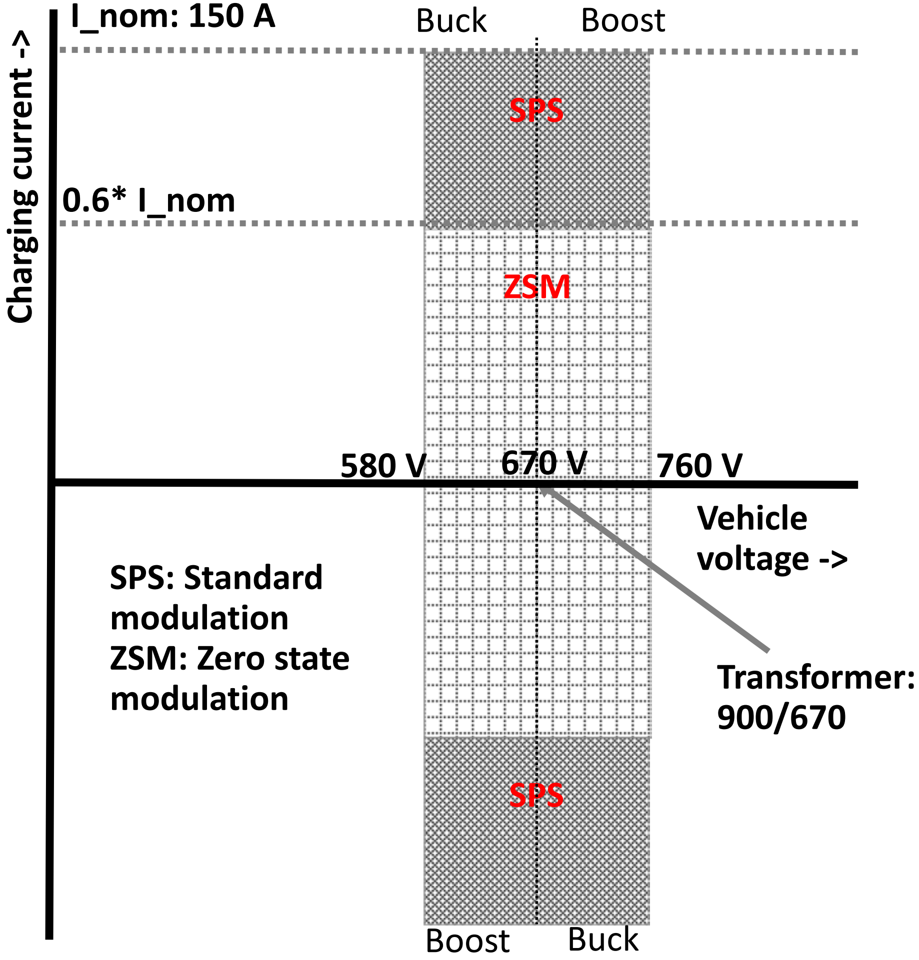
$$D < 0.5(T_s - t_z - t_5)/T_s, V_{bus} \geq V_{veh} \tag{14}$$

Simplified ZSM technique relies on single parameter (duty cycle) control – ease of implementation

Control and Operating Range

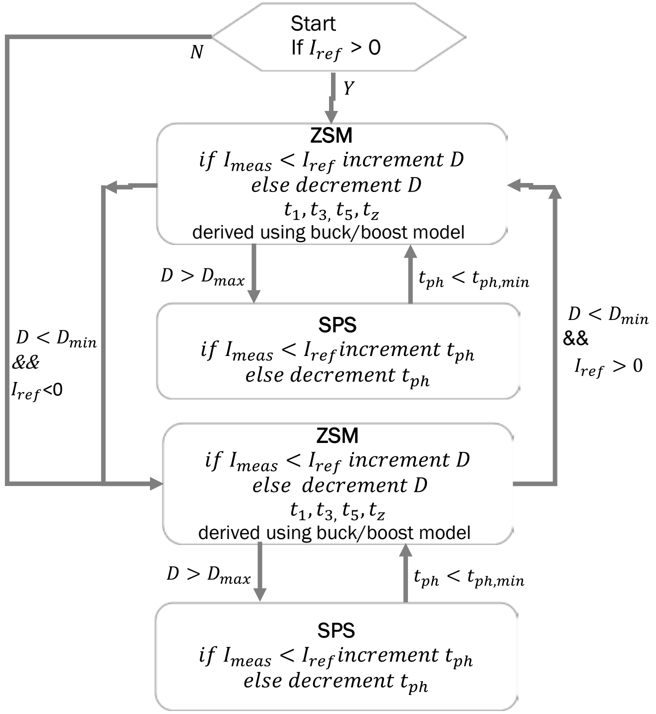
- Operating region divided into eight modes
  - Operating region is divided into positive and negative current region.
  - In each half, region is divided into low current and high current modes and buck/boost modes
- State machine developed to ensure smooth navigation between modes

Proposed DAB Operating Modes



SPS: Standard modulation
ZSM: Zero state modulation

State machine for implementation of proposed control.



Start
If $I_{ref} > 0$

N

Y

ZSM
$if\ I_{meas} < I_{ref}\ increment\ D$
$else\ decrement\ D$
t_1, t_3, t_5, t_z
derived using buck/boost model

$D > D_{max}$

$t_{ph} < t_{ph,min}$

SPS
$if\ I_{meas} < I_{ref} increment\ t_{ph}$
$else\ decrement\ t_{ph}$

$D < D_{min}$
&&
I_{ref}<0

$D < D_{min}$
&&
$I_{ref} > 0$

ZSM
$if\ I_{meas} < I_{ref}\ increment\ D$
$else\ decrement\ D$
t_1, t_3, t_5, t_z
derived using buck/boost model

$D > D_{max}$

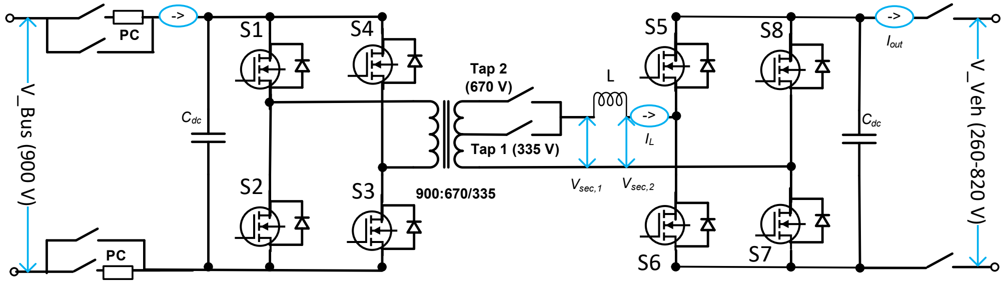
$t_{ph} < t_{ph,min}$

SPS
$if\ I_{meas} < I_{ref} increment\ t_{ph}$
$else\ decrement\ t_{ph}$

Proposed implementation combines the advantages of standard modulation and proposed ZSM techniques to achieve high efficiency and ZVS across the whole operating region

1 kV Class 150 A DC/DC converter Prototype

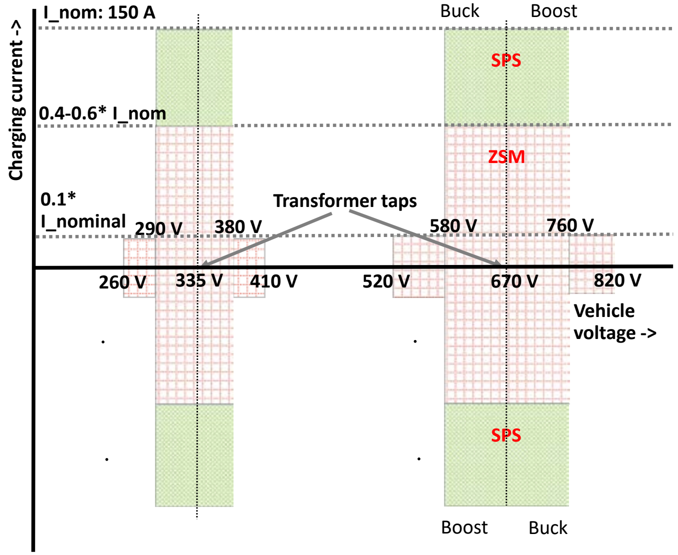
Schematic of UPER Prototype



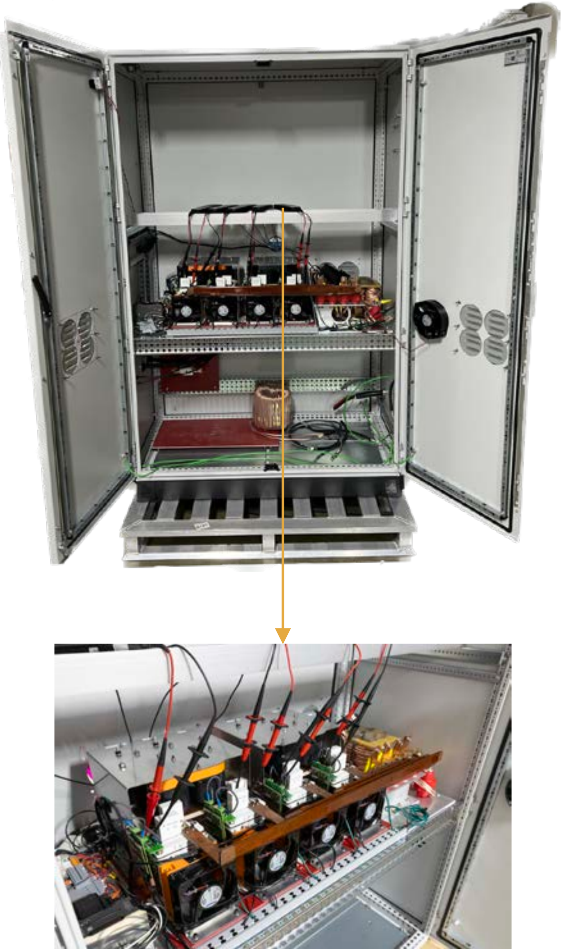
Main components of UPER Prototype

Parameter	Value
Bus voltage V_{bus}	900 V nominal, 950 V peak
Vehicle voltage V_{veh}	250 V – 810 V, 580-760 V and 290-380 V for high current
Devices	1700 V 280 A SiC, MSCSM170AM058CT6LIAG
Peak charging current	150 A
Switching frequency F_s	20 kHz
Transformer turns	13/10 (tap at 5)
Magentizing inductance L_m	1.5 mH referred to primary
Effective phase inductance L_{ph}	16 µH referred to secondary
Filter capacitance C	140 µF

Operating Range



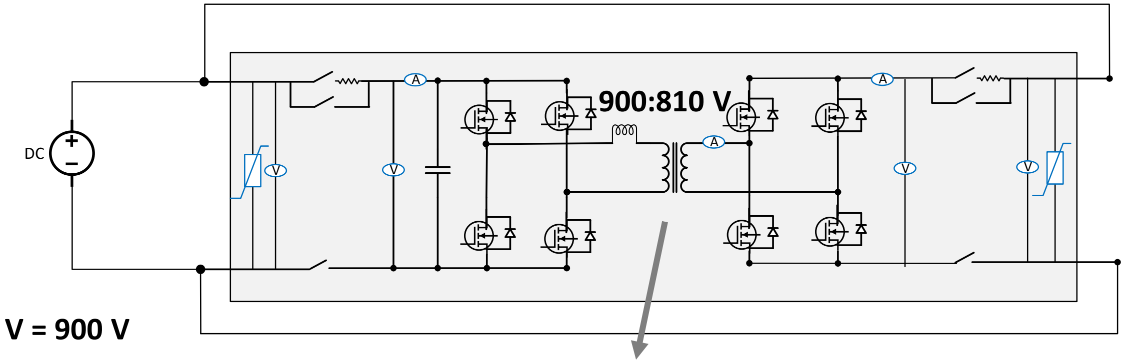
Images of 1 kV class 150 A UPER prototype



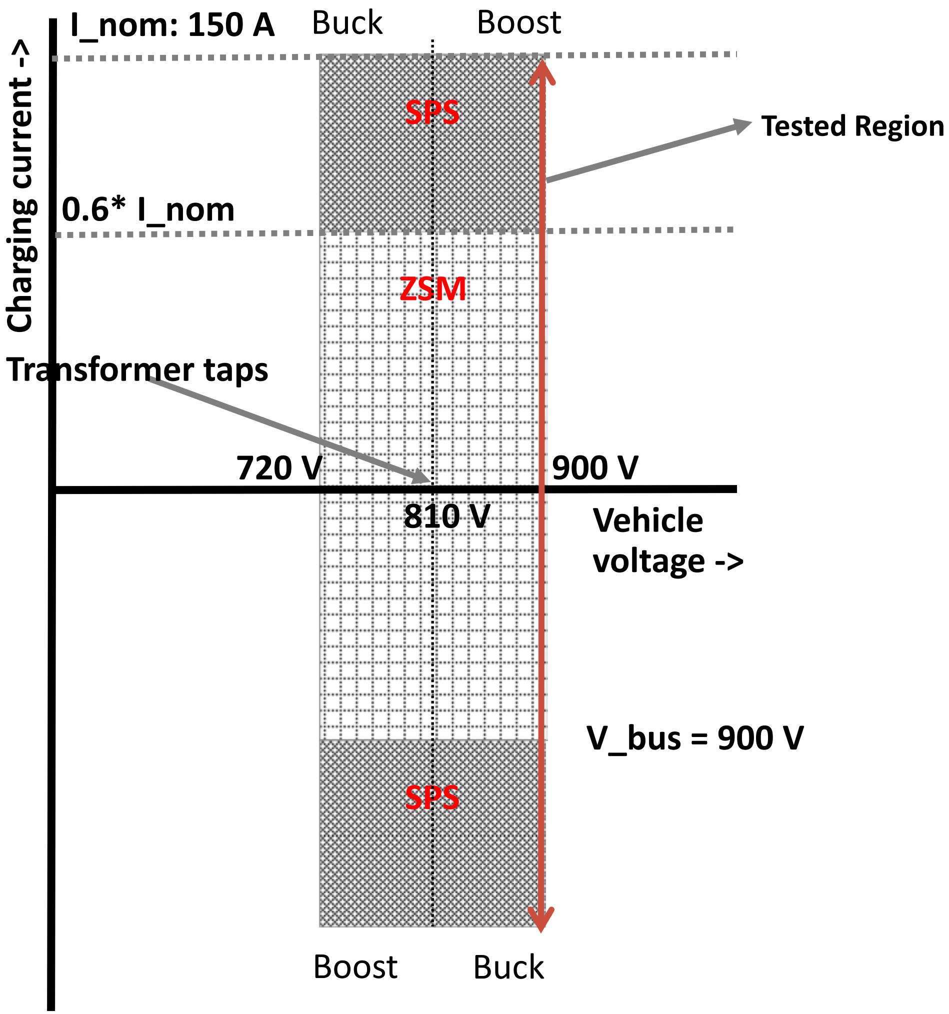
V1: 36”x 20” x 11”
V2 : 30” x 18” 10” (30% reduction)

Test Setup for Buck/Boost Mode Testing

- Transformer turns ratio 11:10 implies the converter can be tested at 11 % in boost mode in forward direction and 11% in buck mode in reverse flow direction
- In terms of absolute value, the buck/boost range of +/- 90 v is same as the eventual configuration

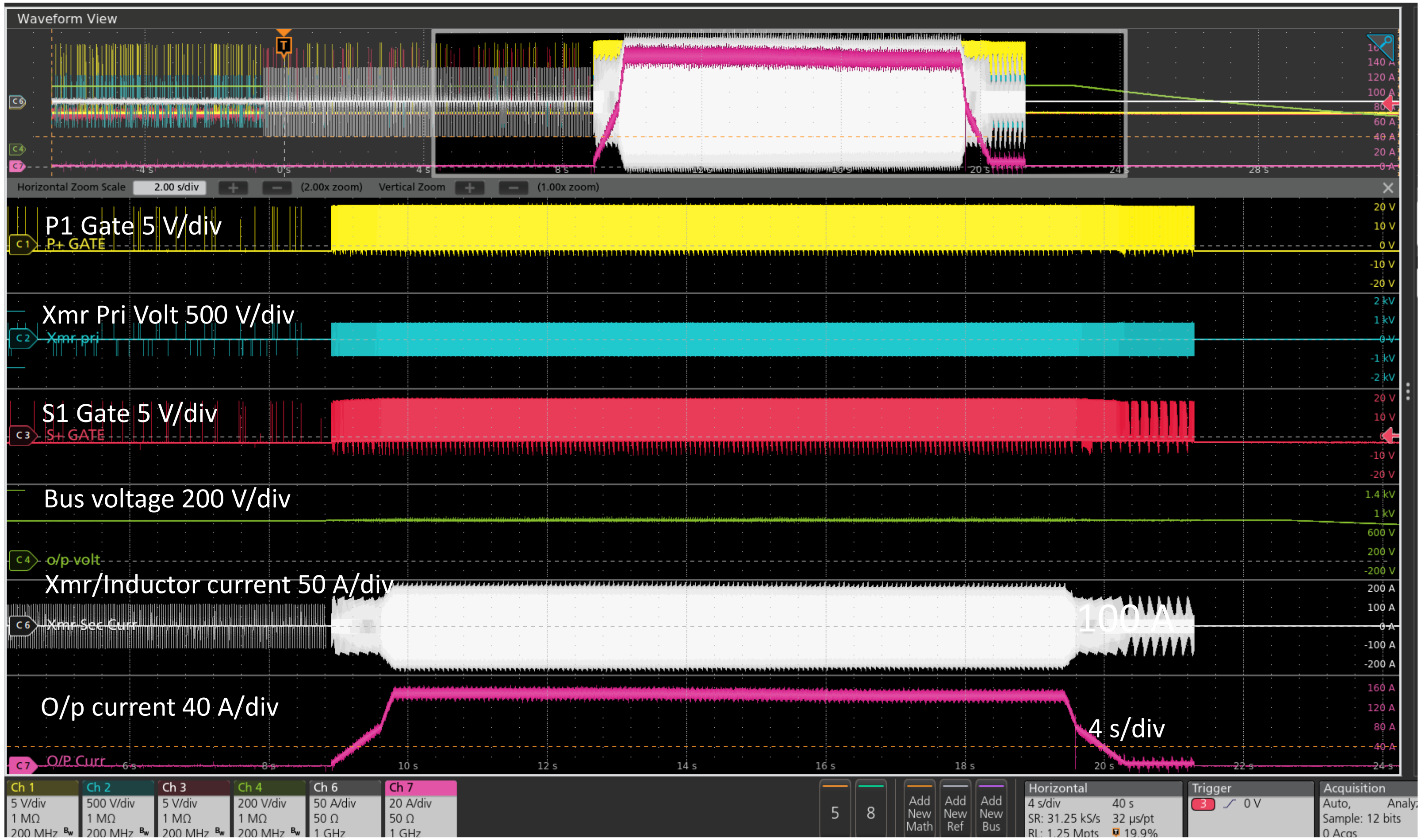


Transformer turns ratio 11:10



Dynamic Current Control at 900 V 145 A

Output current (charging current) varied from 0 to 145A. Control shifts from ZSM at low currents to SPS at higher currents. Transient free operation demonstrated. >100 A/s ramp rate.



