EVs@Scale

U.S. Department of Energy

Electric Vehicles at Scale (EVs@Scale) Laboratory Consortium Deep-Dive Technical Meetings: High Power Charging (HPC) Summary Report

Opening Remarks

Andrew Meintz

Lee Slezak

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

NREL/PR-5400-86407

Approach - Consortium Structure

Leadership Council

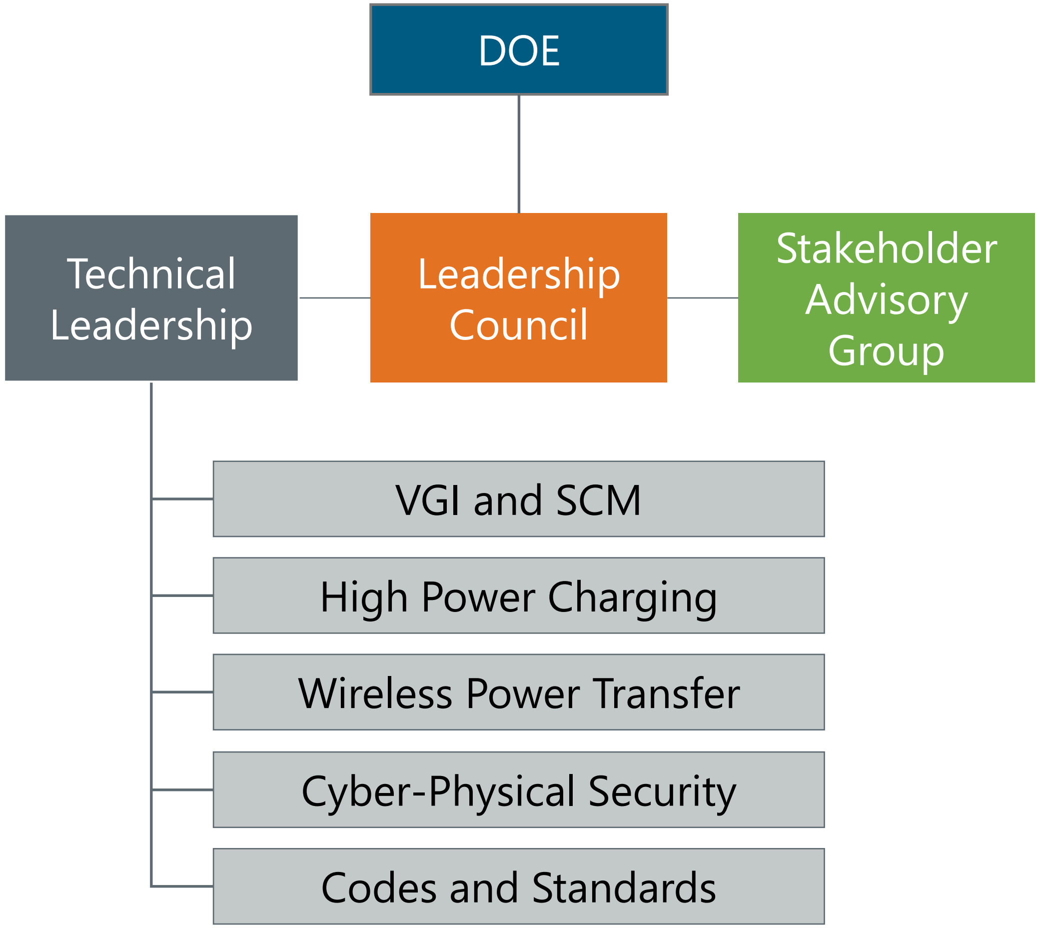
- Andrew Meintz (NREL, chair), Tim Pennington (INL, rotating co-chair), Dan Dobrzynski (ANL), Burak Ozpineci (ORNL), Summer Ferreira (SNL), Rick Pratt (PNNL)

Stakeholder Advisory Group

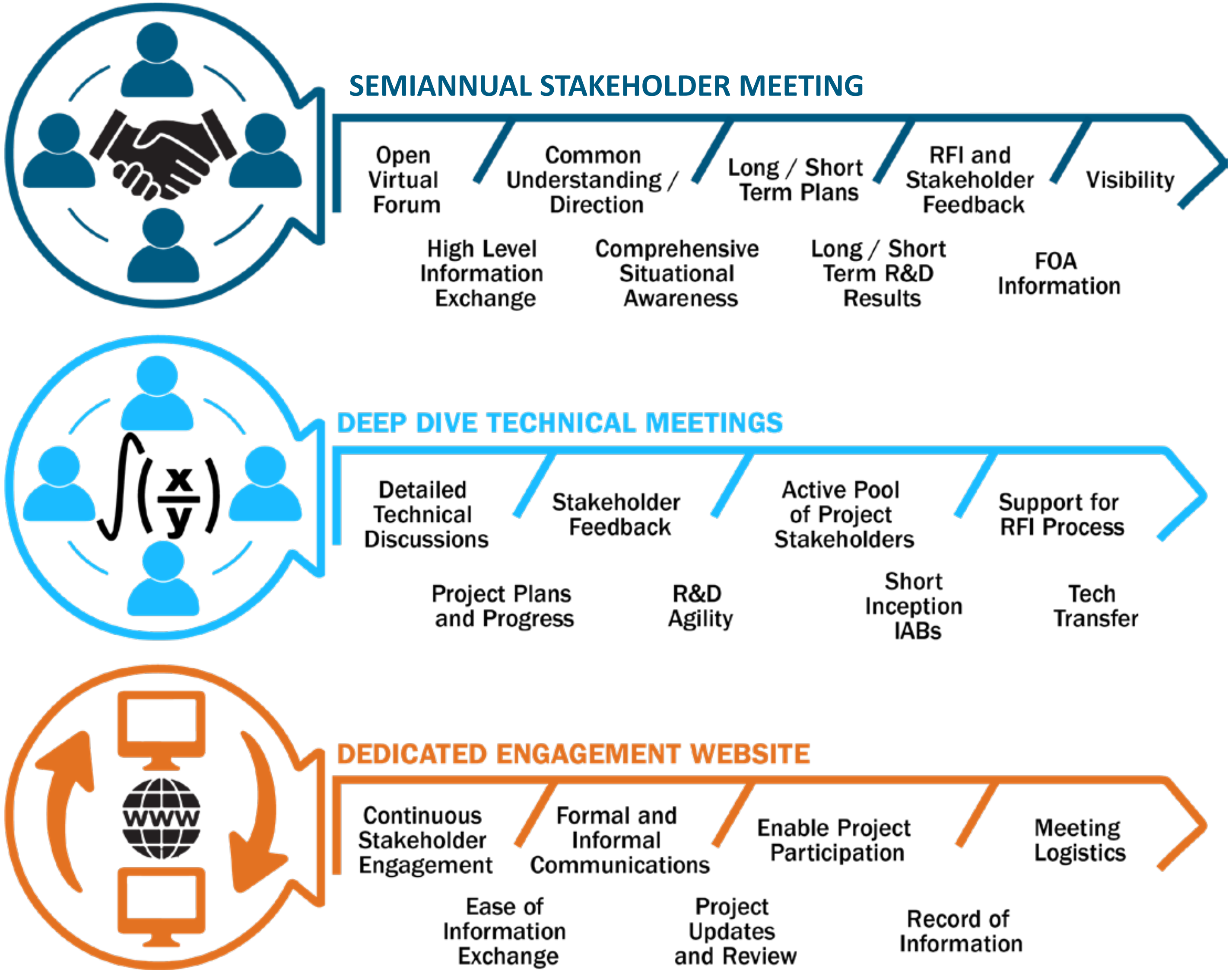
- Utilities, EVSE & Vehicle OEMs, CNOs, SDOs, Gov't, Infrastructure

Consortium Pillars and Technical Leadership

- Vehicle Grid Integration and Smart Charge Management (VGI/SCM): Jesse Bennett (NREL), Jason Harper (ANL)
- High Power Charging (HPC): John Kisacikoglu (NREL)
- Wireless Power Transfer (WPT): Veda Galigekere (ORNL)
- Cyber-Physical Security (CPS): Richard "Barney" Carlson (INL), Craig Rodine (SNL)
- Codes and Standards (CS): Ted Bohn (ANL)



EVs@Scale Lab Consortium Stakeholder Engagement and Outreach



SEMIANNUAL STAKEHOLDER MEETING

- Open Virtual Forum
- Common Understanding / Direction
- Long / Short Term Plans
- RFI and Stakeholder Feedback
- Visibility

- High Level Information Exchange
- Comprehensive Situational Awareness
- Long / Short Term R&D Results
- FOA Information

DEEP DIVE TECHNICAL MEETINGS

- Detailed Technical Discussions
- Stakeholder Feedback
- Active Pool of Project Stakeholders
- Support for RFI Process

- Project Plans and Progress
- R&D Agility
- Short Inception IABs
- Tech Transfer

DEDICATED ENGAGEMENT WEBSITE

- Continuous Stakeholder Engagement
- Formal and Informal Communications
- Enable Project Participation
- Meeting Logistics

- Ease of Information Exchange
- Project Updates and Review
- Record of Information

Collaboration and Coordination

Stakeholder Advisory Group

- Utilities, EVSE & Vehicle OEMs, CNOs, SDOs, Gov't, Infrastructure

Direct interaction for each pillar projects

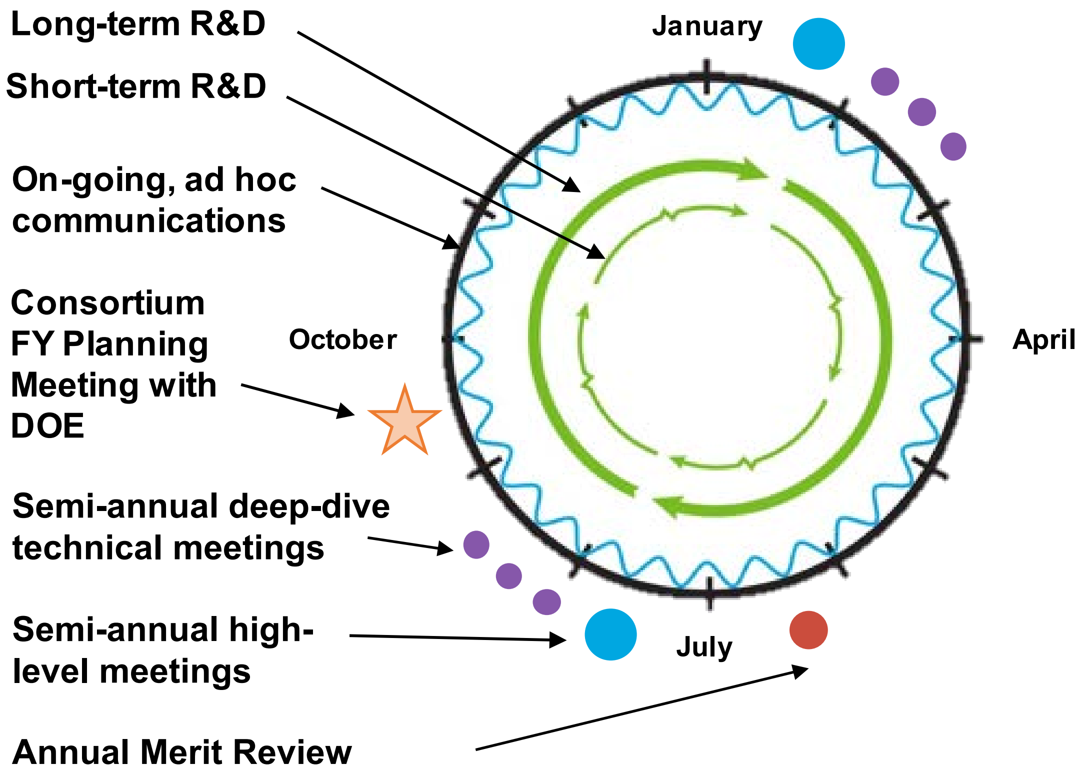
- Utilities, EVSE & Vehicle OEMs, CNOs, SDOs, Gov't, Infrastructure
- Webinars / Project discussions

Semi-annual high-level meetings

- Rotation among labs with discussion on all pillars

Semi-annual deep-dive technical meetings

- VGI/SCM, HPC & WPT, and CPS with C&S incorporated into all meetings



Two semi-annual high-level meetings were held in August 2022 and April 2023 with attendance reaching 100 stakeholders with several attending the follow-on deep dive discussions

High-Power Charging and Wireless Power Transfer (Week 1)

May 02 | Agenda

- **State-of-the-Art HPC Ecosystem** – Discussions on High Power Charging (HPC) Profiles for New Generation EVs and State-of-the-Art HPC Equipment Performance Characterization.
- **Design and Implementation Approach for DC Charging Hub** – Discussions on Overview of DC Charging Hub Approach and Development of Experimental Test Platform; DC-DC Converter (UPER) Development: 1000V and 1500V Class Chargers.
- **Modeling and Control of DC Charging Hub** – Discussions on Integrating Spec II Module with UPER and Site Energy Management System (SEMS); SEMS: Modeling, Control Algorithm Development, and Evaluation.

May 03 | Agenda

- **High Power and Dynamic Wireless Charging R&D** – Review of DWPT system development, validation, characterization, power electronics and control system design, advanced control techniques, and use case analysis

Deep-Dive Technical Meetings

Smart Charge Management and Vehicle Grid Integration (Week 2)

May 18 | Agenda

- **Smart Charge Management and FUSE Project Modeling & Analysis** – Discussions on grid, vehicle charge modeling and analysis for EVS@Scale as well as RD&D efforts for smart charge management.

Codes & Standards (Week 3)

May 22 | Agenda

- **Codes & Standards Pillar** – To be announced

Cyber-Physical Security (Week 3)

May 24 | **Agenda**

- **Development of HPC Mitigation Solutions and the Cyber Workforce** – Reports from INL on threat detection, response, and recovery mitigations for control systems in high-power charging stations, and on their support for the Cyber Auto Challenge.
- **Zero Trust** – A report from PNNL on their work to map Zero Trust principles, architecture, and controls across the EV charging infrastructure.
- **Future Presentations** – Previews from ANL on their Autumn, 2023 Deep-Dive presentations on EVSE UpstAnD (Upstream Analysis and Design), and from ORNL on eVision (Resilient High Power Charging Facility).

May 25 | **Agenda**

- **More Cyber Workforce Development** – An update from Sandia on CyberStrike Training for Network Defenders.
- **Exploring EV charging PKI** – A report from the combined NREL+Sandia team describing their work on large-scale simulation of the emerging EV charging Public Key Infrastructure (PKI), and cyber-range experiments designed to test PKI operational and cyber vulnerabilities.
- **Special event** – We’ve got an exciting panel discussion in the works, please watch this space!

Importance of the Deep Dives

These deep-dives are open to industry experts to help us better shape the R&D efforts for EVs@Scale.

We need your input to identify:

- **Partners** for our R&D efforts to help with insight, data, and other resources.
- **Progress** in our activities to ensure timely research is available to key stakeholders
- **Priorities** for R&D that accelerates the transition to EVs at Scale.

Thank you for your participation in this very important activity!

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U.S. Department of Energy

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

May 2, 2023

Agenda

Time (EST)	Session	Presentation
11:20AM-12:00PM	**Session 1:** State-of-the-Art HPC Ecosystem [40min]	• High Power Charging Profiles (HPC) for New Generation EVs (15 min), **Sam Thurston (ANL)** QandA (5min) • State-of-the-Art HPC Equipment Performance Characterization (15 min), **Barney Carlson (INL)** QandA (5min)
5-min Break		
12:05PM-12:55PM	**Session 2:** Design and Implementation Approach of DC Charging Hub [50min]	• Overview of DC Charging Hub Approach and Development of Experimental Test Platform (20 min), **Alastair Thurlbeck and John Kisacikoglu (NREL)** QandA (5min) • DC-DC Converter (UPER) Development: 1000V and 1500V Class Chargers (20 min), **Prasad Kandula (ORNL)** QandA (5min)
5-min Break		
12:55PM-1:45PM	**Session 3:** Modeling and Control of DC Charging Hub [50min]	• Integrating Spec II Module with UPER and Site Energy Management System (SEMS) (20 min), **Akram Ali (ANL)** QandA (5min) • SEMS: Modeling, Control Algorithm Development, and Evaluation (20 min), **Emin Ucer (NREL)** QandA (5min)
1:45PM-2:55PM	**Cross-cutting Discussions and Feedback Gathering:** Next Steps and R&D Needs [70min]	**Break-out Sessions** (45 min): **(i)** State-of-the-Art HPC Ecosystem; **(ii)** Design and Implementation Approach of DC Charging Hub; **(iii)** Modeling and Control of DC Charging Hub. Summarizing breakout sessions: **Session moderators** (15 min) Closing Remarks: **Lee Slezak** (10min)

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 distributed energy resources through predefined compatibility with standards that will ensure interoperability and reduce upfront engineering expense

Outcomes:

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

- **John Kisacikoglu (PI)**
- Shafquat Khan
- Rasel Mahmud
- Alastair Thurlbeck
- Emin Ucer
- Ed Watt
- Mingzhi Zhang

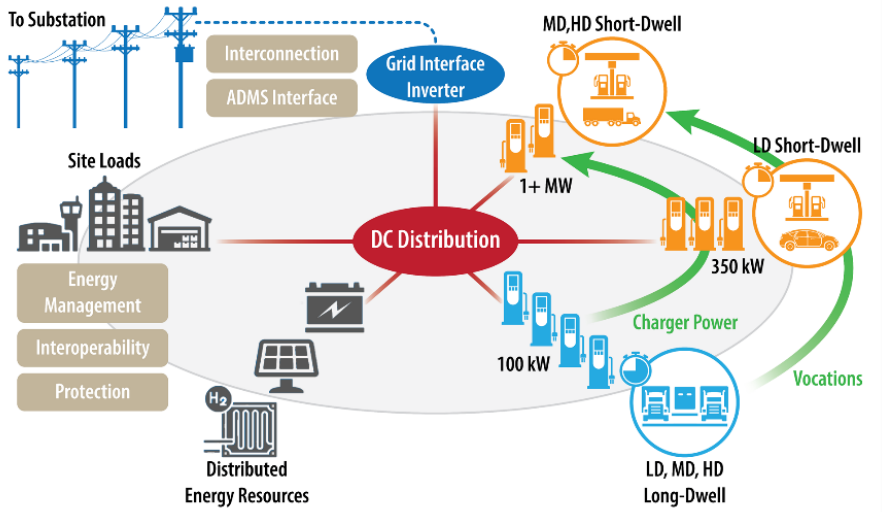
- **Jason Harper**
- Akram Ali
- Bryan Nystrom

- **Prasad Kandula**
- Steven Campbell
- Madhu Chinthavali
- Jonathan Harter
- Brian Rowden
- Michael Starke
- Rafal Wojda

NREL NATIONAL RENEWABLE ENERGY LABORATORY

Argonne NATIONAL LABORATORY

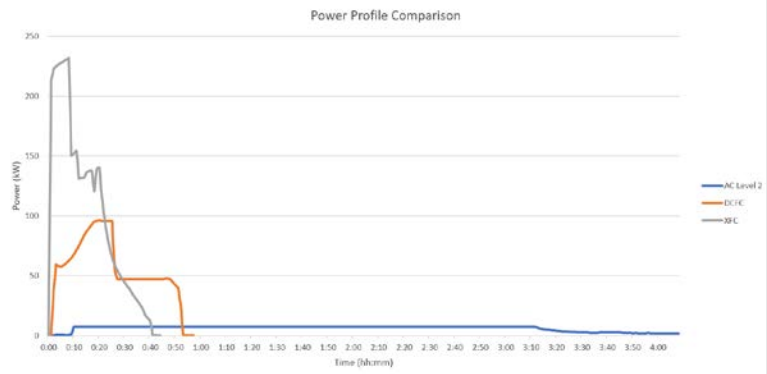
OAK RIDGE National Laboratory



Next-Generation Charging Profiles (NextGen Profiles)

Objective: Assess the likely portfolio of EV and EVSE that are expected to utilize High Power Charing. (>200kW)

- **EV Profile Capture** – Charging system characterization of EV and EVSE combination
- **EVSE Performance Characterization** – Independent EVSE assessment
- **Fleet Utilization** – Long-term electrified fleet charge behavior tracking and analysis



Outcomes:

- Industry reviewed testing processes and methodologies
- Private and public datasets
- Charge performance analysis on the most recent state of technology

- **Dan Dobrzynski (PI)**
- Sam Thurston
- Landon Wells

Argonne NATIONAL LABORATORY

- **Keith Davidson**
- Ed Watt
- Andrew Meintz
- Shafquat Khan

NREL NATIONAL RENEWABLE ENERGY LABORATORY

- **Barney Carlson**
- Benny Varghese

INL Idaho National Laboratory

- **Omer Onar**

OAK RIDGE National Laboratory

EVs@ Scale

U.S. Department of Energy

"Next-Gen Charge Profiles" Project

Deep Dive: EV Profile Capture

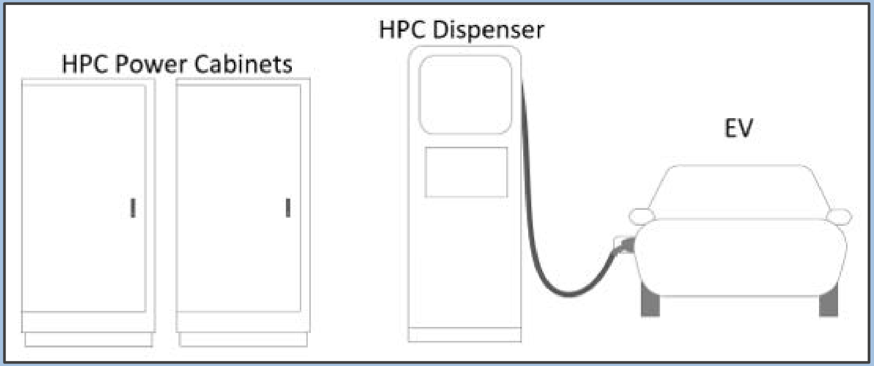
Sam Thurston

May 2, 2023

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

Overview: EV Profile Capture

- **EV Assets:**
  - Production EVs, either ~400VDC or ~800VDC HV battery topology
  - OEM rated in the range of 150-350kW peak charge rates
- **EVSE Assets:**
  - Production DCFCs, capable up to 1000VDC/500A Max
  - Typically, a dual power cabinet/single dispenser topology
  - Preferably allows for OCPP curtailment
  - Possible port types are CCS, Tesla, Pantograph, WPT
- **Nominal test conditions**
  - 10-100% EV state of charge
  - Nominal (23°C/75°F) ambient temperature
  - EV pre-driven for 30-40min
  - DCFC full power available
- **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
  - Single Power Cabinet (EVSE Limited)
  - OCPP Curtailed (65A for 2min)



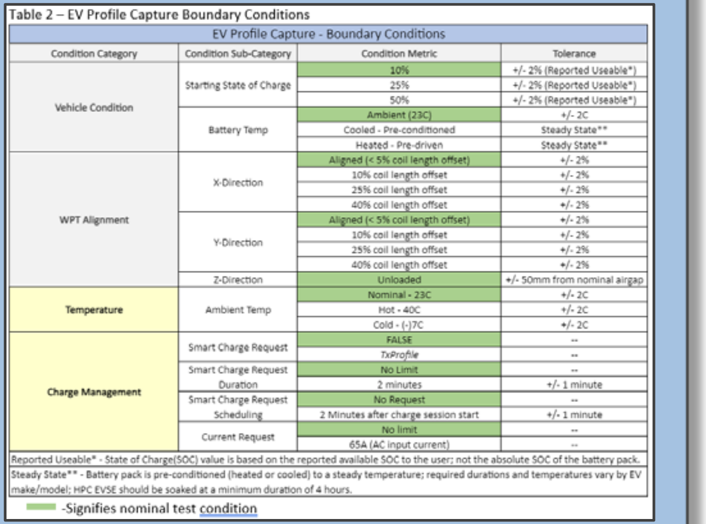


Table 2 – EV Profile Capture Boundary Conditions

EV Profile Capture - Boundary Conditions			
Condition Category	**Condition Sub-Category**	**Condition Metric**	**Tolerance**
Vehicle Condition	Starting State of Charge	🟩 10%	+/- 2% (Reported Useable*)
		25%	+/- 2% (Reported Useable*)
		50%	+/- 2% (Reported Useable*)
	Battery Temp	🟩 Ambient (23C)	+/- 2C
		Cooled - Pre-conditioned	Steady State**
		Heated - Pre-driven	Steady State**
WPT Alignment	X-Direction	🟩 Aligned (< 5% coil length offset)	+/- 2%
		10% coil length offset	+/- 2%
		25% coil length offset	+/- 2%
		40% coil length offset	+/- 2%
	Y-Direction	🟩 Aligned (< 5% coil length offset)	+/- 2%
		10% coil length offset	+/- 2%
		25% coil length offset	+/- 2%
		40% coil length offset	+/- 2%
	Z-Direction	🟩 Unloaded	+/- 50mm from nominal airgap
Temperature	Ambient Temp	🟩 Nominal - 23C	+/- 2C
		Hot - 40C	+/- 2C
		Cold - (-)7C	+/- 2C
Charge Management	Smart Charge Request	🟩 FALSE	--
		TxProfile	--
	Smart Charge Request Duration	🟩 No Limit	--
		2 minutes	+/- 1 minute
	Smart Charge Request Scheduling	🟩 No Request	--
		2 Minutes after charge session start	+/- 1 minute
	Current Request	🟩 No limit	--
		65A (AC input current)	--

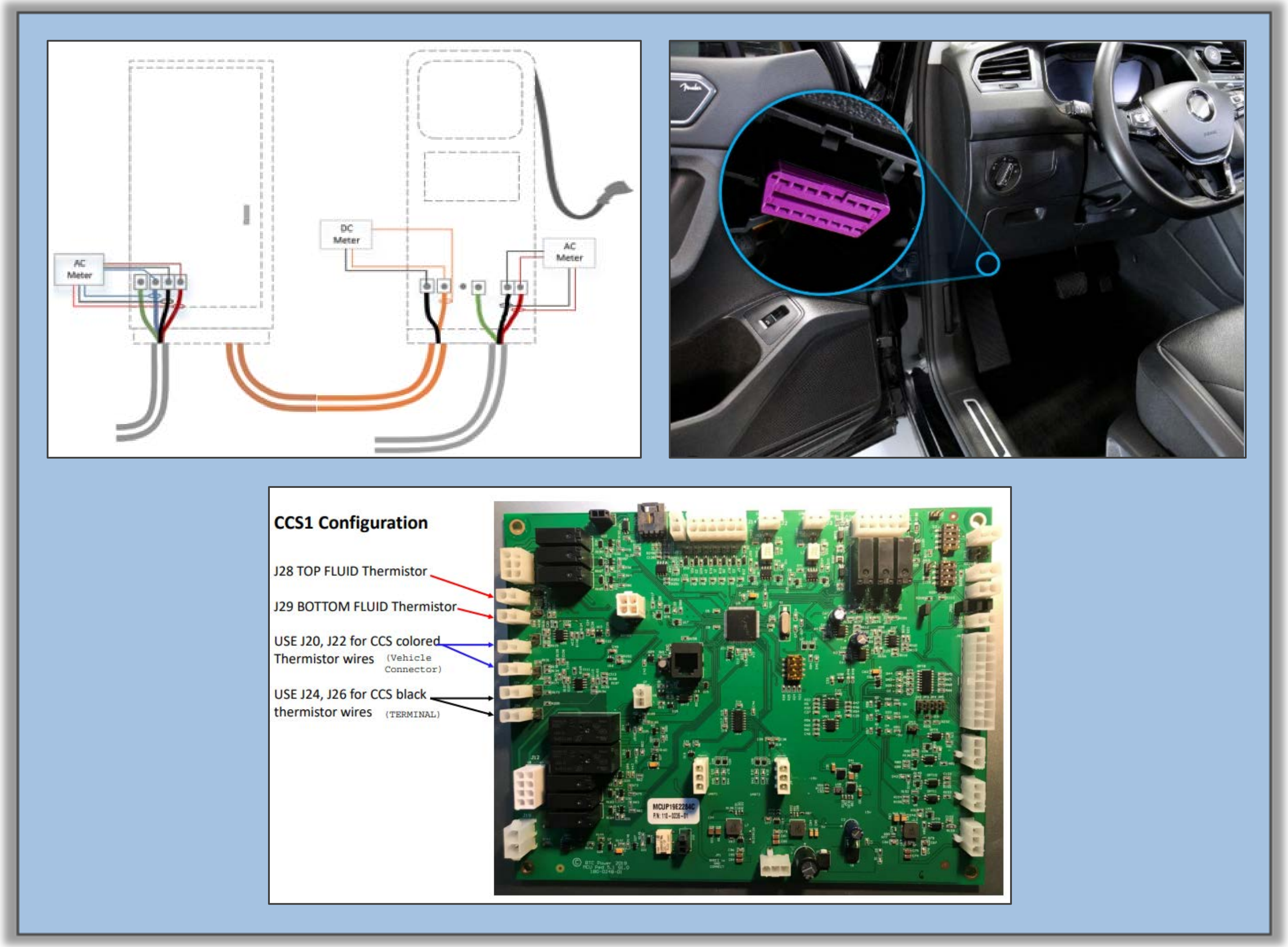
Reported Useable* - State of Charge(SOC) value is based on the reported available SOC to the user; not the absolute SOC of the battery pack.

Steady State** - Battery pack is pre-conditioned (heated or cooled) to a steady temperature; required durations and temperatures vary by EV make/model; HPC EVSE should be soaked at a minimum duration of 4 hours.

🟩 -Signifies nominal test condition

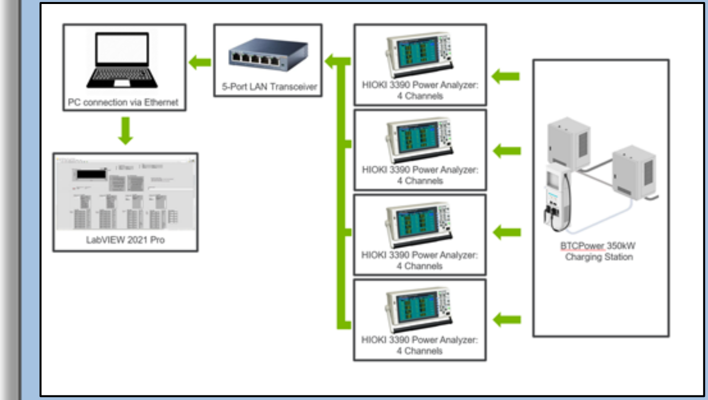
EV Profile Measurement Points

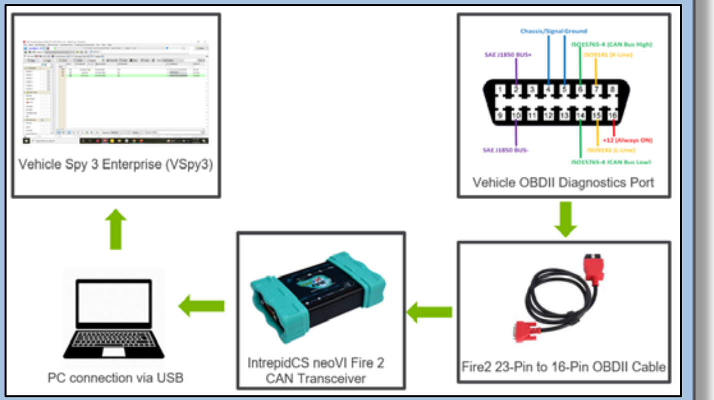
- **EVSE DAQ:**
  - AC grid input:
    - 3-phase current, voltage, and frequency
    - Real power, reactive power, power factor
    - Current THD, Harmonics (3rd, 5th, 7th, 9th)
  - DC output from power cabinets:
    - DC current, voltage, power, energy charged
  - Auxiliary loads:
    - Ancillary loads 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

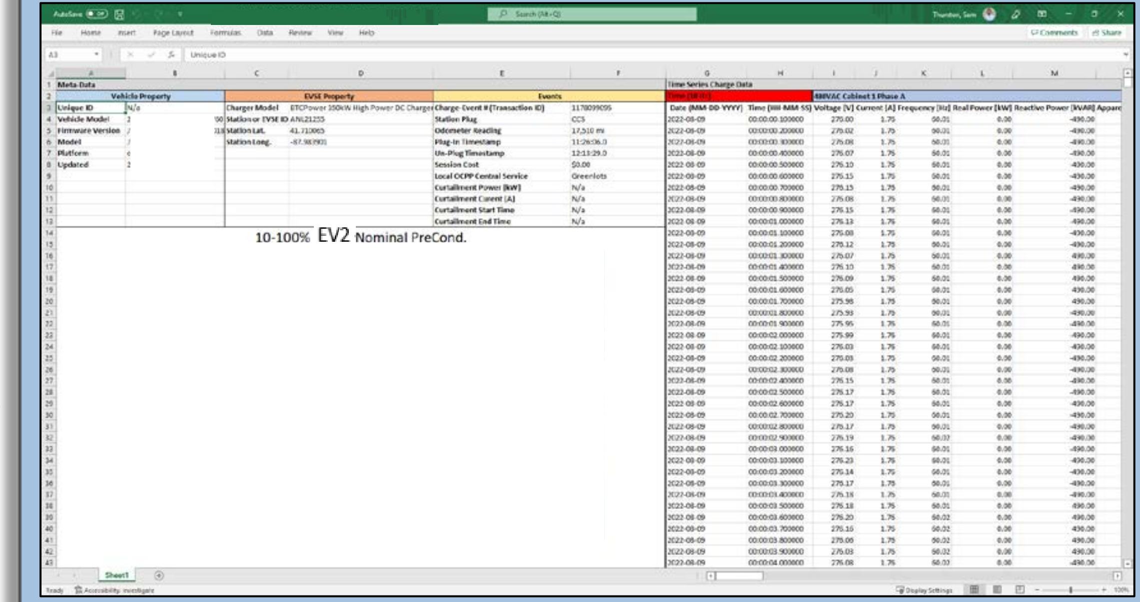


DAQ Hardware

- **EVSE DAQ:**
  - (x4) HIOKI PW3390-01 Power Analyzers
  - (x8) CT6845-05 AC/DC Current Probes, 500A, DC to 100kHz
  - Software: LabVIEW 2021
- **EV DAQ:**
  - (x1) IntrepidCS neoVI Fire 2 CAN Transceiver
  - (x1) Autel MaxiSYS Ultra Vehicle Scan Tool
  - Software: Vehicle Spy 3 Enterprise (VSpy3)
- **Data processing:**
  - Both EV & EVSE data is recorded at 10Hz and exported to separate .csv documents.
  - These documents are time-sync'd and formatted into one time-series document with session meta data.
  - Formatted time-series are anonymized and shared with OEM project collaborators.
  - Software: Python 3.9.3







Meta-Data

Vehicle Property		EVSE Property		Events	
Unique ID	N/a	Charger Model	BTCPower 350kW High Power DC Charger	Charge-Event # (Transaction ID)	1178099095
Vehicle Model	[redacted]	Station or EVSE ID	ANL21255	Station Plug	CCS
Firmware Version	[redacted]	Station Lat.	41.710065	Odometer Reading	17,510 mi
Model	[redacted]	Station Long.	-87.983901	Plug-In Timestamp	11:26:06.0
Platform	[redacted]			Un-Plug Timestamp	12:13:29.0
Updated	[redacted]			Session Cost	$0.00
				Local OCPP Central Service	Greenlots
				Curtailment Power [kW]	N/a
				Curtailment Current [A]	N/a
				Curtailment Start Time	N/a
				Curtailment End Time	N/a

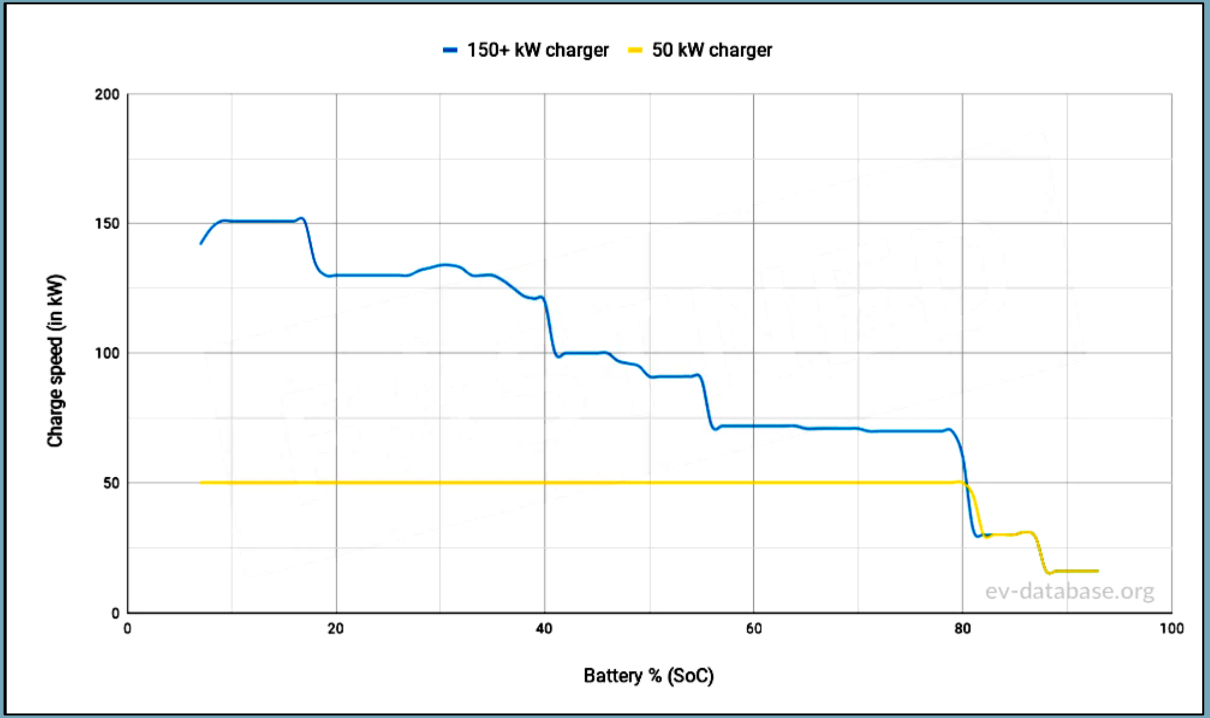
10-100% EV2 Nominal PreCond.

Time Series Charge Data

Time (10 Hz)		480VAC Cabinet 1 Phase A				
Date (MM-DD-YYYY)	Time (HH:MM:SS)	Voltage [V]	Current [A]	Frequency [Hz]	Real Power [kW]	Reactive Power [kVAR]
2022-08-09	00:00:00.100000	275.00	1.75	60.01	0.00	-490.00
2022-08-09	00:00:00.200000	275.02	1.75	60.01	0.00	-490.00
2022-08-09	00:00:00.300000	275.08	1.75	60.01	0.00	-490.00
2022-08-09	00:00:00.400000	275.07	1.75	60.01	0.00	-490.00
2022-08-09	00:00:00.500000	275.10	1.75	60.01	0.00	-490.00
2022-08-09	00:00:00.600000	275.15	1.75	60.01	0.00	-490.00
2022-08-09	00:00:00.700000	275.15	1.75	60.01	0.00	-490.00
2022-08-09	00:00:00.800000	275.08	1.75	60.01	0.00	-490.00
2022-08-09	00:00:00.900000	275.15	1.76	60.01	0.00	-490.00
2022-08-09	00:00:01.000000	275.13	1.76	60.01	0.00	-490.00
2022-08-09	00:00:01.100000	275.08	1.75	60.01	0.00	-490.00
2022-08-09	00:00:01.200000	275.12	1.75	60.01	0.00	-490.00

480VAC Phase A (CAB1)
480VAC Phase B (CAB1)
480VAC Phase C (CAB1)
120VAC Single Phase (DISP)
480VAC Phase A (CAB2)
480VAC Phase B (CAB2)
480VAC Phase C (CAB2)
TEMP Cable- Sensor
800VDC+ (DISP)
800VDC- (DISP)
800VDC (CAB2)
TEMP Cable+ Sensor
TEMP Top Fluid Sensor
TEMP Bottom Fluid Sensor
TEMP Connector+ Sensor
TEMP Connector- Sensor

Research Significance



HPC profiles are diverse – and vary across vehicle classes and OEM

- Variances include **peak power draw, ramp-up/down rates, and shape**.
- Profiles are engineered to balance **charge performance, safety** and **battery longevity**.
- Charging performance varies with external factors – **Battery SOC, temperature**, etc.

Open Questions

What are the system limitations and efficiencies of HPC?

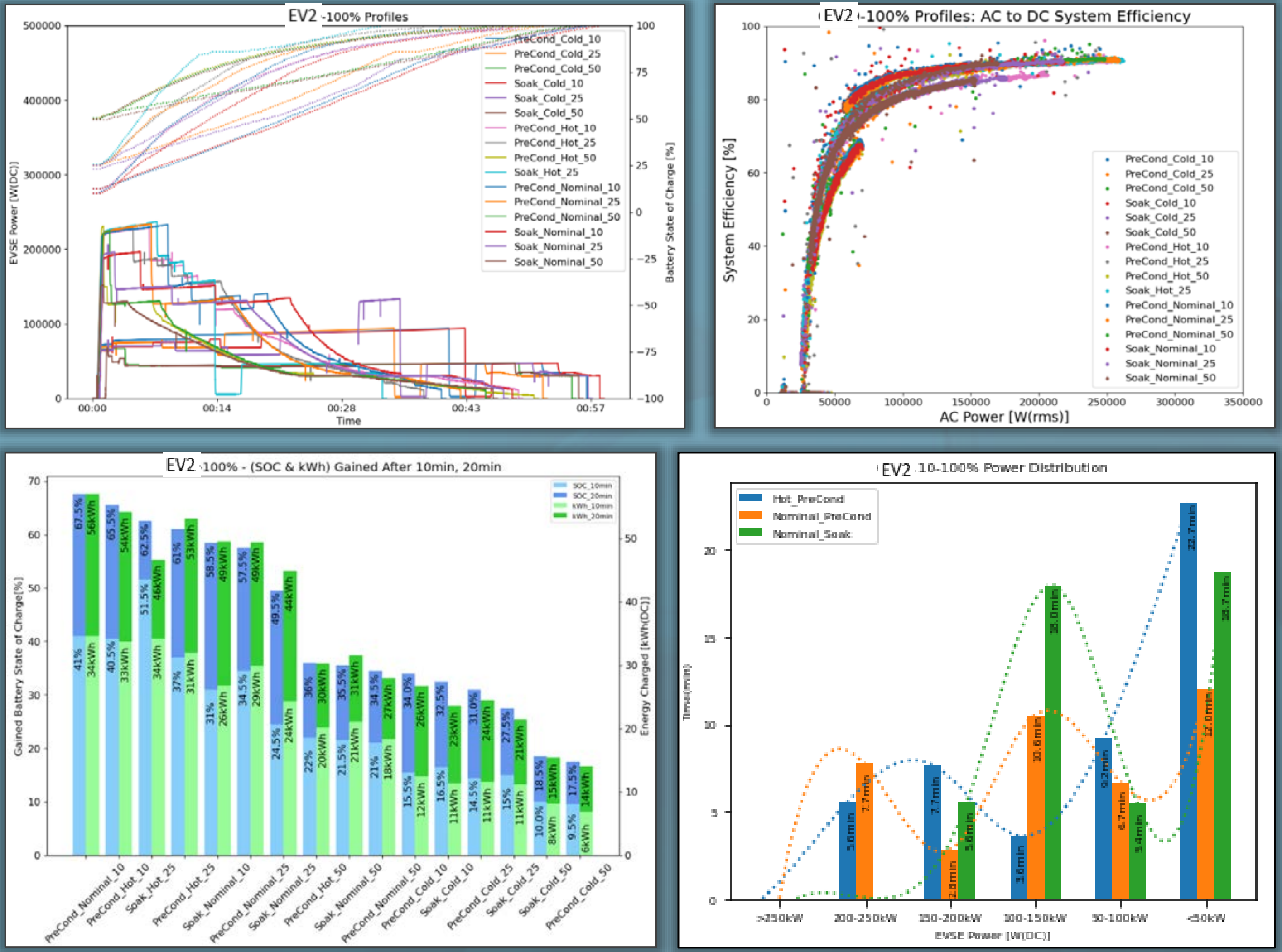
What are the HPC demand profiles that the grid will encounter?

How do boundary conditions affect the charging limits, efficiencies, and demand profiles?

Findings: Single EV Charge Profiles

- **Goal:** To understand how a single EV performs under different boundary conditions
- **Findings:**
  - Charge profiles are very diverse based on initial conditions of the EV
  - OEM rated "peak performance" is difficult to achieve when starting at higher SOCs, and under hot and cold starting temperatures.
  - Even with a Nominal Soak condition, peak power is not always achieved
  - Data allows us to analyze EV charging performance, AC grid impacts, system efficiency, etc.
  - Analyzing data from a consumer standpoint with 10min & 20min data

EV Profile Set Analysis



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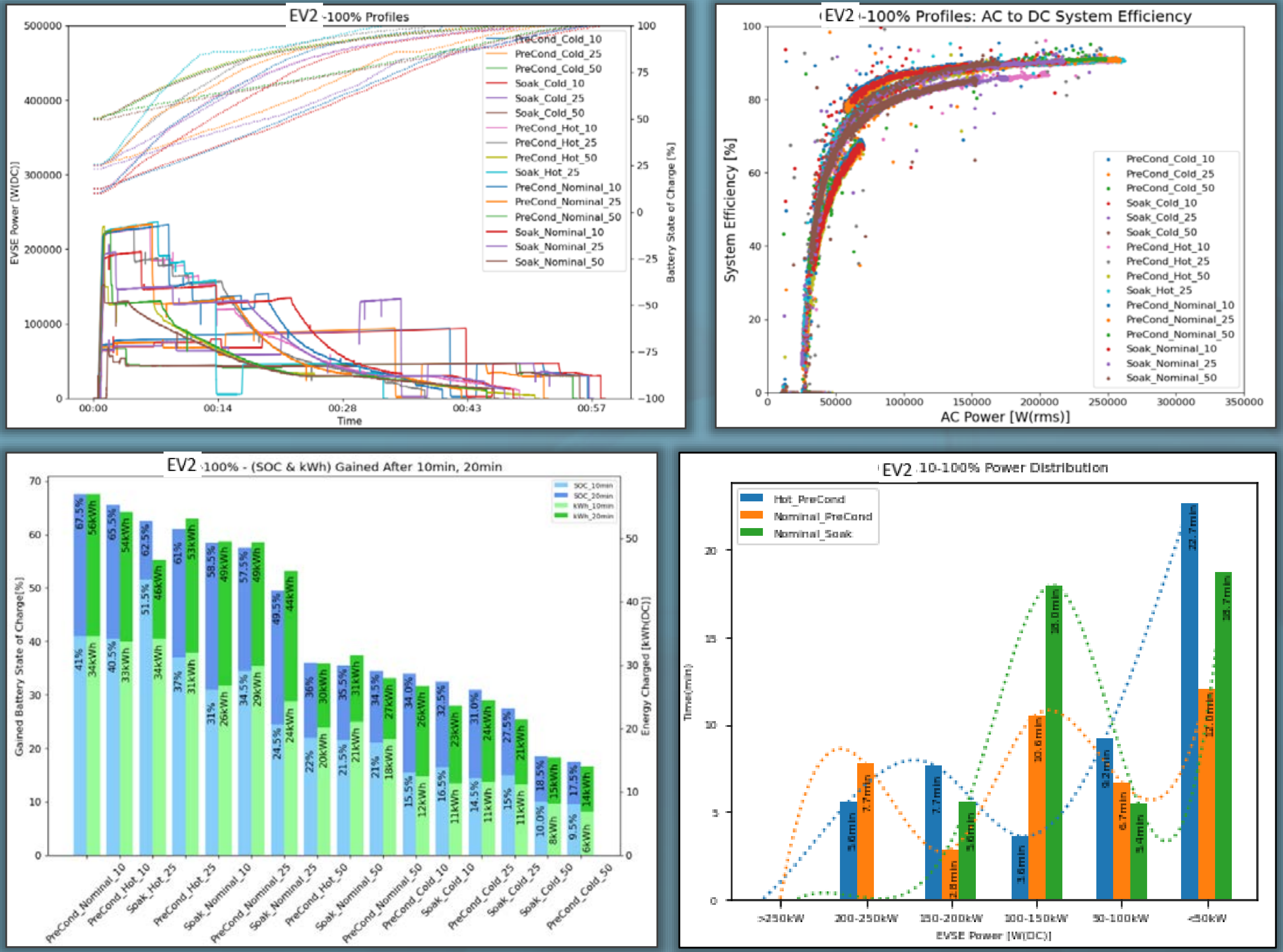
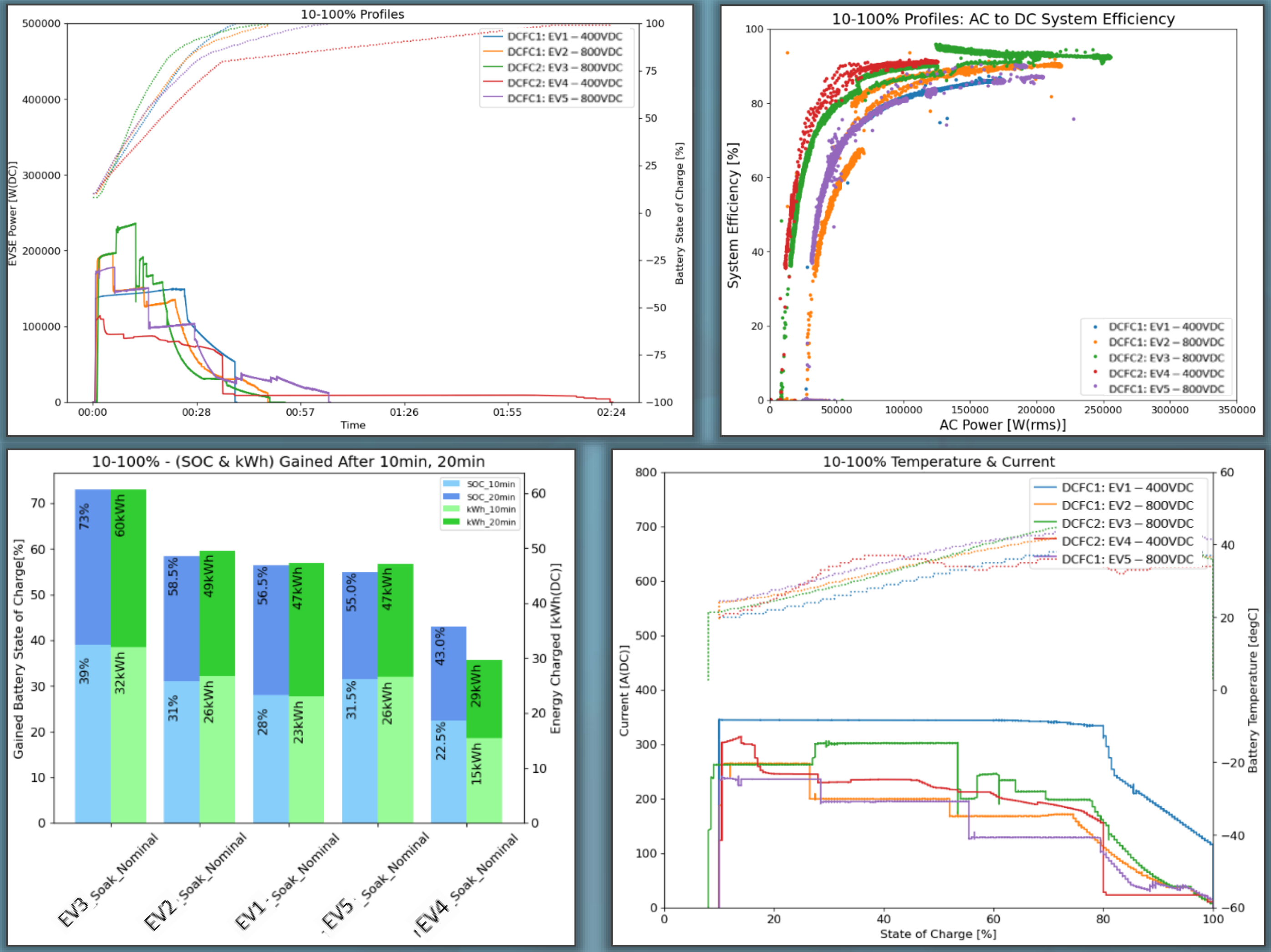


Findings: Different Battery Topologies & DCFCs

- **Goal:** To understand how different EV topologies & DCFC charge performance compete with one another in similar conditions
- **Findings:**
  - To match the power output for a 800VDC system, 400VDC topologies pull double the current
    - Exploring thermal issues
    - Potential DCFC power limitation (500A max for our dual cabinet setup)
  - SOC gained is not entirely reflective of performance, kWh shows the relative battery pack size being charged
  - System efficiencies of 400VDC & 800VDC vary on different DCFC manufacturers
    - ABB DCFC: Red, Green
    - BTC DCFC: Blue, Orange, purple

Comparing EV Captures (10-100% Nominal Soak)

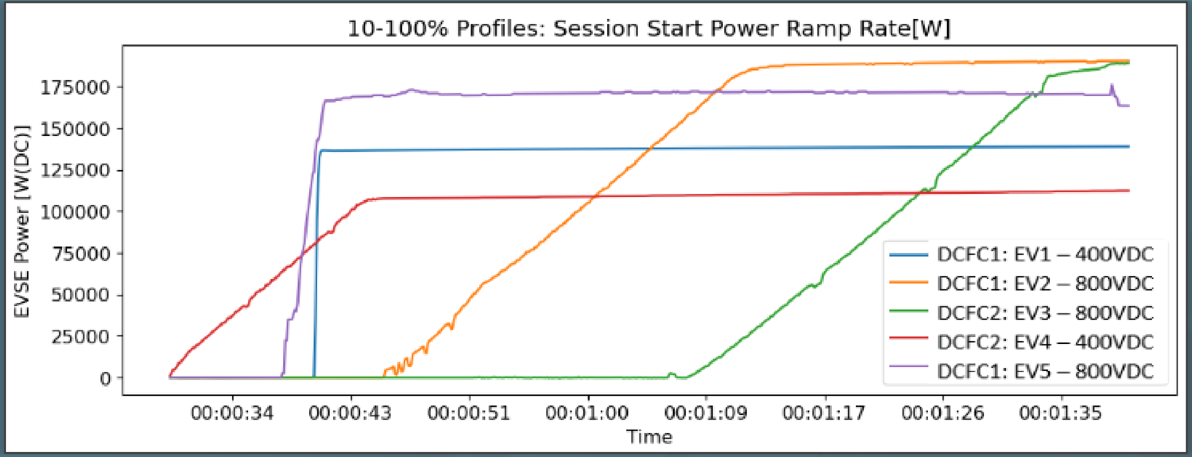


Findings: EV Ramp Rates & EVSE Limited Testing

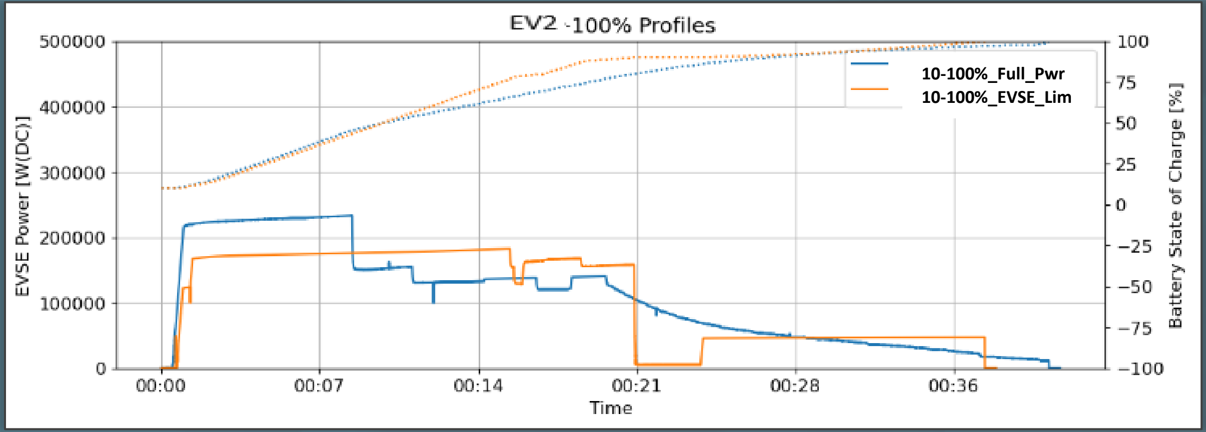
- **Goal:** Examine how fast different EVs ramp to full power
- **Findings:**
  - Ramp rates of EV's vary, dependant on the implemented control strategy on the EV BMS
  - The EV controls how much power the DCFC delivers though "Current Request" messages sent over PLC

- **Goal:** Examine charge performance when power limited by the DCFC
- **Findings:**
  - In some cases, limiting DCFC available current can result in a much different, more consistent charge curve.
  - Less DC power means less thermal strain on the EV battery, which can sometimes result in earlier 10-100% charge times.

EV Ramp Rates



Full Power vs Limited Power



Conclusions & Next Steps

Review

- Electric Vehicle Profile Capture is ongoing, currently 16 EV assets in our study with more to come
  - Results
    - Nominal Conditions required to meet OEM charge power ratings (in some cases)
    - High degree of variance when testing off-nominal conditions
    - Unique charge strategy approaches between different EVs
    - EVSE limited testing proved useful results
    - Industry is challenged with finding a meaningful way of quantifying EV/DCFC charge performance

Next steps

- Continued profile capture and data analysis
- Continue to quantify our findings in a way that will help educate/inspire industry.

Thank You!

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U.S. Department of Energy

Open Feedback: EV Profile Capture

- Q1: Are our methodologies towards capturing charge performance comprehensive enough?   (e.g., sampling rate, measurement points, test variations, etc.)

- Q2: What are specific areas of performance that we can highlight in our analysis that may prove useful for consumers/industry?

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U.S. Department of Energy

“Next-Gen Charge Profiles” Project

Deep Dive: EVSE Characterization

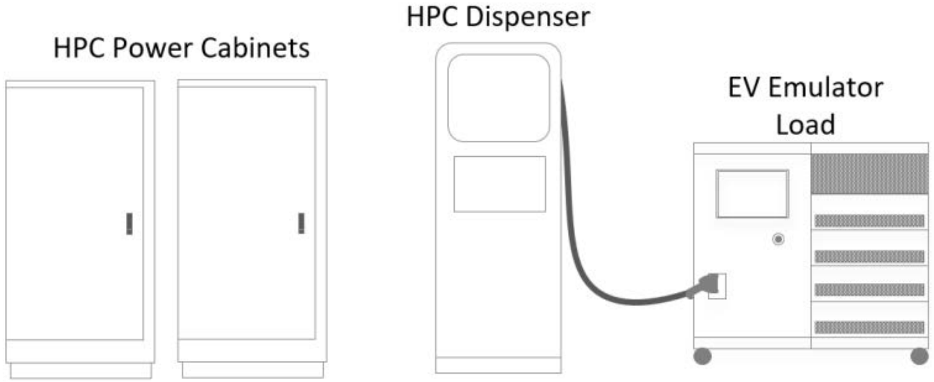
Barney Carlson

May 2, 2023

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

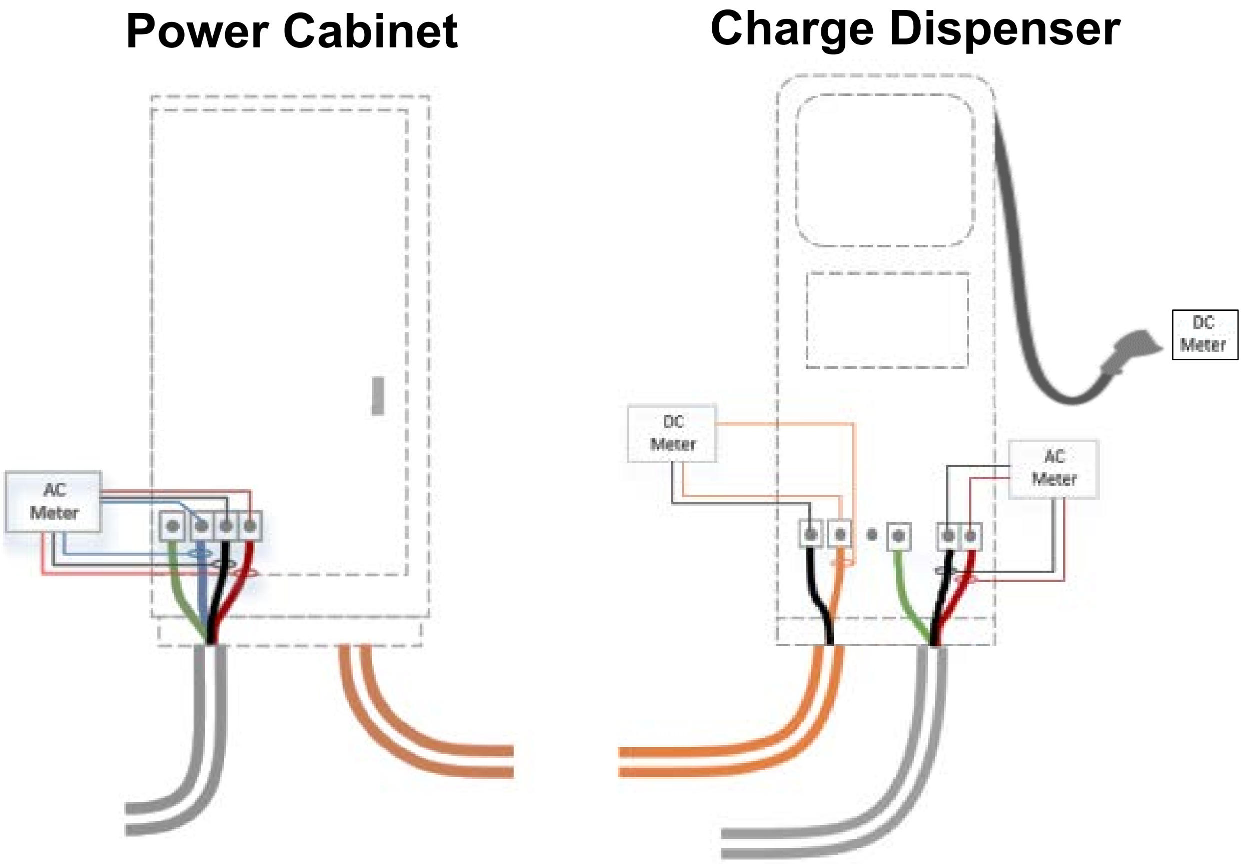
Overview: EVSE Characterization

- **EV emulator (load bank) used instead of a vehicle**
  - Enables repeatable, wide range of voltage test conditions and current loading
  - No need to discharge ESS between tests
- **Nominal test conditions**
  - Steady State characterization: Five voltage ranges, 50A to 500A
  - High Utilization testing: three repeated full power charge session
  - Stand-by power consumption
- **Off-nominal test conditions**
  - Off-nominal grid input conditions
    - Voltage deviation, Frequency deviation, Harmonics Injection
  - Hot or cold ambient test conditions
  - Smart energy management transient response
    - Power curtailment, current curtailment



EVSE Characterization Measurements

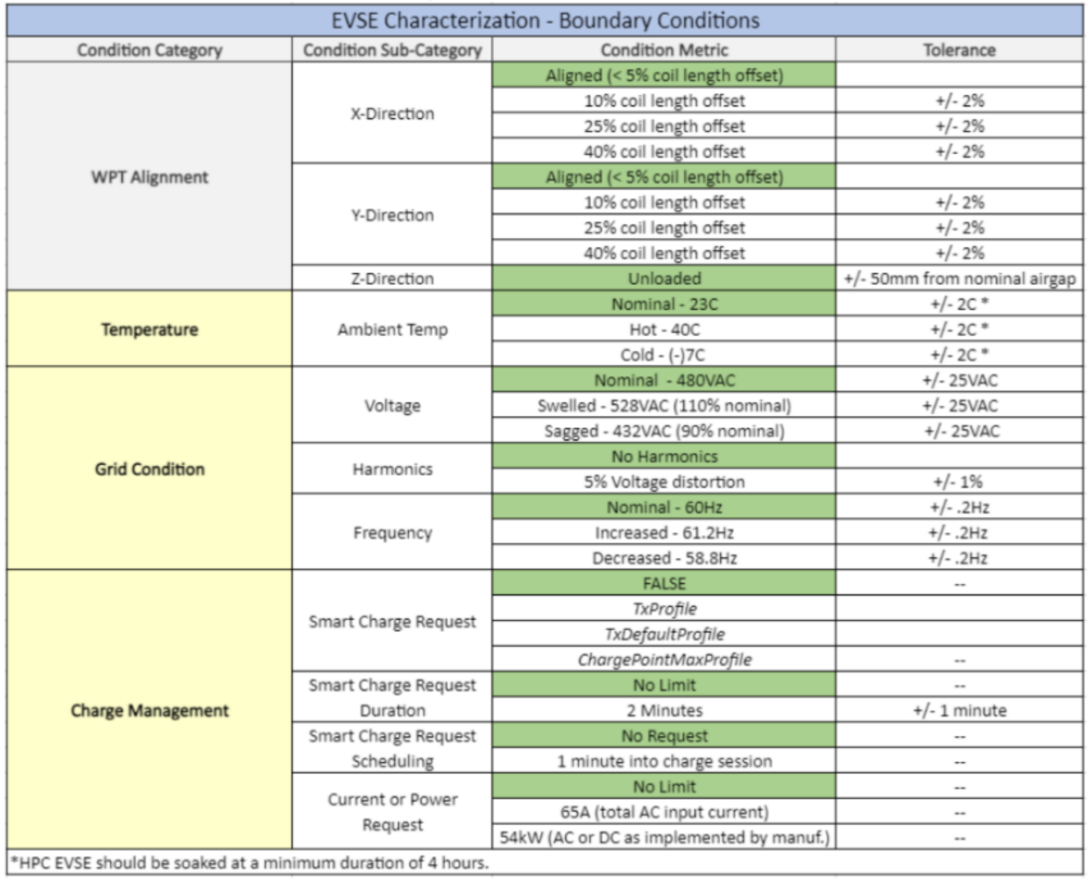
- AC grid input
  - 3-phase current, voltage, and frequency
  - Real power, reactive power, power factor
  - Current THD
  - Harmonics (3rd, 5th, 7th, 9th, 11th, and 13th)
- DC output from power cabinets
  - DC current and voltage
- DC output at the CCS vehicle inlet port
  - DC current and voltage
- Auxiliary loads
  - Thermal management systems power
  - Ancillary loads power (i.e. 12V, 24V, 120V, 240V, etc.)
- Component temperatures
  - Liquid-cooled CCS connector temperature
  - Liquid-cooled CCS cable temperature
  - Power cabinet internal air temperature



Test Conditions and Procedures Overview

- **Nominal Test Conditions**
  - Voltage: 300V, 400V, 650V, 750V, 850V
  - Current: 50 to 500A
  - Temperature: 23°C
  - Grid supply: 480VAC, 60Hz, no harmonics
  - WPT coils aligned

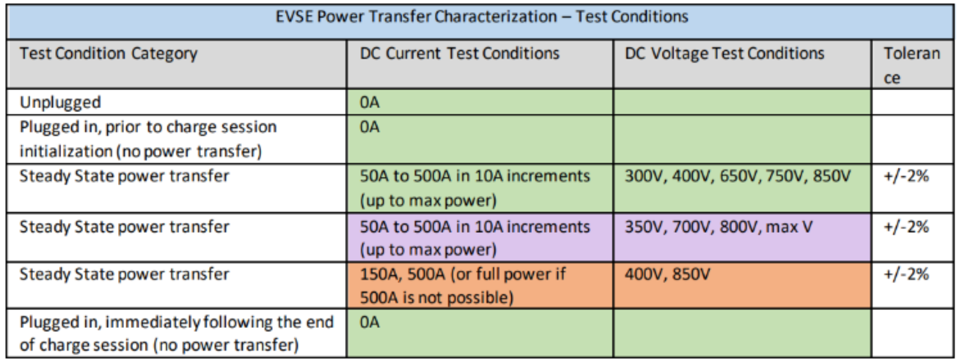
- **Off-Nominal Test Conditions**
  - Temperature: -7°C, 40°C
  - Grid supply:
    - 538VAC to 432VAC
    - 58.8Hz to 61.2Hz
    - 5% voltage distortion
  - OCPP curtailment requests:
    - 2-minute curtailment duration
    - *TxProfile, TxDefaultProfile,* and *ChargePointMaxProfile*
    - 65A, and 54kW



EVSE Characterization - Boundary Conditions

Condition Category	Condition Sub-Category	Condition Metric	Tolerance
WPT Alignment	X-Direction	Aligned (< 5% coil length offset)	
		10% coil length offset	+/- 2%
		25% coil length offset	+/- 2%
		40% coil length offset	+/- 2%
	Y-Direction	Aligned (< 5% coil length offset)	
		10% coil length offset	+/- 2%
		25% coil length offset	+/- 2%
		40% coil length offset	+/- 2%
	Z-Direction	Unloaded	+/- 50mm from nominal airgap
Temperature	Ambient Temp	Nominal - 23C	+/- 2C *
		Hot - 40C	+/- 2C *
		Cold - (-)7C	+/- 2C *
Grid Condition	Voltage	Nominal - 480VAC	+/- 25VAC
		Swelled - 528VAC (110% nominal)	+/- 25VAC
		Sagged - 432VAC (90% nominal)	+/- 25VAC
	Harmonics	No Harmonics	
		5% Voltage distortion	+/- 1%
	Frequency	Nominal - 60Hz	+/- .2Hz
		Increased - 61.2Hz	+/- .2Hz
		Decreased - 58.8Hz	+/- .2Hz
Charge Management	Smart Charge Request	FALSE	--
		TxProfile	
		TxDefaultProfile	
		ChargePointMaxProfile	--
	Smart Charge Request Duration	No Limit	--
		2 Minutes	+/- 1 minute
	Smart Charge Request Scheduling	No Request	--
		1 minute into charge session	--
	Current or Power Request	No Limit	--
		65A (total AC input current)	--
		54kW (AC or DC as implemented by manuf.)	--

*HPC EVSE should be soaked at a minimum duration of 4 hours.