Ch 1: 5 V/div, 1 MΩ, 200 MHz
Ch 2: 500 V/div, 1 MΩ, 200 MHz
Ch 3: 5 V/div, 1 MΩ, 200 MHz
Ch 4: 200 V/div, 1 MΩ, 200 MHz
Ch 6: 50 A/div, 50 Ω, 1 GHz
Ch 7: 20 A/div, 50 Ω, 1 GHz

Horizontal: 4 s/div, 40 s, SR: 31.25 kS/s, 32 µs/pt, RL: 1.25 Mpts, 19.9%

Trigger: 3, 0 V

Acquisition: Auto, Analy, Sample: 12 bits, 0 Acqs

Forward Power flow (Boost Mode) at 900 V 145 A

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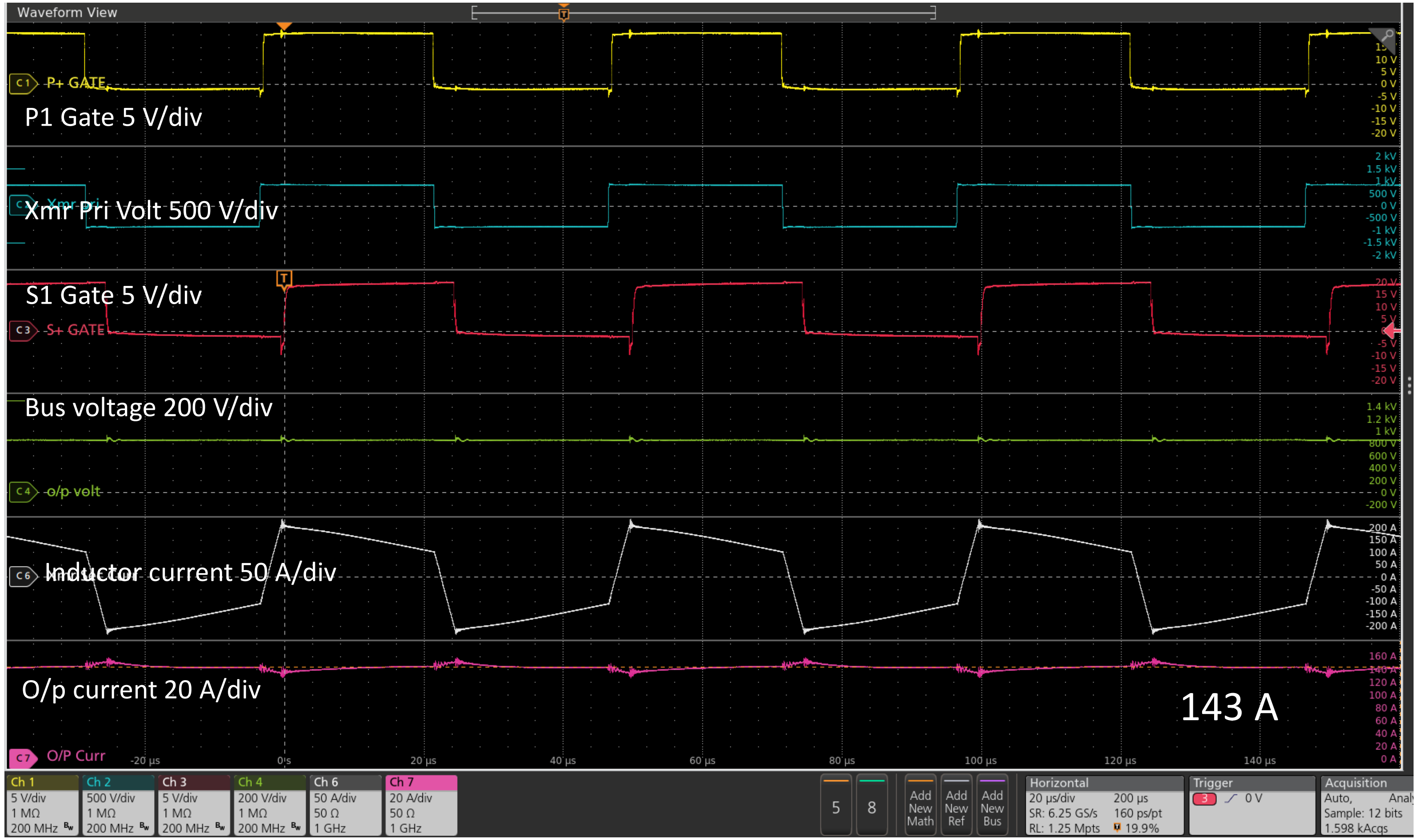
U.S. Department of Energy

Zoomed in results at 900 V 145 A with UPER in boost mode. Inductor current showing shape of boost waveform. O/p current ripple < +/-10A. No transients in Xmr voltage indicating ZVS



Ch 1
5 V/div
1 MΩ
200 MHz

Ch 2
500 V/div
1 MΩ
200 MHz

Ch 3
5 V/div
1 MΩ
200 MHz

Ch 4
200 V/div
1 MΩ
200 MHz

Ch 6
50 A/div
50 Ω
1 GHz

Ch 7
20 A/div
50 Ω
1 GHz

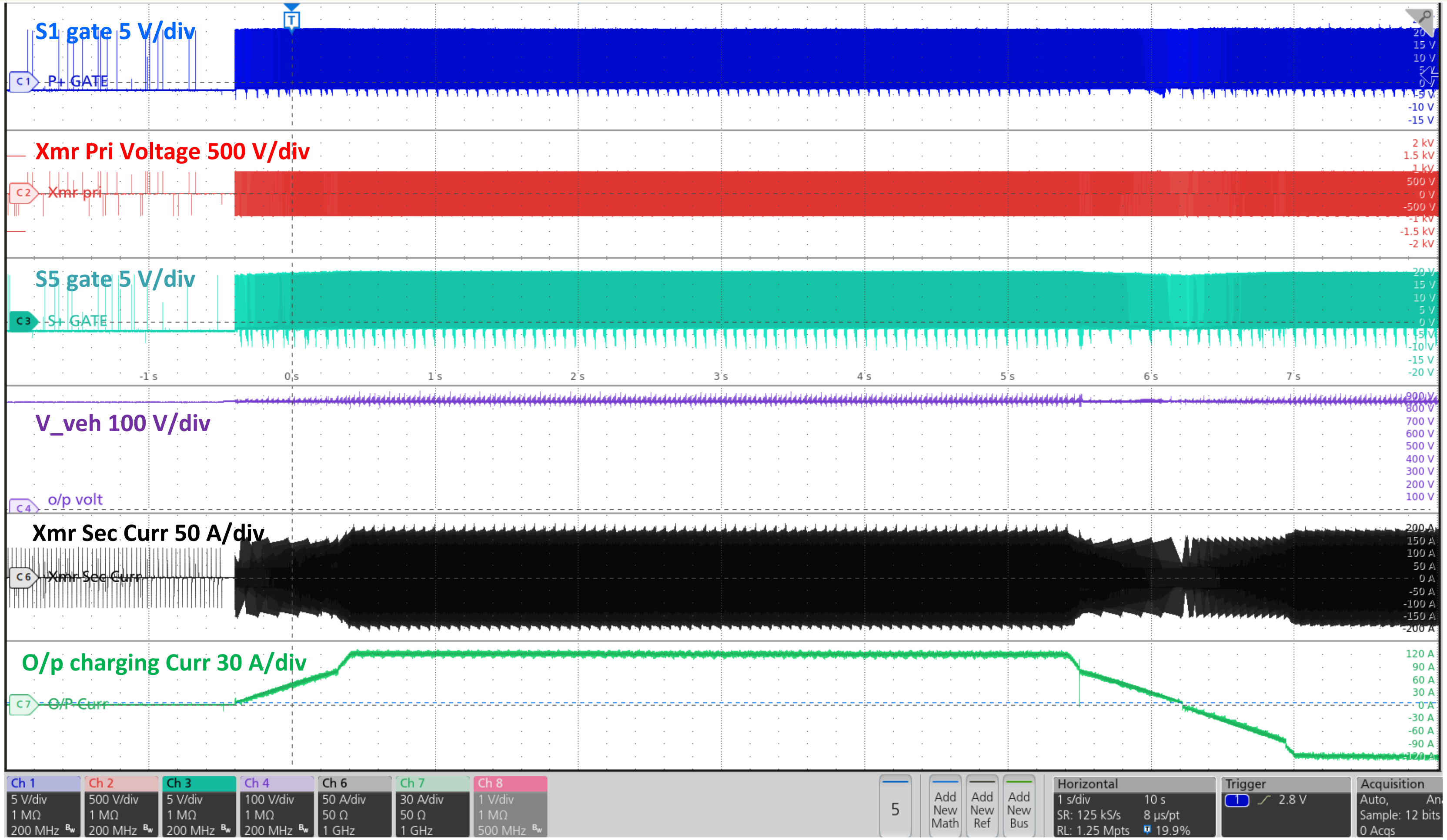
Horizontal
20 µs/div 200 µs
SR: 6.25 GS/s 160 ps/pt
RL: 1.25 Mpts 19.9%

Trigger
3 0 V

Acquisition
Auto, Anal
Sample: 12 bits
1.598 kAcqs

Bidirectional Control of Current at 900 V 120 A

Output current (charging current) varied from -120 A to 120A. Control shifts across four different regions. >100 A/s ramp rate. Transient free operation demonstrated.



Ch 1
5 V/div
1 MΩ
200 MHz

Ch 2
500 V/div
1 MΩ
200 MHz

Ch 3
5 V/div
1 MΩ
200 MHz

Ch 4
100 V/div
1 MΩ
200 MHz

Ch 6
50 A/div
50 Ω
1 GHz

Ch 7
30 A/div
50 Ω
1 GHz

Ch 8
1 V/div
1 MΩ
500 MHz

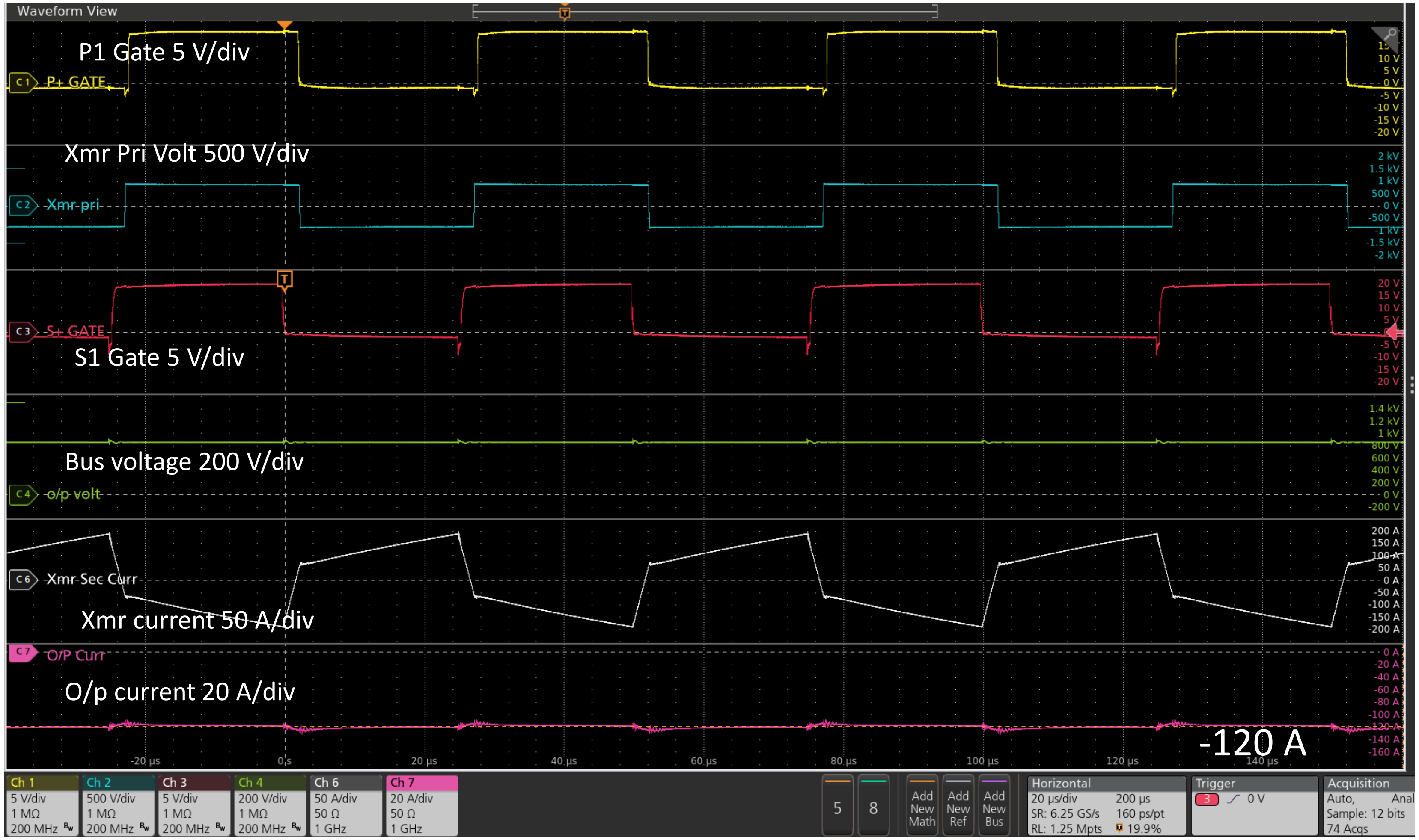
Horizontal
1 s/div 10 s
SR: 125 kS/s 8 µs/pt
RL: 1.25 Mpts 19.9%

Trigger
1 2.8 V

Acquisition
Auto,
Sample: 12 bits
0 Acqs

Reverse Power Flow (Buck) Results 900 V 120 A

Zoomed in results at 900 V 120 A with UPER in buck mode and reverse power flow. Inductor current showing shape of buck waveform. No transients in Xmr voltage indicating ZVS



P1 Gate 5 V/div

Xmr Pri Volt 500 V/div

S1 Gate 5 V/div

Bus voltage 200 V/div

Xmr current 50 A/div

O/p current 20 A/div

-120 A

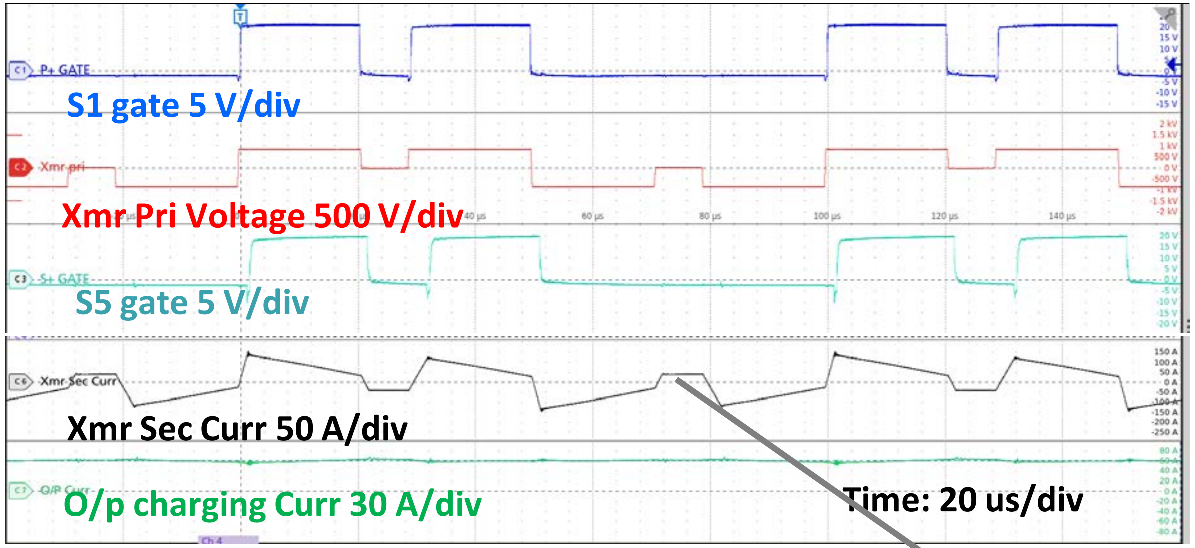
Ch 1 5 V/div 1 MΩ 200 MHz
Ch 2 500 V/div 1 MΩ 200 MHz
Ch 3 5 V/div 1 MΩ 200 MHz
Ch 4 200 V/div 1 MΩ 200 MHz
Ch 6 50 A/div 50 Ω 1 GHz
Ch 7 20 A/div 50 Ω 1 GHz