EVSE Power Transfer Characterization – Test Conditions

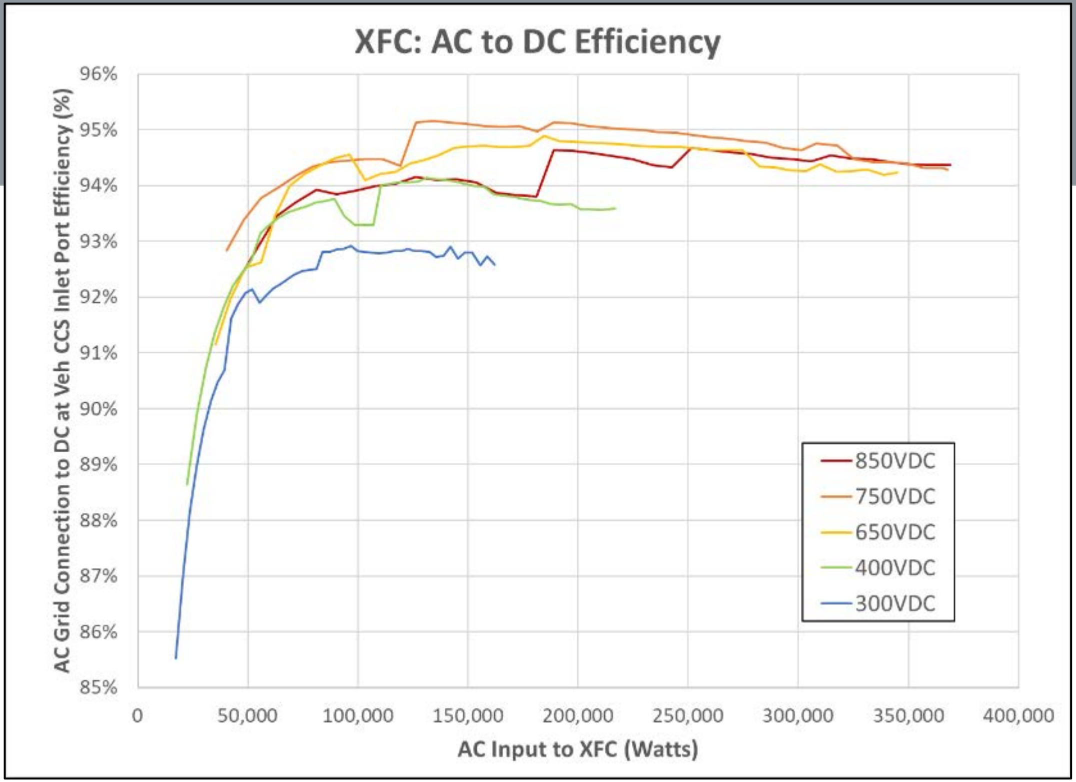
Test Condition Category	DC Current Test Conditions	DC Voltage Test Conditions	Tolerance
Unplugged	0A		
Plugged in, prior to charge session initialization (no power transfer)	0A		
Steady State power transfer	50A to 500A in 10A increments (up to max power)	300V, 400V, 650V, 750V, 850V	+/-2%
Steady State power transfer	50A to 500A in 10A increments (up to max power)	350V, 700V, 800V, max V	+/-2%
Steady State power transfer	150A, 500A (or full power if 500A is not possible)	400V, 850V	+/-2%
Plugged in, immediately following the end of charge session (no power transfer)	0A		

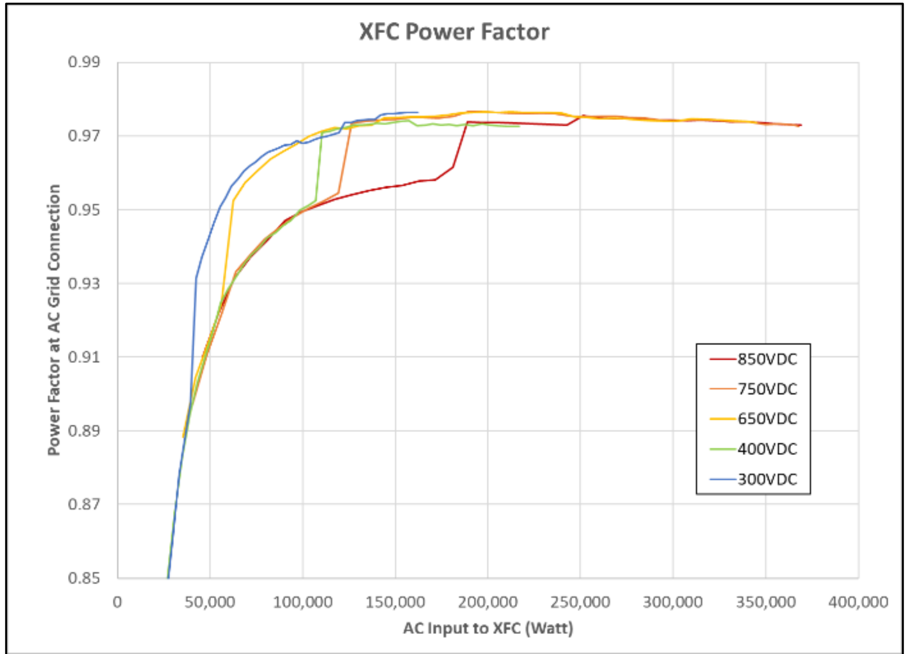
🟩 -Signifies required tests during *nominal* test conditions
🟧 -Signifies required tests during *off-nominal* test conditions
🟪 -Signifies optional tests during *nominal* test conditions

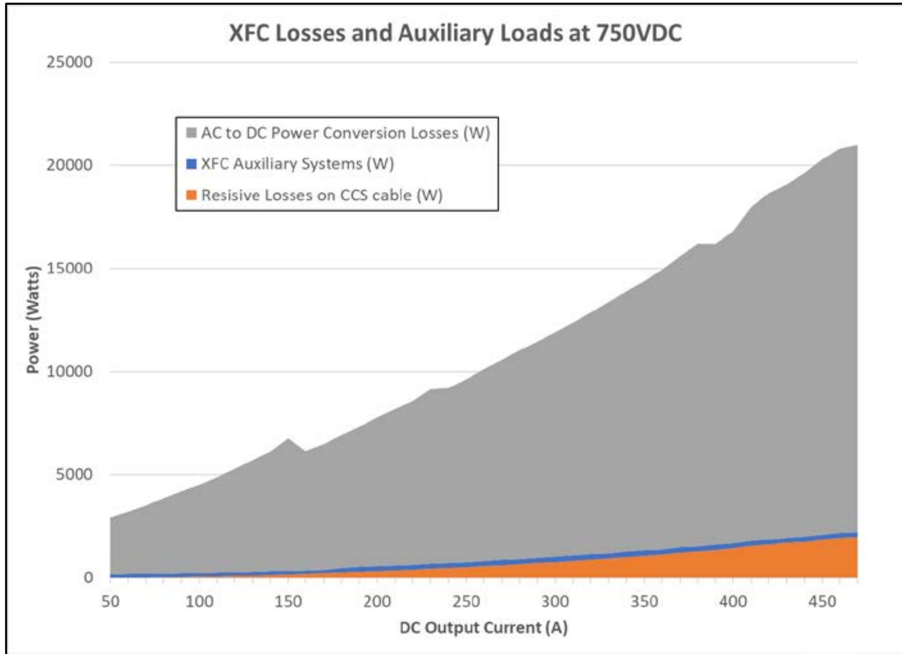
Steady State EVSE Characterization Procedure Overview and Results

<u>Objective</u>: Characterize EVSE performance and operation across a wide range of voltage and current test conditions

- **Test procedure**
  - Power transfer at each test conditions for 180sec. to achieve steady state
  - Once steady state is achieved: collected measurements at 10Hz for 30sec. duration
- **Five voltage ranged**
  - 300, 400, 650, 750, 850VDC
- **Forty-six currents**
  - 50A to 500A
  - 10A increments
- **Results include:**
  - AC to DC Efficiency
  - Power quality (PF, iTHD)
  - AC current imbalance
  - Cable losses
  - Aux. loads
  - Stand-by power draw



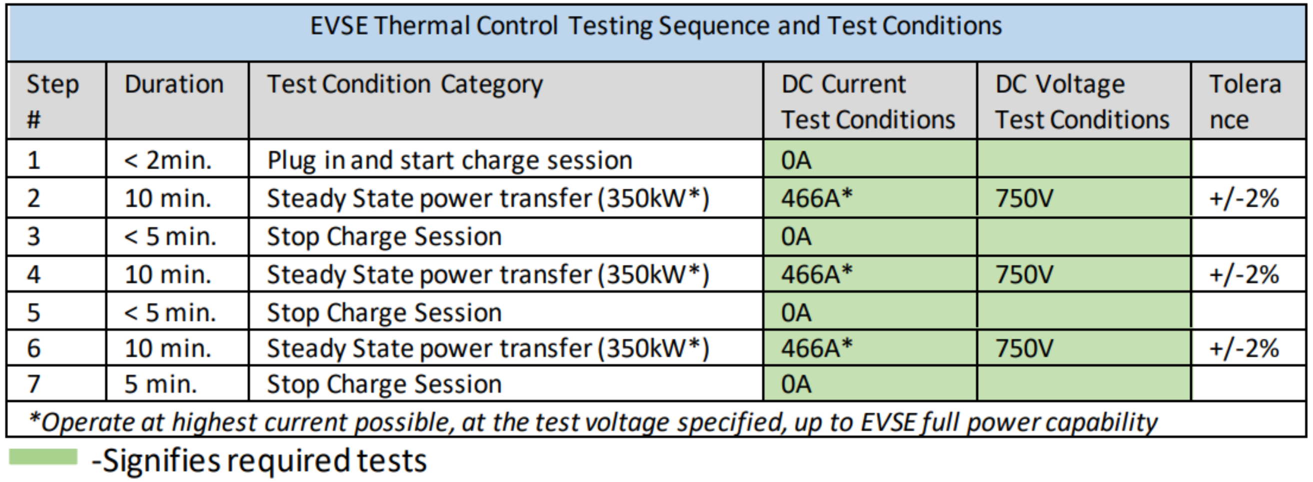




High Utilization Test Procedure Overview

<u>Objective</u>: determine EVSE performance for consecutive 10min. full power charge sessions

- **Test Sequence**
  - Soak EVSE at nominal temperature for ≥ 4 hrs. in stand-by condition prior to test sequence
  - Conduct 10 min. charge session at 350kW at 750V DC (350kW)
  - Stop charge session 4 min. (+/- 1 min.)
    - Unplug CCS cable from vehicle & hang CCS cable in charge pedestal cable holder
  - Repeat sequence three times for a total of:
    - Three 10 min. charge sessions
    - Two 4 min. rest period between charge sessions



EVSE Thermal Control Testing Sequence and Test Conditions

Step #	Duration	Test Condition Category	DC Current Test Conditions	DC Voltage Test Conditions	Tolerance
1	< 2min.	Plug in and start charge session	0A		
2	10 min.	Steady State power transfer (350kW*)	466A*	750V	+/-2%
3	< 5 min.	Stop Charge Session	0A		
4	10 min.	Steady State power transfer (350kW*)	466A*	750V	+/-2%
5	< 5 min.	Stop Charge Session	0A		
6	10 min.	Steady State power transfer (350kW*)	466A*	750V	+/-2%
7	5 min.	Stop Charge Session	0A		

**Operate at highest current possible, at the test voltage specified, up to EVSE full power capability*

🟩 -Signifies required tests

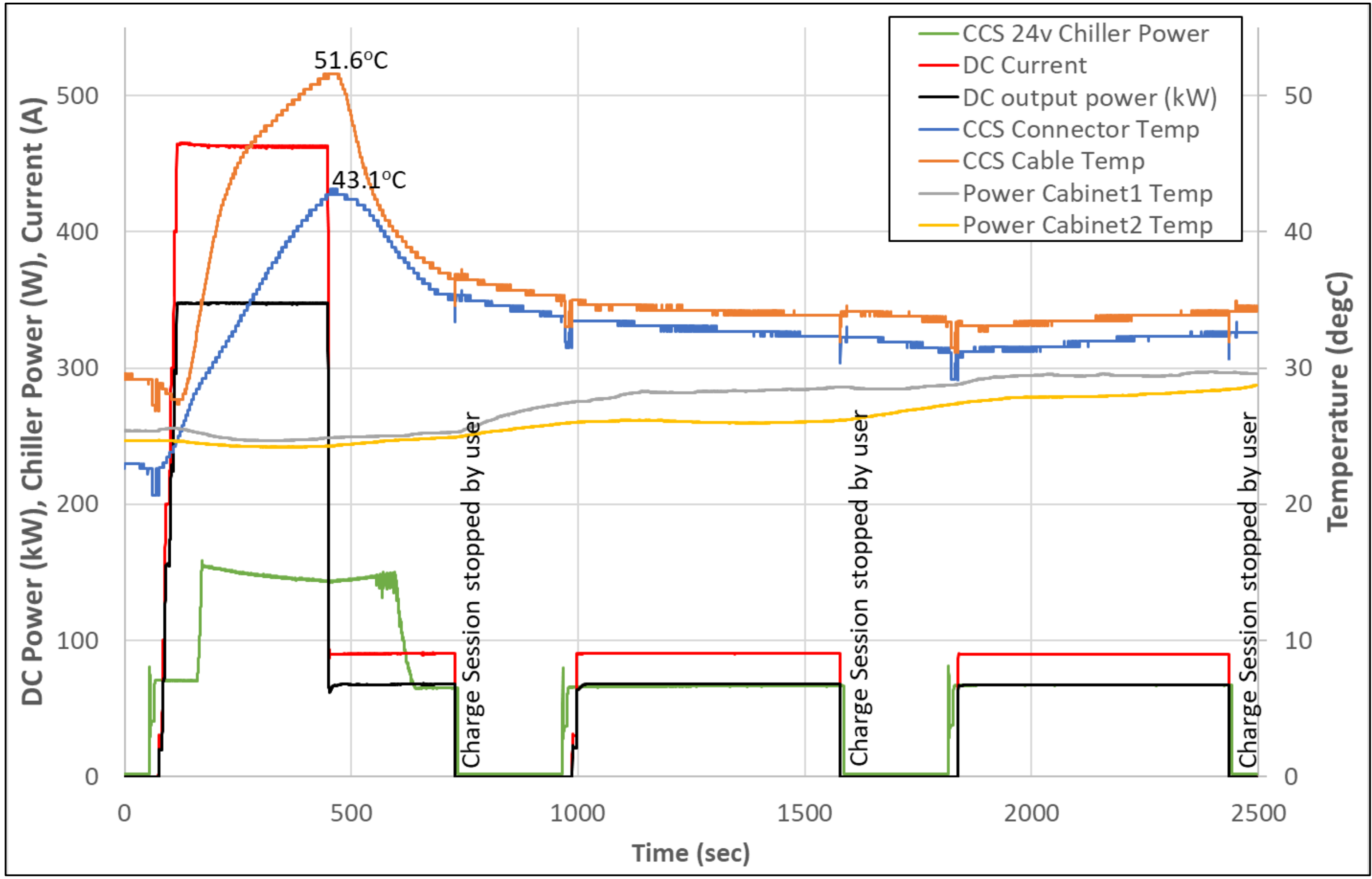
High Utilization Test Results– Consecutive 350kW Charge Sessions

- **Each charge session:**
  - 500A requested during each 10-min. charge session
    - 465A delivered due to EVSE 350kW power limitation
  - Load bank controlled to 750VDC
  - Test operator ends each charge session after 10 min. duration
- **Rest between charge sessions**
  - 4-minute duration (+/- 1 min.)
  - CCS cable unplugged from EV inlet port and returned to charge pedestal

Result:

- **Cable thermal limit exceeded after ~6min. of full power transfer (350kW) resulting in current limitation to 90A DC until reboot**

Consecutive 10-minute 350kW charge sessions on a 350kW XFC



Smart Energy Management Characterization Test Procedure Overview

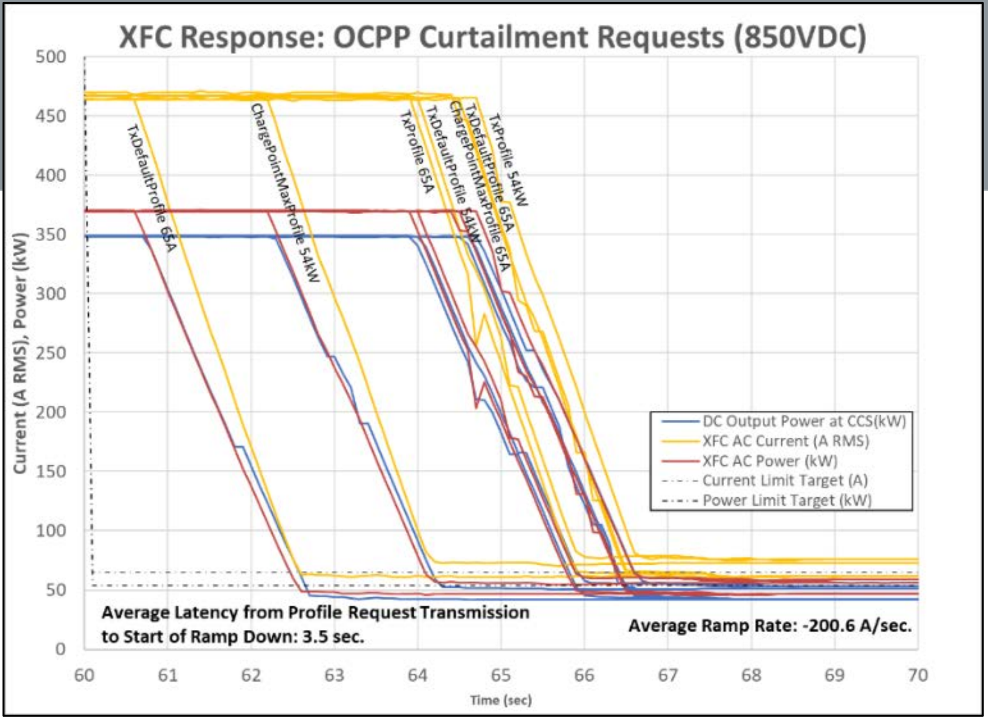
Objective: Characterize EVSE performance, latency, and ramp rates during energy management curtailments

- **Four Power Transfer Test Conditions**
  - 850V, 150A
  - 850V, 500A (or max. power)
  - 400V, 150A
  - 400V, 500A
- **Test Sequence:**
  - Operate the EVSE at each of the four power transfer test conditions
  - Initiate the Smart Energy Management Curtailment Request
    - *TxProfile, TxDefaultProfile,* and *ChargePointMaxProfile*
    - 65A, and 54kW
    - Continue each curtailment for 120 sec. duration
  - Initiate the command *ClearChargingProfile* to end the curtailment

Profile Type	**Current or Power Value**
TxProfile	65A
TxProfile	54kW
TxDefaultProfile	65A
TxDefaultProfile	54kW
ChargePointMaxProfile	65A
ChargePointMaxProfile	54kW

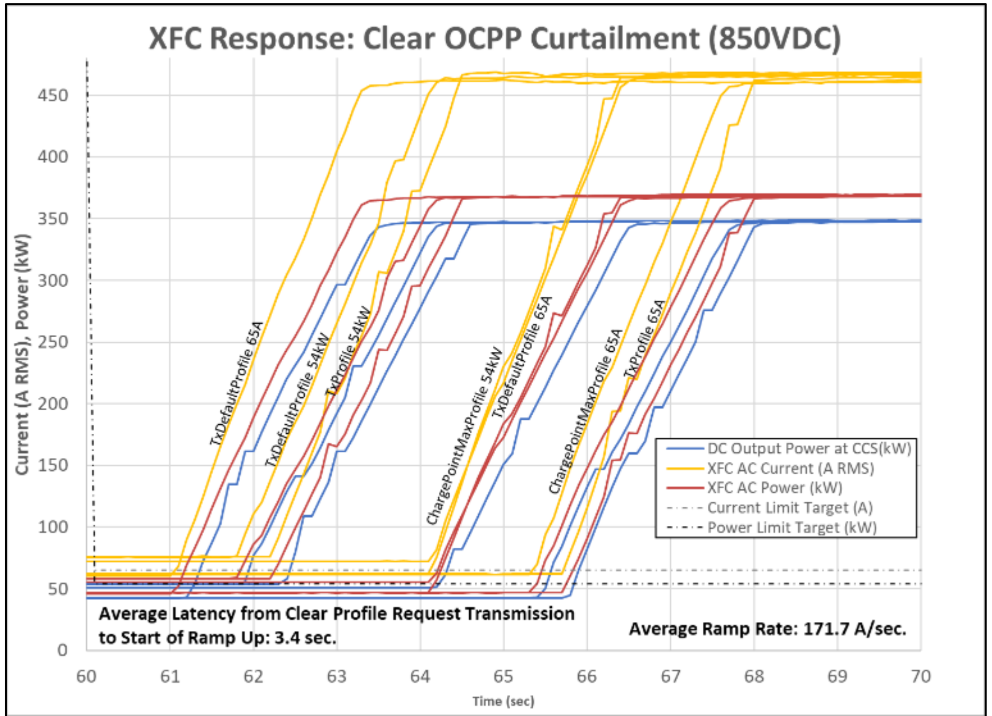
Smart Energy Management Characterization Results

- **Testing conducted using SteVe OCPP 1.6J**
- **Response latency varies considerably**
  - Range: 1 to 11 seconds
  - Average latency is ~3 seconds
- **Steady State power transfer during active curtailment request:**
  - For AC current limited profiles:
    - AC current < AC current limit
  - For DC power limited profiles:
    - DC power < DC output power limit
  - For AC power limited profiles:
    - AC power *is* ***<u>slightly greater</u>*** the AC input power limit
- **Curtailment ramp rate depends upon power transfer initial & final values**
  - Between -27A/sec. to -200A/sec.
  - Between 23A/sec. to 172A/sec.


XFC Response: OCPP Curtailment Requests (850VDC)

Average Latency from Profile Request Transmission to Start of Ramp Down: 3.5 sec.

Average Ramp Rate: -200.6 A/sec.


XFC Response: Clear OCPP Curtailment (850VDC)

Average Latency from Clear Profile Request Transmission to Start of Ramp Up: 3.4 sec.

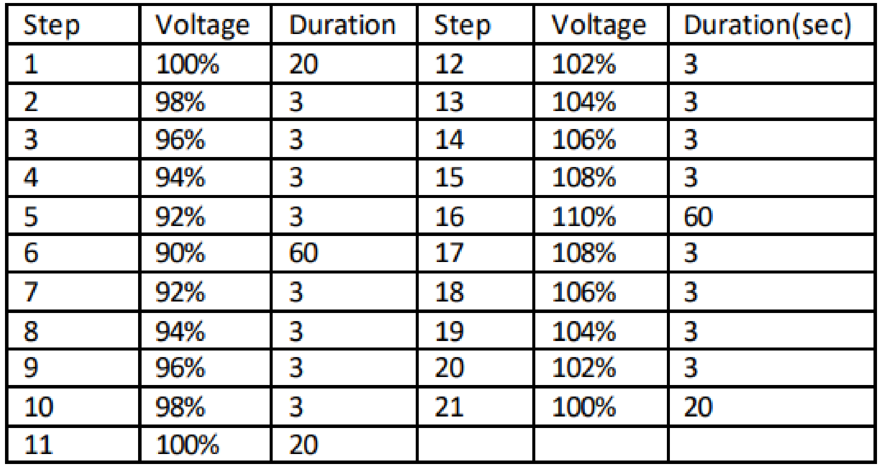
Average Ramp Rate: 171.7 A/sec.

Off-Nominal Grid Input Test Procedure Overview

Objective: Characterize EVSE performance during voltage deviation, frequency deviation, and voltage harmonics grid conditions

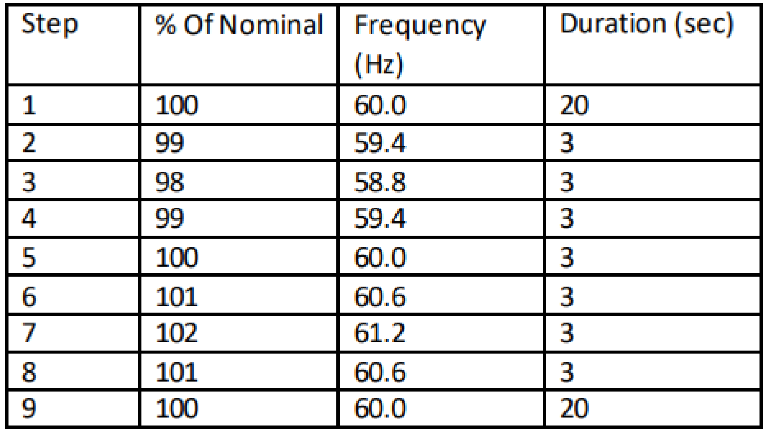
- **Four power transfer test conditions**
    - 850V, 150A
    - 850V, 500A (or max. power)
    - 400V, 150A
    - 400V, 150A
- **Test Sequence: Voltage deviation**
    - – 3 sec. at each input voltage condition ranging from 90% to 110% of nominal
- **Test Sequence: Frequency deviation**
    - – 3 sec. at each input frequency condition ranging from 58.8Hz to 61.2Hz
- **Test Sequence: Harmonics injection**
    - – After achieving the power transfer test condition, inject 5% THD voltage distortion for 60sec. duration

EVSE Voltage Variation Test



Step	Voltage	Duration	Step	Voltage	Duration(sec)
1	100%	20	12	102%	3
2	98%	3	13	104%	3
3	96%	3	14	106%	3
4	94%	3	15	108%	3
5	92%	3	16	110%	60
6	90%	60	17	108%	3
7	92%	3	18	106%	3
8	94%	3	19	104%	3
9	96%	3	20	102%	3
10	98%	3	21	100%	20
11	100%	20			

EVSE Frequency Variation Steps

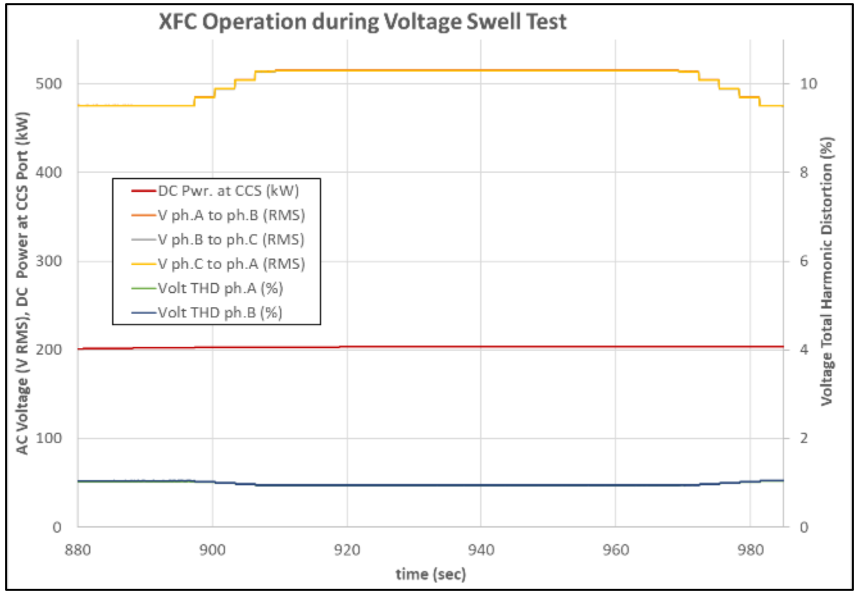


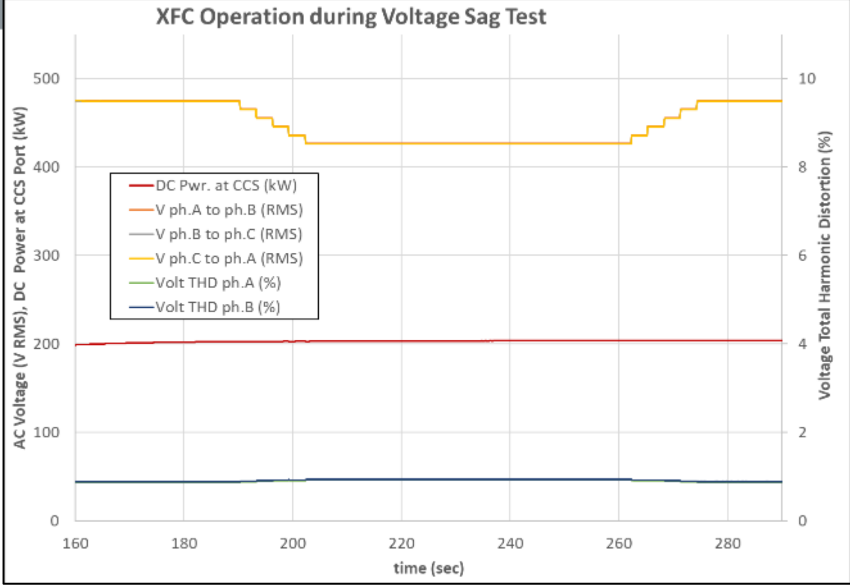
Step	% Of Nominal	Frequency (Hz)	Duration (sec)
1	100	60.0	20
2	99	59.4	3
3	98	58.8	3
4	99	59.4	3
5	100	60.0	3
6	101	60.6	3
7	102	61.2	3
8	101	60.6	3
9	100	60.0	20

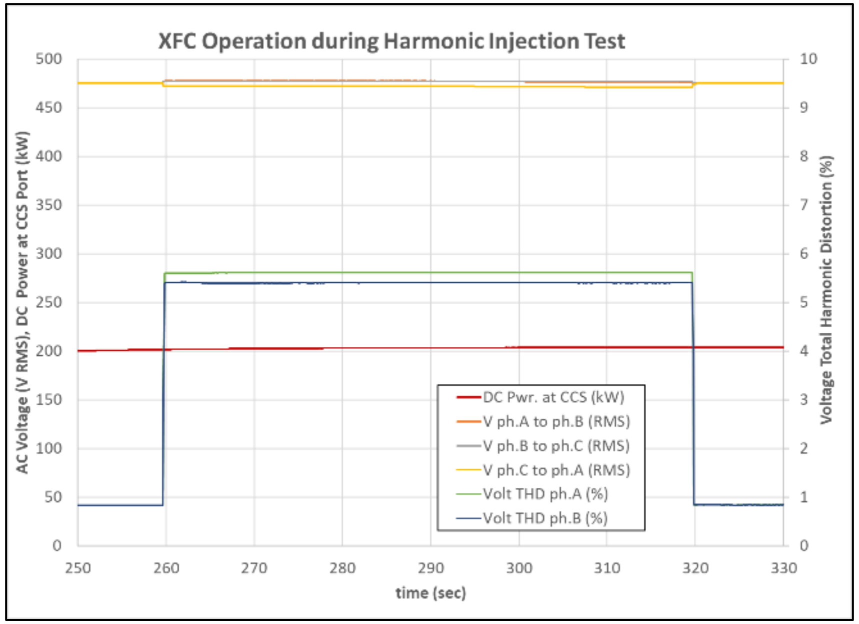
Off-nominal Grid Input Test Results

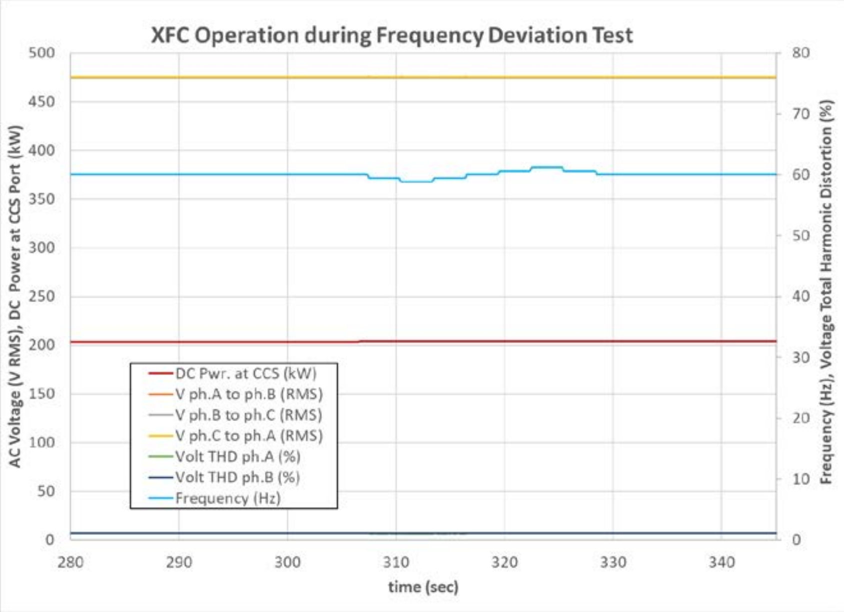
- **400VDC and 850VDC**
- **150A and 500A** (or 350kW)
- **Voltage deviation**
  - Sag to 426VAC
  - Swell to 518VAC
- **Frequency deviation**
  - Up to 61.2 Hz
  - Down to 58.8 Hz
- **Harmonics injection**
  - 5% THD

Result: DC power transfer continues uninterrupted and unperturbed during all off-nominal grid test conditions


XFC Operation during Voltage Swell Test


XFC Operation during Voltage Sag Test

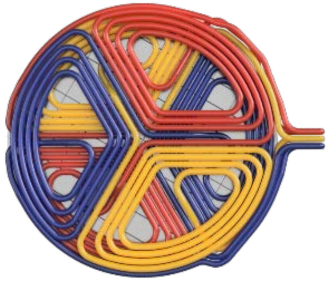

XFC Operation during Harmonic Injection Test

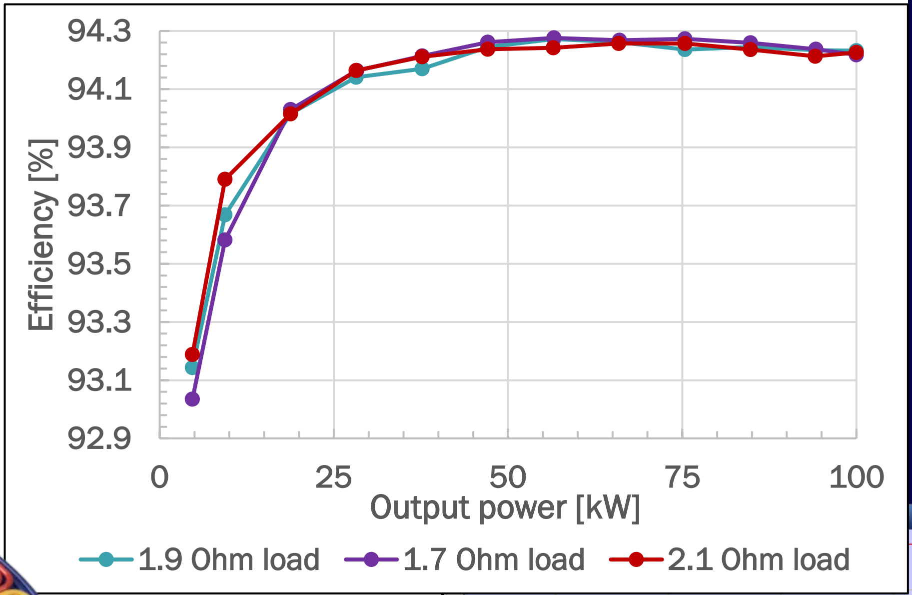

XFC Operation during Frequency Deviation Test

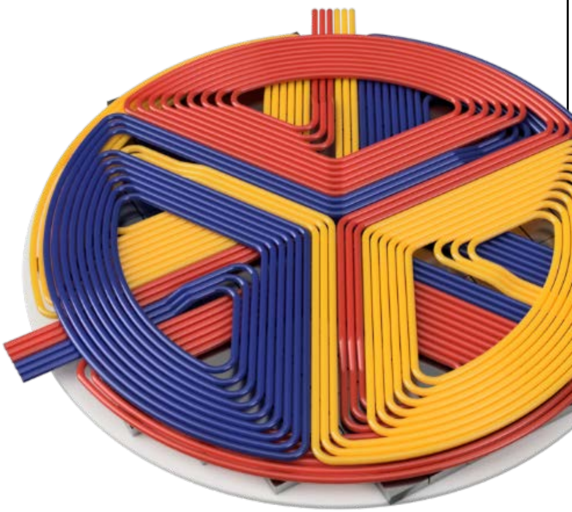
Characterization: Polyphase Wireless Charging

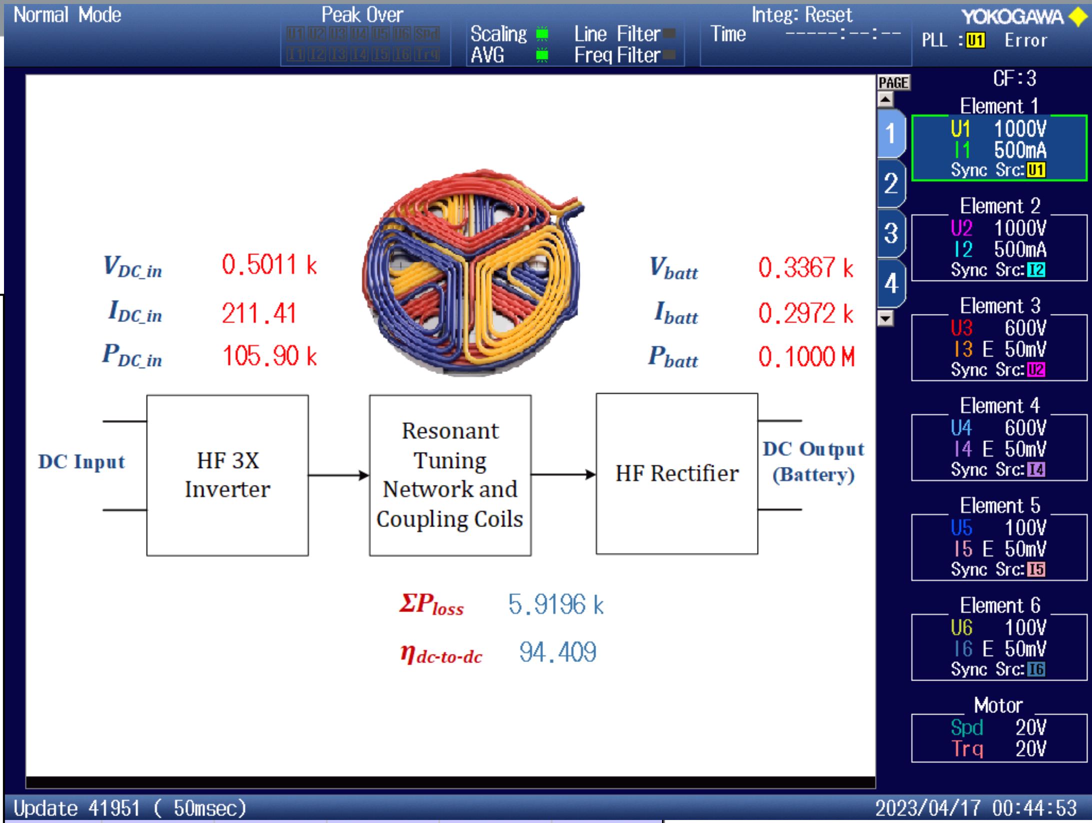
ORNL's 100kW polyphase wireless power transfer (WPT)

- 94.41% efficiency at 100kW power transfer
- 17.8 uT RMS (25.2 uT peak) at 0.8m from coil center during 100kW









Integ: Reset
-----:--:--
PLL : U1 Error
CF:3

Element 1
U1 1000V
I1 500mA
Sync Src: U1

Element 2
U2 1000V
I2 500mA
Sync Src: I2

Element 3
U3 600V
I3 E 50mV
Sync Src: U2

Element 4
U4 600V
I4 E 50mV
Sync Src: I4

Element 5
U5 100V
I5 E 50mV
Sync Src: I5

Element 6
U6 100V
I6 E 50mV
Sync Src: I6

Motor
Spd 20V
Trq 20V

V_{DC_in} 0.5011 k
I_{DC_in} 211.41
P_{DC_in} 105.90 k

V_{batt} 0.3367 k
I_{batt} 0.2972 k
P_{batt} 0.1000 M

DC Input → HF 3X Inverter → Resonant Tuning Network and Coupling Coils → HF Rectifier → DC Output (Battery)

ΣP_{loss} 5.9196 k
$\eta_{dc\text{-}to\text{-}dc}$ 94.409

Update 41951 (50msec)
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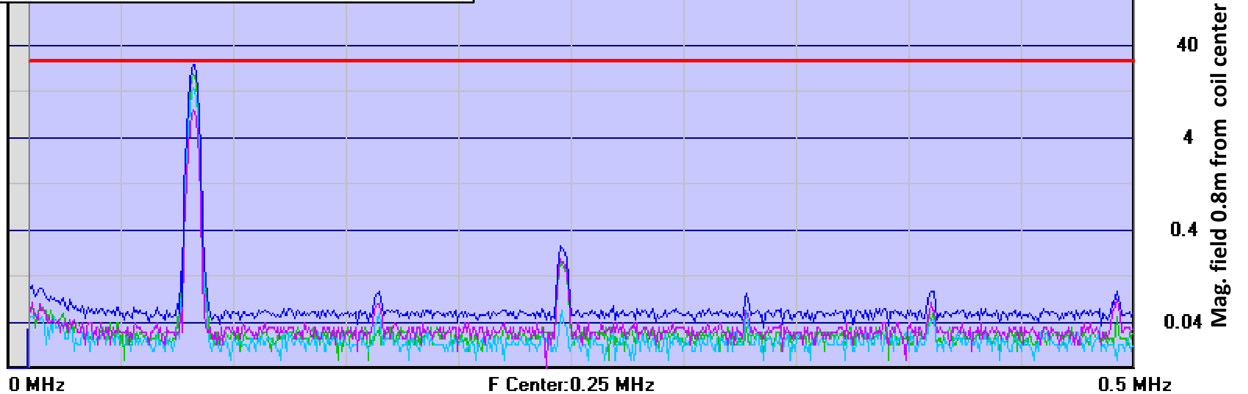


Conclusion and Next Steps

Review

- High Power Charger Characterization is completed for one 350kW EVSE
  - Nominal conditions results
    - AC to DC efficiency is between 92.0% to 95.2% when power transfer is ≥50kW
    - Liquid-cooled cable thermal management is a limiting factor for long duration, high-power charge sessions
  - Off-nominal conditions results
    - No disruption in power transfer during off-nominal grid input (V, f, Harm.)
    - Smart Energy Management curtailment requests have wide range of latency (1 to 11 seconds)
- Characterization testing of two additional 350kW EVSE are in progress and planned

Next steps

- Continued test execution and data gathering
- Develop impactful analysis that can guide performance standards and inform industry.

Thank You!

EVs@ Scale

U.S. Department of Energy

Open-Feedback: Cyber-Physical Security Pillar

Ranking question (or multiple choice is an acceptable back-up option)

- **What classes EV charging infrastructure is characterization data most needed?**
  A. High-power 350kW DC
  B. High-power 150kW DC
  C. Mega-watt charging (~1.5 MW)
  D. Bi-directional DC charging
  E. Bi-directional AC charging

Characterization: WAVE 250kW WPT

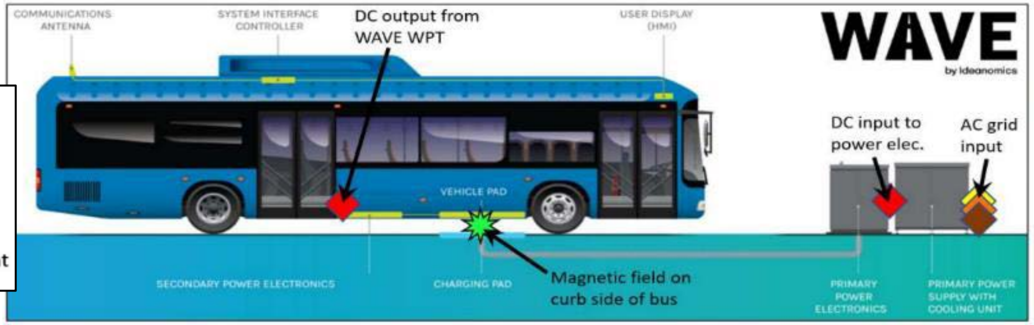
Test Results: Wireless Charging

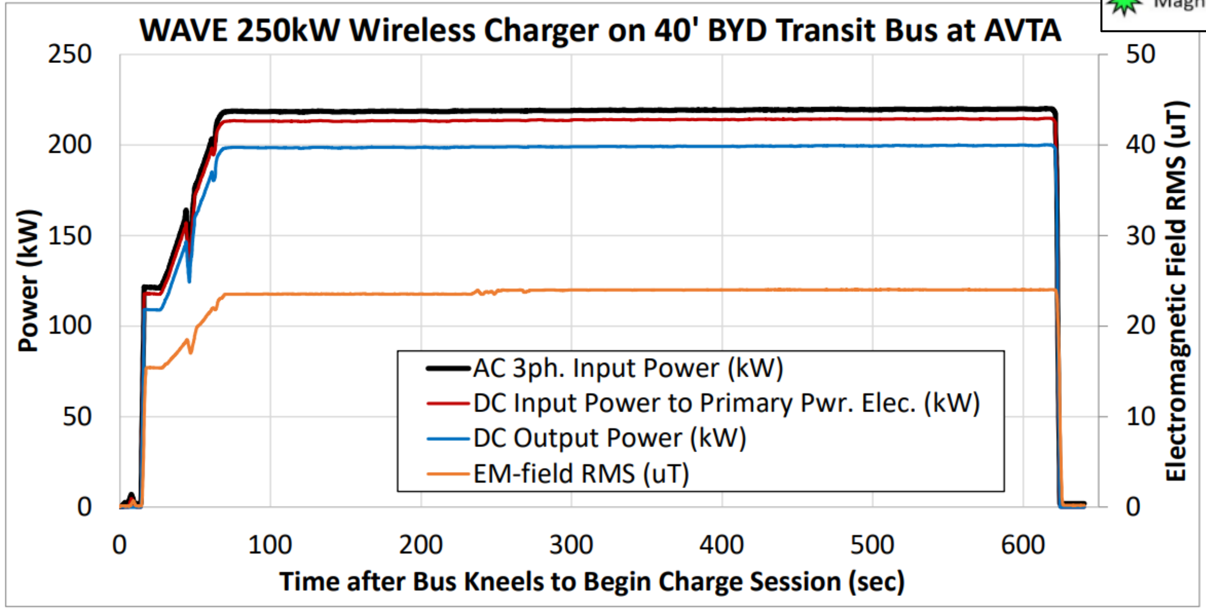
	Fully Aligned	Max. Misalignment
Coil Alignment	0,0 mm	120,0 mm
DC Output Power (battery limited)	199.7 kW	192.8 kW
Full System AC to DC efficiency	90.89%	90.55%
DC Input to DC Output efficiency	93.13%	92.70%
EM-field RMS (curb-side at bus edge)	24.0 uT	25.9 uT
AC Power Factor	0.933	0.989
AC Current Total Harmonic Distortion	6.31%	6.60%

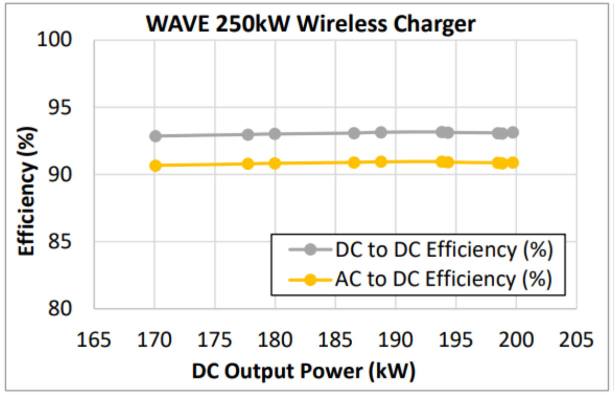
◆ 3ph. AC current & voltage measurement

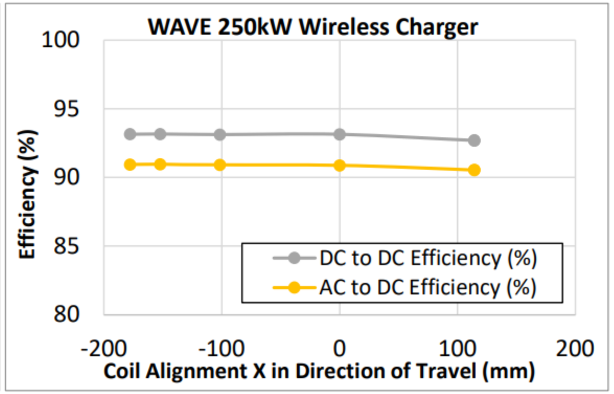
◆ DC current & voltage measurement

✷ Magnetic field measurement





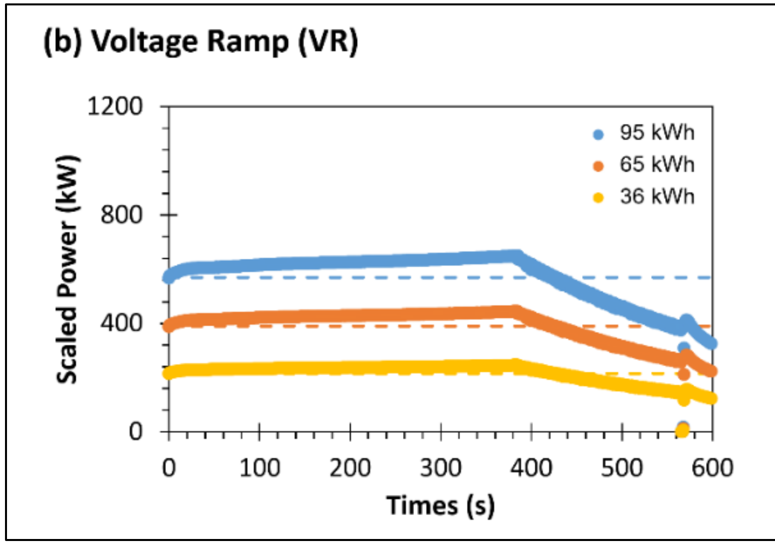


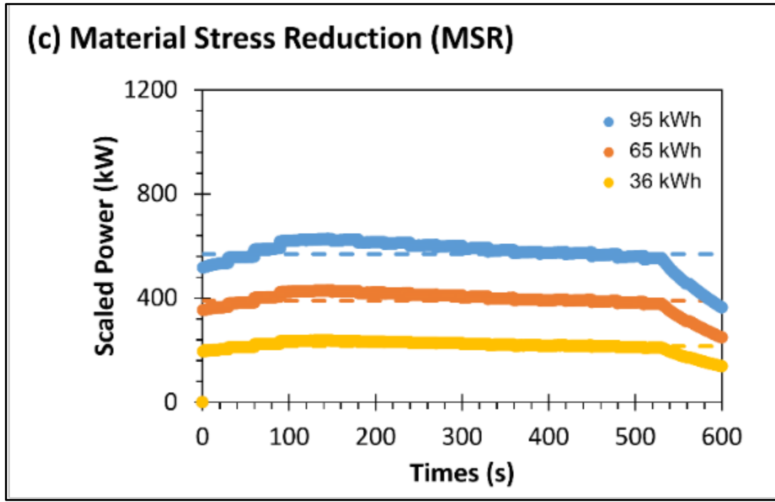


XCEL Charge Profiles Scaled for 350kW XFC Limits

Scope: Charge 0% to 100% SOC in 10 minutes

- **Two charge profiles developed** *(Kim et al, Energy Technology, 2022, 2200303)*
  - Voltage Ramp (VR) profile
  - Material Stress Reduction (MSR) cell charge profiles
- **Profiles scaled up from single cell test for ESS charging on 350kW XFC**
  - 192 series cells
  - 50 kWh ESS capacity
- **Two charge replacements of each profile tested on 350kW XFC**
  - 100% (0% to 100%) within 10 minutes
  - 90% (10% to 100% SOC)



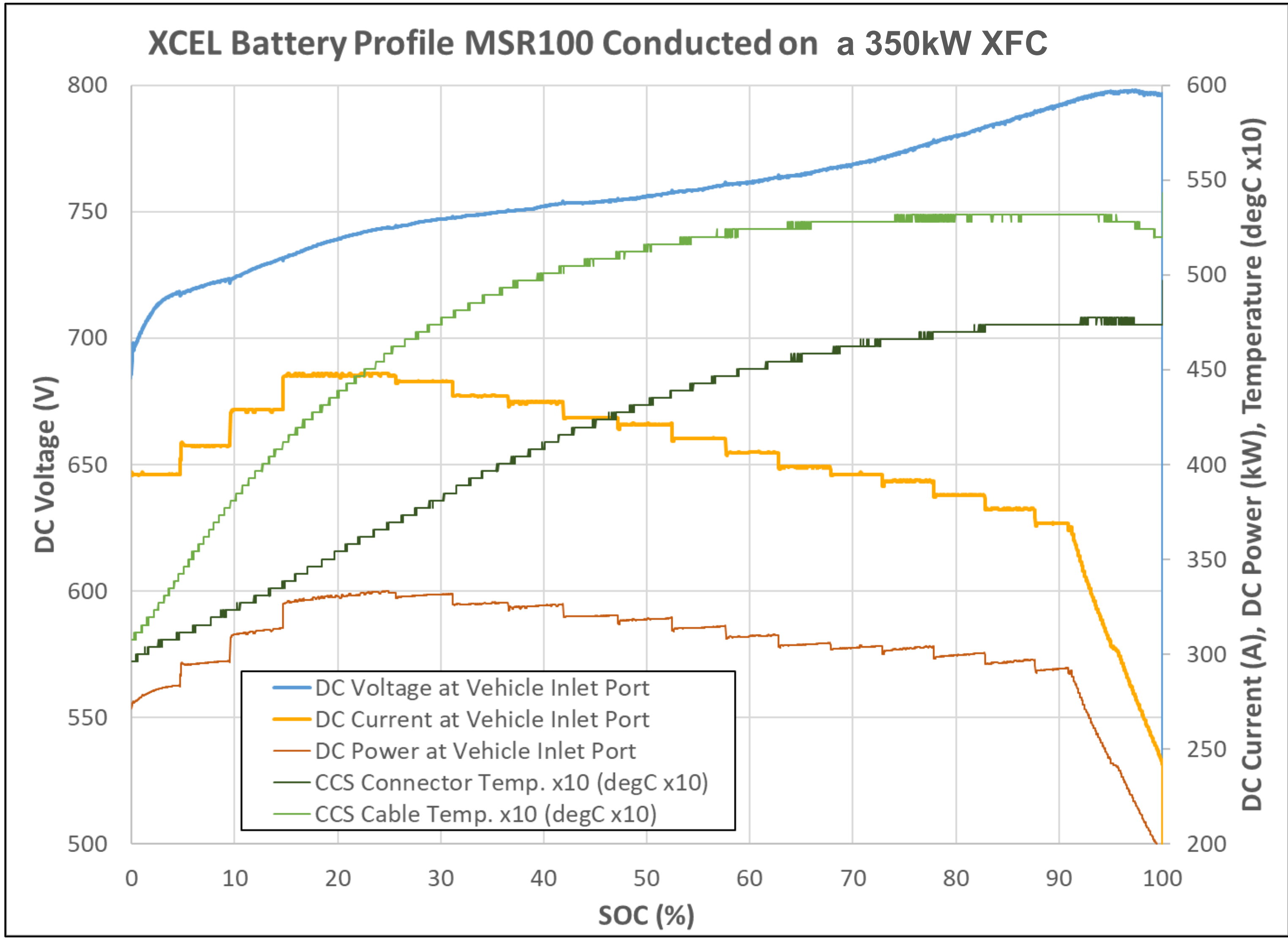


XCEL MSR Charge Profile: 0% to 100%

- Material Stress Reduction
- 600 seconds duration
- 50.5 kWh DC delivered at vehicle CCS inlet port
- 53ºC max. CCS cable temperature measured during charge session
  - Initial temperature: 30ºC

Note:

- For long-range EVs (~100kWh) higher power charging (700+ kW) will be needed to complete the charge session in 10 minutes

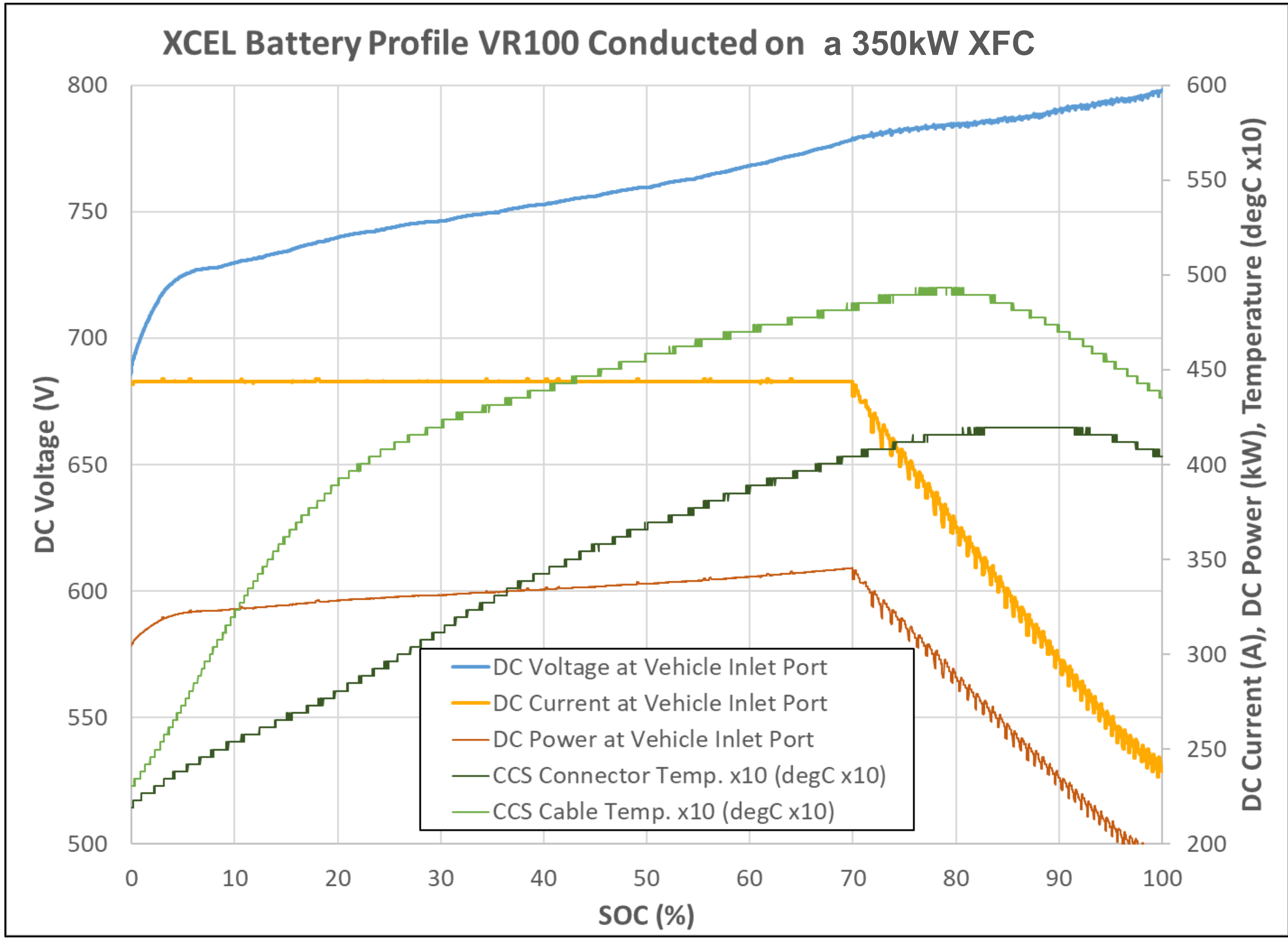


XCEL VR Charge Profile: 0% to 100%

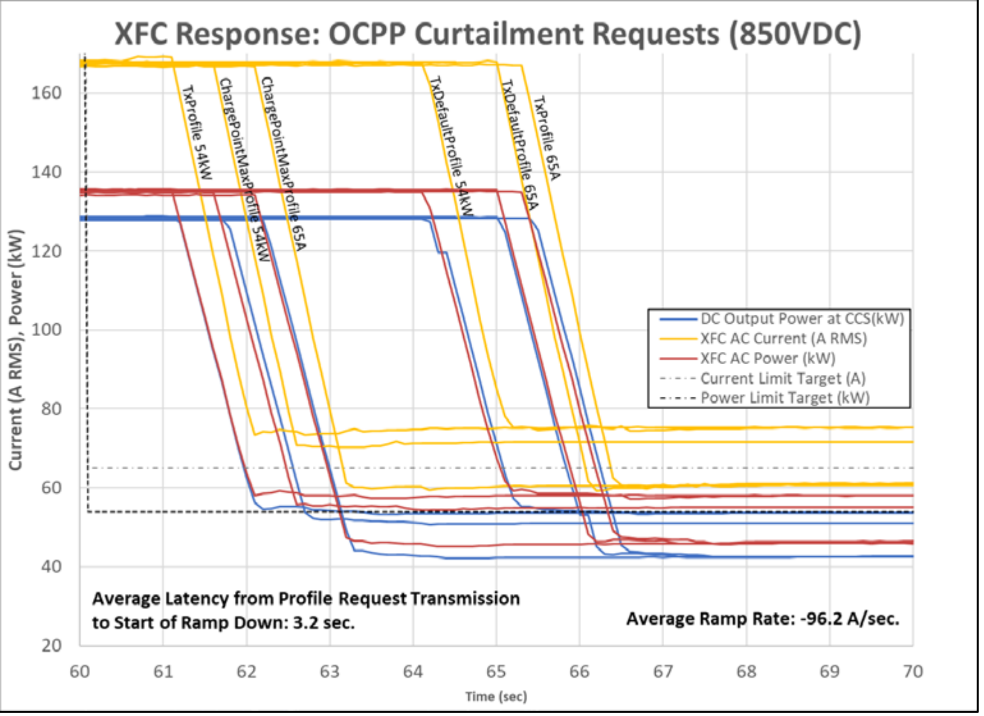
- Voltage Ramp
- 600 seconds duration
- 50.7 kWh DC delivered at vehicle CCS inlet port
- 50°C max. CCS cable temperature measured during charge session
  - Initial temperature: 23°C

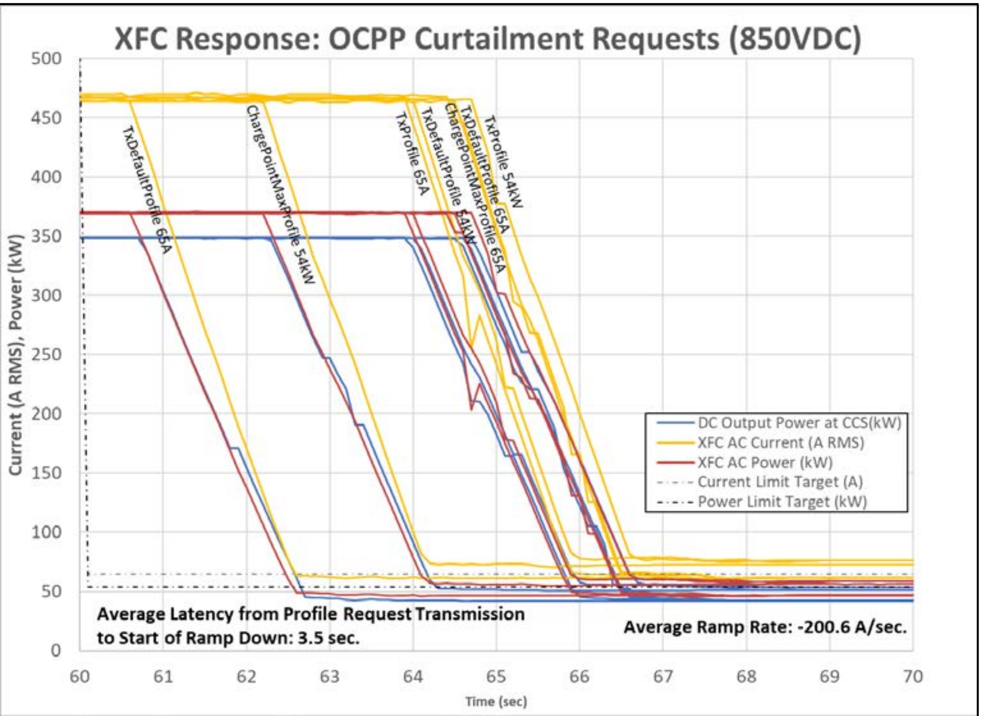
Note:

- For long-range EVs (~100kWh) higher power charging (700+ kW) will be needed to complete the charge session in 10 minutes

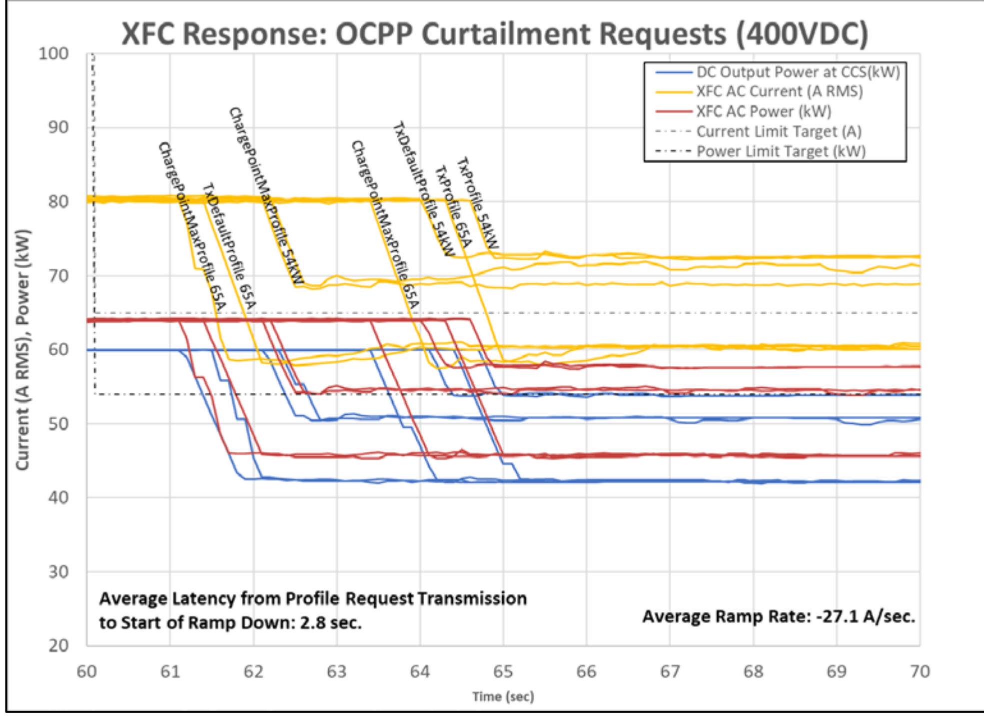


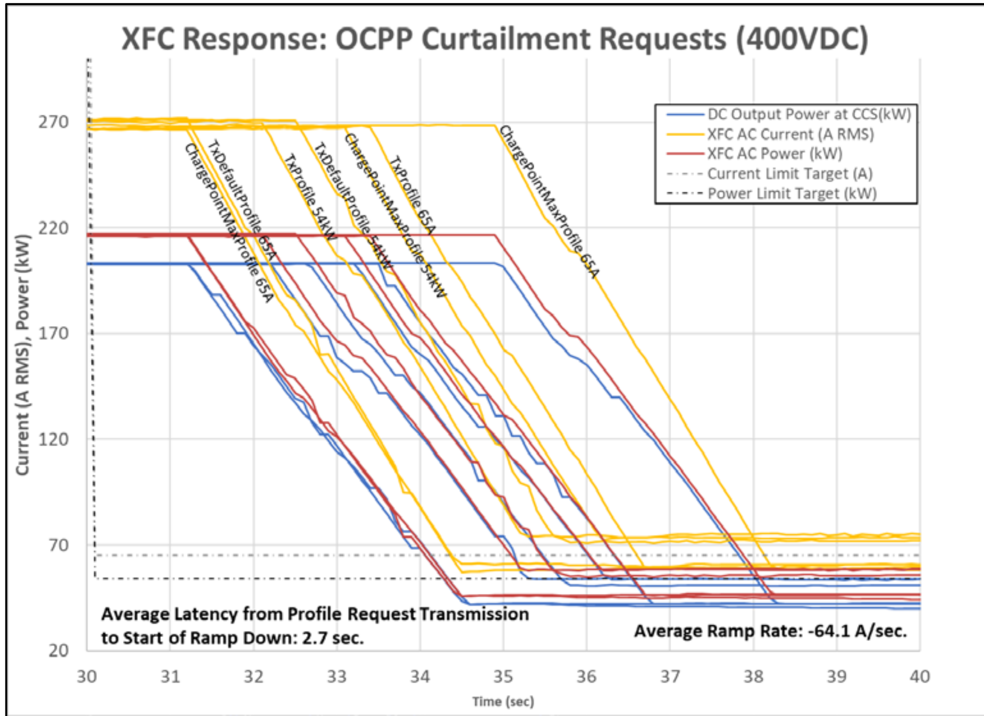
OCPP Curtailment Request: Ramp Rate and Latency



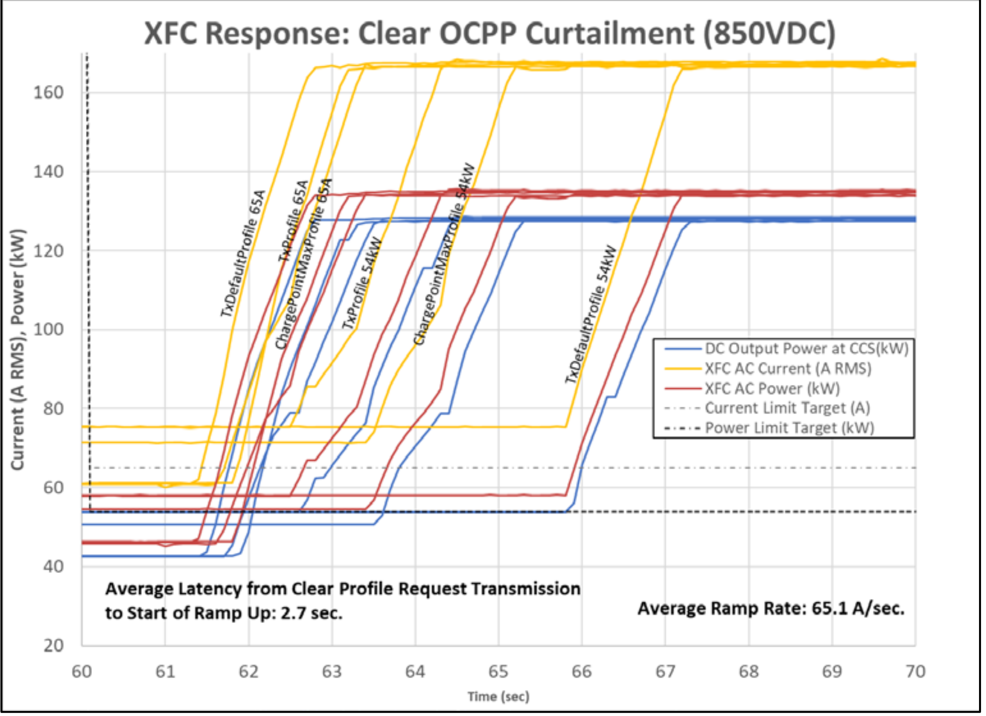


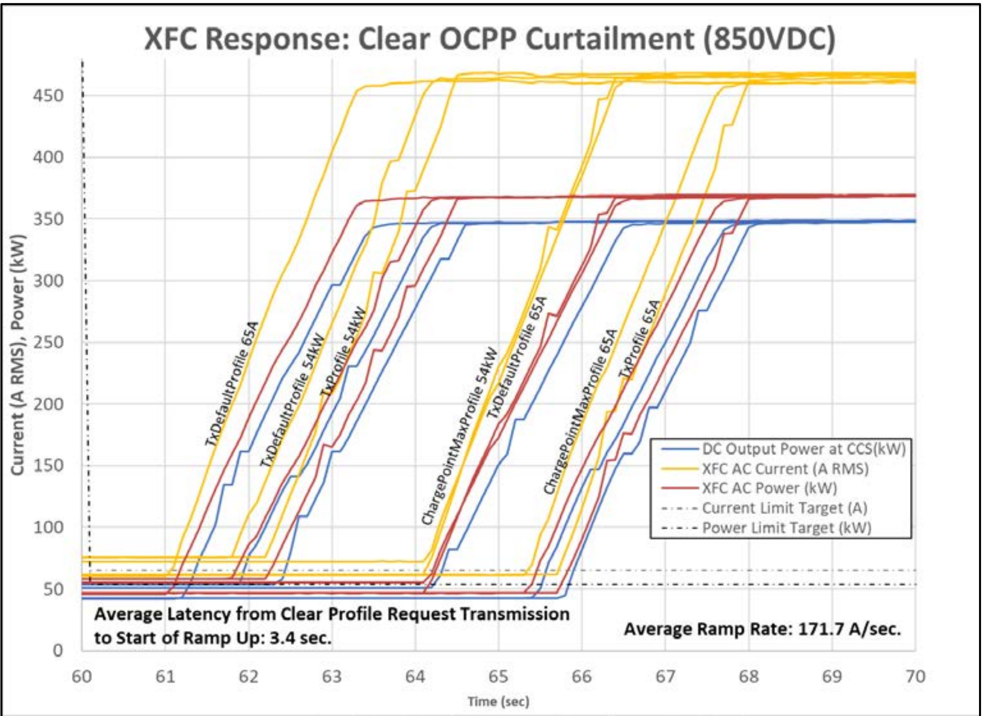
- Latency from command to start of current ramp down varies from 0.6 to 5.3 sec.
- Ramp rate depends upon total change in current or power
  - Range from: -200A/sec to -27A/sec



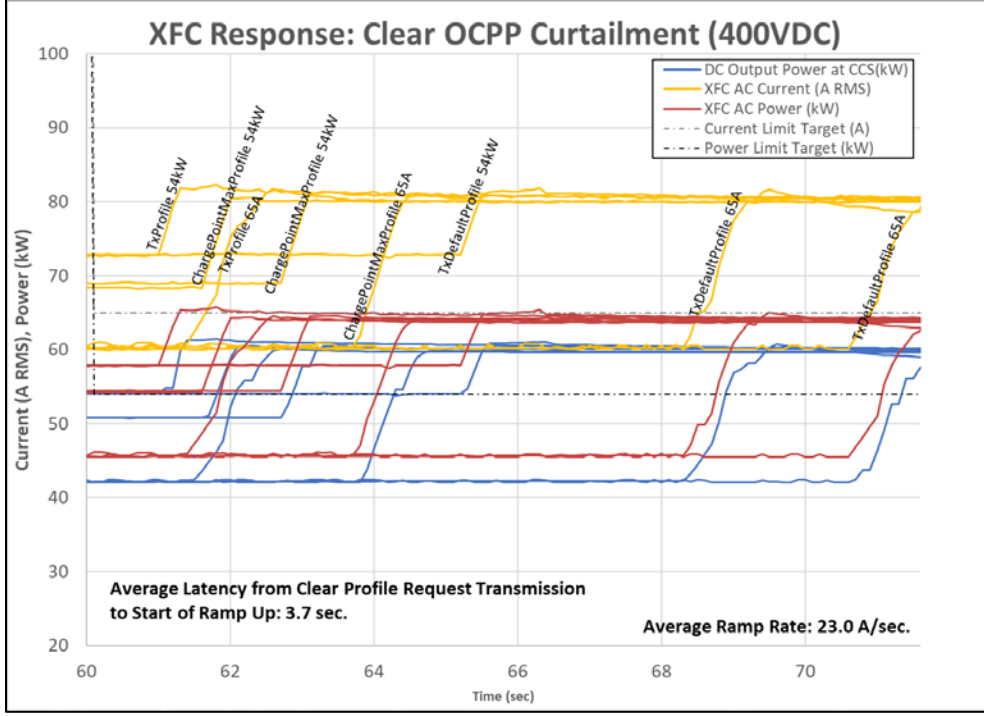


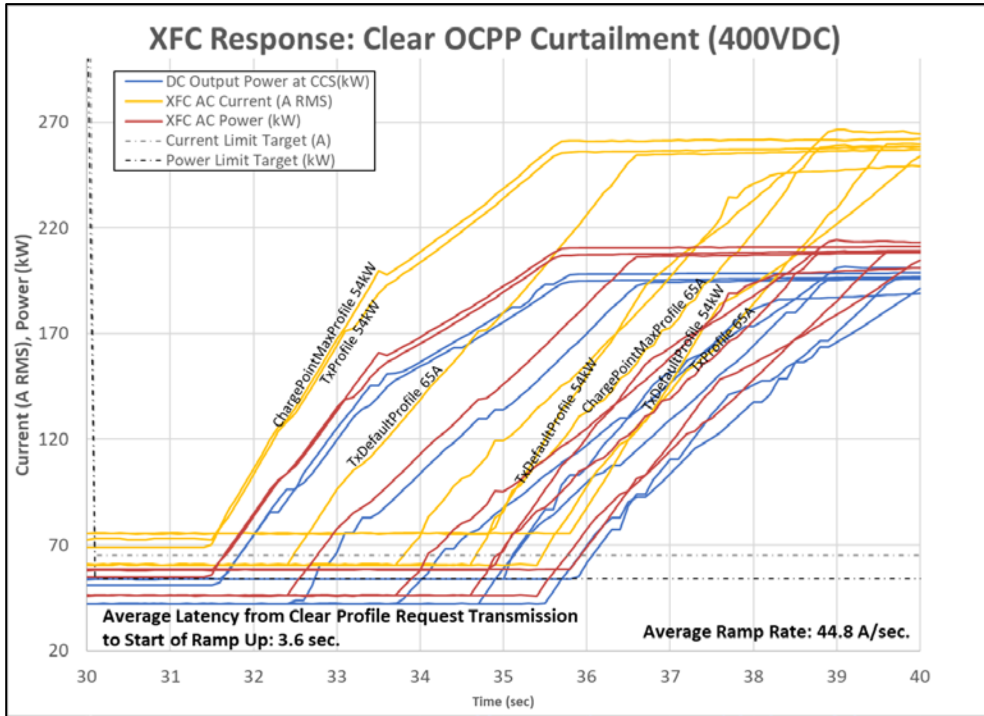
OCPP Clear Curtailment Request: Ramp Rate and Latency





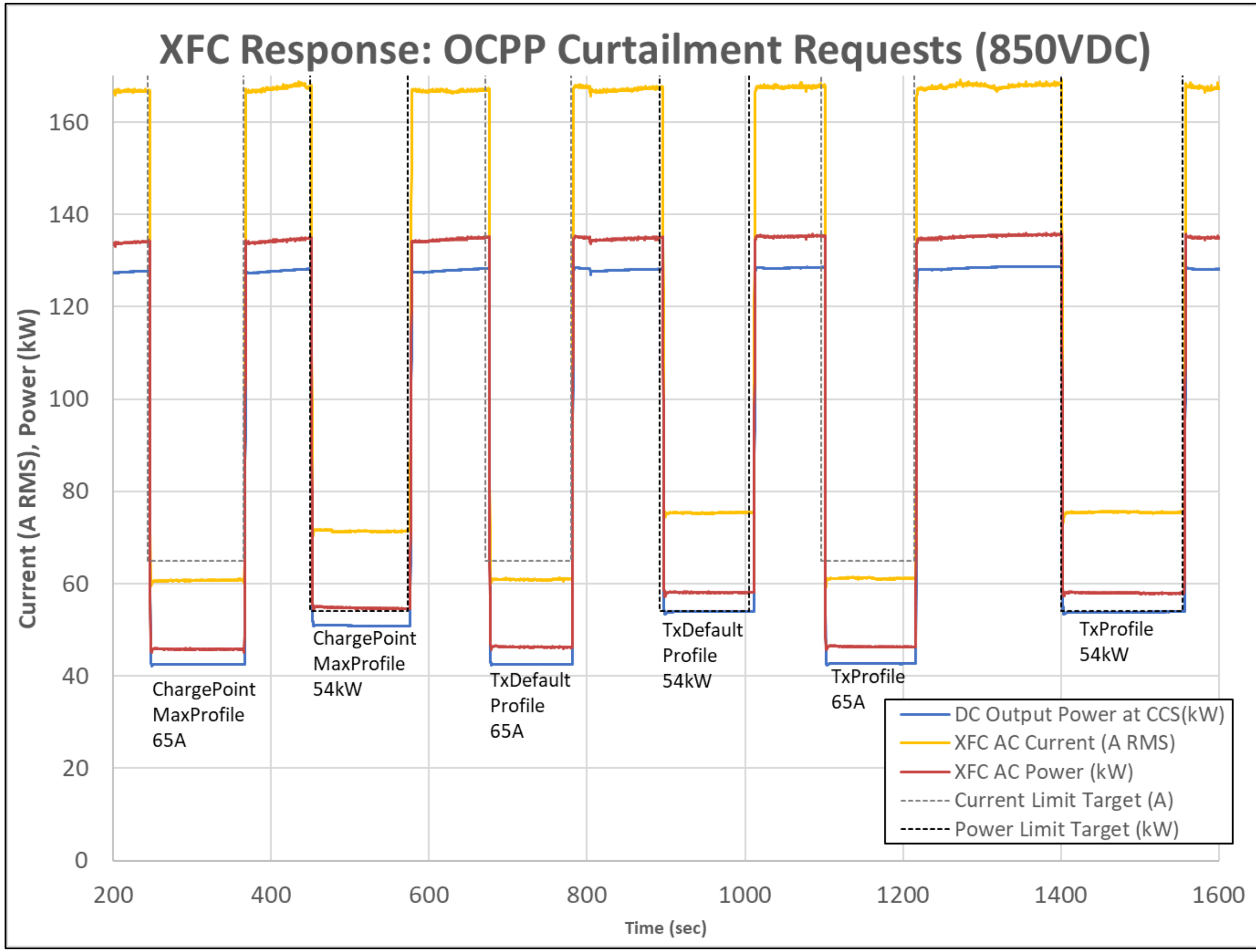
- Latency from command to start of current ramp down varies from 1.0 to 10.7 sec.
- Ramp rate depends upon total change in current or power
    - Range from 172A/sec to 23A/sec