Horizontal: 20 µs/div, 200 µs, SR: 6.25 GS/s, 160 ps/pt, RL: 1.25 Mpts, 19.9%
Trigger: 3, 0 V
Acquisition: Auto, Anal, Sample: 12 bits, 74 Acqs

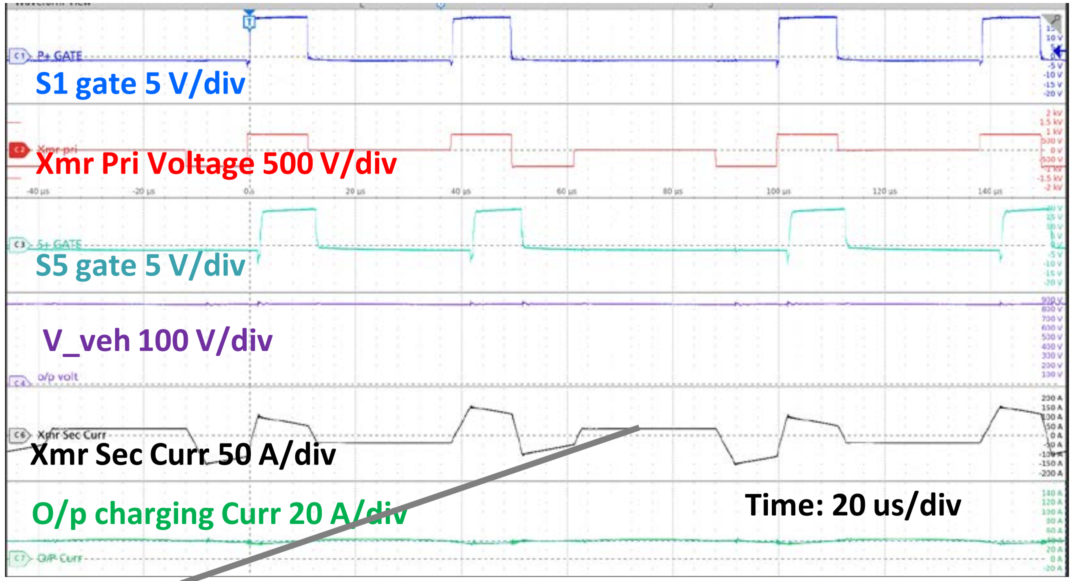
ZSM Results at Lower Currents

Zoomed in results at 900 V and lower currents. UPER in ZSM mode. Inductor current showing signature shape of ZSM in boost modes. No transients in Xmr voltage indicating ZVS

Results at 900 V 60 A using simplified ZSM modulation

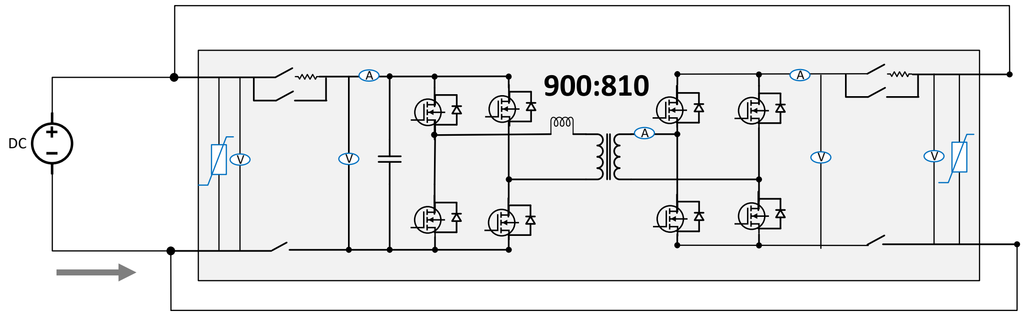


Results at 900 V 40 A using simplified ZSM modulation



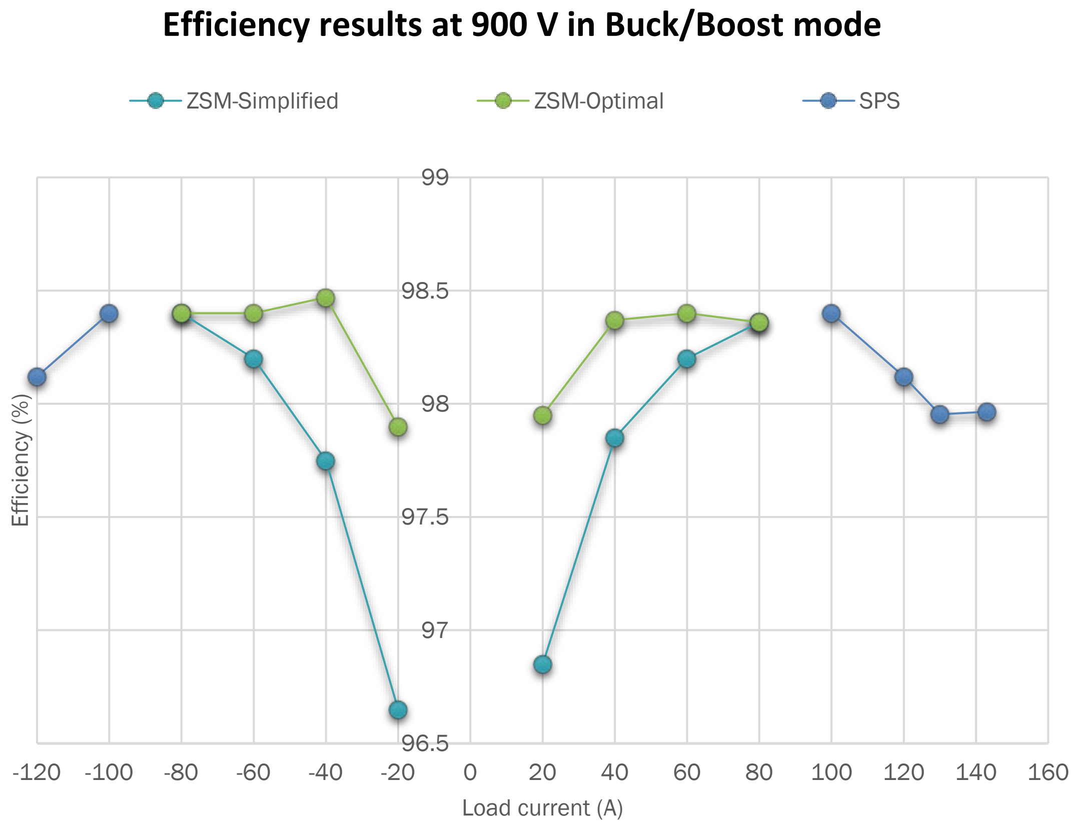
Increased zero state at lower currents

Efficiency Results



P from source is equal to losses in the converter

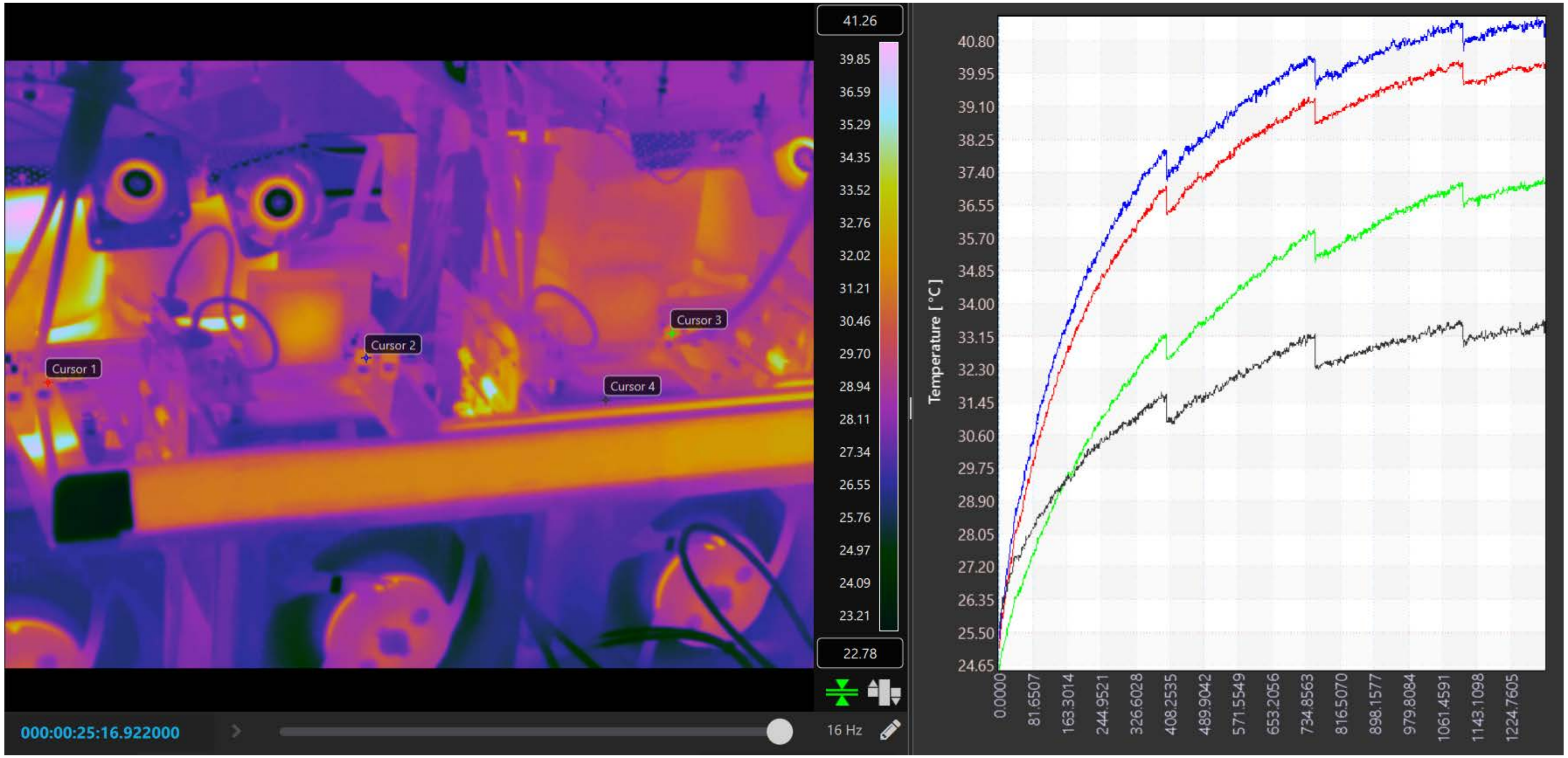
- The converter maintains 98% efficiency from 15-100% of the load current
- The results are at the highest end of boost/buck mode – worst case for efficiency


Efficiency results at 900 V in Buck/Boost mode

Thermal Results

Test Conditions: Converter tested at 80,100, 120 A till semiconductor temperatures stabilized which is about 20-30 min

120 A for 20 mins



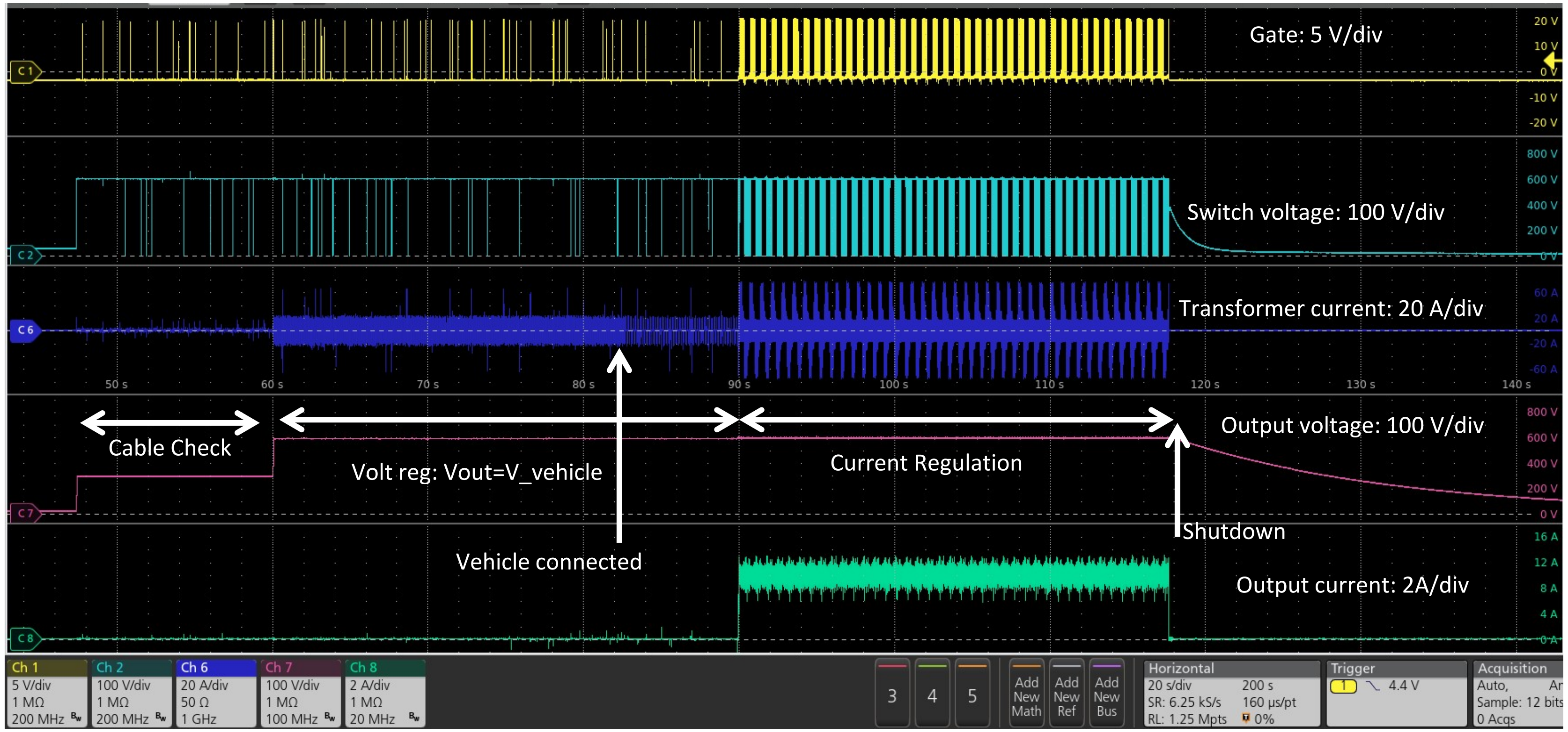
Time (s) ->

Thermal camera position

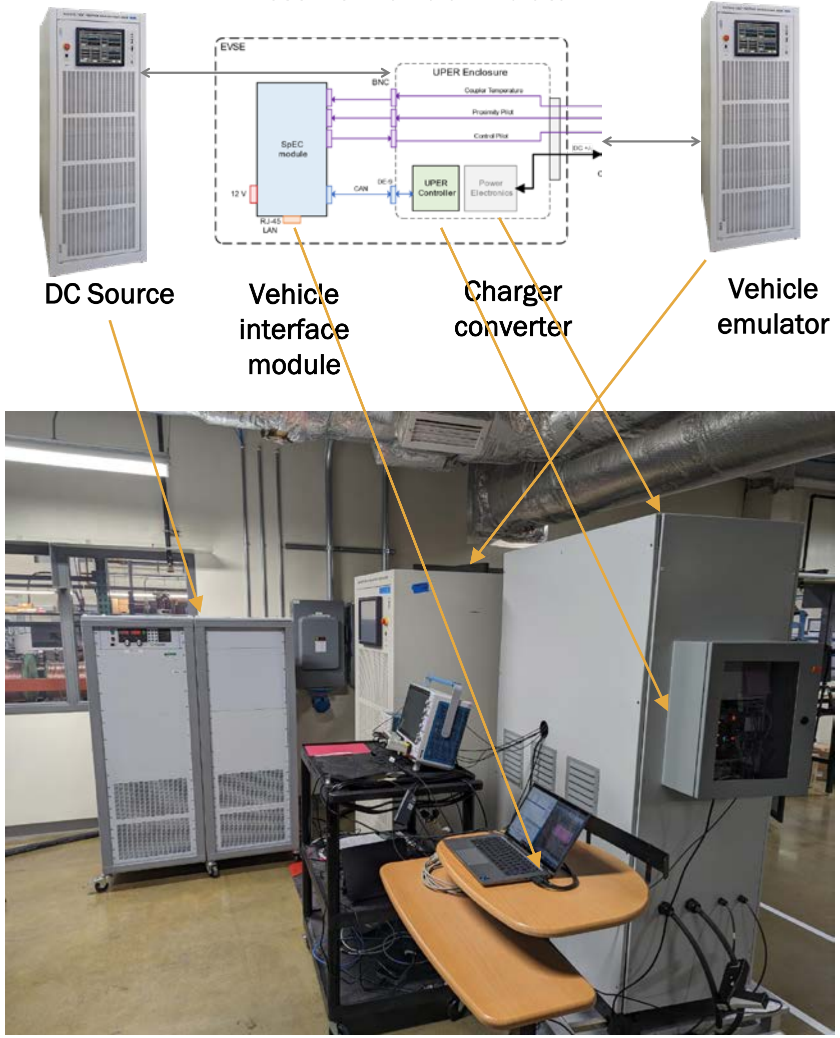
Charger Specific Development : Comm Interface