OCPP Response: 150A at 850V

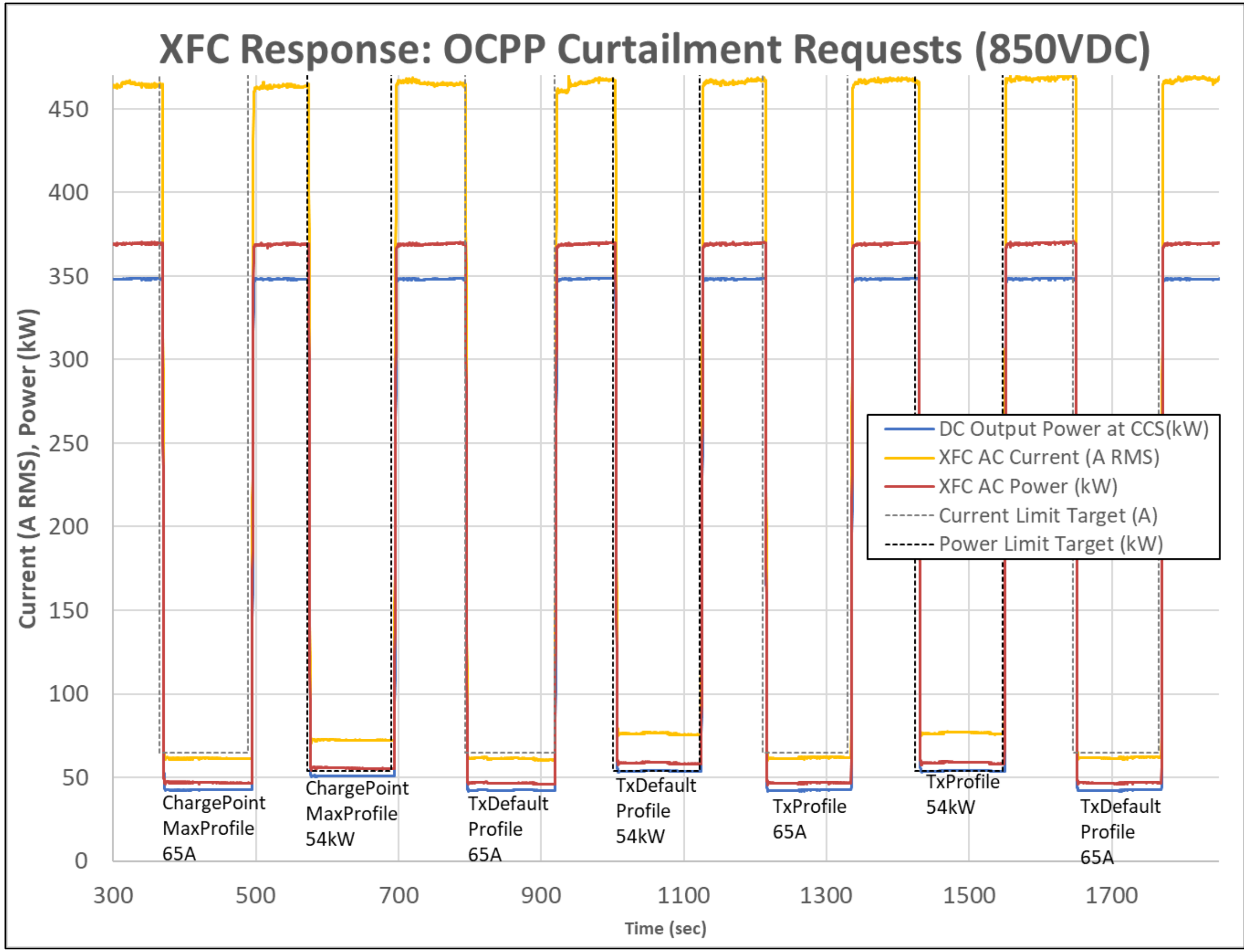
- Curtailment profiles based on current:
  - XFC operates well below the **AC current** limit request
    - *ChargePointMaxProfile*
    - *TxDefaultProfile*
    - *TxProfile*
- Curtailment profiles based on power:
  - XFC operates slightly <u>above</u> the **AC output power** limit request
    - *ChargePointMaxProfile*
  - XFC operates very close to the **DC output power** limit request
    - *TxDefaultProfile*
    - *TxProfile*



OCPP Response: 350kW at 850V

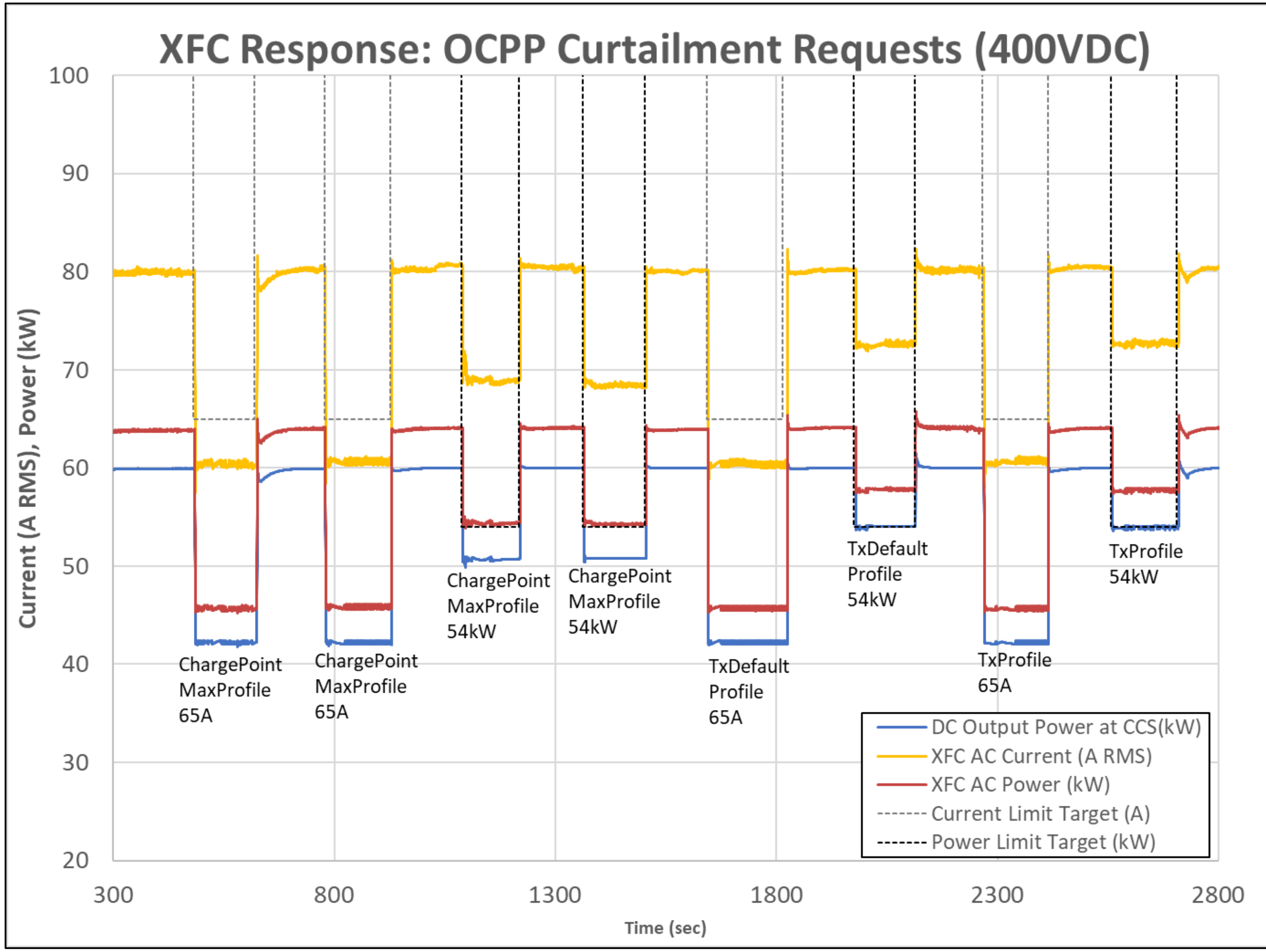
- Curtailment profiles based on current:
  - XFC operates slightly below the **AC current** limit request
    - *ChargePointMaxProfile*
    - *TxDefaultProfile*
    - *TxProfile*

- Curtailment profiles based on power:
  - XFC operates slightly <u>above</u> the **AC output power** limit request for
    - *ChargePointMaxProfile*
  - XFC operates very close to the **DC output power** limit request
    - *TxDefaultProfile*
    - *TxProfile*



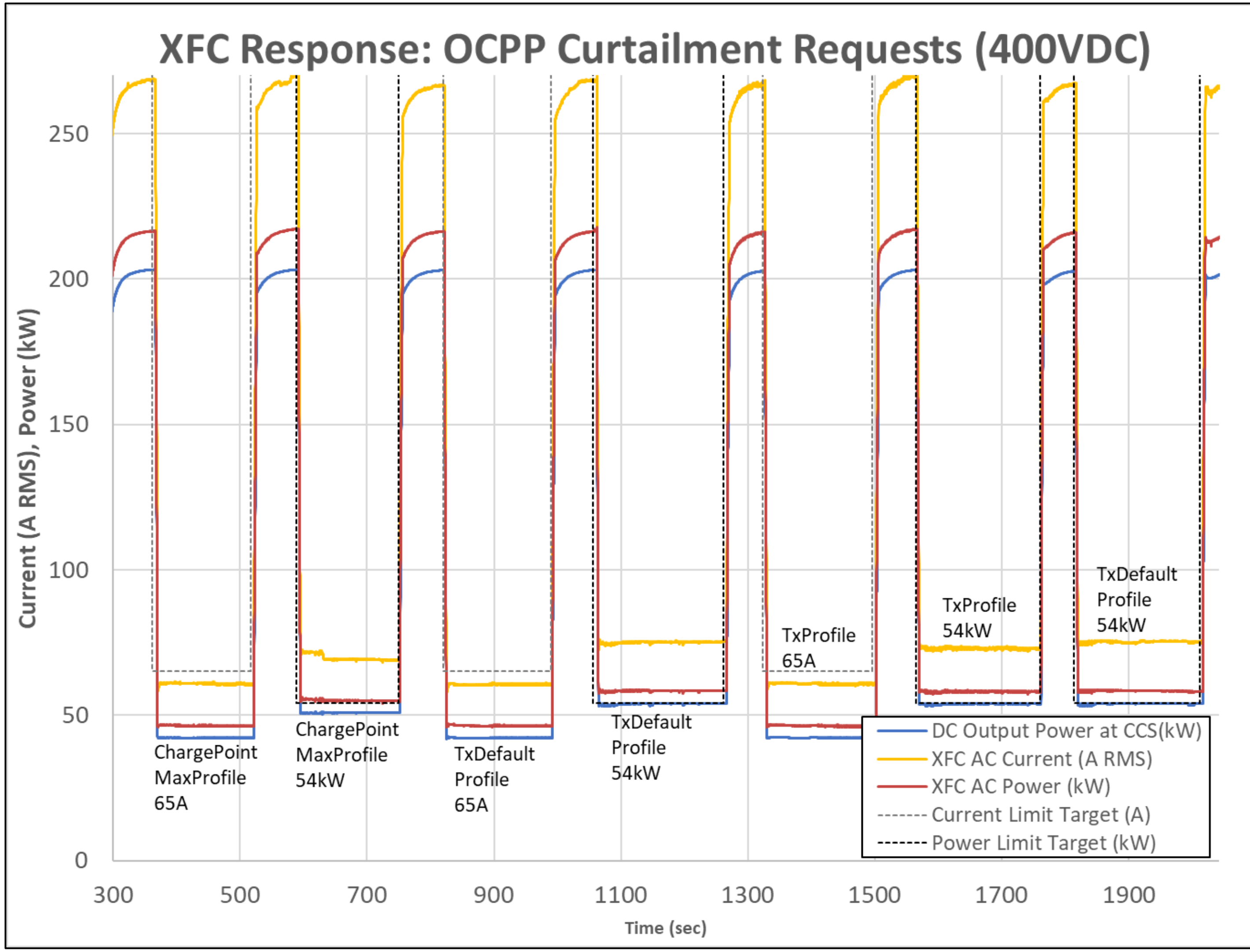
OCPP Response: 150A at 400V

- Curtailment profiles based on current:
  - XFC operates well below the **AC current** limit request
    - *ChargePointMaxProfile*
    - *TxDefaultProfile*
    - *TxProfile*
- Curtailment profiles based on power:
  - XFC operates slightly <u>above</u> the **AC output power** limit request
    - *ChargePointMaxProfile*
  - XFC operates very close to the **DC output power** limit request
    - *TxDefaultProfile*
    - *TxProfile*



OCPP Response: 500A at 400V

- Curtailment profiles based on current:
  - XFC operates below the **AC current** limit request
    - *ChargePointMaxProfile*
    - *TxDefaultProfile*
    - *TxProfile*
- Curtailment profiles based on power:
  - XFC operates slightly <u>above</u> the **AC output power** limit request
    - *ChargePointMaxProfile*
  - XFC operates very close to the **DC output power** limit request
    - *TxDefaultProfile*
    - *TxProfile*



EVs@Scale
U.S. Department of Energy

Overview of DC Charging Hub Approach and Development of Experimental Test Platform

Alastair Thurlbeck, NREL
John Kisacikoglu, NREL

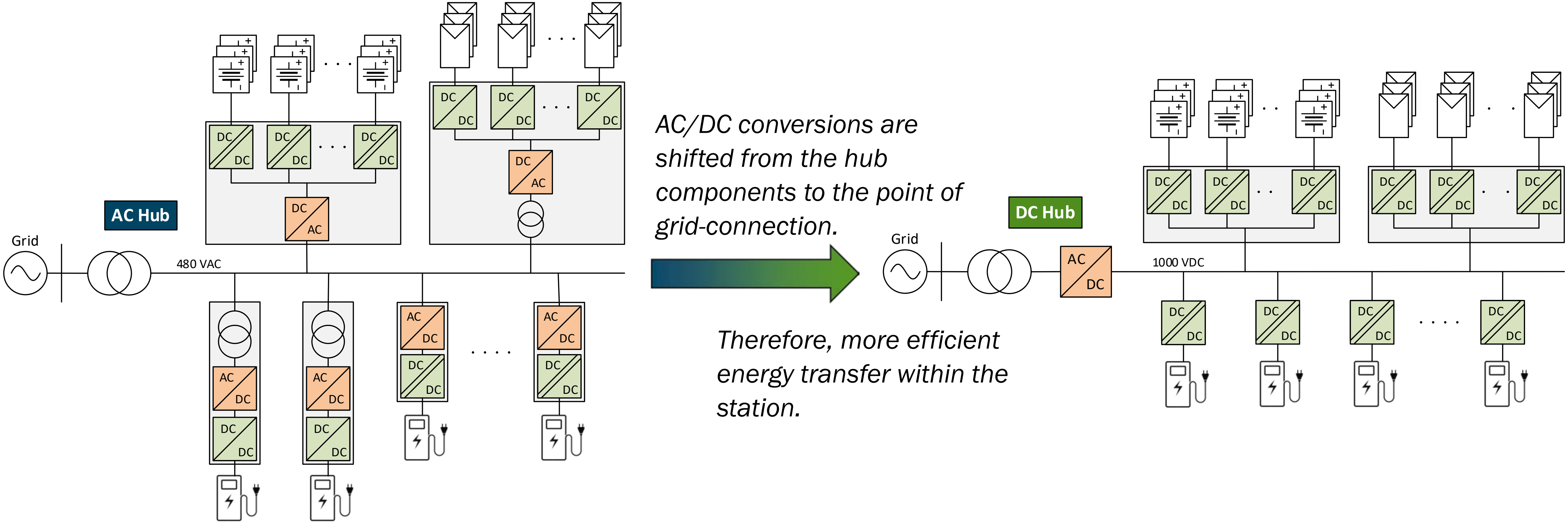
April 25, 2023

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

Overview of AC and DC Hub Approaches

AC Hub: High-power charging station with an AC-coupled architecture

DC Hub: High-power charging station with a DC-coupled architecture



AC/DC conversions are shifted from the hub components to the point of grid-connection.

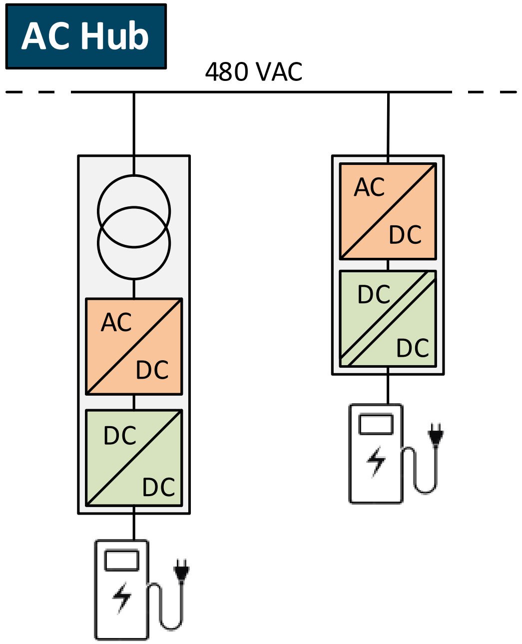
Therefore, more efficient energy transfer within the station.

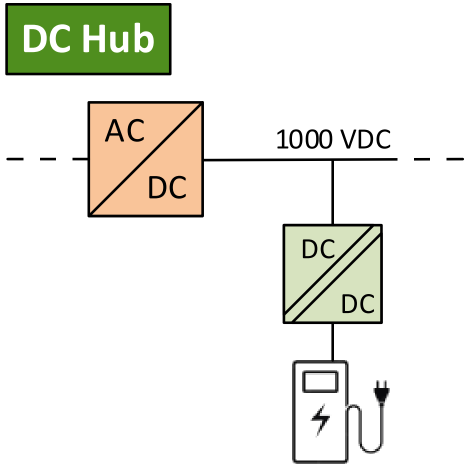
DC Fast Chargers / EVSEs

DC Hub EVSEs

- The DC hub approach moves the AC/DC conversion stage from within each EVSE to the grid connection point.
- Simplified controls at each EVSE.
- An individual EVSE has higher efficiency, but the overall efficiency from the grid to vehicle is comparable or sees slight improvement.
- If the charging power is supplied by an energy storage system or PV generation, there is a significant efficiency improvement due to two AC/DC conversions being eliminated.

	AC Hub EVSE		DC Hub EVSE
Architecture	Transformer Isolation	HFT Isolation	HFT Isolation
Transformers	1	0	0
# Conversion Stages	2	2	1: Isolated DC-DC
Conversion Topologies	Active rectifier (VSI) / Passive rectifier with boost PFC / Vienna rectifier		Phase shifted full-bridge / Full or half bridge LLC resonant / DAB
	Interleaved buck	Phase shifted full-bridge / Full or half bridge LLC resonant	
Required Controls	Charging power + PFC + grid-synchronization		Charging power
Efficiency	Medium	Medium	High





Integration of Energy Storage and PV Generation

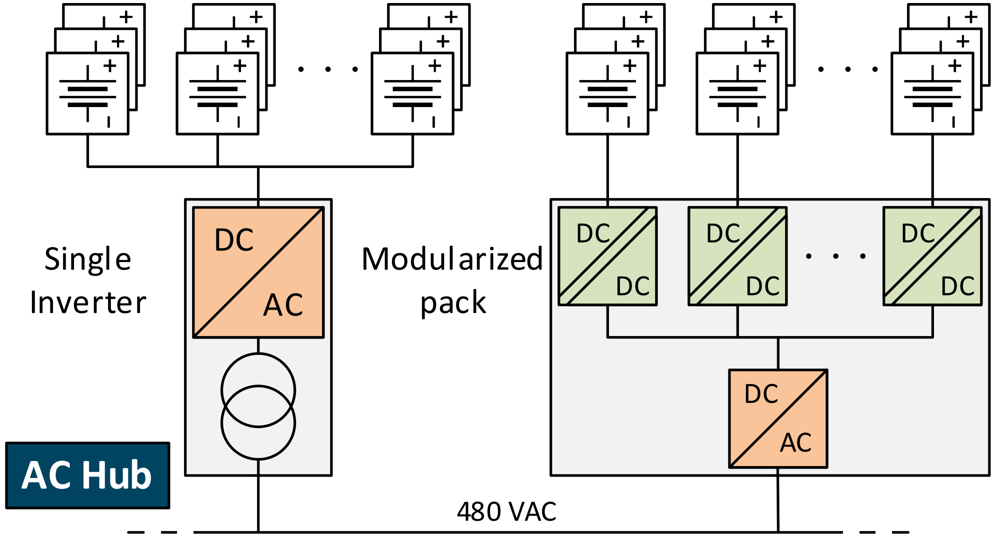
DC Hub Battery Energy Storage System (ESS)

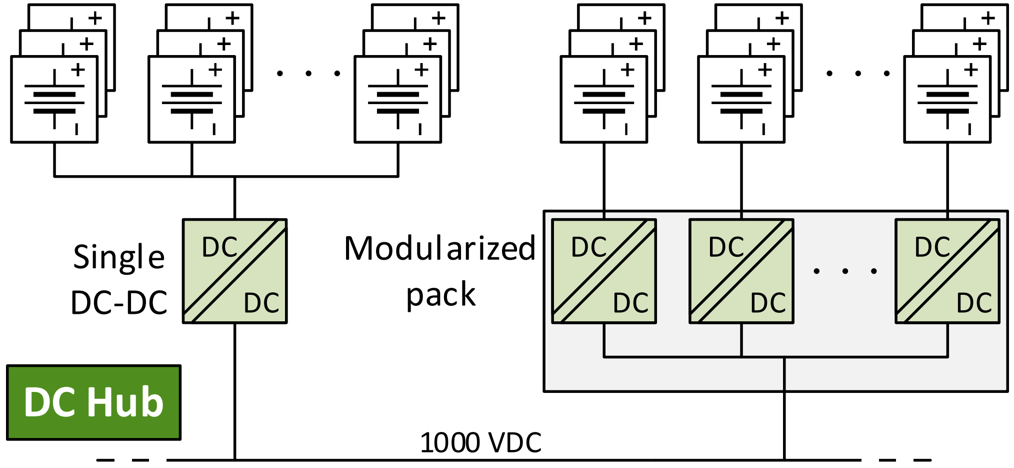
- Simplified controls and in many cases a conversion stage is removed.
- Comparable efficiency when ESS charges / discharges through the grid-connection.
- Significant efficiency improvement when supplying power to a charger or charging from PV generation.

	AC-coupled		DC-coupled	
Architecture	Single Inverter	Modularized Pack	Single DC-DC	Modularized Pack
Transformers	1	0	0	
# Conversion Stages	1	2	1	1
Conversion Topologies	-	Dual-active bridge / bidirectional flyback	Dual-active bridge / bidirectional flyback	
	VSI / NPC / ANPC			
Required Controls	Charge / Discharge + BMS + Grid-feeding controls		Charge / Discharge + BMS	
Efficiency	High	Medium	High	

DC Hub PV Generation

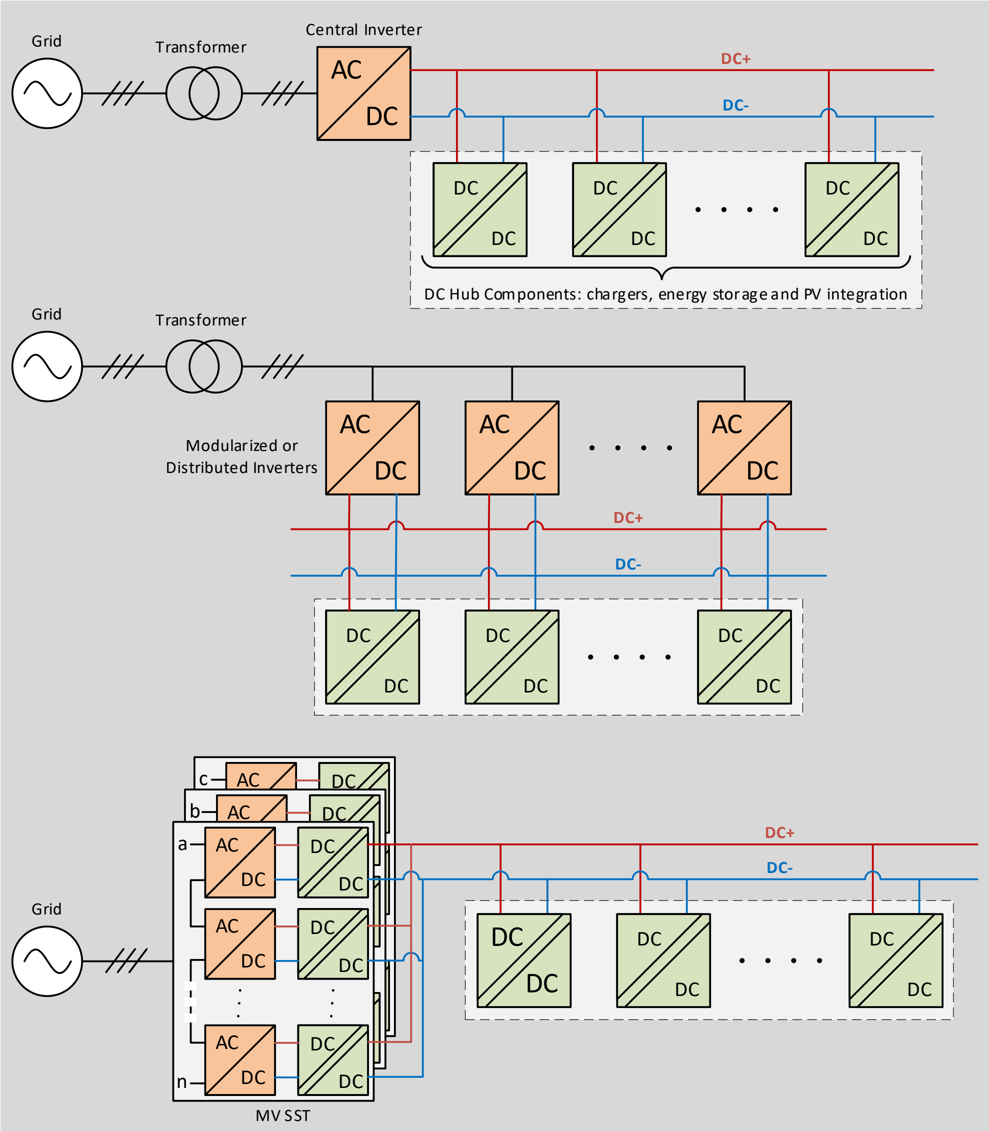
- Similar effects and connection architectures.
- However, PV does not require bidirectional conversion topologies.

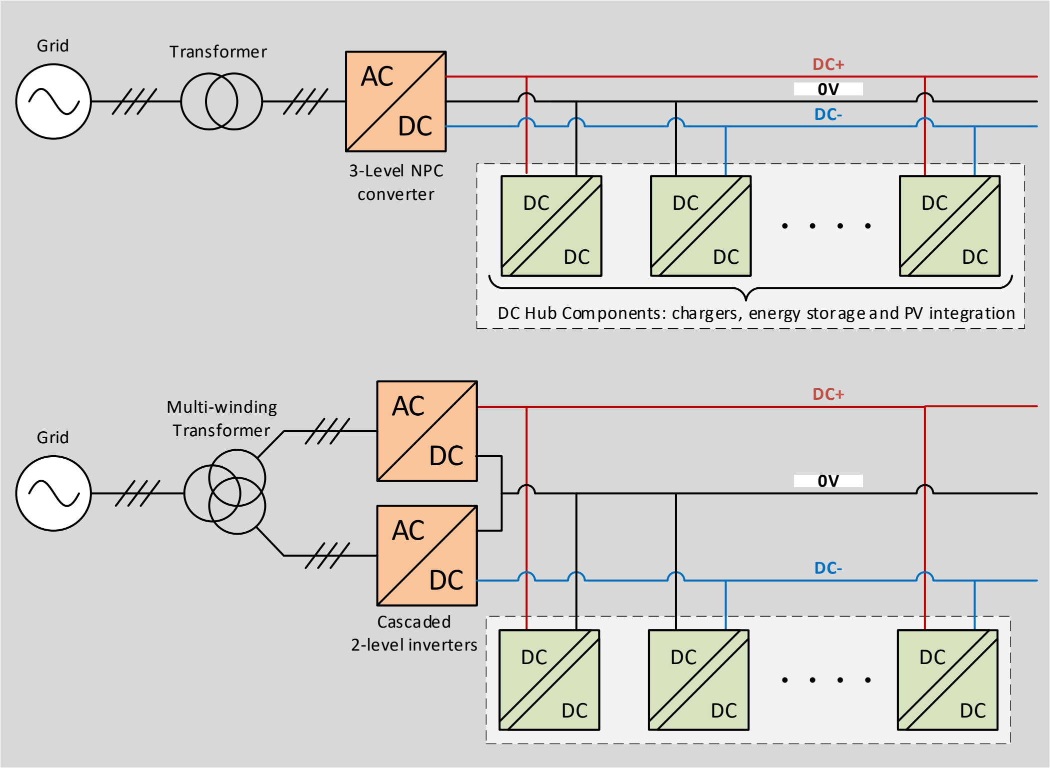




DC Hub Architectures

Unipolar
DC Bus

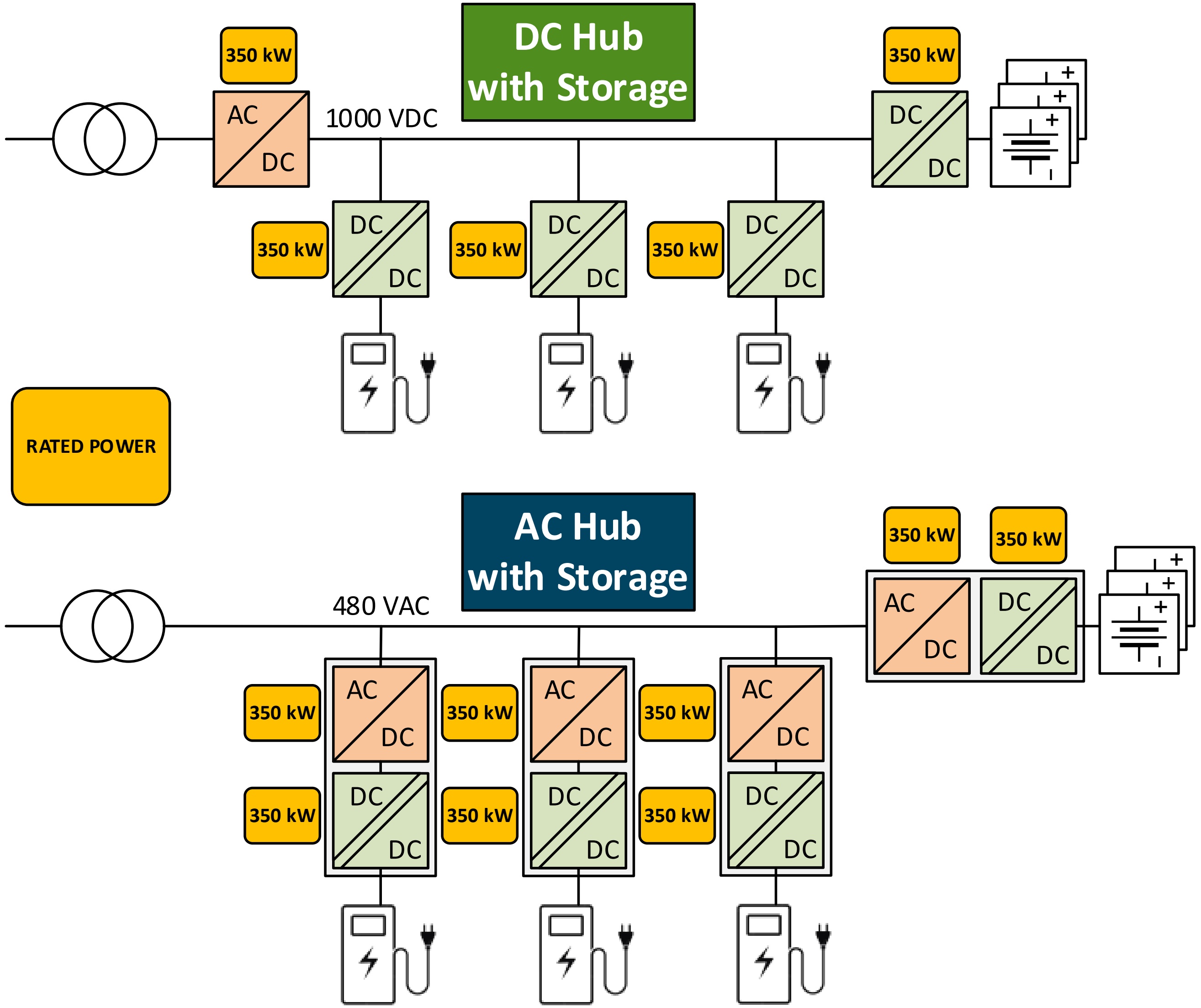




Bipolar DC Bus

AC/DC Converter Sizing Effects

- Central inverter capacity can be derated compared to the total installed EVSE capacity (provided an energy management system can limit EVSE powers when necessary).
  - Since vehicle charging is highly stochastic, minimal effect on service.
  - Centralized AC/DC conversion sees higher utilization rate than the AC/DC stages in the AC hub approach.
- When energy storage is added to the system, central inverter can be sized closer to the average charging power demand (depending on energy storage system sizing).

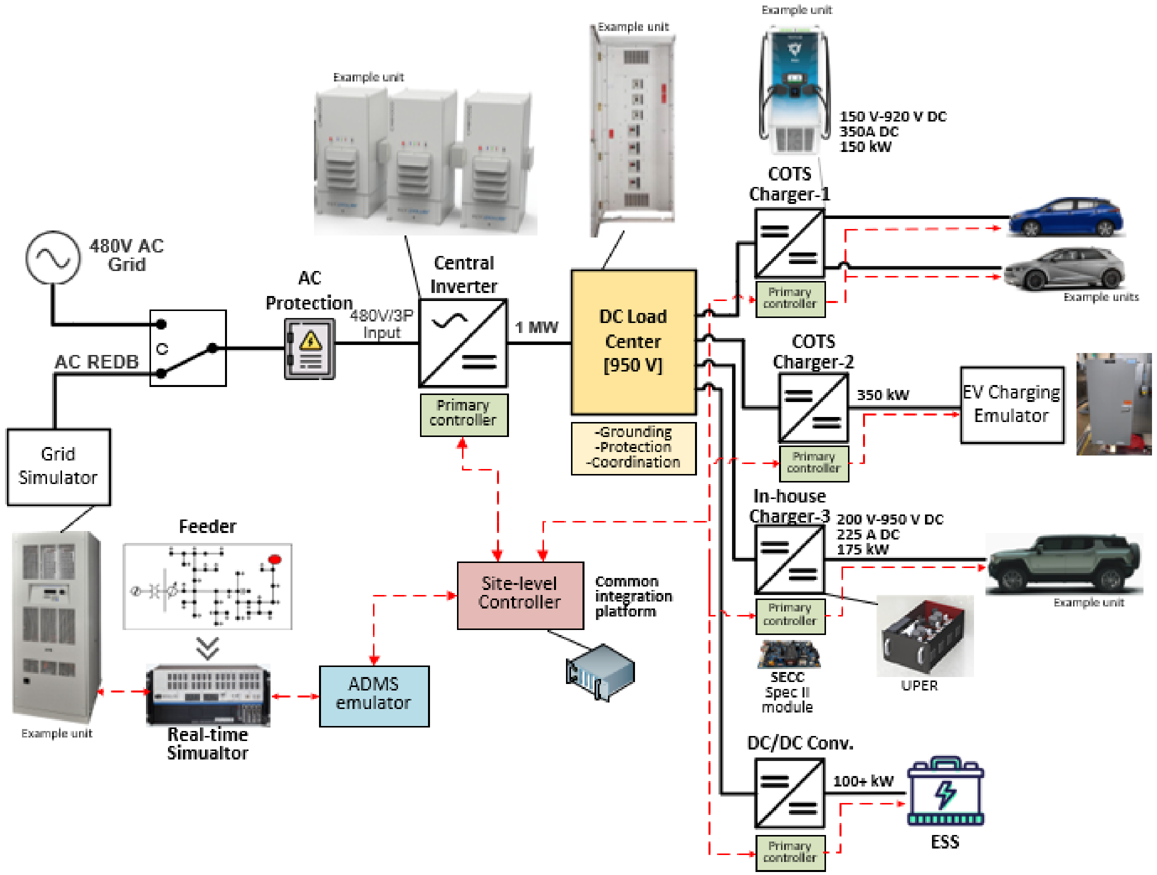


DC Hub System Level Effects

- **Increased efficiency**, especially considering power transfer within the hub
  - power transfer between distributed generation, energy storage, and charging vehicles.
- **Reduced cable sizing** due to DC distribution
  - Comparing 1000 VDC vs 480 VAC: DC bus cable copper volume is less than 20% of AC bus copper volume for the same losses / efficiency.
  - Even for the same voltage levels, DC bus delivers a one third reduction in copper volume compared to an AC bus.
- **No reactive power flow** in DC hub leads to more efficient power distribution.
- **Reduced grid integration impact.** Grid power demand can be smoothed out by energy storage. Reduced peak power demand and higher utilization rate of inverters.
- Central inverter can provide **advanced grid functions**
  - Reactive power compensation
  - Harmonic compensation
  - Virtual inertia
  - Grid-forming capability
- **Simplified controls.** The central inverter is the only hub component that needs to synchronize to or interact with the grid.
- DC bus voltage enables **distributed control strategies** using DC voltage signaling or droop methods.

Overview of DC-Hub HPC Station Architecture

- We are building a representative power and communication architecture for DC-hub chargers.
- Three research topics are investigated currently:
  - Power architecture development
    - Unipolar and bipolar DC-hub configurations
  - Site energy management (SEM)
    - Optimized and distributed controller implementation
  - Grid integration and implementation of grid services
    - V1G, V2B, V2V, and in general V2X use cases
    - Improve resiliency of charging hub



DOE Report: High-Power Electric Vehicle Charging Hub Integration Platform (eCHIP) DC Charging Hub Approach: Design Guidelines and Specifications, to be published in 2023

Inverter Selection and DC Load Center Design

EPC Power CAB1000 Utility-grade inverter is selected for project as for the centralized inverter.

Specifications:

- DC Link
  - Voltage: 720 - 1250 VDC
  - Current: 1400 ADC
  - Power: 1043 kW
- Communications / Control:
  - CAN
  - Modbus RTU (Modbus TCP/IP w/ adapter)

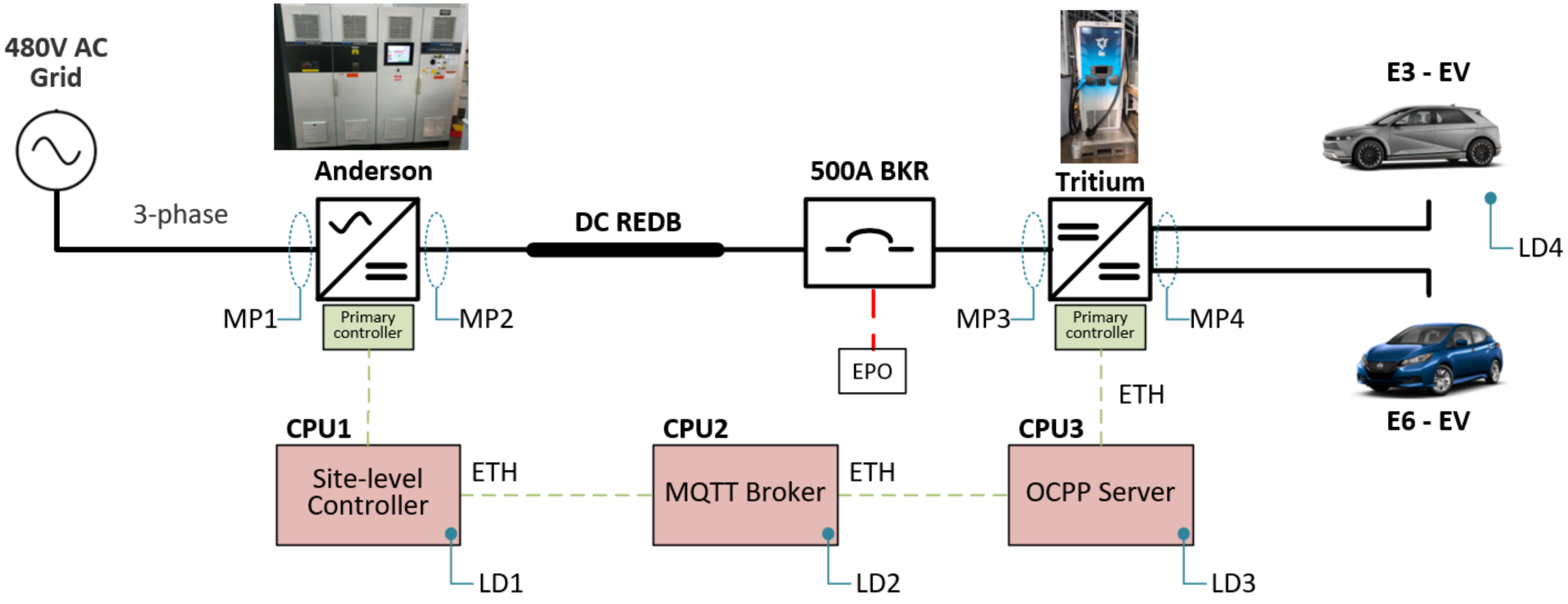
Operation and Control Modes:

- Grid forming mode (standalone and parallel)
- Grid following mode
  - Grid support via current source control
  - Command real (P) and reactive (Q) power
  - <u>DC link voltage - Command DC bus voltage setpoint</u>

DC Load Center Design Specs:

- Rated at 2000 VDC and 6000 ADC
- Bipolar configuration
- Total of six nodes to enable connection of chargers, DERs, and ESS.
- DC bus voltage sensing and current sensing per each node
- NEMA 3R rated for outdoor use

Current Setup Overview and Specifications



LD: Logged data
MP: Measurement point
ETH: Ethernet
EPO: Emergency power off
REDB: Research Electr. Dist. Bus

Component Type	Voltage Rating	Current/Power Rating
Inverter/Rectifier	265-1000 VDC	660 kW
DC Bus	1000 VDC	500 A
DC Breaker	1000 VDC	500 A
DC-DC Charger	Input: 950V DC	150 kW
	Output: 150-920 VDC	
EV Battery-1	800 VDC	235 kW
EV Battery-2	400 VDC	72 kW

Test Cases and Results-1

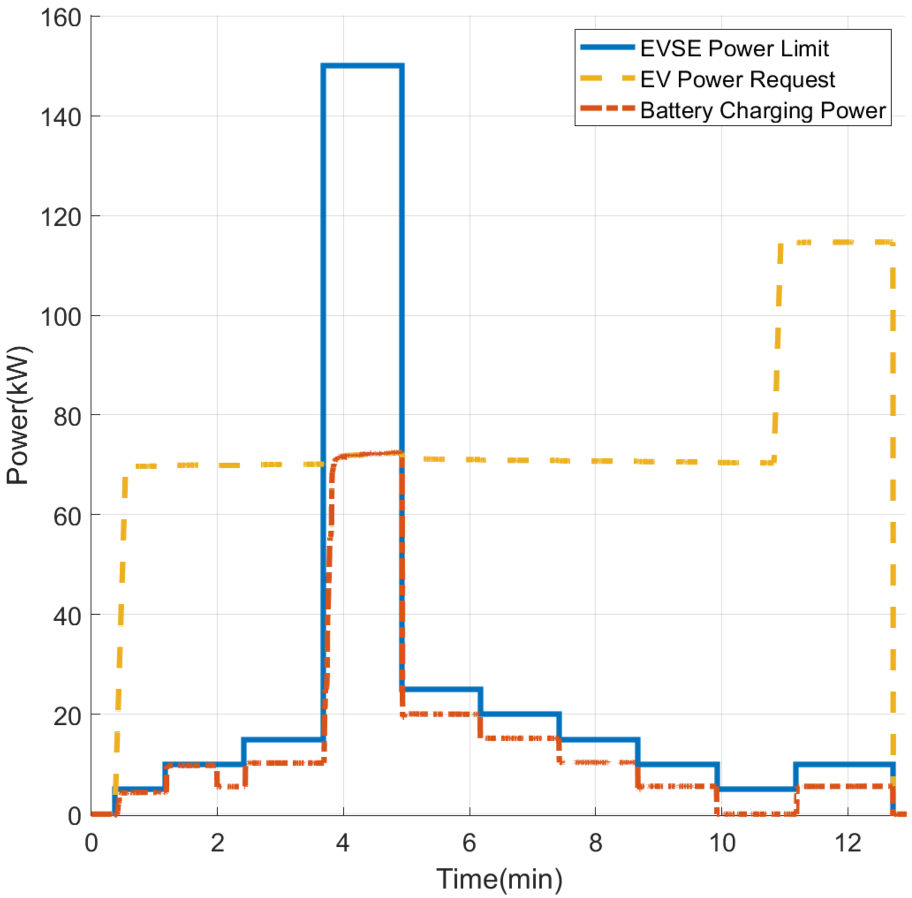
SEM provides power references for EVSE units with dynamically variable power reference.


Photo Credit: NREL

Highlights:

- Power reference (P_{ref}) is updated throughout session at instances of time T_{cmd} which is 1 min.
- Though EV requests more power (P_{EV_req}), power is limited to varying dynamic power limit.

Dynamic power control of Ioniq5 charge session showing power curves with setpoint command using OCPP1.6-J.



Test Cases and Results-1

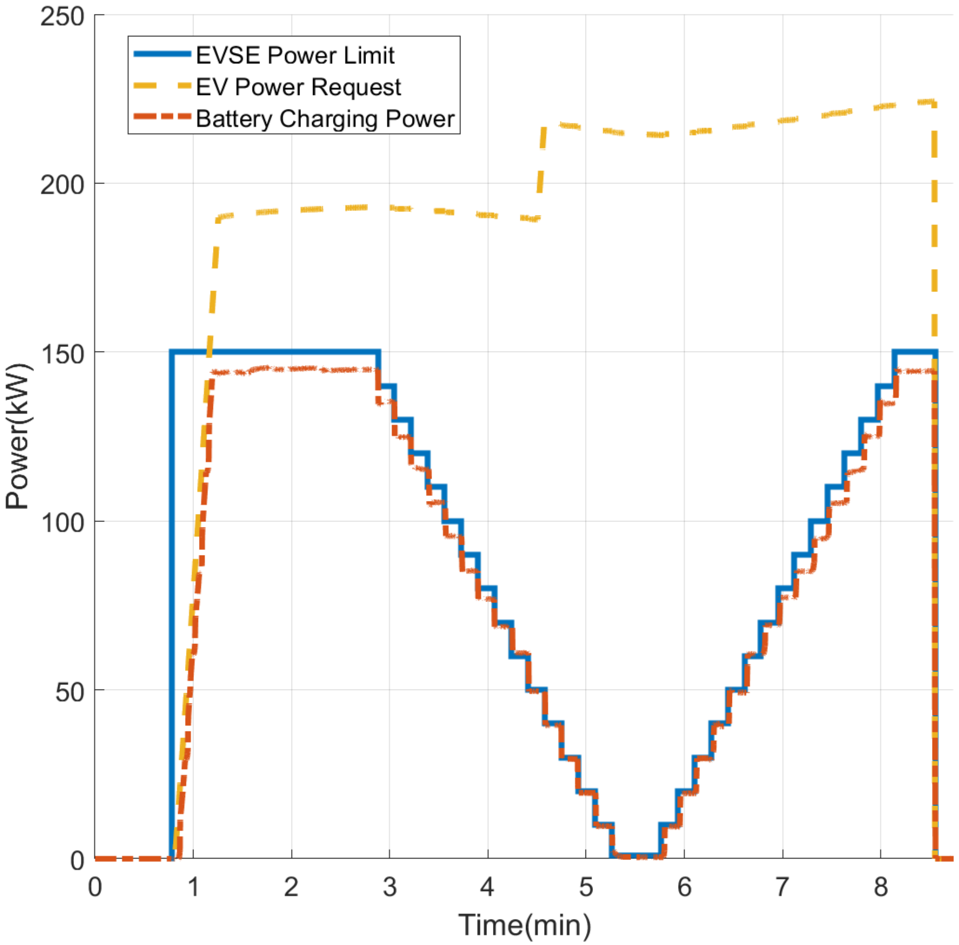
SEM provides power references for EVSE units with dynamically variable power reference.


Photo Credit: NREL

Highlights:

- Power reference (P_{ref}) is updated throughout session at instances of time T_{cmd} which is 10 sec.
- Ramp-up rate is limited more than ramp-down.

Dynamic power control of Ioniq5 charge session showing power curves with setpoint command using OCPP1.6-J.



Test Cases and Results-2

SEM provides power references for two EVSE units with dynamically variable power reference.

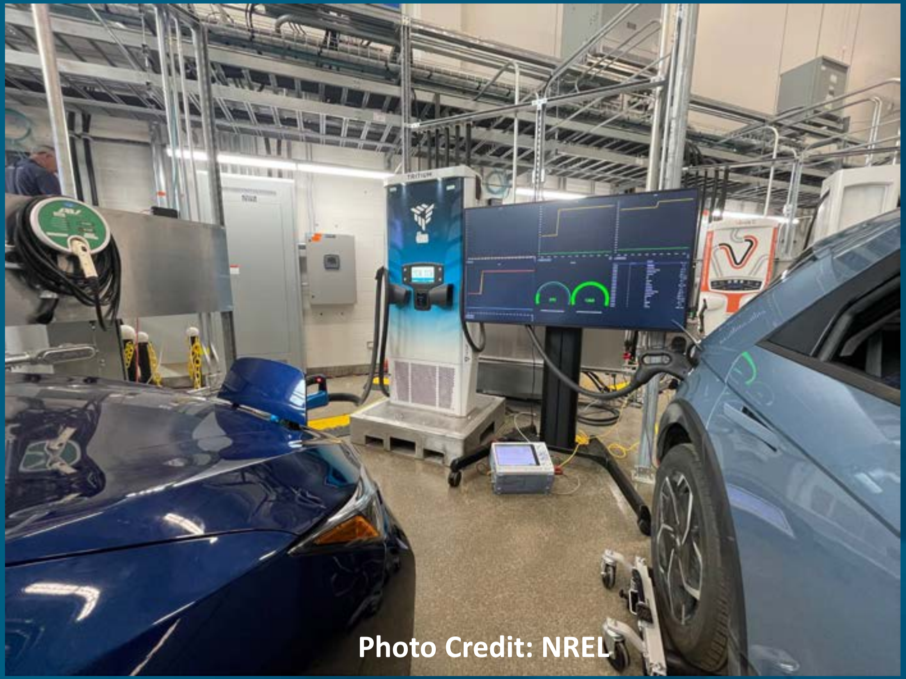
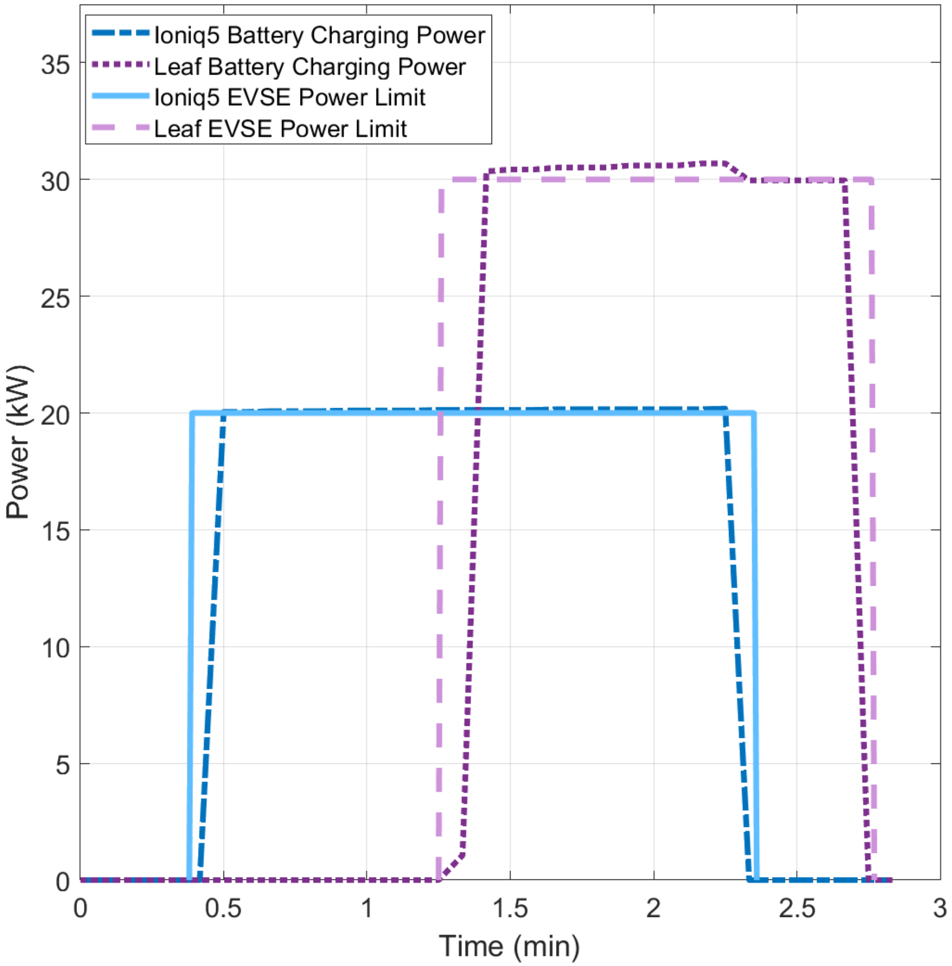


Photo Credit: NREL

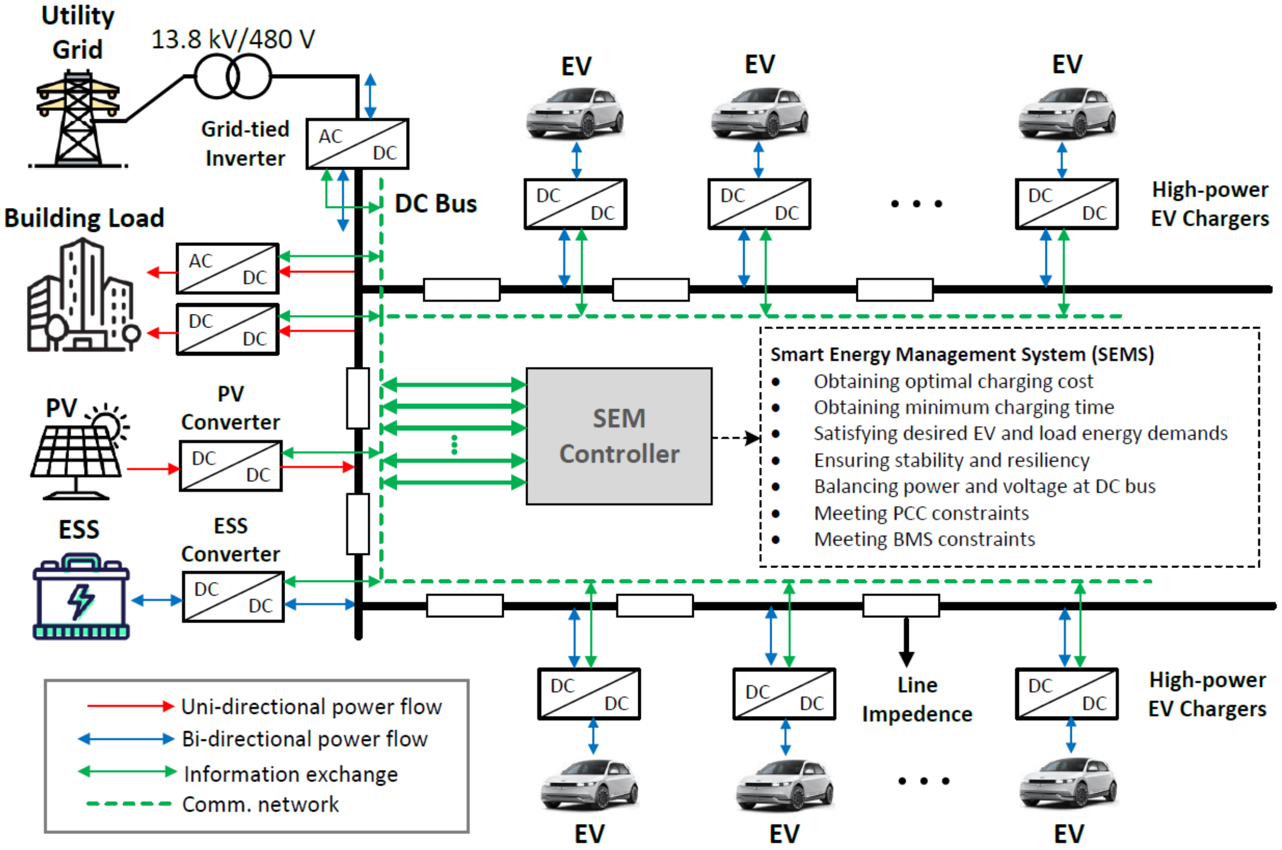
Highlights:
- Two EVs can be independently controlled without exceeding power limits.
- Ability to connect and control more than one EV to the DC hub.

Power limit control of Ioniq5 and Leaf charge sessions showing input power to each vehicle.



Site Energy Management System (SEMS) Implementation

- Development, testing, and comparison of different SEMS strategies
- Development of testing **use-cases**
- Specifying SEMS requirements



Smart Energy Management System (SEMS)

- Obtaining optimal charging cost
- Obtaining minimum charging time
- Satisfying desired EV and load energy demands
- Ensuring stability and resiliency
- Balancing power and voltage at DC bus
- Meeting PCC constraints
- Meeting BMS constraints

Conclusion and Next Steps

Review

- Technology Status on DC Charging Hub
- Advantages of DC charging hub
- DOE Report on Design Guidelines and Specifications
- DC Charging Hub Hardware Development
- SEMS development and integration
- Testing with Hyundai Ioniq-5 and Nissan Leaf

Next steps

- Testing with ESS and improving grid integration
- Evaluation and comparison of various SEMS control algorithms
- Testing Spec-II module integration with UPER
- Integration of 1000 V Class Charger with DC Hub
- Development of 2000 V Class Charger

Thank You!

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John.Kisacikoglu@nrel.gov

EVs@
Scale
U.S. Department of Energy

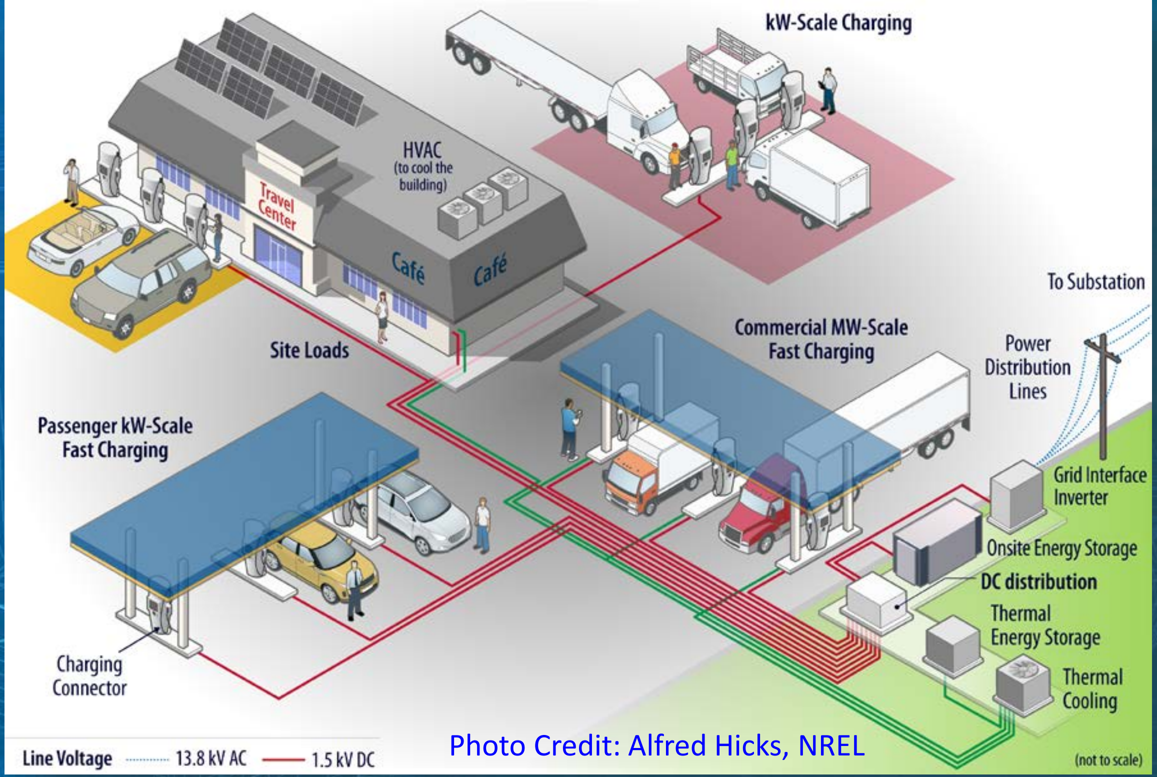
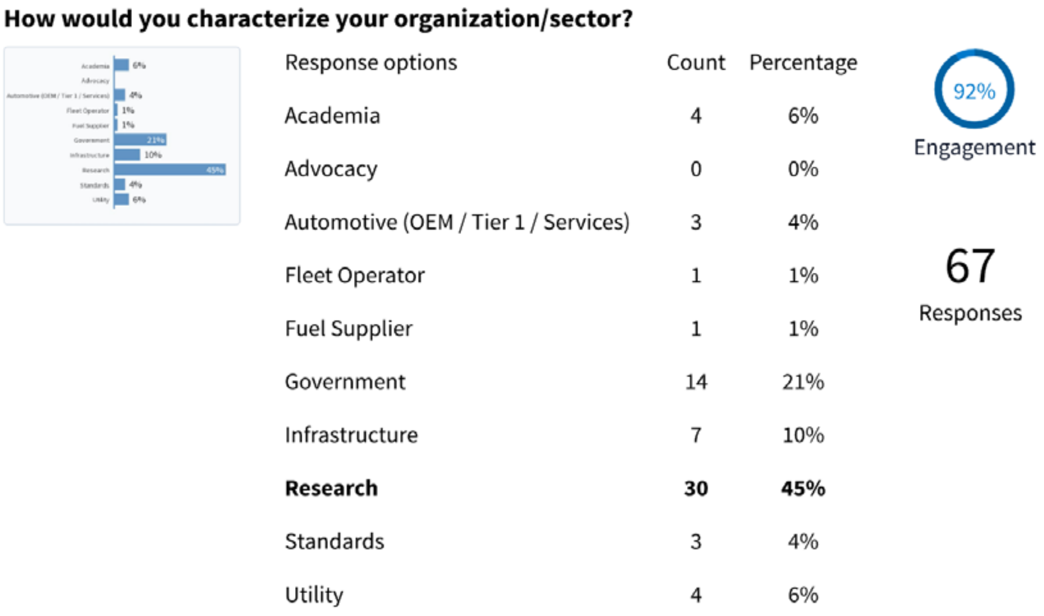


Photo Credit: Alfred Hicks, NREL

Attendance Questions: Consortium Stakeholder Meetings

Aug. 2022



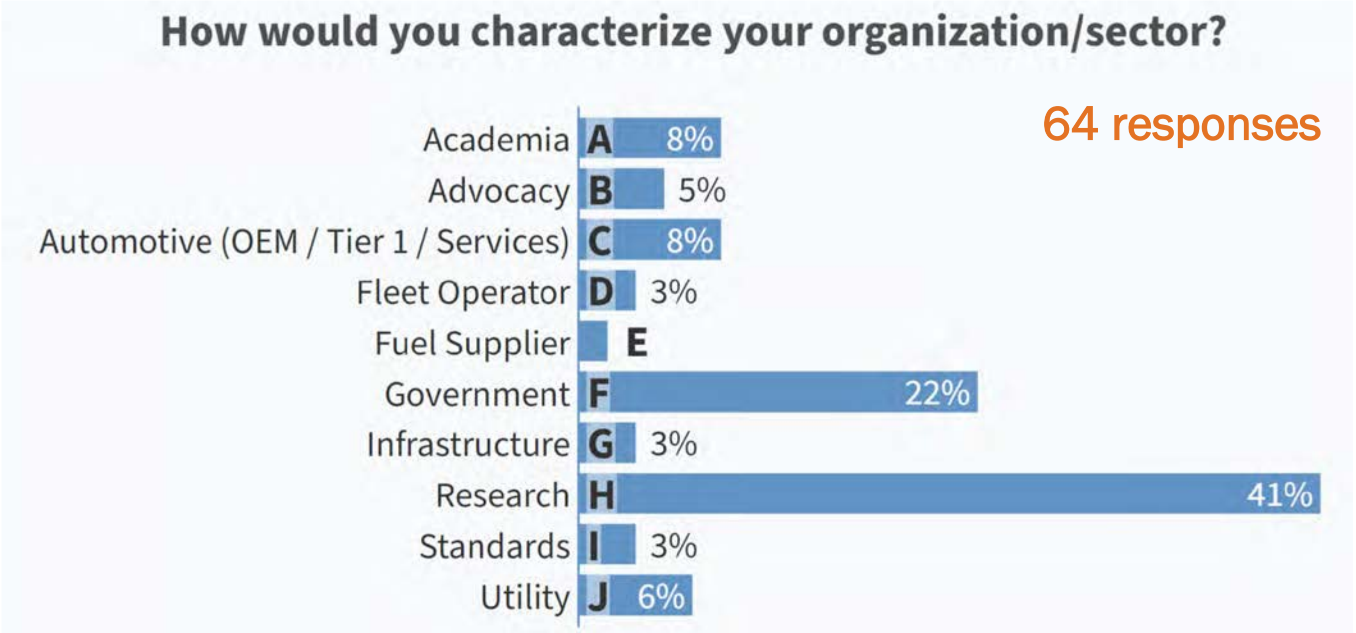
How would you characterize your organization/sector?

Response options	Count	Percentage
Academia	4	6%
Advocacy	0	0%
Automotive (OEM / Tier 1 / Services)	3	4%
Fleet Operator	1	1%
Fuel Supplier	1	1%
Government	14	21%
Infrastructure	7	10%
Research	**30**	**45%**
Standards	3	4%
Utility	4	6%

92%
Engagement

67
Responses

Apr. 2023



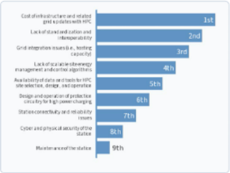
How would you characterize your organization/sector?

64 responses

eCHIP Questions-Barriers

Aug. 2022

Please rank the below listed research challenges with high power charging (HPC) in the order of urgency and priority:

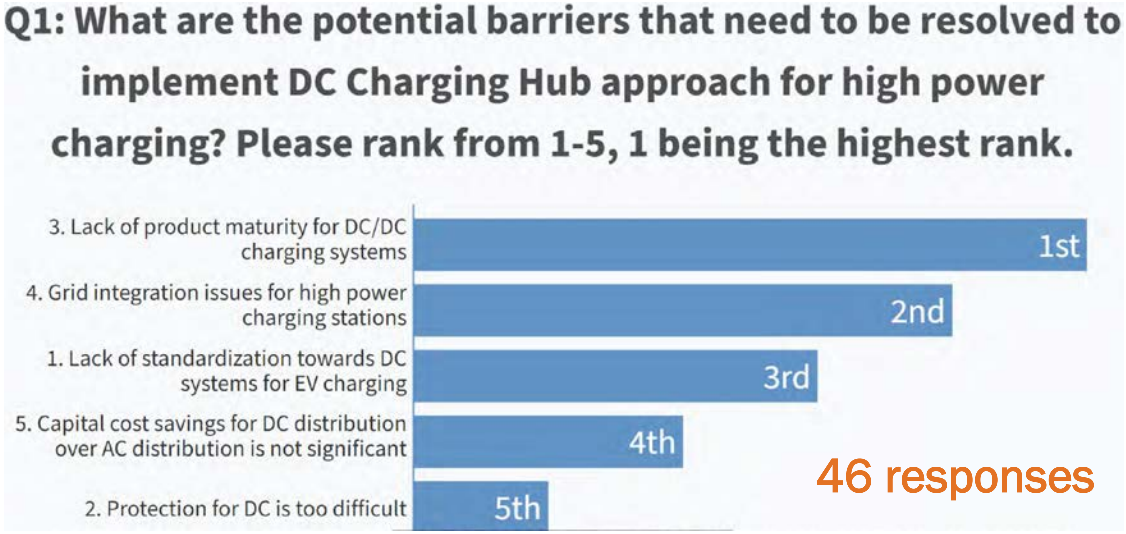


Response options	Rank
Cost of infrastructure and related grid updates with HPC	1st
Lack of standardization and interoperability	2nd
Grid integration issues (i.e., hosting capacity)	3rd
Lack of scalable site energy management and control algorithms	4th
Availability of data and tools for HPC site selection, design, and operation	5th
Design and operation of protection circuitry for high power charging	6th
Station connectivity and reliability issues	7th
Cyber and physical security of the station	8th
Maintenance of the station	9th

67%
Engagement

35
Responses

Apr. 2023

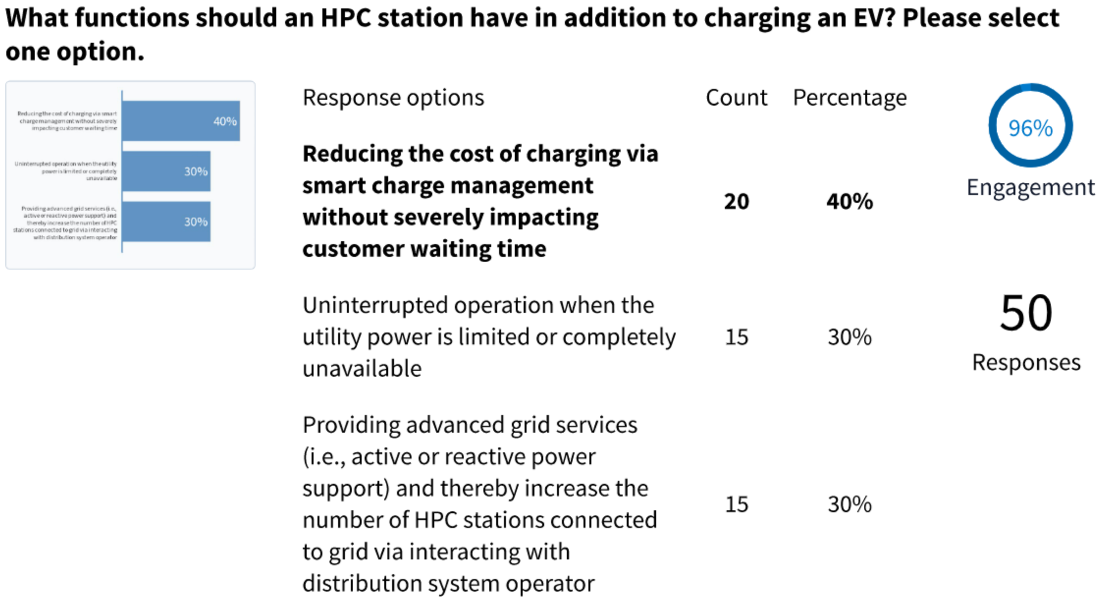


Q1: What are the potential barriers that need to be resolved to implement DC Charging Hub approach for high power charging? Please rank from 1-5, 1 being the highest rank.

46 responses

eCHIPQuestions-Use Cases/Functions

Aug. 2022



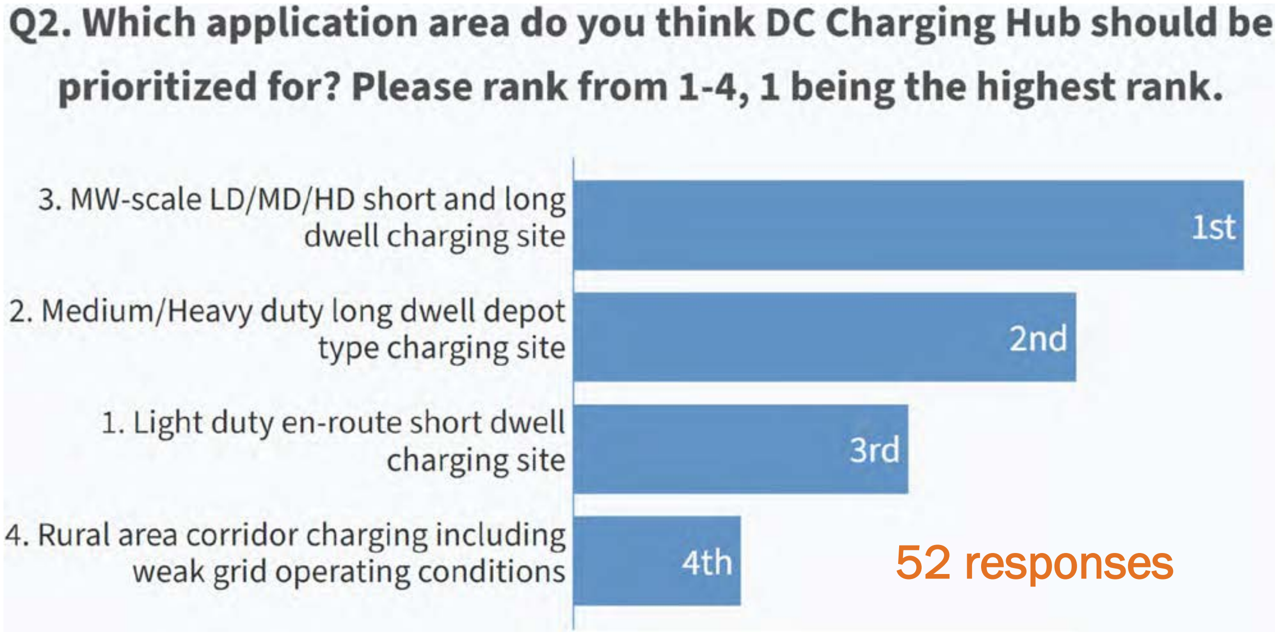
What functions should an HPC station have in addition to charging an EV? Please select one option.