- Commands issued from SPEC equivalent DBC file to the charger
- Vehicle emulator manually controlled
- Verification of cable check, Precharge and voltage/current regulation modes

Interface testing: Charger Test Results at 600 V and 10 A



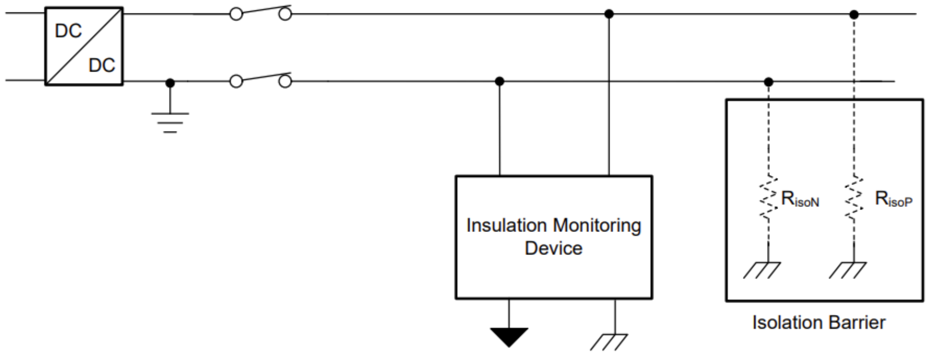
Test with Vehicle Emulator



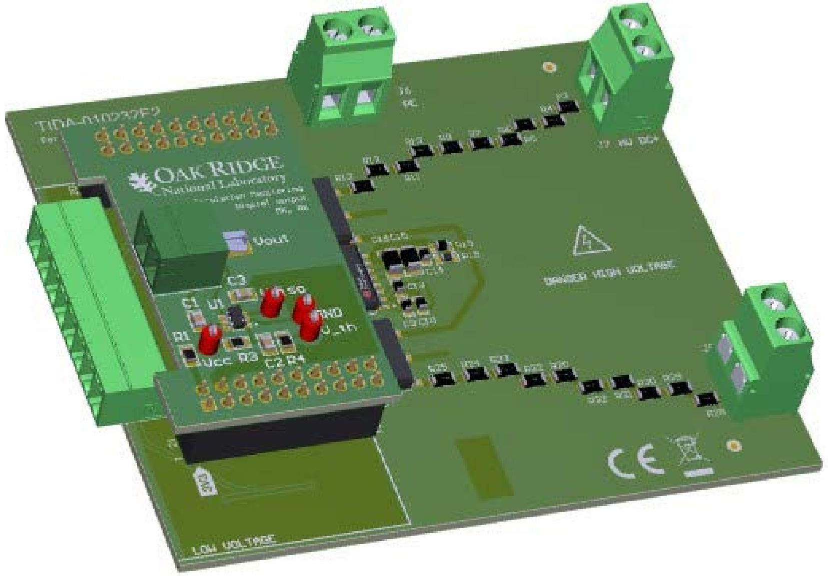
Charger Specific Development : Isolation Monitoring

- During the cable check state, isolation from bus to ground needs to be monitored
- A custom isolation monitoring device is being developed (BOM ~$25)
- Full control over the design implies easy migration to 1500 V class isolation monitors

Isolation Monitoring Concept



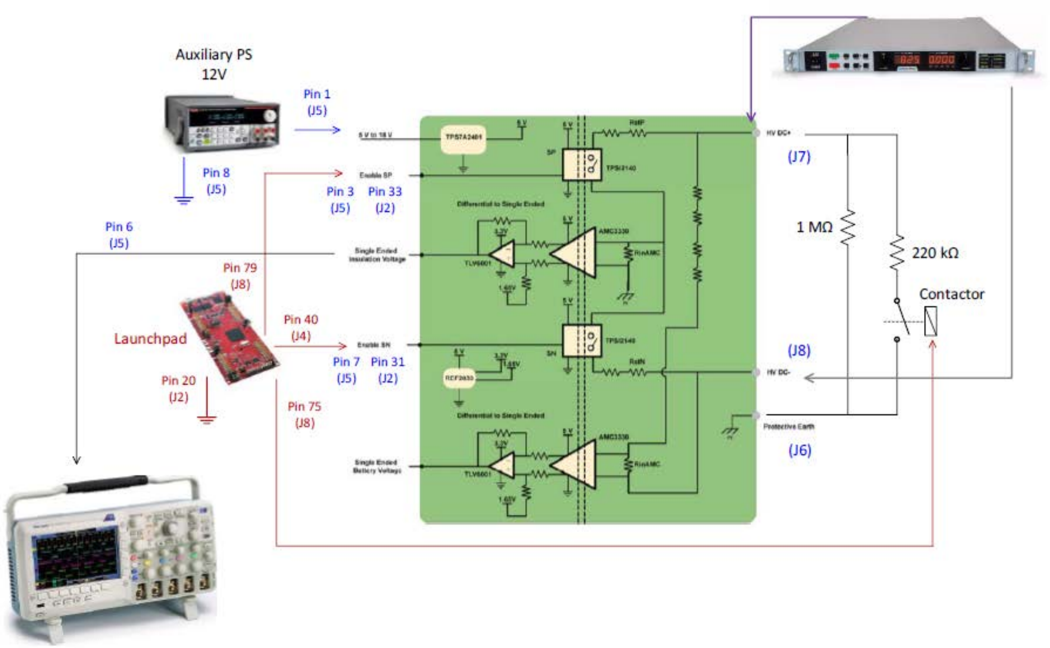
1000 V class Isolation Monitor PCB



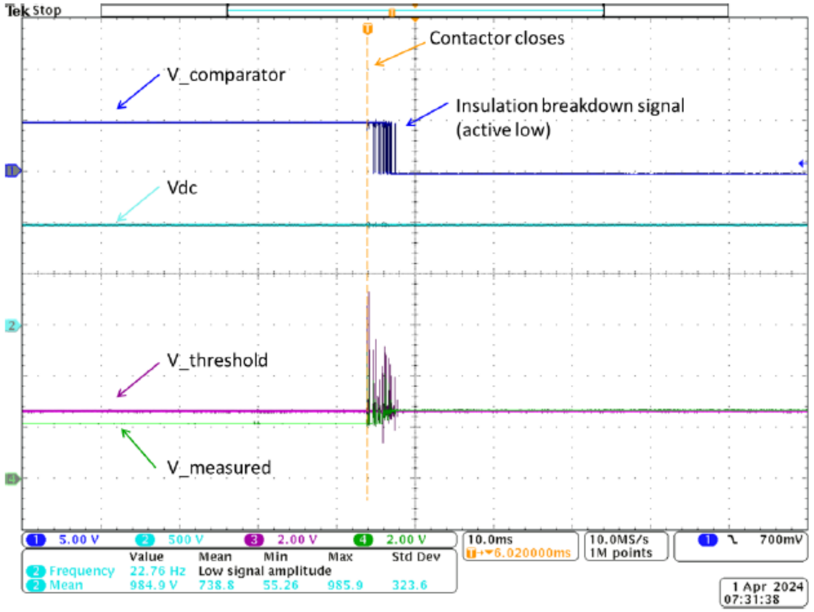
Insulation Monitor Test Results

- Insulation Monitor verified for detection of low bus to ground resistance

Test setup for Isolation Monitor: Switch ground impedance from 1 MOhm to 220 kOhms



Test results for Isolation Monitor: Insulation failure signal on closing of 220 kOhm impedance between bus and ground



```
                Value      Mean   Min     Max     Std Dev
2 Frequency     22.76 Hz   Low signal amplitude
2 Mean          984.9 V    738.8  55.26   985.9   323.6
```

Next steps

- Integrating charger specific developments: communications
- Adding advanced functionalities such as droop
- Development of front-end grid interfacing converter and integrating with UPER

Conclusions

- A bidirectional DC/DC converter based on DAB for 1 kV class fast charger applications is presented
- A novel modulation technique called zero state modulation (ZSM) is proposed to ensure ZVS across the entire voltage and current range of a typical 800 V class vehicle.
- Converter was tested at 900 V 145 A in boost mode (14%), demonstrating ZVS. For the reverse power flow, the converter was tested at 900 V 120 A in buck mode (14%), again demonstrating ZVS.
- A center tap for the transformer is proposed to achieve an additional 28% voltage range around 335 V for the 400 V class vehicle.
- Bidirectional current control from +120 A to -120 A was shown to demonstrate smooth transition between ZSM at lower currents and SPS at higher currents.
- Peak efficiency of 98.5% was demonstrated at 70% of the nominal load
- Thermal testing was completed at 900 V 120 A , verifying the thermal design

Conclusions

- Proposed converter implementation allows a full range ZVS bidirectional isolated DC/DC converter, compatible with 400 V and 800 V class vehicles and which delivers >98% efficiency from 15-100% of the nominal load.

Multi-Dimensional Improvement v/s SOA

High power Building block
Enable MW+ Charging
Tested at 150 kW

Power density
Frequency > 20 kHz, η > 99%
Enable Two men carry < 80 Lbs
Freq target is achieved, peak η about 98.5%

Higher Working voltages
DC Distribution increased to 2 kV from 950 V
Vehicle voltage increased from 900 V to 1500 V
2 kV charger in progress

Bidirectional Power (V2X)
Controls to enable bidirectional power transfer while maintaining low loss
Bi-directional power flow demonstrated

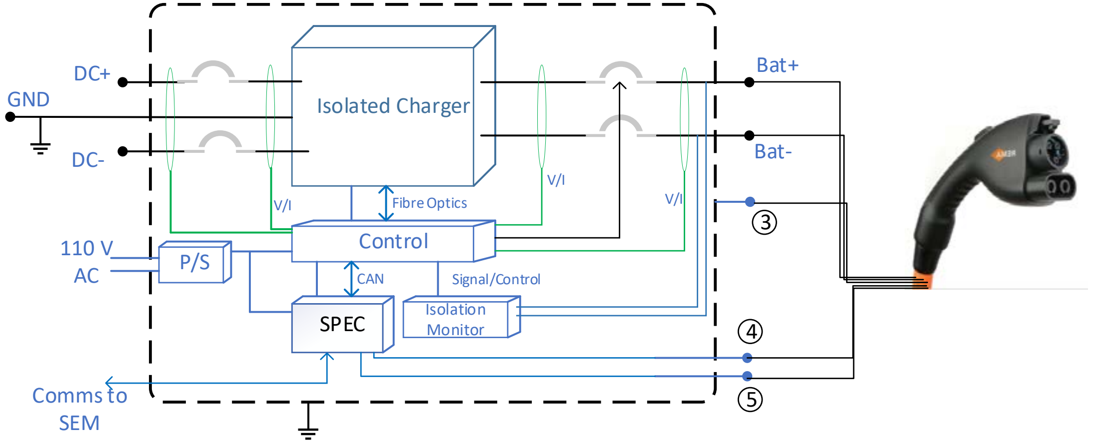
Impact

- **Developed isolated DC/DC technology is being applied to three other applications, under other DOE programs**
  - Li based storage interface converter
  - Flow battery-based storage interface converter
  - PV interface converter
  - DC/DC converter as building block for MV converters
- **Industry Collaboration**
  - Collaboration with industrial partner for storage interface converter development
  - Currently in negotiations with one more industrial partners
- **Publication: Prasad K, et.al, “1 kV 150 A Bidirectional Isolated DC/DC Converter With Full Range ZVS For Charger Application” ITEC 2024**
- **Invention Disclosure:** Prasad K, et.al, “Electric Vehicle Bi-Directional Isolated DC-DC Charger: Architecture and Modulation for Wide Operating Range “

Thanks, and Questions

Converter Design

Charger (DC-DC) Specifications	
Output power	175 kW Module (Scalable to 0.5 MW)
Bidirectional	Yes
Output voltage (DC)	580-760 V / 290 -380 V @ max rated current. 250-900V @ <50 A
Output current (DC)	0- 200 A
Input voltage (DC)	900 V +/-5%
Efficiency	> 99 %
Operating temperature	TBD to 40 degC
Dimensions (Module)	10"h x 30" w x 18" d
Dimensions (Enclosure)	60"h x 36" w x 25" d
Weight	TBD
Environmental	Indoor only
Cooling	Forced air
CONNECTORS	CCS Type2 (can be modified)
EV comm protocols	DIN 70121 & ISO-15118
Control power	110 V AC, 10 A
Station Connectivity	RJ45



1000 V, 175 kW DC/DC charger Module

SOA

- **EVSE DC/DC building block limited in size**
  - Commercial DC/DC converters are typically 25-100 kW
  - High-power building block (350 kW) to meet heavy duty (1 MW+) charging requirements is required
- **Bi-directionality is lacking**
- **Limited peak charging voltage**
  - Current SOA is <1000 V for the DC bus and charging
  - Off-road vehicles like the battery-locomotives, eVTOLs may transition to 1500 V
    - Battery locomotives driven by high power
    - eVTOLs driven by need for extreme fast charging
  - DER integration will require 1500 V class DC/DC converters

SOA 1000 V class AC/DC and DC/DC converters

Vendor 1: 175 kW building block with 60 Hz isolation

Vendor 2: 75/100 kW building block w/ HF isolation

Vendor3: 125 kW building block w/ HF isolation – only up to 500 V

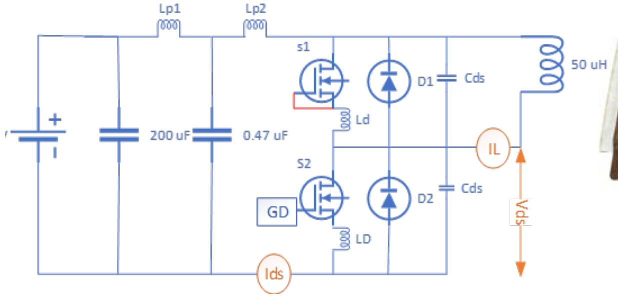
Vendor 4: 25 kW building block w/ HF isolation

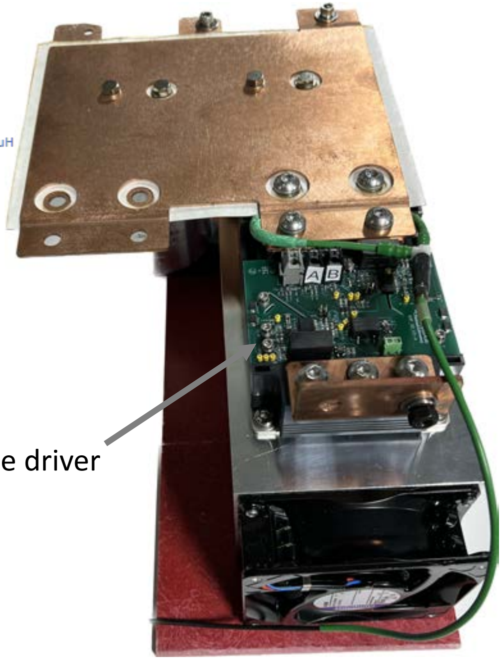
High power, high voltage and bidirectional DC/DC module is a critical enabling component for medium/heavy duty applications

2000 V Class Charger Development

- 3.3 kV SiC device (Wolfspeed) has been characterized at 2 kV and 450 A
- Includes verification of custom-built gate driver : 5 kV isolation, 10 A peak current, optical interface
- Next steps include building the complete 2 kV class charger

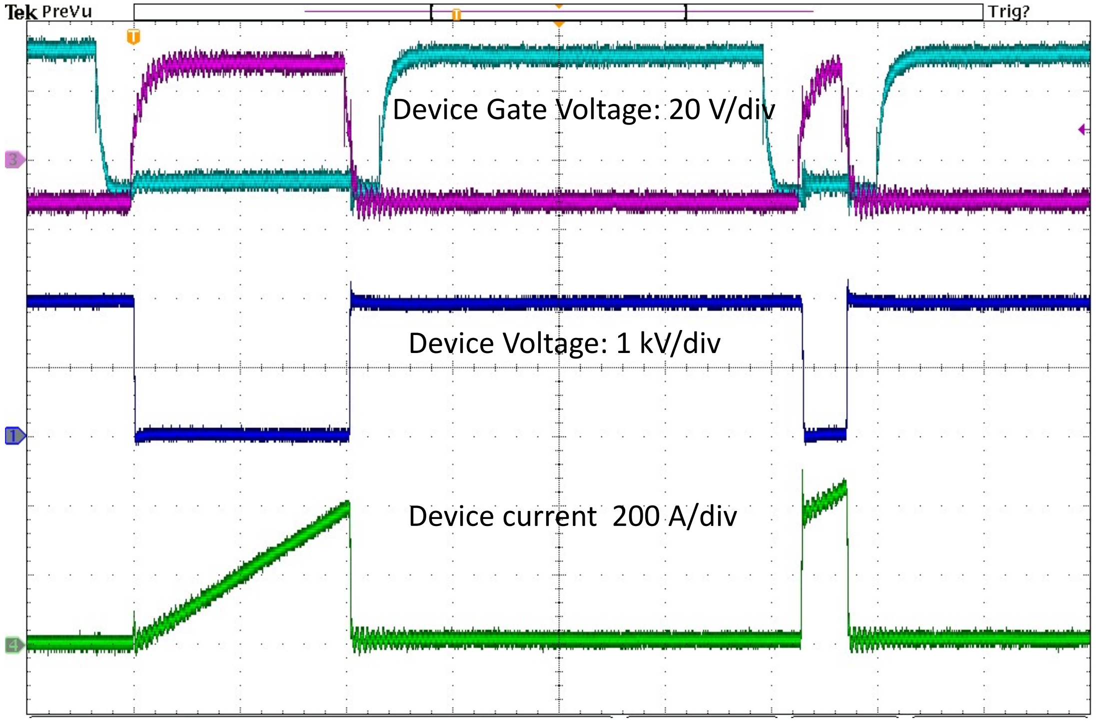
Double Pulse Test Setup



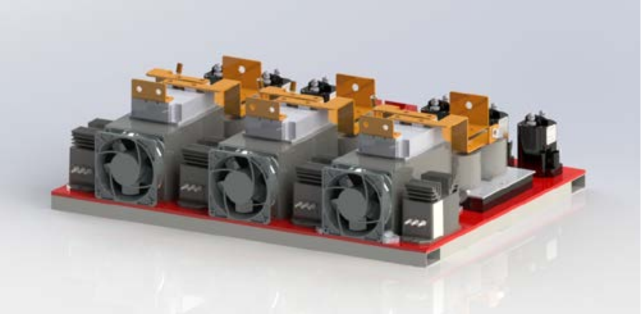


ORNL 3.3 kV SiC Gate driver

Characterization results of 3.3 kV SiC at 2 kV and 450 A



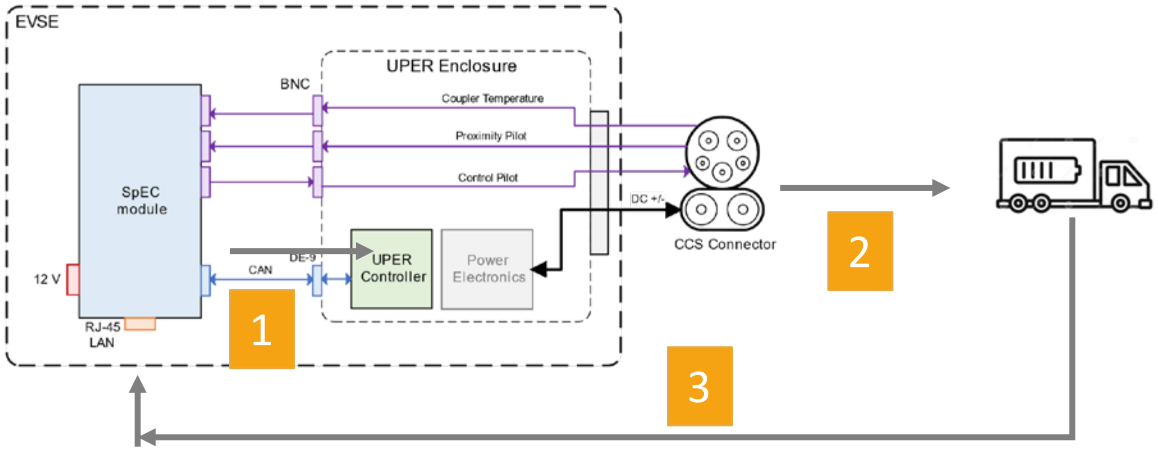
2 kV class 175/350 kW DC/DC charger CAD



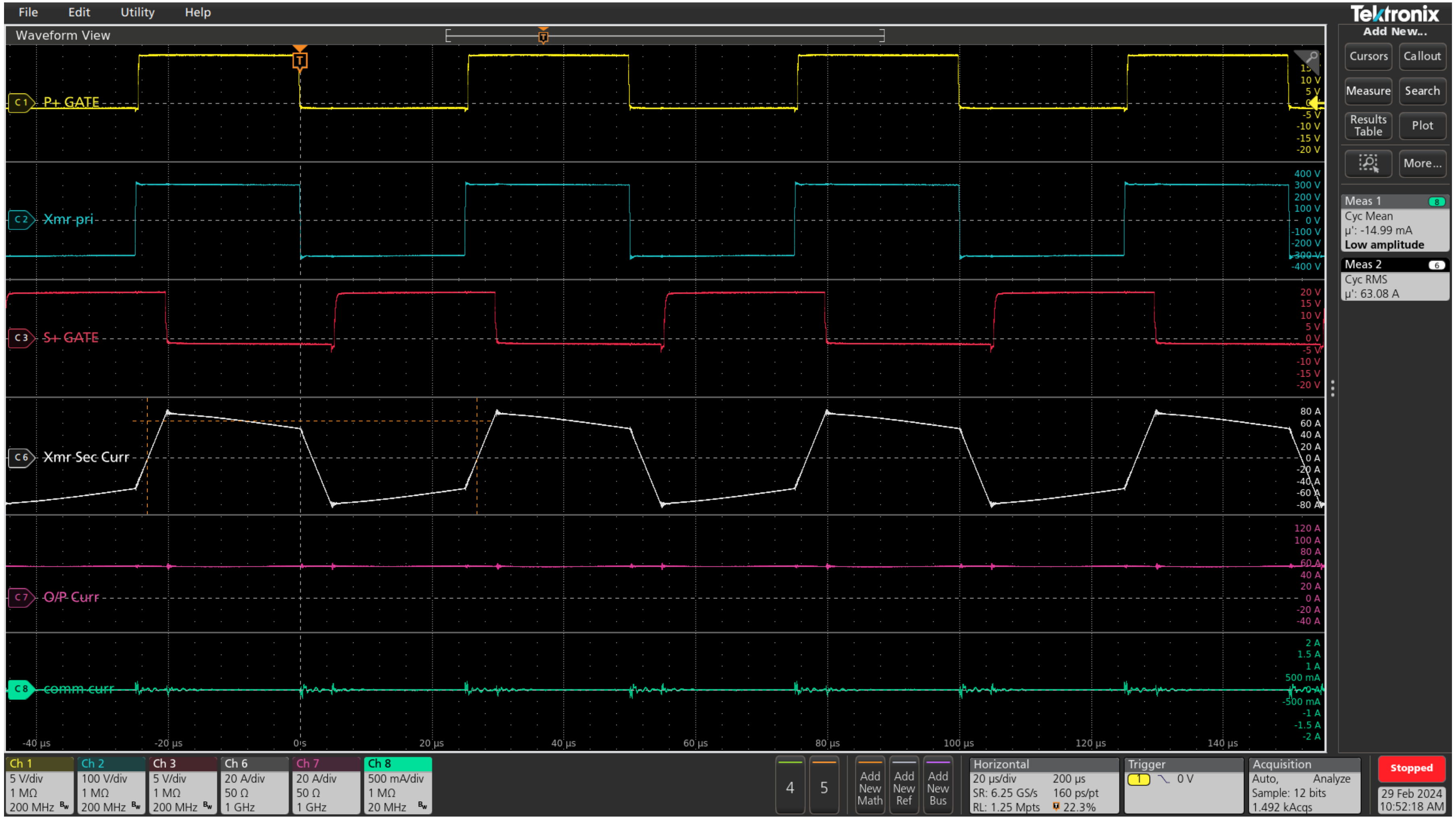
Integration and Communication Interface

Three major comms/interfaces to be tested

No.	Interface	Status
1	SPEC-UPER	Tested using SPEC equivalent DBC and UPER DSP
2	UPER-Vehicle	Power interface is tested.
		Comms interface has to be routed to SPEC
3	Vehicle – SPEC	Tested at ANL
1-2	SPEC-UPER-Vehicle	Tested
1-2-3	SPEC-UPER-Vehicle-SPEC	In progress



Common mode current



Meas 1 8
Cyc Mean
µ': -14.99 mA
Low amplitude

Meas 2 6
Cyc RMS
µ': 63.08 A

Ch 1
5 V/div
1 MΩ
200 MHz B_W

Ch 2
100 V/div
1 MΩ
200 MHz B_W

Ch 3
5 V/div
1 MΩ
200 MHz B_W

Ch 6
20 A/div
50 Ω
1 GHz

Ch 7
20 A/div
50 Ω
1 GHz

Ch 8
500 mA/div
1 MΩ
20 MHz B_W

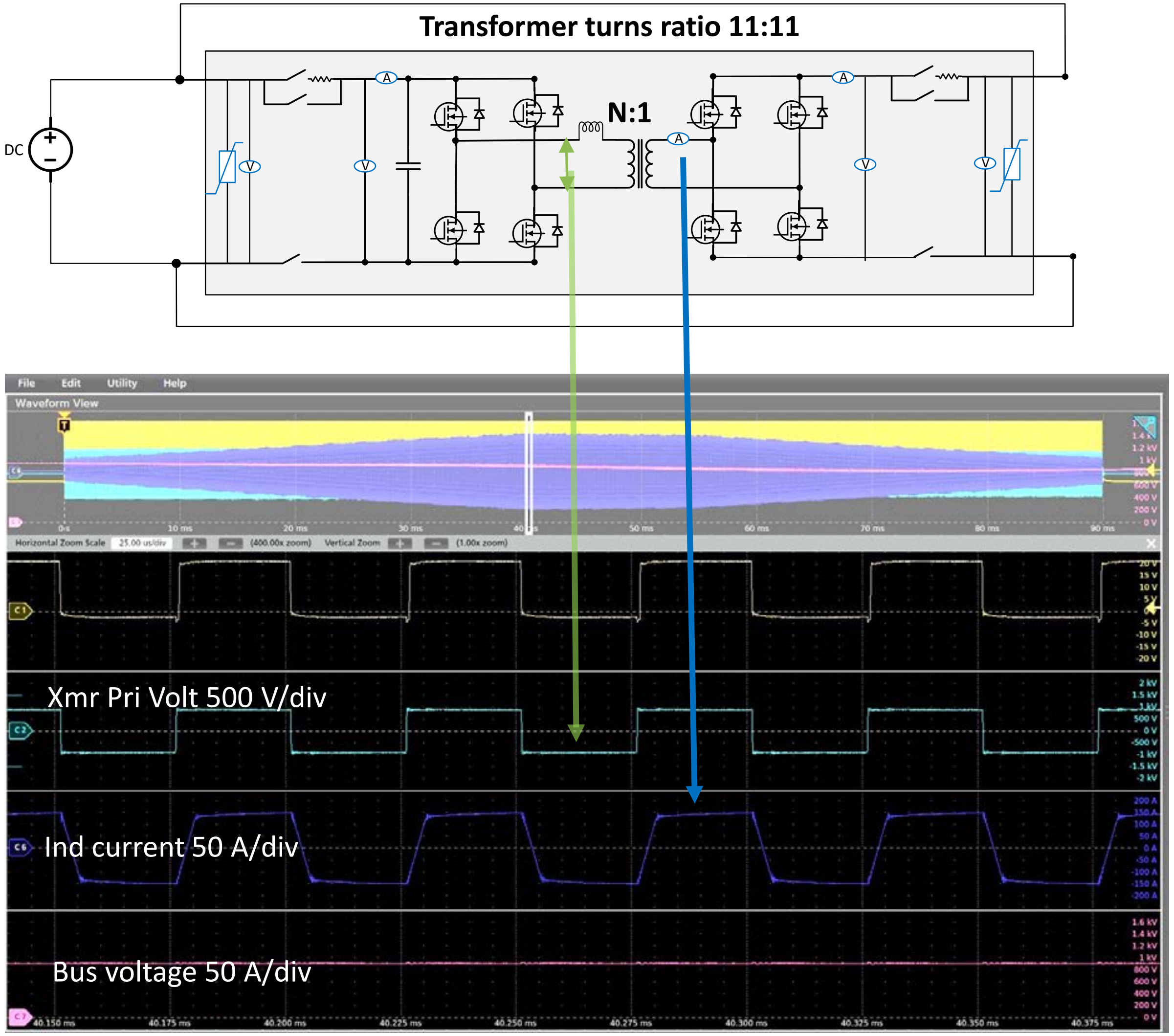
Horizontal
20 µs/div 200 µs
SR: 6.25 GS/s 160 ps/pt
RL: 1.25 Mpts 22.3%

Trigger
1 0 V

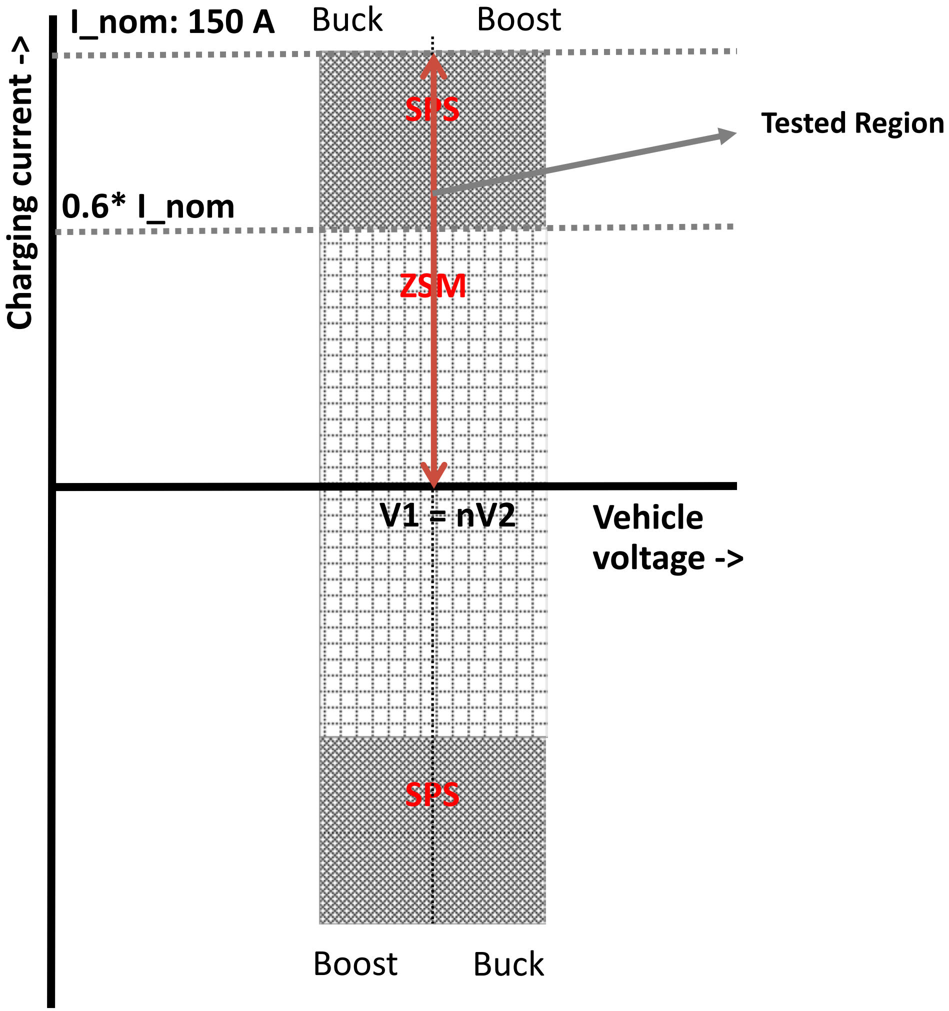
Acquisition
Auto, Analyze
Sample: 12 bits
1.492 kAcqs

Stopped
29 Feb 2024
10:52:18 AM

Test Results at 950 V, 150 A



Charger Test Results at 950 V and 150 A: ~150 kW



EVs@Scale
U.S. Department of Energy

High-Power Charging Pillar: eCHIP

High-Power **E**lectric Vehicle **C**harging **H**ub **I**ntegration **P**latform

SpEC II module integration with COTS DC/DC converter

Deep-Dive

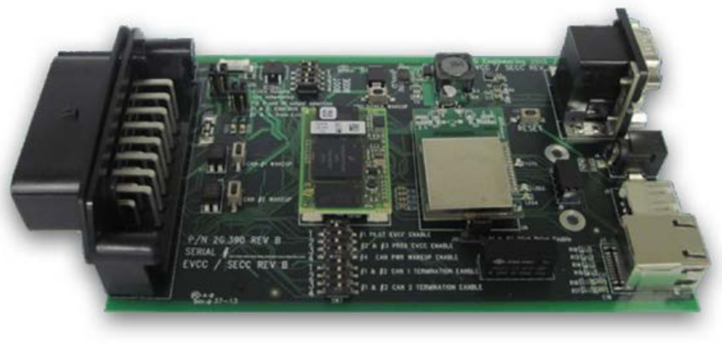
Akram Syed Ali
ANL EV-Smart Grid Interoperability Center
Advanced Mobility and Grid Integration Technology