Response options	Count	Percentage
Reducing the cost of charging via smart charge management without severely impacting customer waiting time	**20**	**40%**
Uninterrupted operation when the utility power is limited or completely unavailable	15	30%
Providing advanced grid services (i.e., active or reactive power support) and thereby increase the number of HPC stations connected to grid via interacting with distribution system operator	15	30%

96%
Engagement

50
Responses

Apr. 2023



Q2. Which application area do you think DC Charging Hub should be prioritized for? Please rank from 1-4, 1 being the highest rank.

52 responses

EVs @ Scale
U.S. Department of Energy

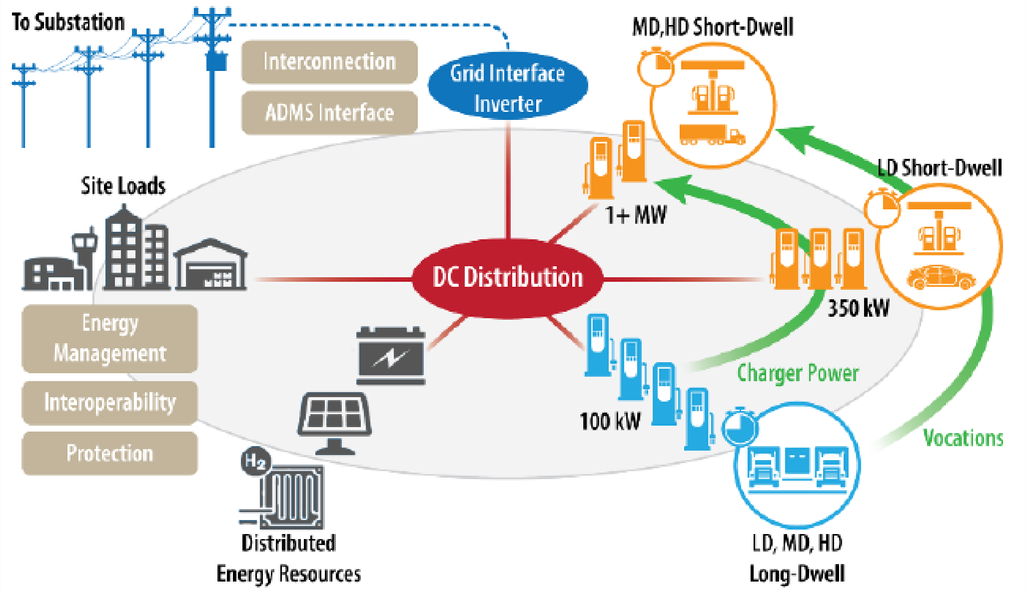
Design of Universal Power Electronics Regulator as a Charger Module in eCHIP

Prasad Kandula, Brian Rowden, Madhu Chinthavali, Rafal Wojda, Jonathan Harter, Steven Campbell, Christian Boone

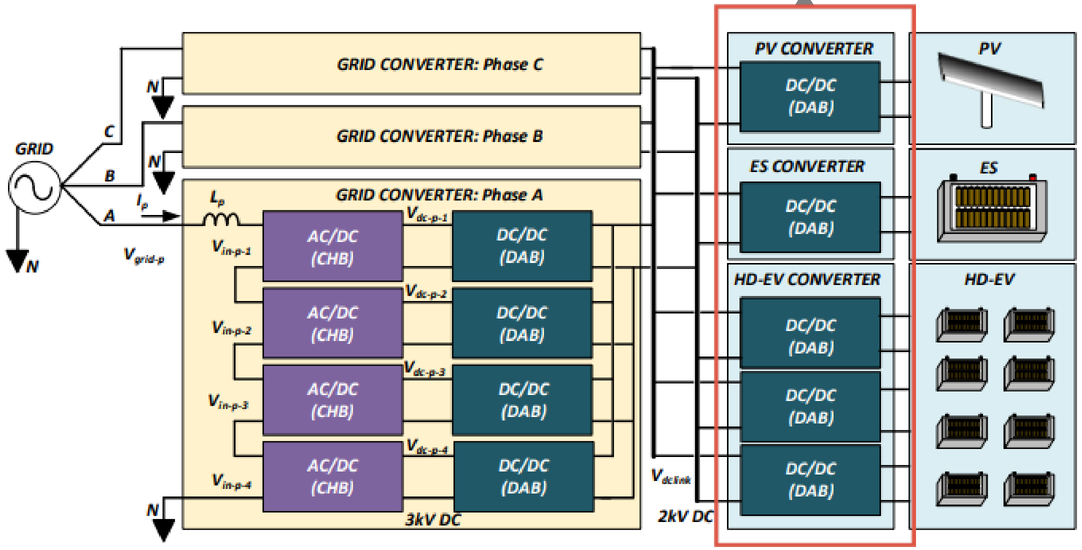
May 2nd, 2023

Overall Objective

- **Develop universal converter module for DC distribution to interface**
    - LD/MD/HD charging
    - Renewables
    - Grid interface converter
    - Local loads

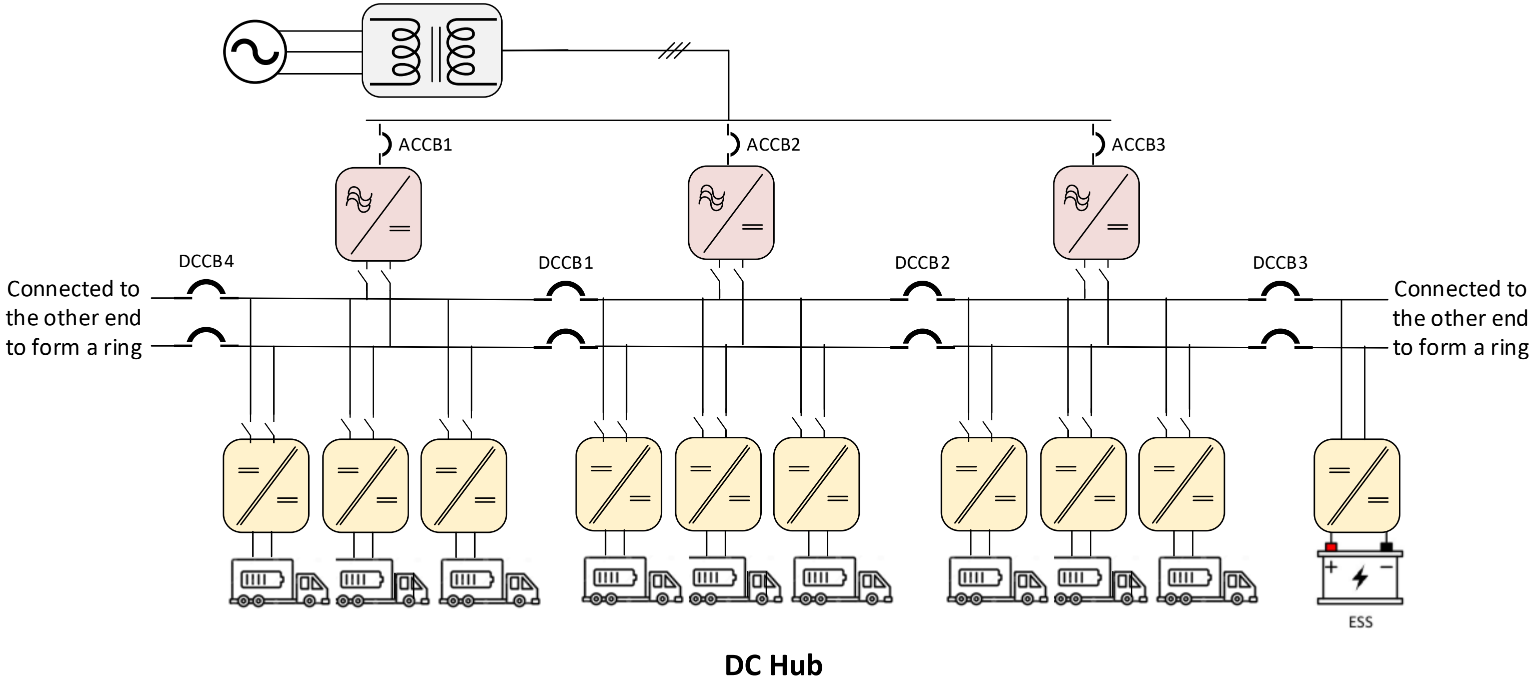


Universal Power Electronics Regulator (UPER)



M. Starke *et al*., "A MW scale charging architecture for supporting extreme fast charging of heavy-duty electric vehicles," *2022 IEEE Transportation Electrification Conference & Expo (ITEC)*, Anaheim, CA, USA, 2022, pp. 485-490.

Motivation



*Data derived from actual installations

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

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 is a significant element to realize such a system

SOA

EVSE DC/DC Building Block

- Commercial DC/DC converters are in the range of 50-125 kW
- High-power building block (350 kW) to meet heavy duty (1 MW+) charging requirements is required

Peak Charging Voltage

- Current SOA is <1000 V for the DC bus and charging
- Off-road vehicles like the battery-locomotives, eVTOLs (electric Vertical take-off vehicles) 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 for MCS

Vendor 1: 175 kW building block with 60 Hz isolation

Vendor 2: 150 kW building block w/ HF isolation

Vendor3: 125 kW building block

Vendor 4: 25 kW building block

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

Proposed Charger Development

A 2000 V class 350 kW charger and a 1000 V class 175/350 kW charger are being built

1700 V, 280 A/560 A, SiC

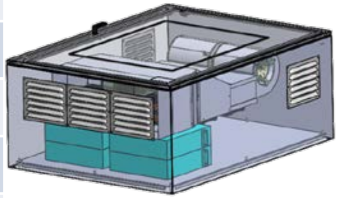
1000 V class 175 kW/350 kW charger	
Vin	800-1200 V (TBD)
Vout	200-950 V
Imax	225 A/ 450 A
Eff	>98.5%
Temp	-30°C to 50°C
Comms	CAN
Powerflow	Bidirectional

34” x 20” x 12”

3300 V, 500 A SiC

2000 V class 350 kW charger	
Vin	1500-2000 V (TBD)
Vout	500-1500 V
Imax	250 A
Eff	>99%
Temp	-30°C to 50°C
Comms	CAN
Powerflow	Bidirectional

40” x 30” x 15”



Specifications of charger under development

Multi-Dimensional Improvement v/s SOA

High power Building block
Enable MW+ Charging
350 KW instead of 125-150 kW

Power density
Frequency > 20 kHz, η > 99%
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

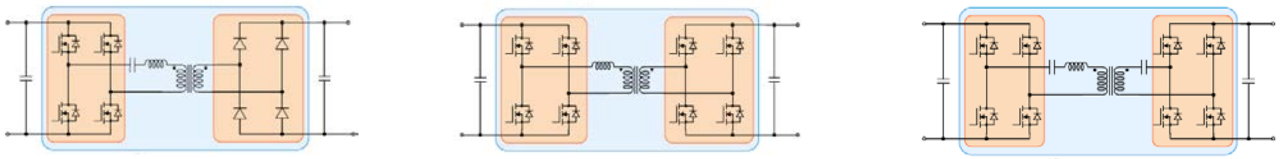
Bidirectional Power (V2X)
Controls to enable bidirectional power transfer while maintaining low loss

Each of these goals are a challenge in itself

EVSE DC/DC Configuration: LLC v/s DAB v/s CLLC

- **Special requirements for EV charging:**
  - Bidirectionality
  - Isolation
  - Wide voltage range
  - Small output current ripple

Selected DAB



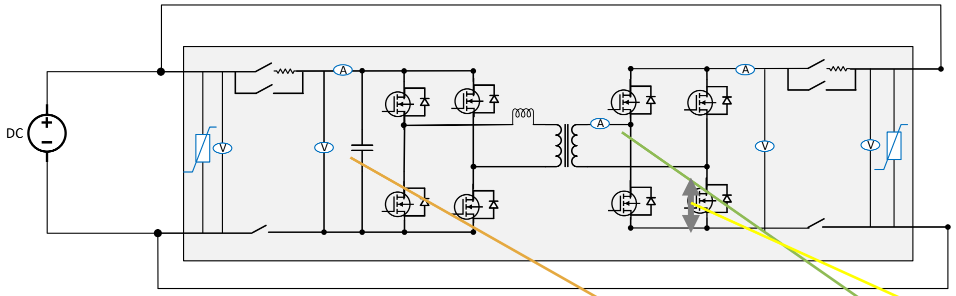
	LLC	Dual Active Bridge (DAB)	CLLC
Efficiency: ZVS range	🟨 Not good for wide voltage range	🟨 Not good for wide voltage range	🟨 Not good for wide voltage range
Controllability: Light load power regulation	🟨 Medium	🟩 High	🟨 Medium
DC bias currents- Transformer saturation	🟩 Caps block DC	🟥 Control based	🟩 Caps block DC
Voltage/Current Stress	🟨 Resonant cap has high voltage stress	🟩	🟩
Bidirectionality	🟥 Not well suited	🟩	🟩
Output current ripple	🟥 Large filter cap required	🟩	🟥 Large filter cap required
Leakage inductor	🟩	🟨 Relatively larger: high circulating reactive power	🟩
Medium freq Xmr stress	🟩 Sinusoidal voltages	🟨 Square voltages	🟩 Sinusoidal voltages

Green: Good, Yellow: Manageable, Red: Major constraint

Initial 1000V Class Charger Experimental Results

1000 V class Charger was built and tested at 950 V, 100 kW.

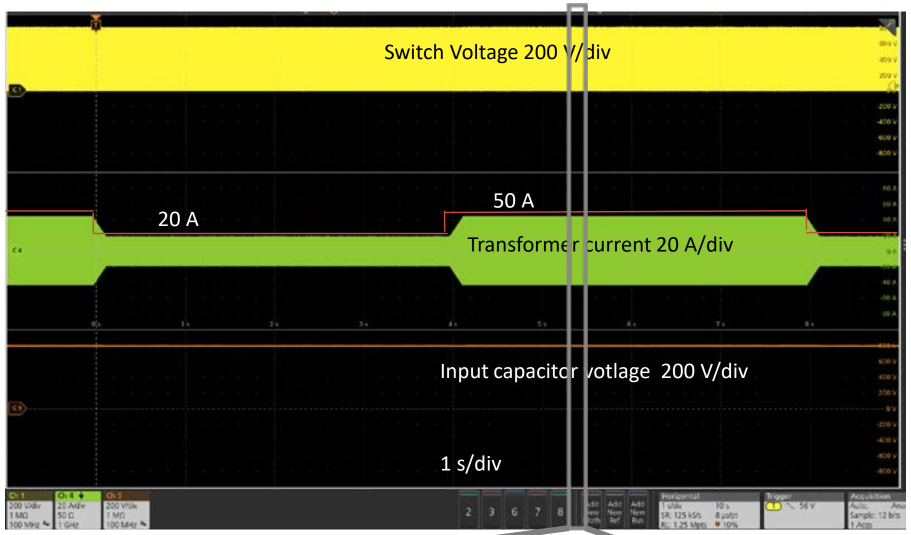
Schematic of charger test setup

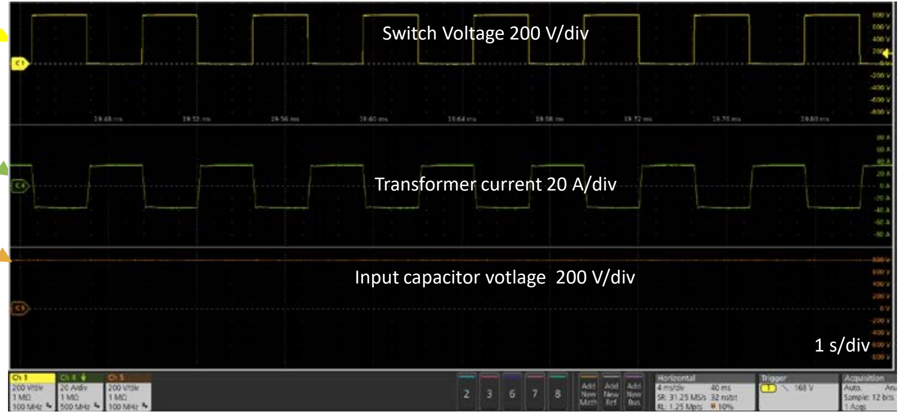


1000 V, 175 kW, 20 kHz DC/DC Charger

34” x 20” x 15”

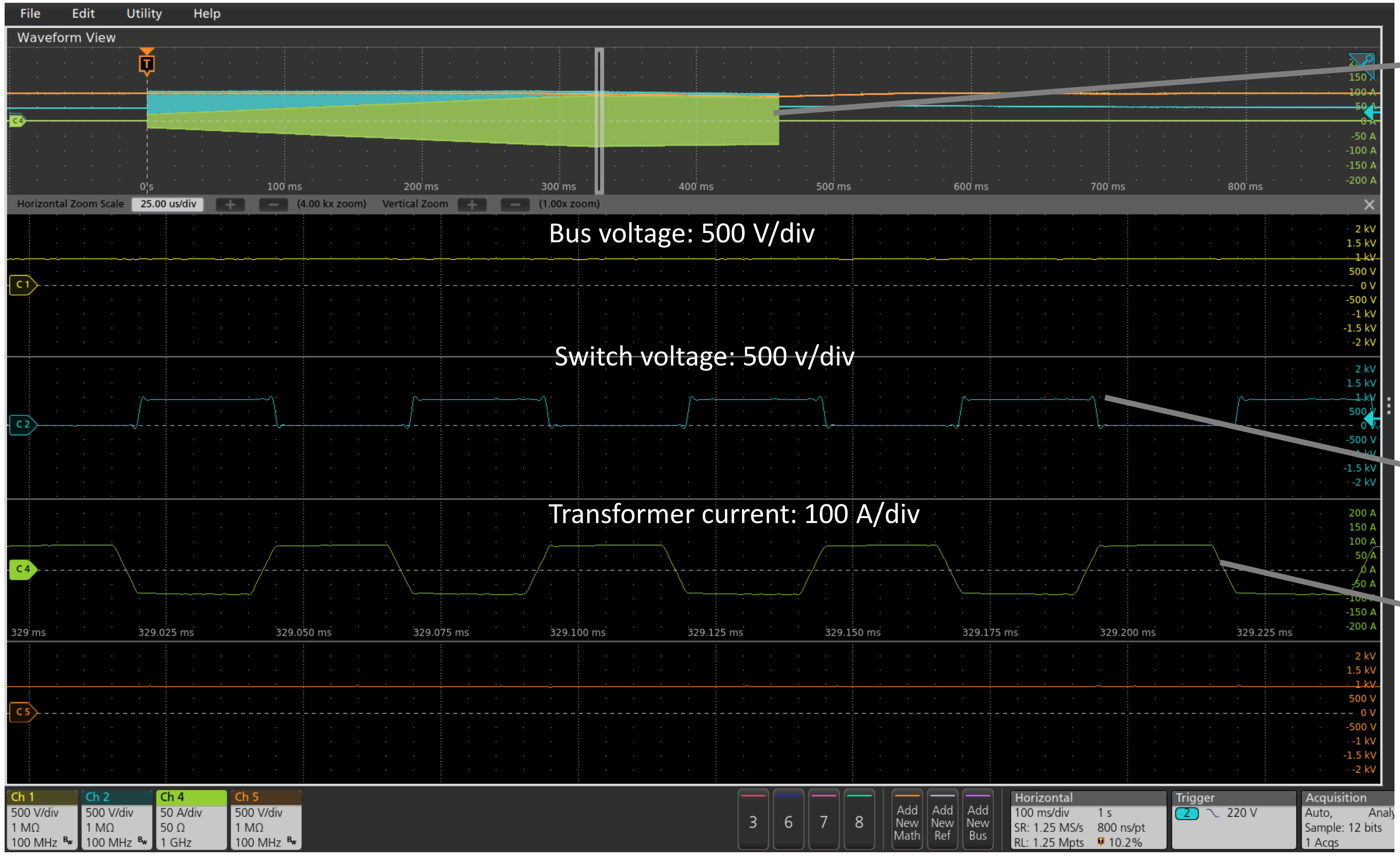
Initial Results at 800 V and 60 A





Initial 1000V Class Charger Experimental Results

Initial Results at 950 V and 100 A: ~100 kW



Bus voltage: 500 V/div

Switch voltage: 500 v/div

Transformer current: 100 A/div

Ch 1
500 V/div
1 MΩ
100 MHz Bw

Ch 2
500 V/div
1 MΩ
100 MHz Bw

Ch 4
50 A/div
50 Ω
1 GHz

Ch 5
500 V/div
1 MΩ
100 MHz Bw

Horizontal
100 ms/div 1 s
SR: 1.25 MS/s 800 ns/pt
RL: 1.25 Mpts 10.2%

Trigger
2 220 V

Acquisition
Auto, Analy
Sample: 12 bits
1 Acqs

Ramp rate : ~200 A/s

400 Watts loss @ 100 kW: 99.6 %

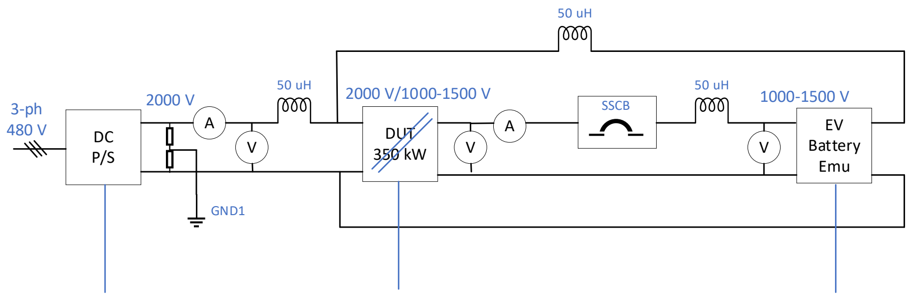
- Testing under best case for DAB
- Losses will be proportional to I^2
- Extrapolated efficiency at 200 A : 99 %

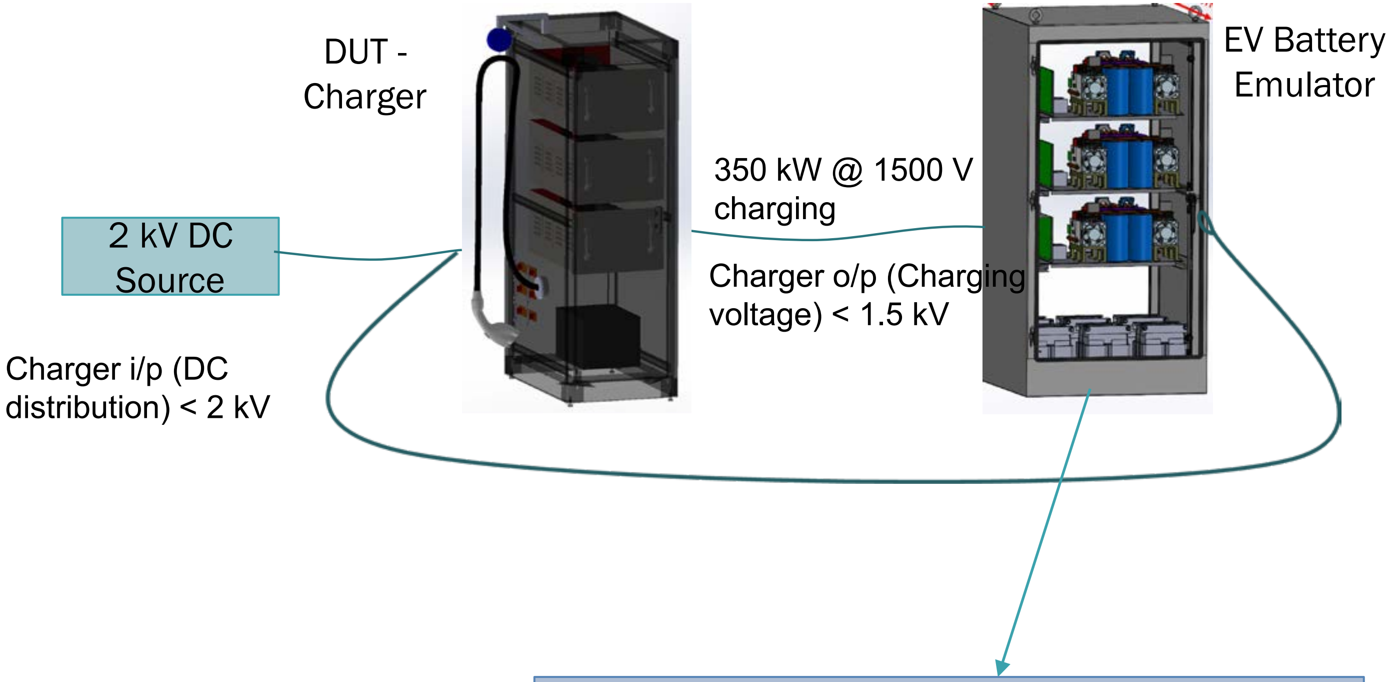
Minimal voltage overshoot

Minimal DC bias in the current

2 kV DC 350 kW Test Bed For Functional Testing

How to test the charger at different voltages, typical of a car battery?
A 2 kV, 350 kW DC test-bed is being developed




DUT - Charger

EV Battery Emulator

2 kV DC Source

350 kW @ 1500 V charging

Charger o/p (Charging voltage) < 1.5 kV

Charger i/p (DC distribution) < 2 kV

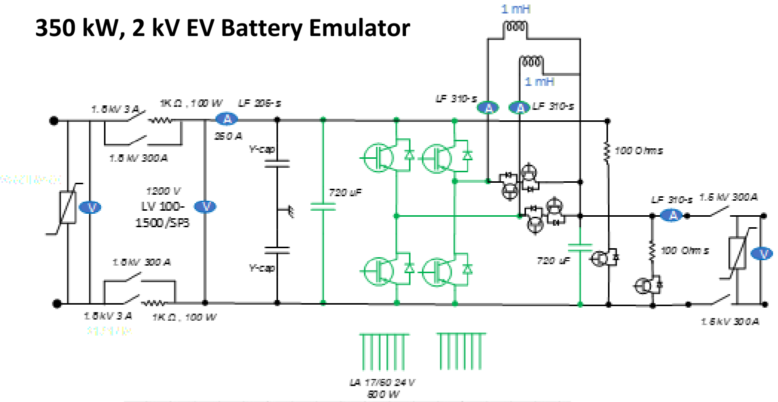
2 kV Class Emulator: Filling a market gap

- Capable of testing building blocks up to 2 kV
- An initial test setup for chargers is being built
- Capable of testing chargers from 200-1500 V
- Modular battery emulator-> can be scaled in the future
- Simultaneous testing of multiple chargers possible -> emulate fleet charging

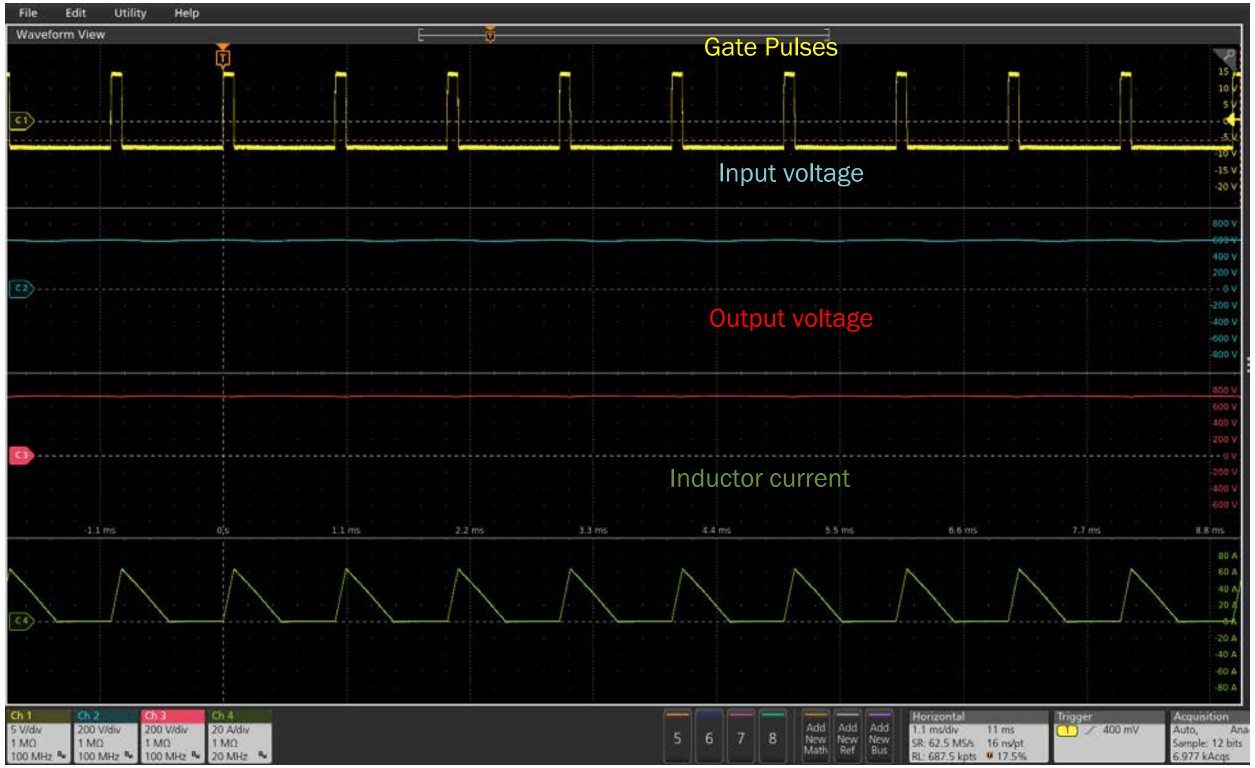
Battery Emulator Testing

- A test setup has been built to test the 2 kV, 400 kW in battery emulator mode
- Converter was designed to operate in DCM mode allowing inductor to sized 40 x smaller

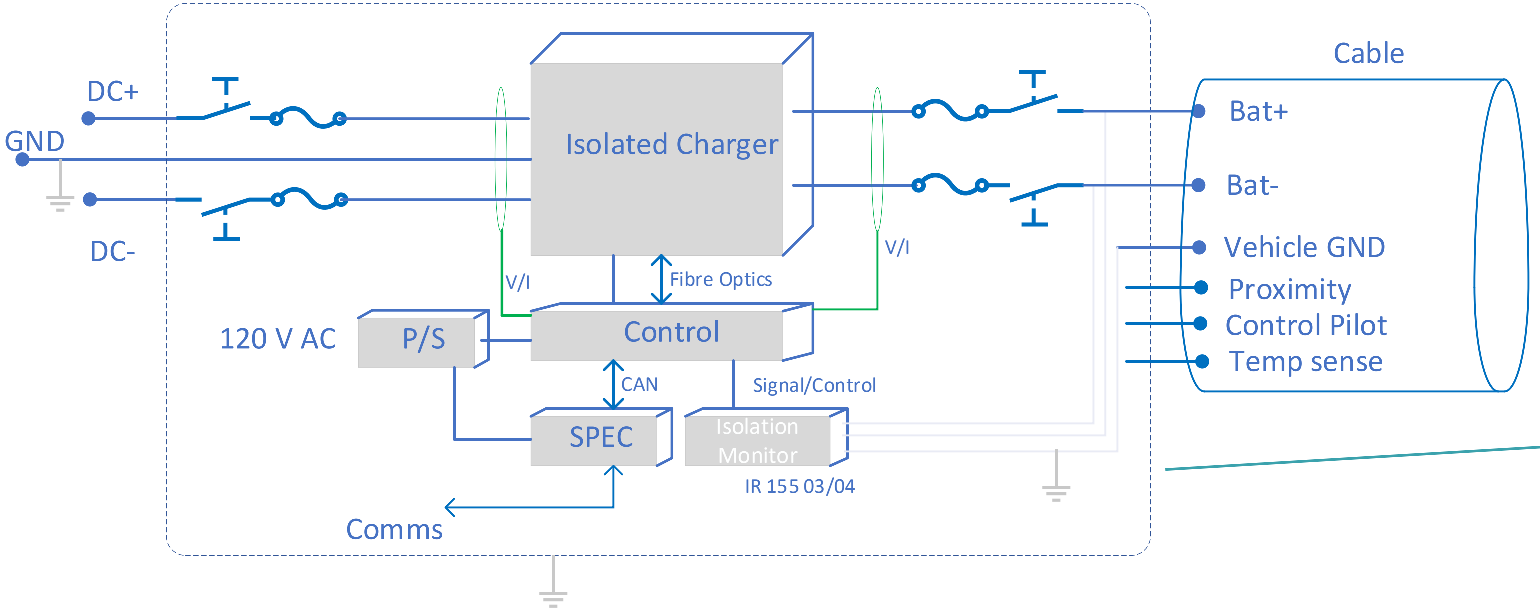
350 kW, 2 kV EV Battery Emulator

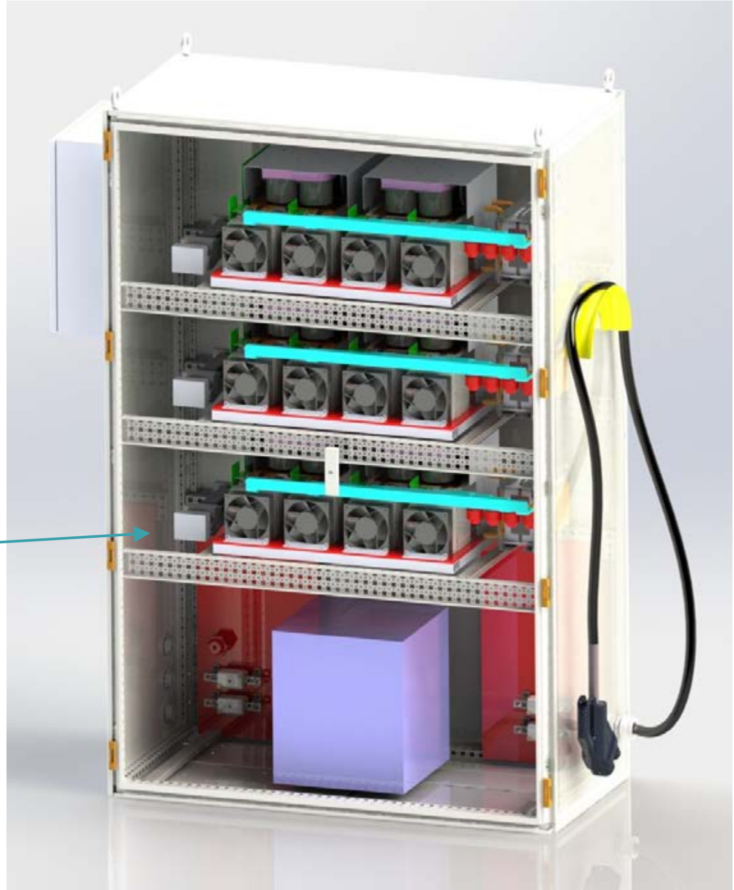


Open Loop Results at 800 V and 12 kW



1000 V Class 500 kW Charger

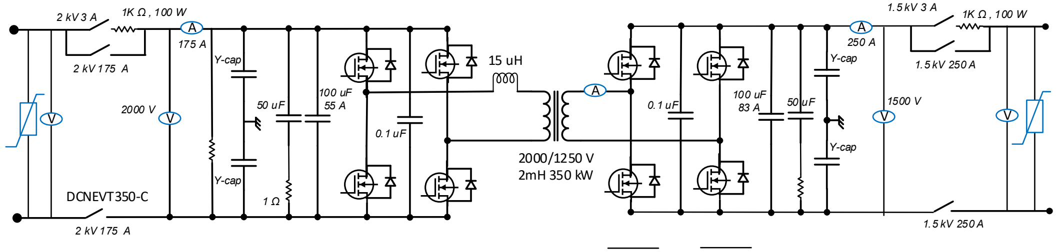


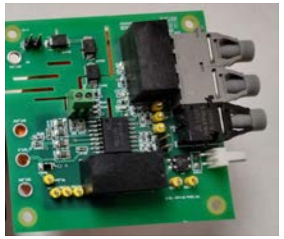


2 kV Class Charger Status

- The design for the 2 kV charger is complete
- Gate driver fully tested
- Full bridge with 3.3 kV Si has been fully tested
- The charger build is held because of the procurement delays with SiC modules
- Multiple risk mitigation approaches considered.

Design of 2 kV Class Charger





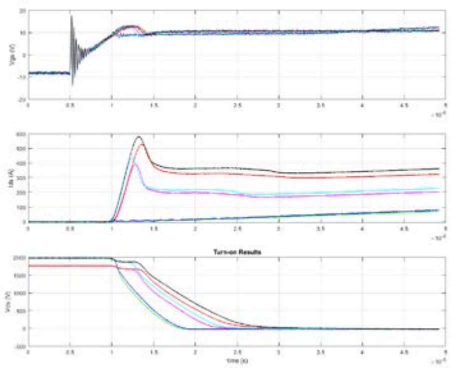
Custom developed 3.3 kV SiC Gate drive , 30 A pk

3.3 kV SiC Module Options

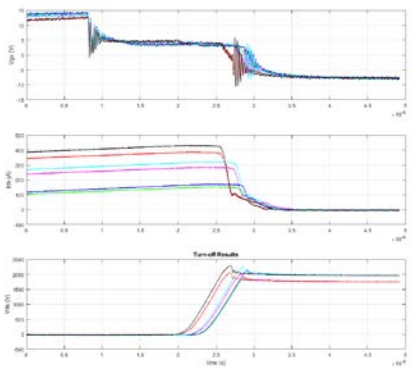
Source	Availability
In-house 100 A device	May 2023
Mitsubishi 375A device	TBD
Cree 600 A device	June 20203

Multiple paths to procure/develop 3.3 kV SiC modules

Turn On Results at 2000 V, Rg_ext = 3.3 Ω



Turn Off Results at 2000 V, Rg_ext = 3.3 Ω

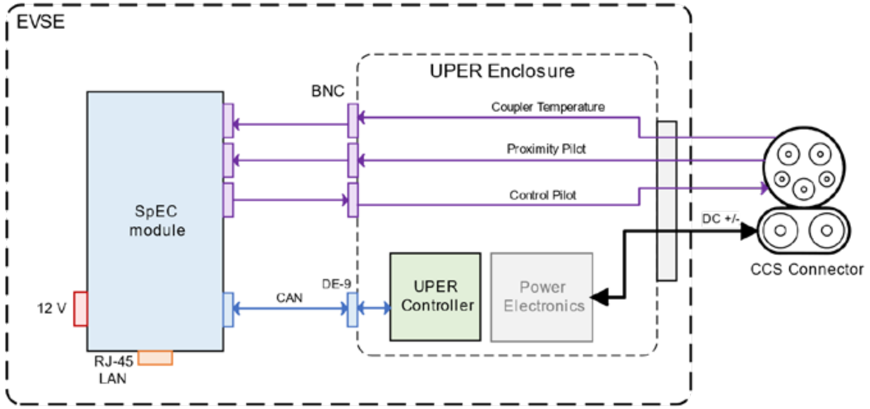


Integration and Communication Interface

- The charger will be integrated with ANL SPEC module to enable interface with both the vehicle and site energy management
- The protocol using CAN interface between the charger controller and ANL/SPEC module is being developed.