April 23, 2024

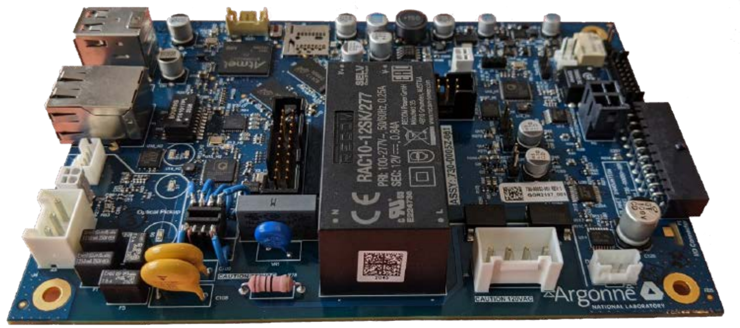
SpEC Module

ANL

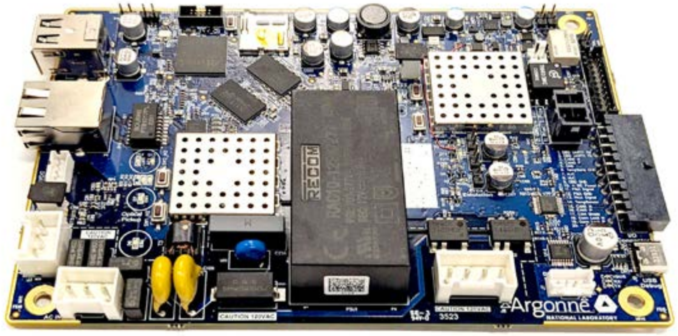
- The SpEC module developed by ANL is a smart plugin EV communication **controller**
- Enables DC fast charging high-level communication between an EV and the charger based on DIN SPEC 70121 and ISO 15118 (-2/-20) standard
- Communication over Control Pilot (CP) on CCS cable (HPGP protocol)



SpEC module (Gen I)
2013



SpEC module (Gen II)
2020



SpEC module (Gen II)
2023

SpEC Module – Gen II

ANL

SpEC module (Gen II)

- Linux Kernel 5.4.81
- Custom Device Tree Overlay
- Power Line Communication ready
- OCPP 1.6J Client (OCTT Self-Certified)
- OCPP 2.0.1 Client (WIP)
- Custom C/C++ Applications
- Design for Manufacture (DFM)

Ubuntu 20.04 LTS
(Focal Fossa)

Node-RED

MQTT

OCPP

USB

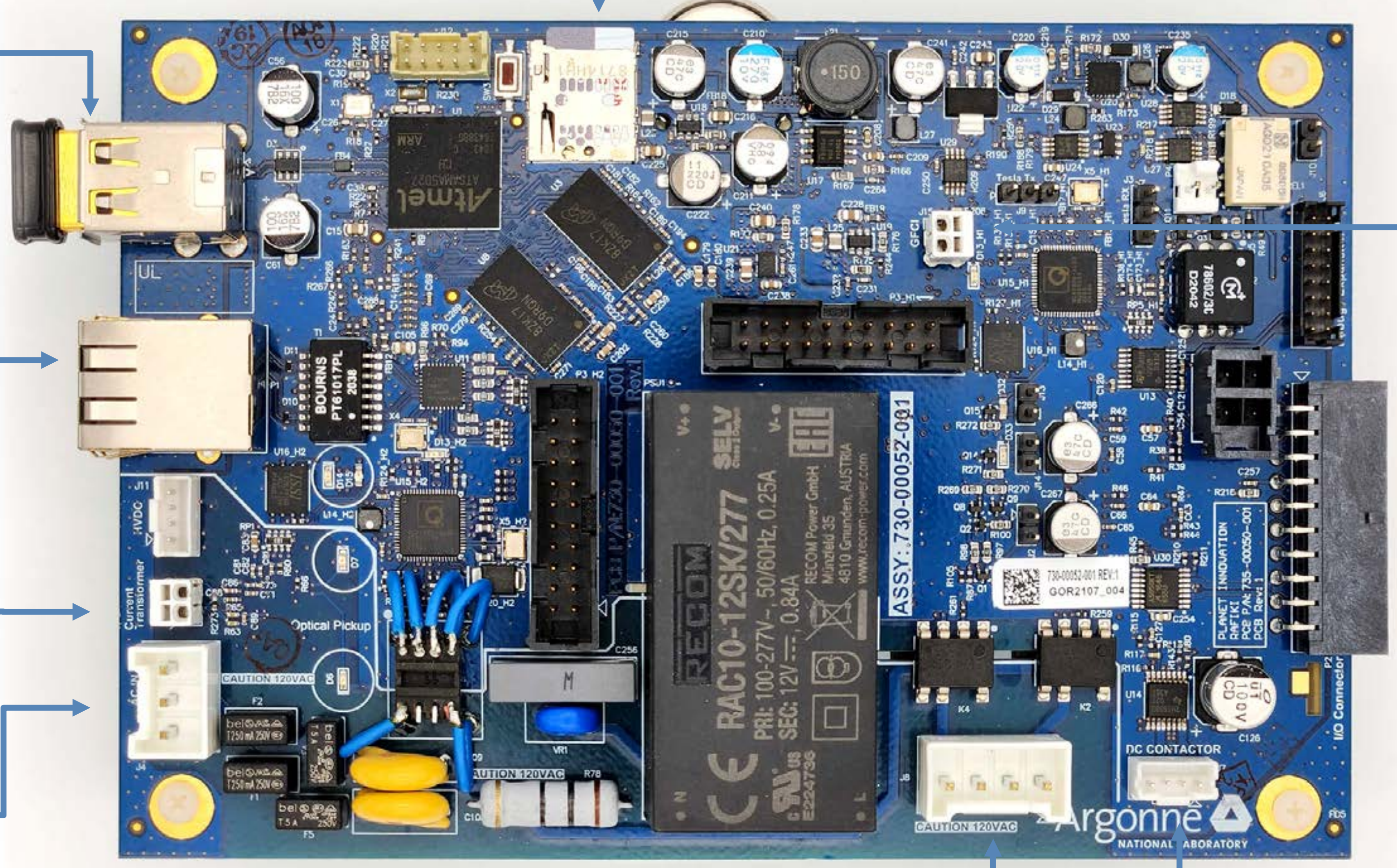
CAN

and many more..

Environmental	Operating Temperature	-40°C to +85°C.
	Storage Temperature	-40°C to +105°C.
Memory and Storage	SDRAM Memory	512 MB DDR3 @ 166MHz
	Flash Memory	4 GB eMMC Flash onboard with additional external micro SD card slot
Interfaces	Power Line Communication	HomePlug Green PHY: AC Mains HomePlug Green PHY: Control Pilot
	USB 2.0	2 HOST controllers
	Ethernet	RJ-45 10/100 Ethernet interface
	Control Pilot	Generation (EVSE) and Emulation (PEV)
	Proximity	Monitoring and Generation
	CAN	2 CAN interfaces
	Tesla (Single Ended Can)	Rx/Tx Single Wire Can over Pilot
	AC Current	Input for CT to measure AC current (AC charging)
	DC Current	Input for DC current sensor to measure DC current (DC charging)
	AC Voltage	Input for AC Voltage for AC meter
	DC Voltage	Input for DC Voltage for DC meter
	12VDC Switches	Dual 2A, 12VDC switches for contactors
	DPDT AC Relays	Quad SPST SSR's for driving external AC contactors
	EV Inlet Lock Driver	12VDC Driver for EV inlet lock
	Temperature Sensor	External input and onboard temperature sensor
	GFCI	Ground Fault Interrupt CT input
	GPIO	5 externally accessible GPIO
	ADC	4 externally accessible ADC
	JTAG	JTAG for Debugging
	UARTS	2 UARTS for serial communication
Power	AC Input Voltage	85-265 VAC
	DC Input Voltage	9-24 VDC
	Quiescent Current	< 200µA in ultra-low power mode
Modes of Operation	EVCC	Electric Vehicle Communication Controller
	SECC	Supply Equipment Communication Controller

SpEC Module – Gen II

ANL



USB

External WiFi modules

Ethernet

Current Transformer

AC Power input (PLC ready)

External Flash memory

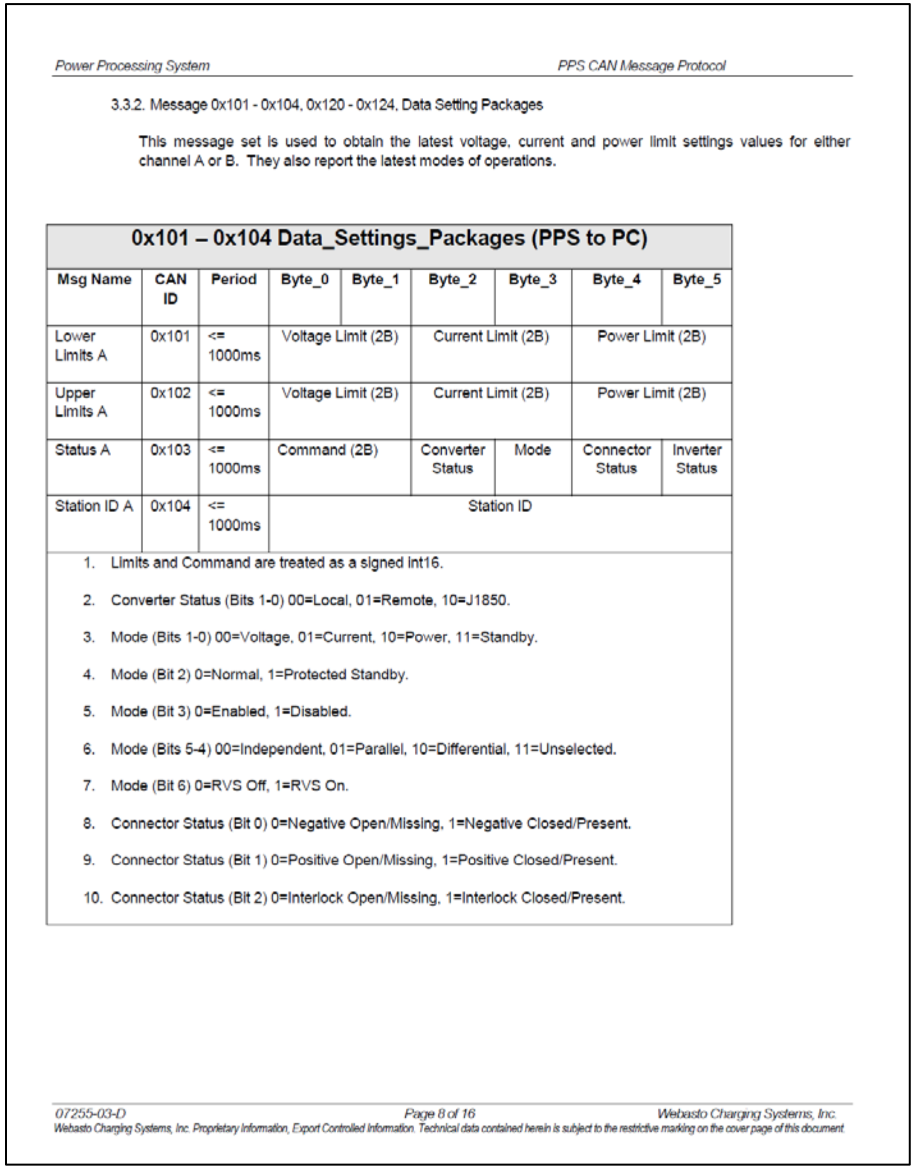
GFCI Input

Digital comms interface

AC & DC Contactor control

SpEC integration with power electronics

- **CAN Protocol** – industry standard for automotive applications
- SpEC module can integrate with <u>all types</u> of CAN messages (CAN 2.0, CAN FD)
- For any power electronics, ANL develops a complete **database** file, develops an **emulator** for testing if needed and develops **custom firmware** support in C/C++
- This includes all CAN messages related to **power requirements, limits, controls, and status**
- Demonstrated previously with ABC-170 and UPER emulator



Power Processing System *PPS CAN Message Protocol*

3.3.2. Message 0x101 - 0x104, 0x120 - 0x124, Data Setting Packages

This message set is used to obtain the latest voltage, current and power limit settings values for either channel A or B. They also report the latest modes of operations.

0x101 – 0x104 Data_Settings_Packages (PPS to PC)

Msg Name	CAN ID	Period	Byte_0	Byte_1	Byte_2	Byte_3	Byte_4	Byte_5
Lower Limits A	0x101	<= 1000ms	Voltage Limit (2B)		Current Limit (2B)		Power Limit (2B)	
Upper Limits A	0x102	<= 1000ms	Voltage Limit (2B)		Current Limit (2B)		Power Limit (2B)	
Status A	0x103	<= 1000ms	Command (2B)		Converter Status	Mode	Connector Status	Inverter Status
Station ID A	0x104	<= 1000ms	Station ID					

1. Limits and Command are treated as a signed int16.
2. Converter Status (Bits 1-0) 00=Local, 01=Remote, 10=J1850.
3. Mode (Bits 1-0) 00=Voltage, 01=Current, 10=Power, 11=Standby.
4. Mode (Bit 2) 0=Normal, 1=Protected Standby.
5. Mode (Bit 3) 0=Enabled, 1=Disabled.
6. Mode (Bits 5-4) 00=Independent, 01=Parallel, 10=Differential, 11=Unselected.
7. Mode (Bit 6) 0=RVS Off, 1=RVS On.
8. Connector Status (Bit 0) 0=Negative Open/Missing, 1=Negative Closed/Present.
9. Connector Status (Bit 1) 0=Positive Open/Missing, 1=Positive Closed/Present.
10. Connector Status (Bit 2) 0=Interlock Open/Missing, 1=Interlock Closed/Present.

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“ABC-170 / 170 CE”, https://webasto.com/en-int/battery/power-cycling-test-systems/ABC-170CE.html.

Identifying COTS DC/DC converter

Emulated EV

- For eCHIP, the COTS DC/DC module should be **isolated, bi-directional,** over **900 V input** with built-in **contactors** for control and require **minimal assembly** to setup and interface with.

- Various DC/DC modules were considered:
  - **Siemens** SINAMICS DCP
  - **Zekalabs** RedPrime 25kW
  - **Phoenix Contact** CHARX PS-M2
  - **Maxwell** MXC95050B
  - **Advantics** MCP-25

Maxwell DC/DC converter

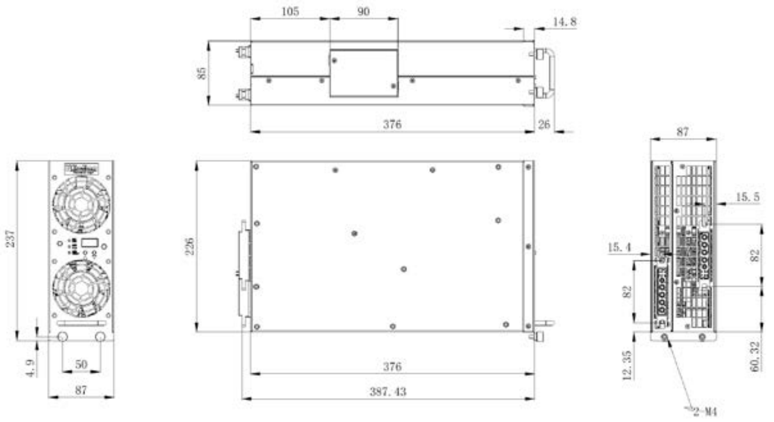
MXC9505B

MAXWELL

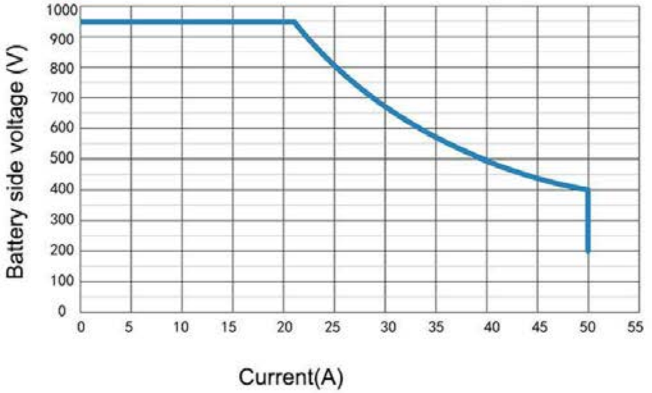
MXC95050B

20 KW Bidirectional DC-DC Power Module

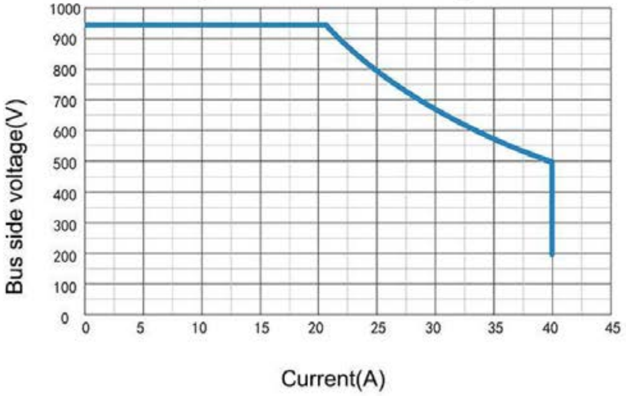
Approx. 15” x 9” x 3.5”



Charge and Discharge on the battery side (500V<Vbus<950V)



Charge & Discharge on bus side (400V<Vbat<950V)



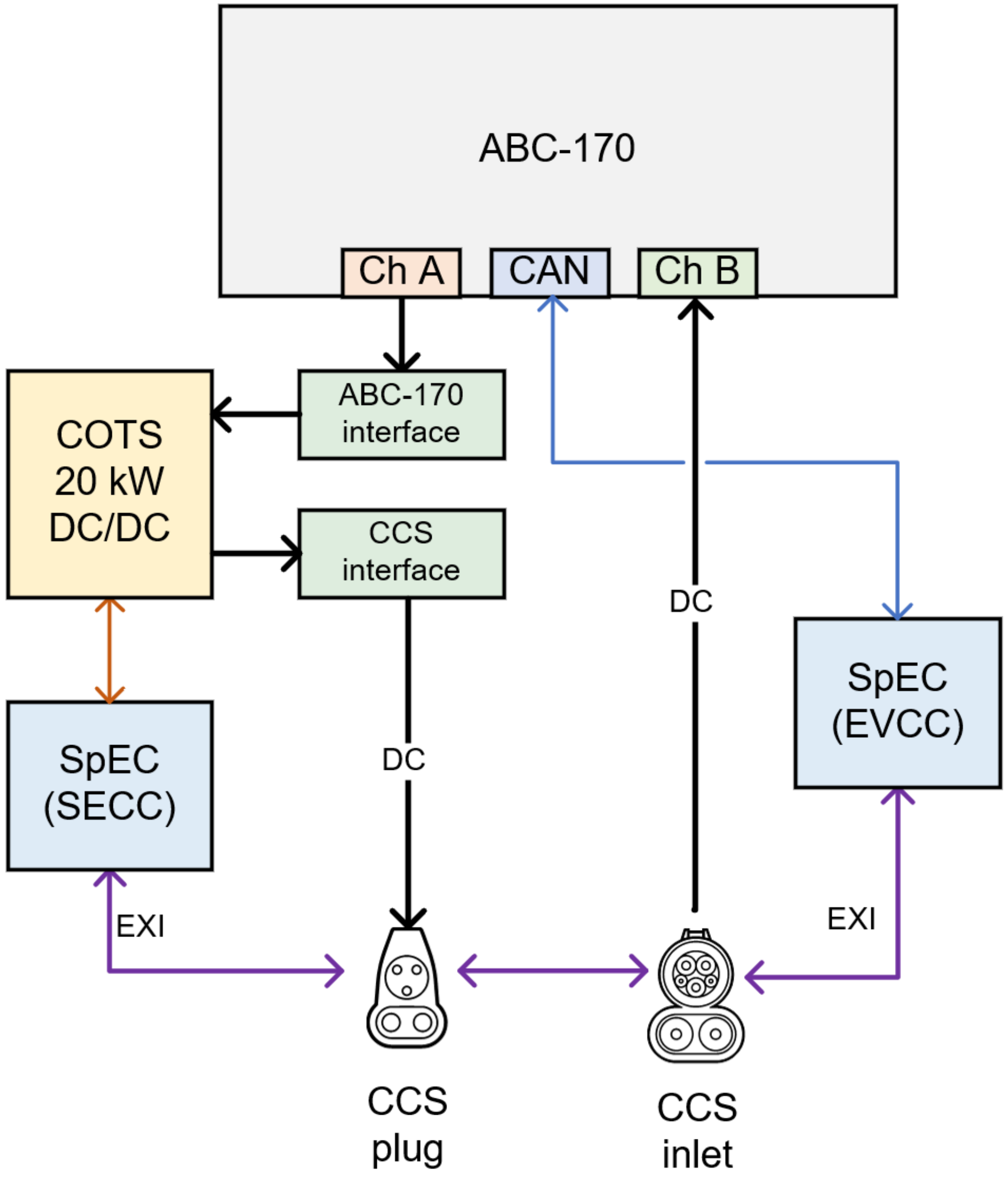
MODEL	MXC95050B
Basic Indicators	
Dimensions	85mm(H)×226mm(W)×376mm(D)
Weight	≤9.5kg
Efficiency(full load)	>98.5%
Cooling Mode	Forced air cooling
Communication Bus Protocol	CAN Bus
No. of Parallel Modules	≤60 pcs
Indicator	Green: normal operation Yellow: protection alarm Red: fault
DC Bus Side	
Voltage Range	200Vdc~950Vdc
Current Range	0A~40A
Stabilized Voltage Precision	≤±0.5%
Stabilized Current Precision	≤±1%(output current 20%~100% rated current)
Ripple Voltage Peak Value	≤1%
Current Sharing Imbalance	≤±5%
Battery Side	
Voltage Range	200Vdc~950Vdc
Current Range	0A~50A
Stabilized voltage Precision	≤±0.5%
Stabilized Current Precision	≤±1%(output current 20%~100% rated current)
Ripple Voltage Peak Value	≤1%
Current Sharing Imbalance	≤±5%
Environmental Specifications	
Operating Temperature	-40℃ ~75℃ , output derating at above 55℃
Storage Temperature	-40℃ ~75℃
Relative Humidity	≤95% RH, non-condensing
Altitude	No derating below 2000m. When the altitude is above1000m, the operating temperature decreases by 1°C for each additional 100 m.
MTBF	>500,000 hours
ROHS	R6

“MXC95050B 20kW DC-DC Bi-Directional Module-Shijiazhuang Maxwell Technology Co., Ltd,” https://maxwellpower.cn/productinfo/2713160.html.

Testing

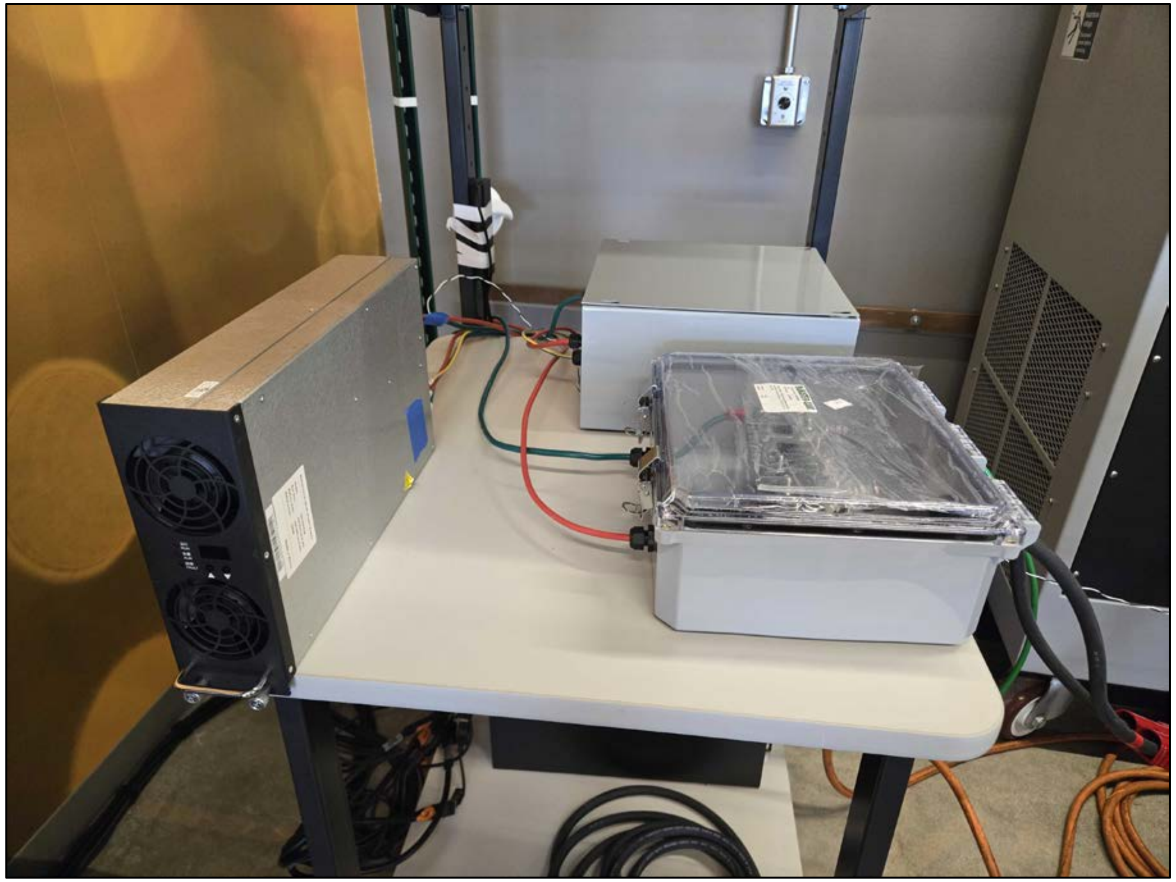
#1 - Emulated EV

- **ABC-170** used as 435 V DC bus
- Custom-built interface to get power in and out of the DC/DC converter
- Independent SpEC modules acting as SECC and EVCC, each controlling CAN interface on DC/DC and ABC-170 respectively
- Successfully performed **DIN 70121** charge session with emulated battery profile on SpEC EVCC
- One module capped at 16 kW due to DC bus



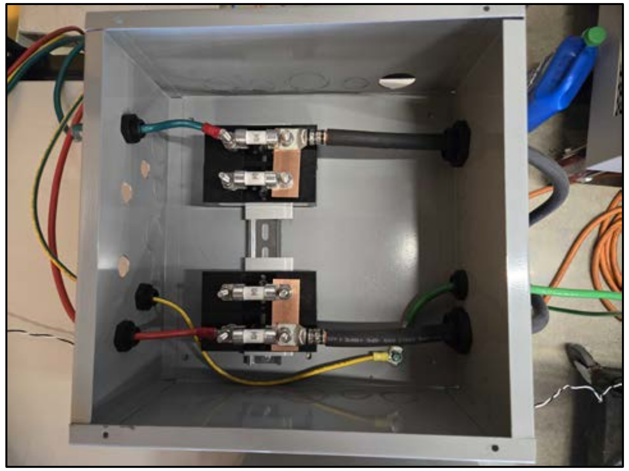
Testing

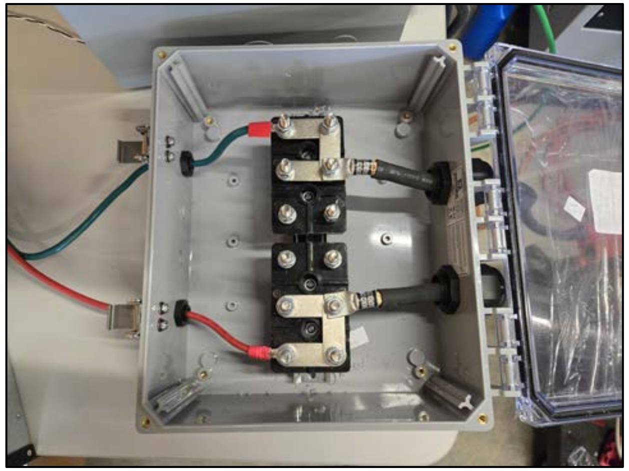
Setup



Interface enclosures

Input with 50 A fuses





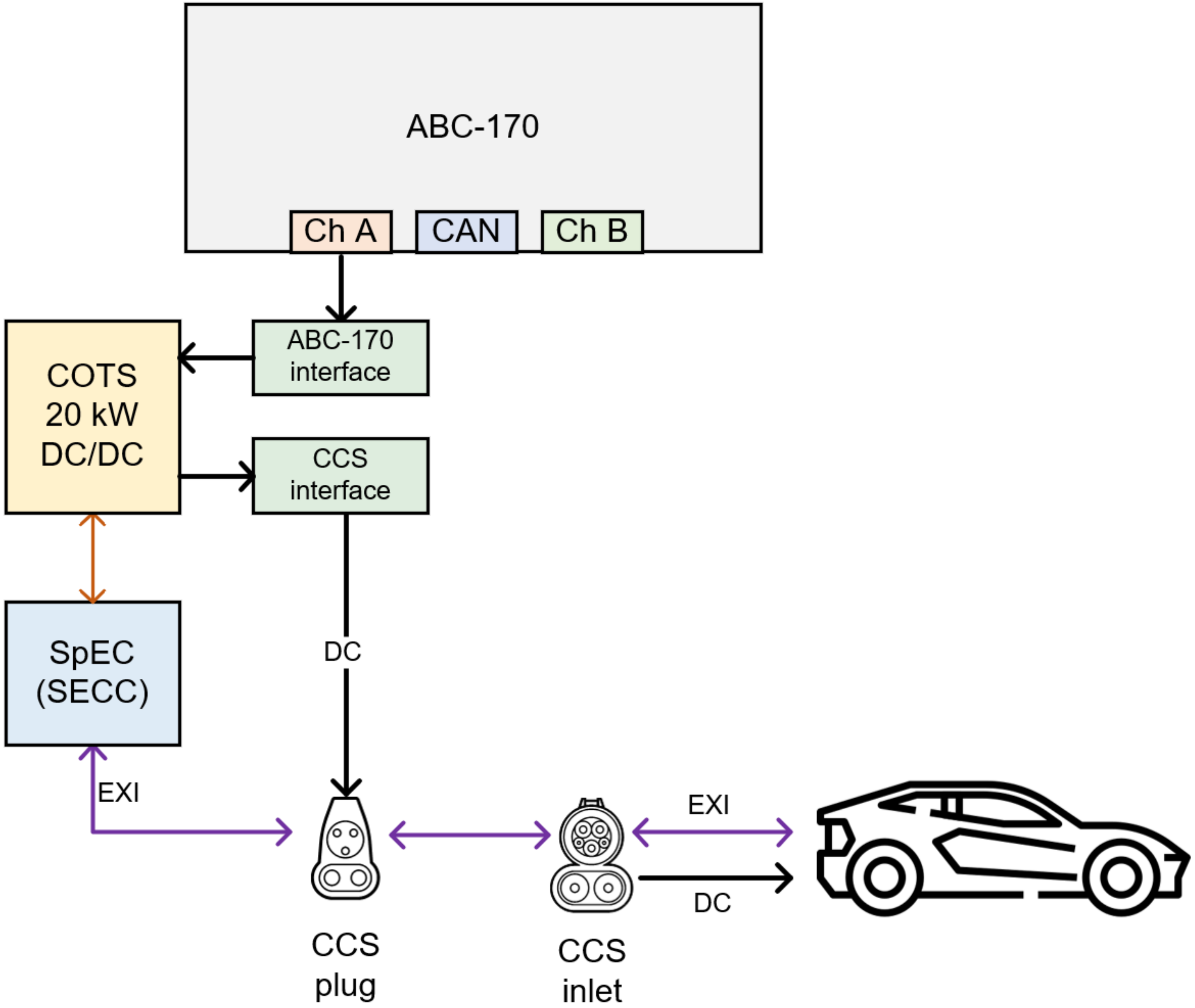
Output

Anderson connector

Testing

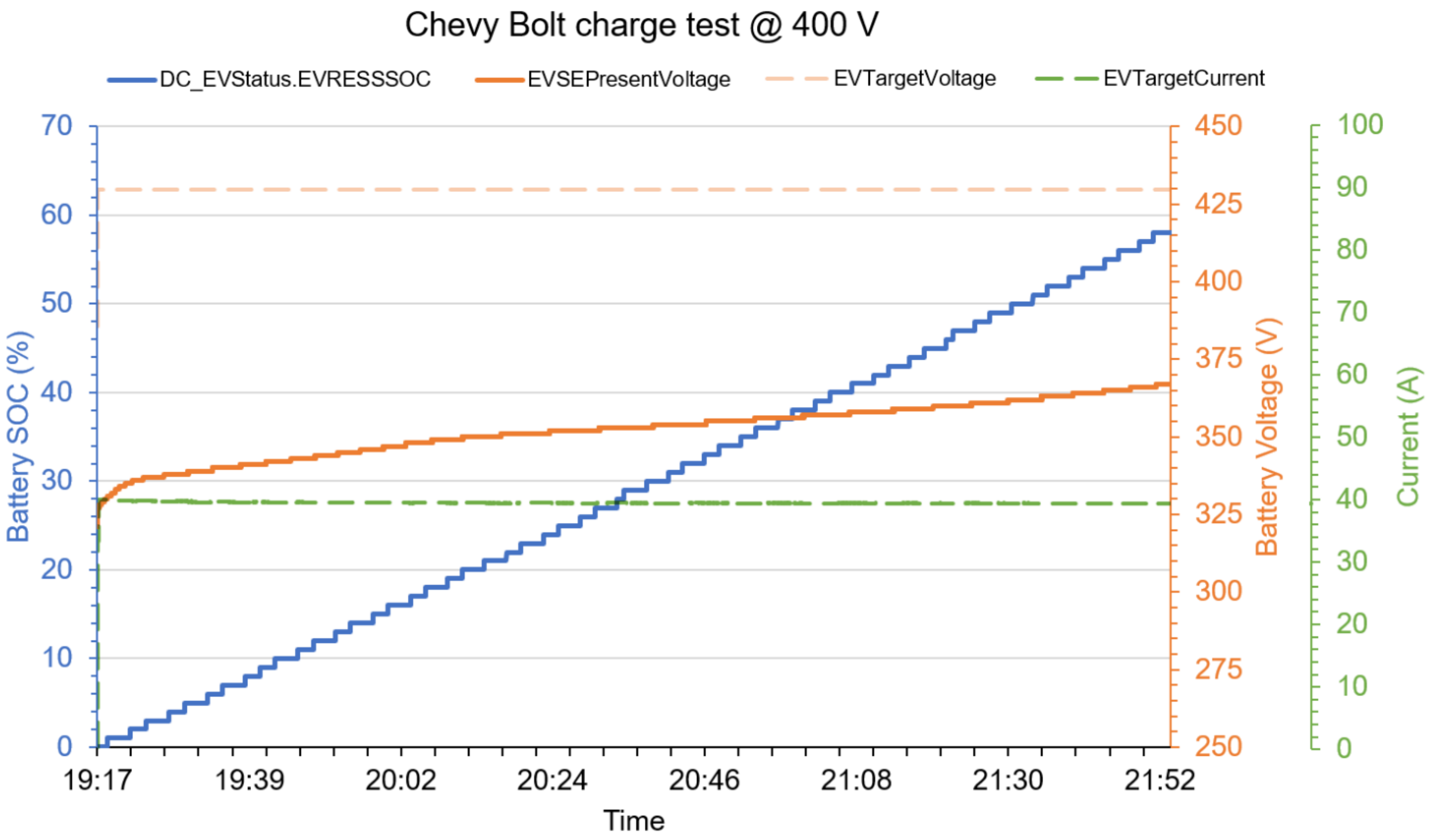
#2 – Chevrolet Bolt

- Repeated same test with **Chevy Bolt** instead of emulated EVCC
- Setup *ChargeParameterDiscoveryRes* and max limits to **450 V, 40 A, 20 kW**
- Successfully performed DIN 70121 charge session
- This test was repeated with a Lucid Air and a Mercedes EQS



Testing

#2 – Chevrolet Bolt



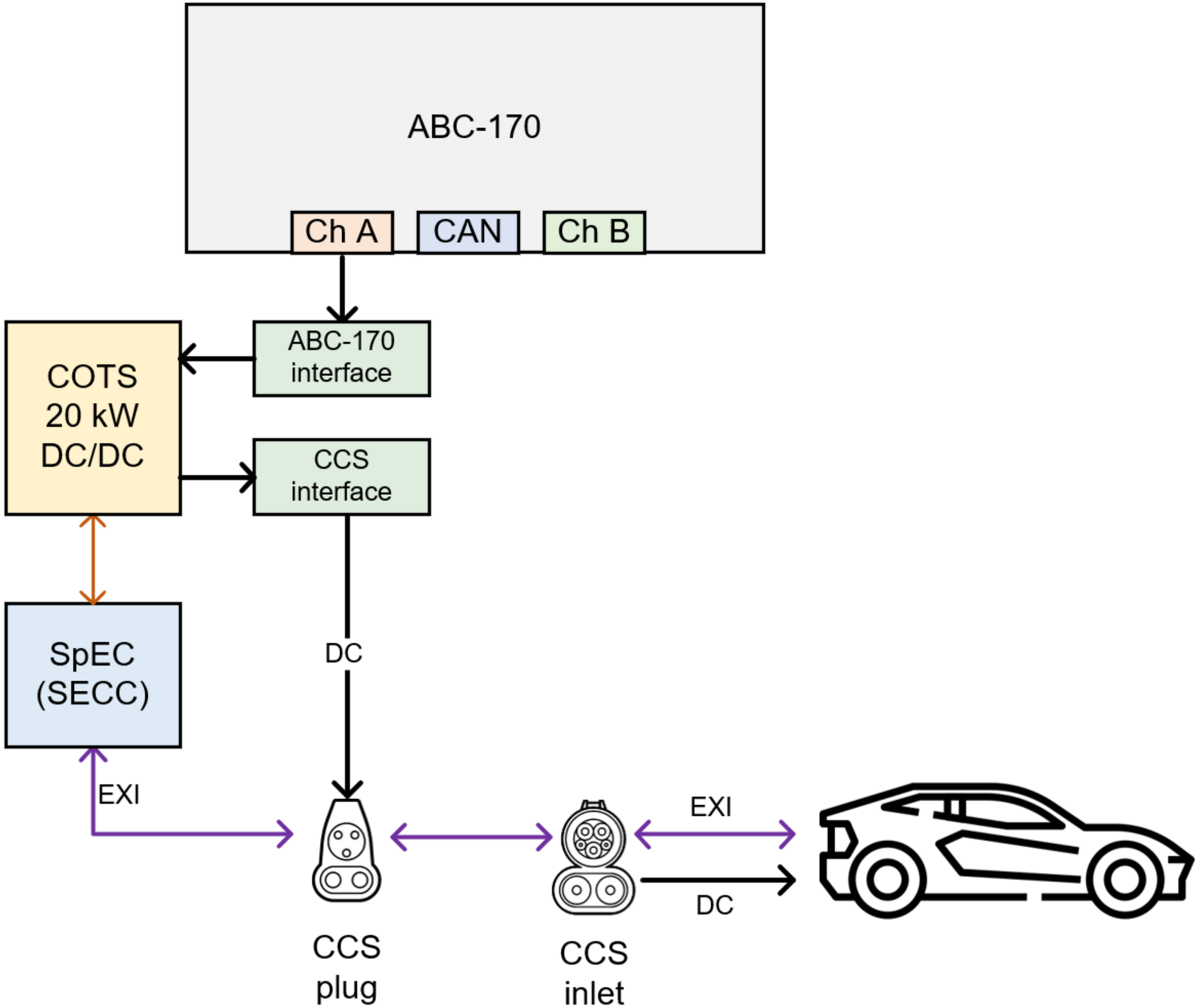
Testing

#2 – Chevrolet Bolt

Testing

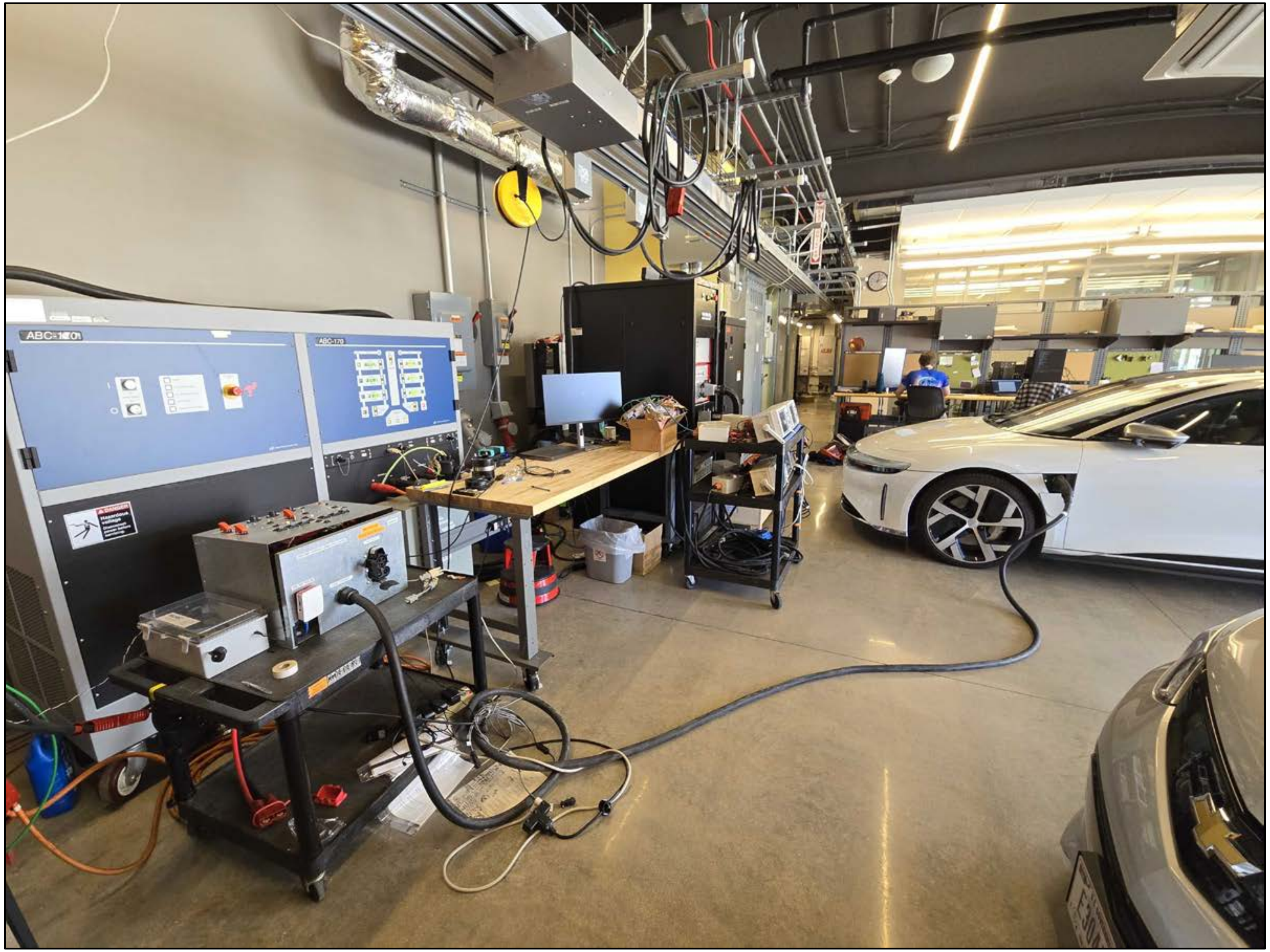
#3 – Lucid Air

- Repeated same test with **Lucid Air**
- Setup *ChargeParameterDiscoveryRes* and max limits to **950 V, 40 A, 20 kW**
- Successfully performed DIN 70121 charge session



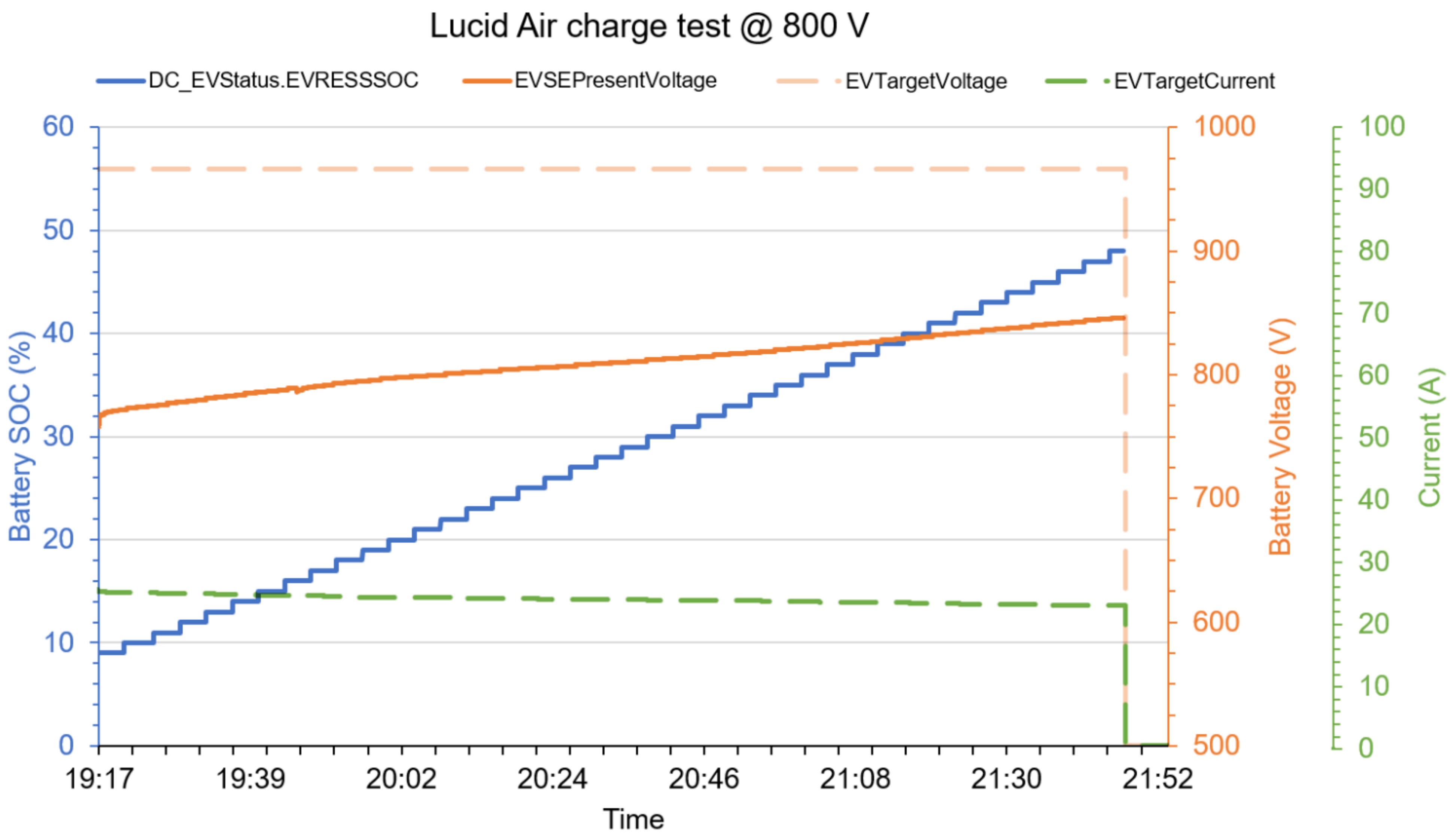
Testing

#3 – Lucid Air



Testing

#3 – Lucid Air



Testing

- These tests verify that the COTS DC/DC module can charge both **400 V** and **800 V** architecture EVs when running on a 435 V DC bus

- The module can also run at a maximum of **950 V** on the DC bus side, which will be tested at ESIF

Bidirectional Capabilities

- The DC/DC converter is capable of operating in reverse mode
- Tested with **ABC-170** using Channel B as source and Channel A as sink
- Successfully demonstrated SpEC + UPER performing a dynamic BPT charge/discharge session with **Lion Electric bus** previously
- Next steps to work on repeating the BPT test using the COTS DC/DC converter

Modularity and Scalability

- The DC/DC converter is modular and can be paralleled to provide higher power output
- Can parallel up to **64** modules (20 kW each) to give a total theoretical output of **1.28 MW**
- All modules can be controlled independently or together
- Next steps is to test 2 modules in parallel to get 40 kW and repeat EV charging tests
- This will verify feasibility of higher power deployment at ESIF

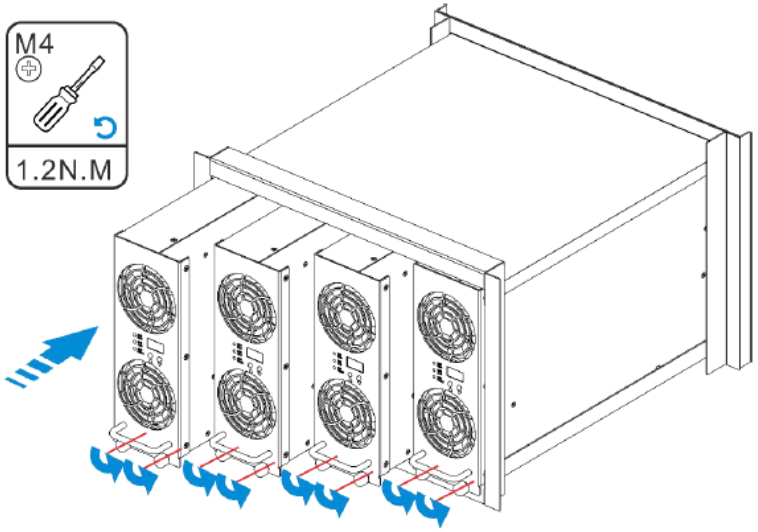


Figure 3-6 Installation diagram of charging module (side mounting)

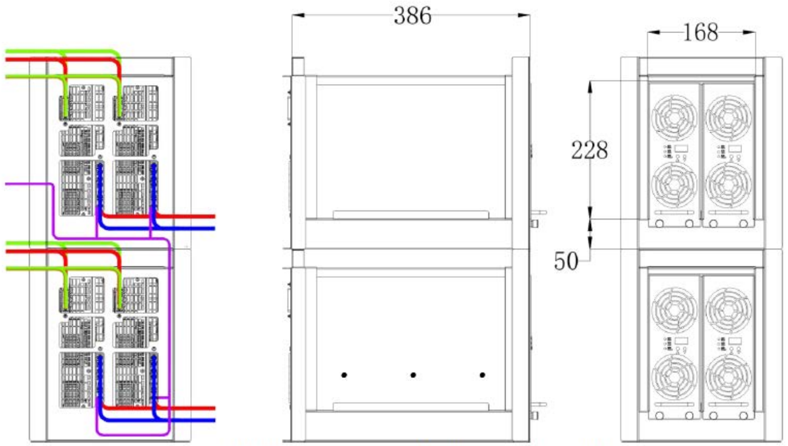


Figure 3-11 Diagram of system wiring (horizontal mounting)

“MXC95050B 20kW DC-DC Bi-Directional Module-Shijiazhuang Maxwell Technology Co., Ltd,” https://maxwellpower.cn/productinfo/2713160.html.

Thank You

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