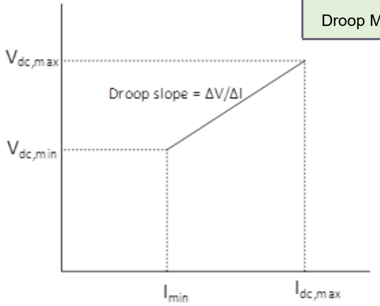
Development of hardware and software integration specifications between SpEC and UPER

- Communication protocol and specifications
- CAN interface messages descriptions
- Physical wiring specifications and interface
- Software implementation and testing



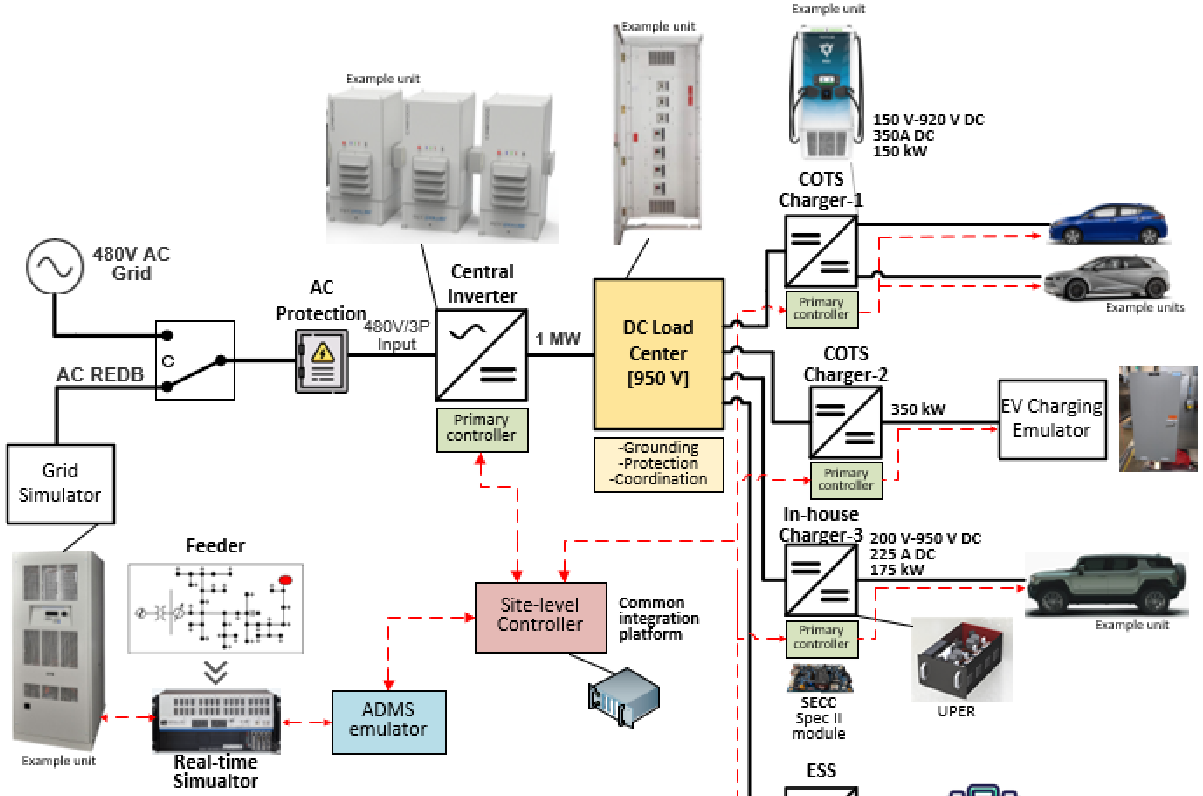
Example CAN Protocol between SPEC and UPER

CAN ID	Interval	Byte 0	Byte 1	Byte 2	Byte 3	Byte 4	Byte 5	Byte 6	Byte 7	Scale	Max
210	15 ms	Slope								0.1 X/bit	6553.5
				Offset						0.1 V/bit	6553.5
						Ramp Rate				5 (A/s)/bit	1275 A/s
								Droop Mode			



Test Plan

- The developed charger will be tested on a vehicle at ORNL campus (at lower power) before shipped to NREL
- The charger will then be integrated with the NREL facility



Summary of Developments

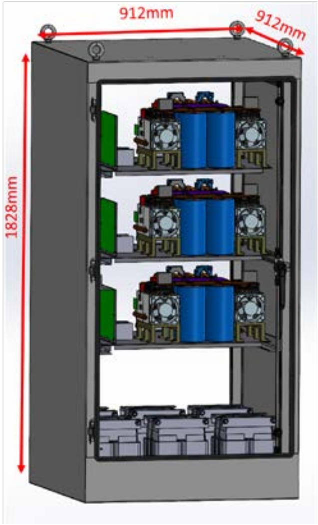
1000 V, 175 kW, 20 kHz DC/DC Charger

Scalable to 1000 V, 0.5 MW

- Custom gate driver and magnetics
- Device characterization
- Control development
- Verification in CHIL
- Prototype build and testing

2000 V, 400 kW, DC/DC Emulator

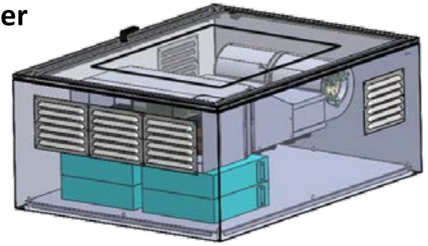
Scalable to 2000 V, 1.2 MW



2000 V, 350 kW, 10 kHz, DC/DC Charger

In-house built 3.3 kV 100 A SiC MOSFET

2000 V class charger



Next steps

- Testing the charger at higher powers: 175 kW
- Testing for thermal performance
- Integrating in an enclosure
- Integrating communications (SPEC) and other accessories like cable insulation monitor
- Testing the charger with an actual vehicle at ORNL campus
- Integrating the charger with NREL test setup
- Adding advanced functionalities such as droop

Thanks, and Questions

EVs@Scale
U.S. Department of Energy

Akram Syed Ali
ANL EV-Smart Grid Interoperability Center
Advanced Mobility and Grid Integration Technology
May 2, 2022

High-Power Charging Pillar: eCHIP

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

SpEC II module integration with power electronics and SEMS

Deep-Dive

Overview

In this presentation, we will do a deep-dive on:

1. **SpEC module**
2. SpEC module integration with **power electronics**
3. SpEC module integration with **Site Energy Management (SEM) system**

Review

Three key components necessary for implementing EV charging:

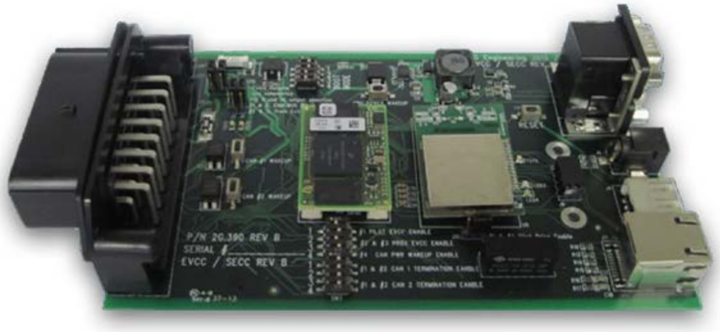
1. **Supply Equipment Communication Controller (SECC)** which will communicate with a vehicle using a charging standard
2. **High-power electronics** that will provide the power needed for charging
3. **Site Energy Management System (SEMS)** that will provide real-time monitoring and control for all sub-systems

These three modules need tight hardware and software integration between them to perform reliable EV charging

SpEC Module

ANL

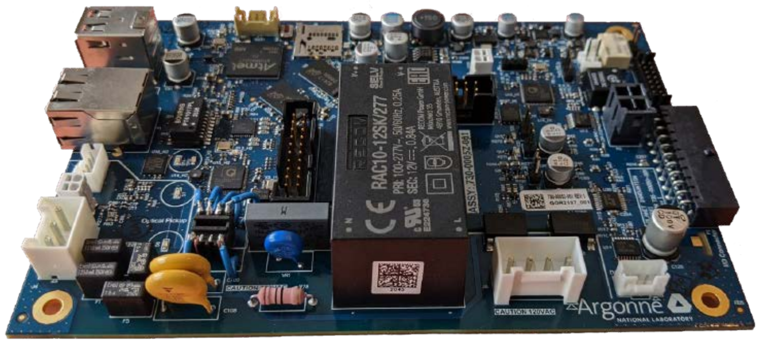
- The SpEC module developed by ANL is a smart plugin EV communication **controller**
- Enables DC fast charging communication between an EV and the charger
- Implements **high-level communication** required for *fast DC charging* based on DIN SPEC 70121 and ISO 15118 standard
- The SpEC module will translate the XML/EXI **messages** to and from the EV, as well as accept **commands** from the SEM system
- Custom C/C++ firmware
- Currently licensed to industry as an SECC



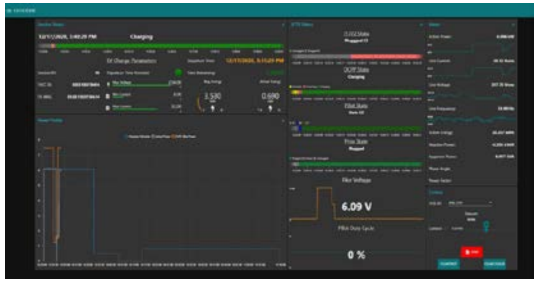
SpEC module (Gen I)

SpEC Module – Gen II

ANL




Ubuntu 20.04 LTS
(Focal Fossa)



Node-RED

MQTT

OCPP

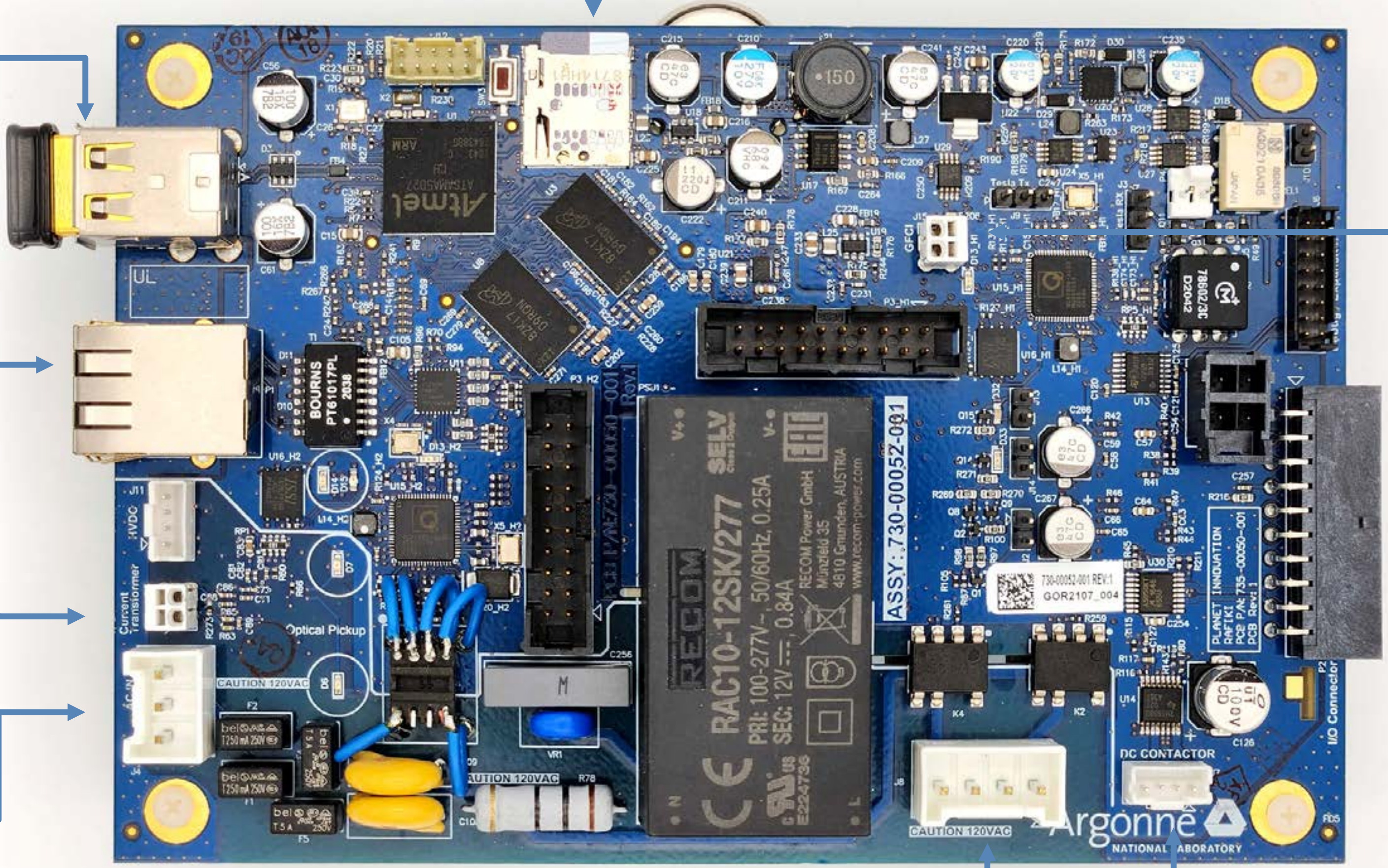
USB

CAN

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



External Flash memory

USB

External WiFi modules

Ethernet

Current Transformer

AC Power input (PLC ready)

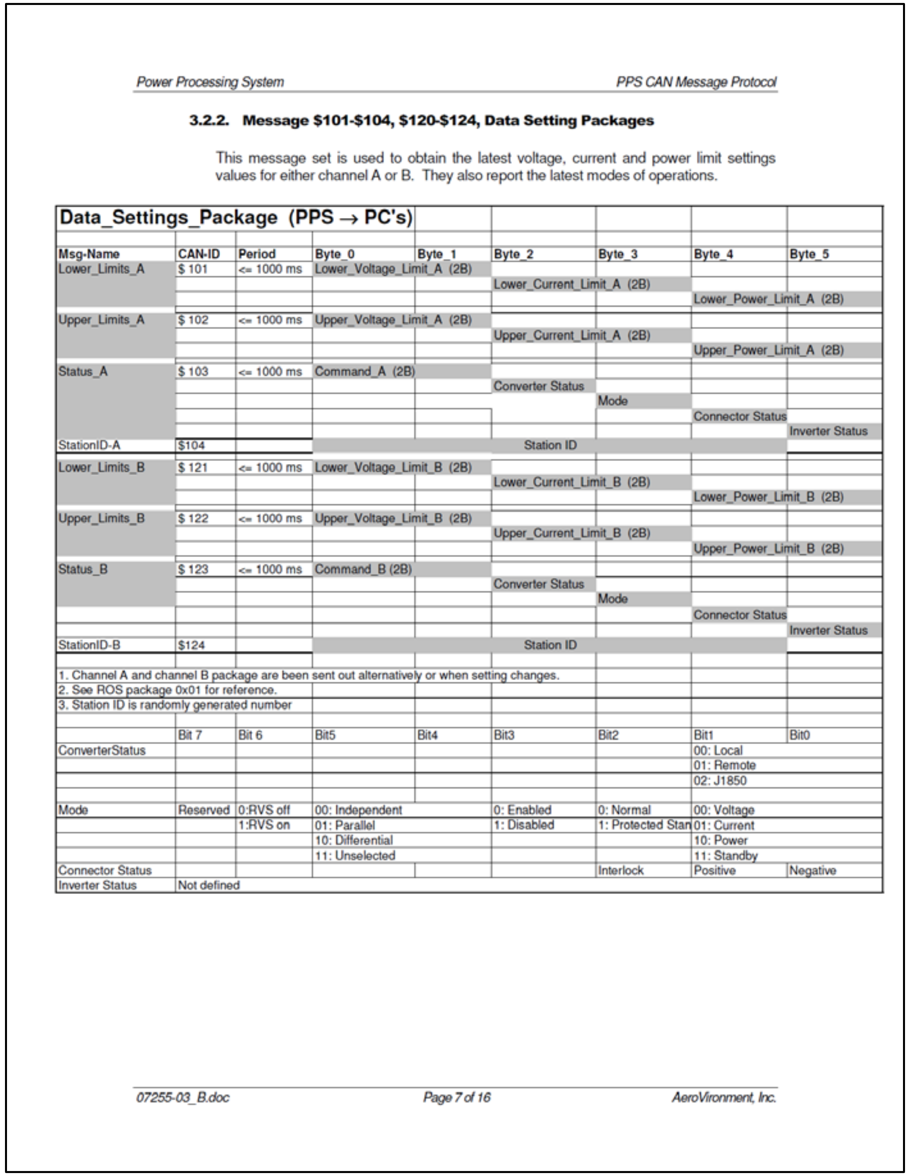
GFCI Input

Digital comms interface

AC & DC Contactor control

SpEC integration with power electronics

- **CAN Protocol** – industry standard for automotive applications
- SpEC module can integrate with all types of CAN messages (CAN 2.0, CAN FD)
- For any power electronics, ANL develops a complete **database** file, develops an **emulator** for the power electronics for testing 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



Power Processing System *PPS CAN Message Protocol*

3.2.2. Message $101-$104, $120-$124, 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.

Data_Settings_Package (PPS → PC's)

Msg-Name	CAN-ID	Period	Byte_0	Byte_1	Byte_2	Byte_3	Byte_4	Byte_5
Lower_Limits_A	$ 101	<= 1000 ms	Lower_Voltage_Limit_A (2B)					
					Lower_Current_Limit_A (2B)			
							Lower_Power_Limit_A (2B)	
Upper_Limits_A	$ 102	<= 1000 ms	Upper_Voltage_Limit_A (2B)					
					Upper_Current_Limit_A (2B)			
							Upper_Power_Limit_A (2B)	
Status_A	$ 103	<= 1000 ms	Command_A (2B)					
					Converter Status			
						Mode		
							Connector Status	
								Inverter Status
StationID-A	$104		Station ID					
Lower_Limits_B	$ 121	<= 1000 ms	Lower_Voltage_Limit_B (2B)					
					Lower_Current_Limit_B (2B)			
							Lower_Power_Limit_B (2B)	
Upper_Limits_B	$ 122	<= 1000 ms	Upper_Voltage_Limit_B (2B)					
					Upper_Current_Limit_B (2B)			
							Upper_Power_Limit_B (2B)	
Status_B	$ 123	<= 1000 ms	Command_B (2B)					
					Converter Status			
						Mode		
							Connector Status	
								Inverter Status
StationID-B	$124		Station ID					

1. Channel A and channel B package are been sent out alternatively or when setting changes.
2. See ROS package 0x01 for reference.
3. Station ID is randomly generated number

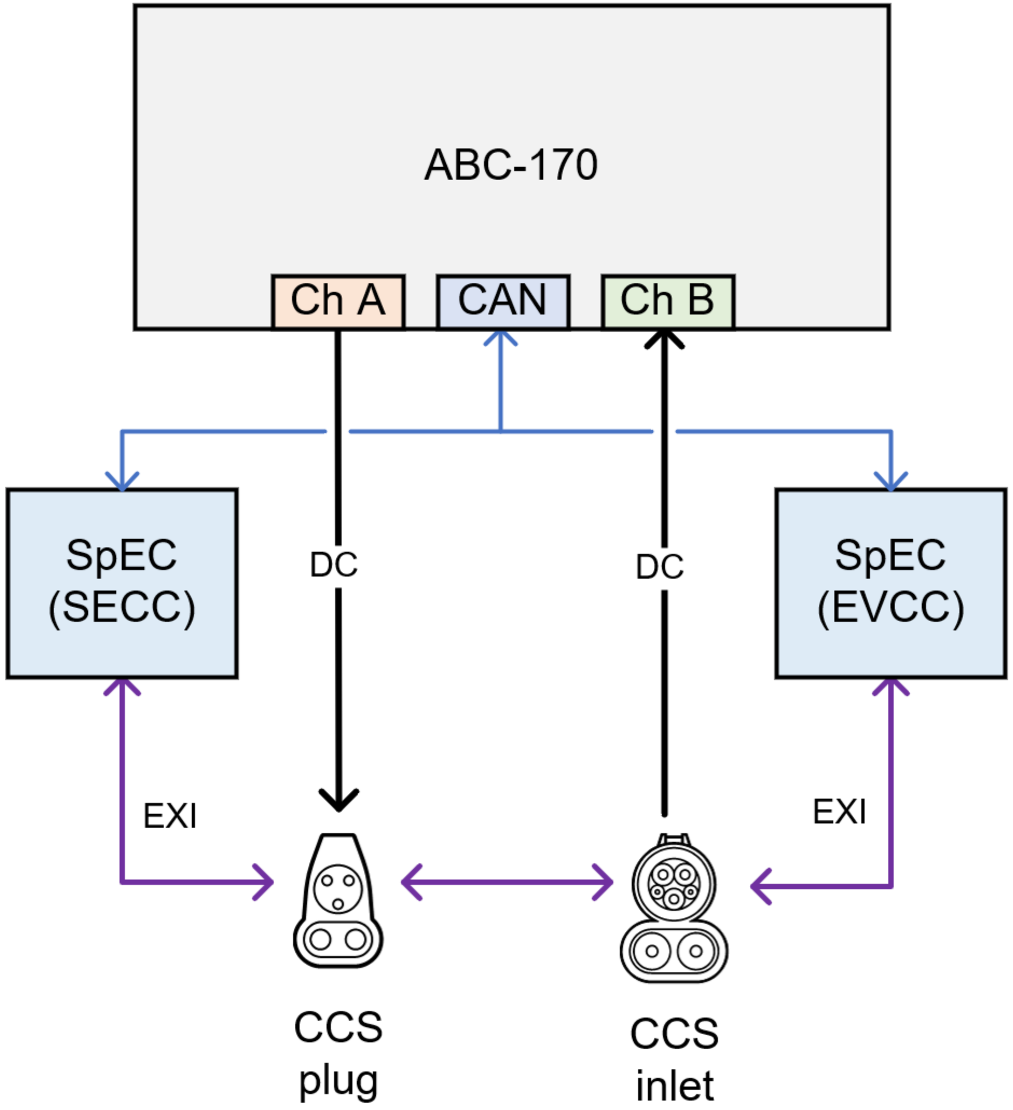
	Bit 7	Bit 6	Bit5	Bit4	Bit3	Bit2	Bit1	Bit0
ConverterStatus							00: Local	
							01: Remote	
							02: J1850	
Mode	Reserved	0:RVS off	00: Independent		0: Enabled	0: Normal	00: Voltage	
		1:RVS on	01: Parallel		1: Disabled	1: Protected Stan	01: Current	
			10: Differential				10: Power	
			11: Unselected				11: Standby	
Connector Status						Interlock	Positive	Negative
Inverter Status	Not defined							

07255-03_B.doc *Page 7 of 16* *AeroVironment, Inc.*

Testing

Emulated EV

- **ABC-170** used to test power delivery
- Independent SpEC modules acting as SECC and EVCC, controlling **CAN interface** on ABC-170
- Power sourced from Channel A, sunk into Channel B via CCS connector
- Successfully performed DIN 70121 charge session with emulated battery profile on SpEC EVCC



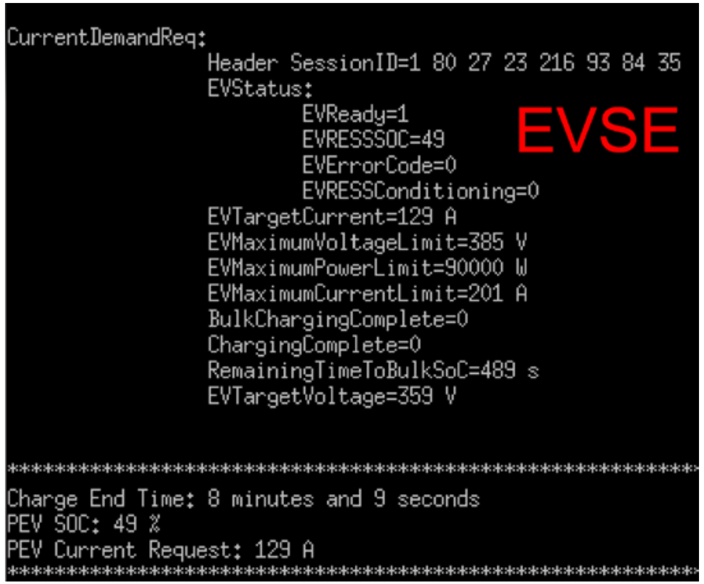
Testing

Emulated EV

Testing

Emulated EV

- **SpEC** module can implement *custom battery profiles* for testing
- Allows flexibility in *modeling* batteries for various OEMs, as well as *simulating* charge sessions at any voltage, current and power setting
- All CAN messages can be tested in Node-RED before running an actual charge session

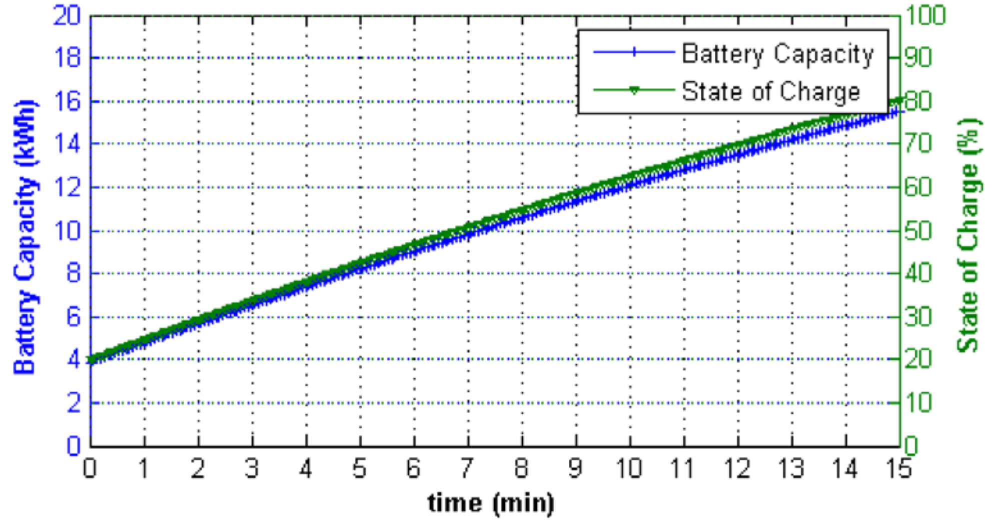


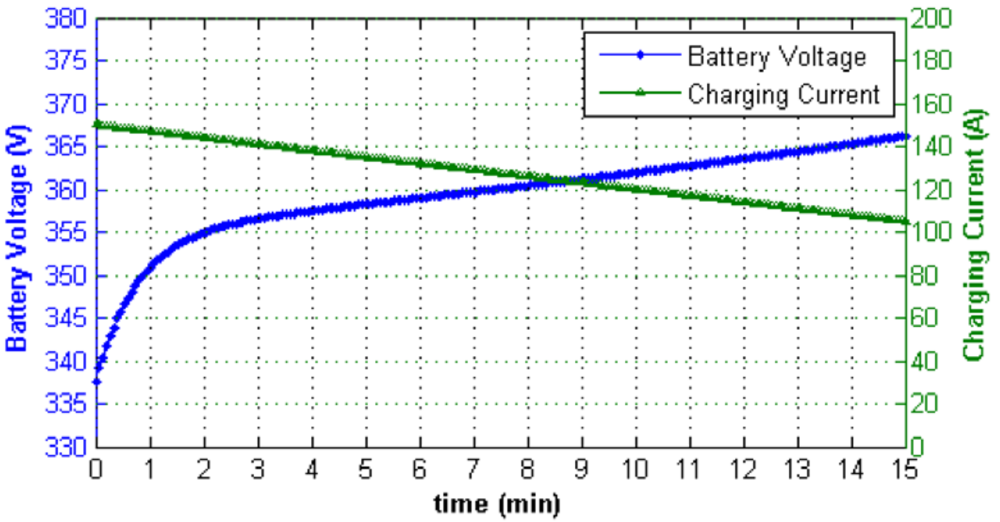
EVSE

```
CurrentDemandReq:
                Header SessionID=1 80 27 23 216 93 84 35
                EVStatus:
                        EVReady=1
                        EVRESSSOC=49
                        EVErrorCode=0
                        EVRESSConditioning=0
                EVTargetCurrent=129 A
                EVMaximumVoltageLimit=385 V
                EVMaximumPowerLimit=90000 W
                EVMaximumCurrentLimit=201 A
                BulkChargingComplete=0
                ChargingComplete=0
                RemainingTimeToBulkSoC=489 s
                EVTargetVoltage=359 V

**************************************************************************
Charge End Time: 8 minutes and 9 seconds
PEV SOC: 49 %
PEV Current Request: 129 A
**************************************************************************
```

PEV

```
CurrentDemandRes:
        Header SessionID=1 80 27 23 216 93 84 35
        ResponseCode=0
        EVSEStatus:
                EVSEIsolationStatus=1
                EVSEStatusCode=1
        EVSEPresentVoltage=360 V
        EVSEPresentCurrent=129 A
        EVSECurrentLimitAchieved=0
        EVSEVoltageLimitAchieved=0
        EVSEPowerLimitAchieved=0
        EVSEMaximumVoltageLimit=420 V
        EVSEMaximumCurrentLimit=201 A
        EVSEMaximumPowerLimit=90000 W

**************************************************************************
Charge End Time: 8 minutes and 9 seconds
BECM Current Request: 129.25 A
Battery Current: -128.86 A
Amp Hours: 15.89 Ah
Battery Voltage: 359.56 V
kWatt Hours: 5.71 kWh
SOC: 50.00 %
**************************************************************************
```

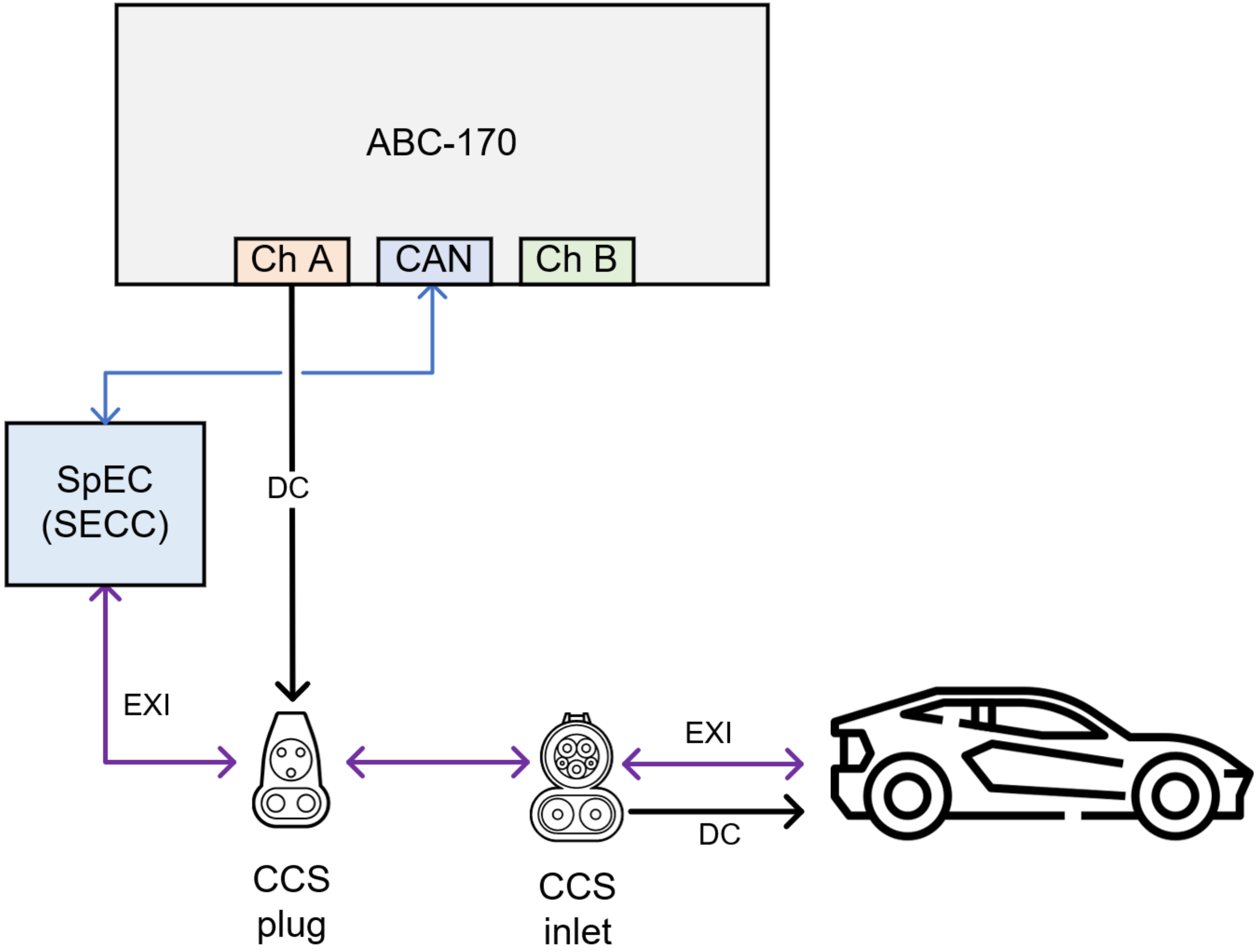




Testing

Actual EV

- Repeated same test with actual EV instead of emulated EVCC
- Successfully performed DIN 70121 charge session with actual EV



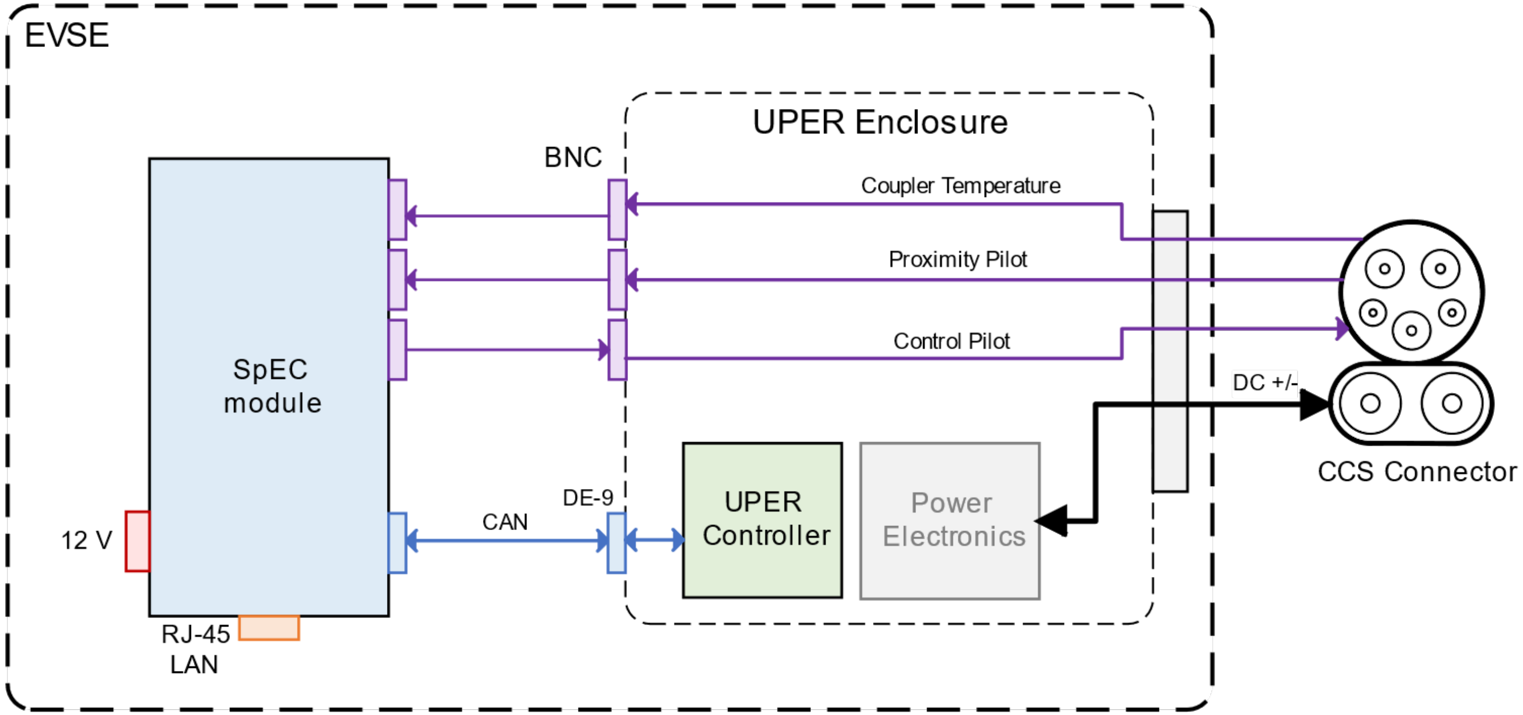
Testing

Actual EV

SpEC integration with UPER

eCHIP

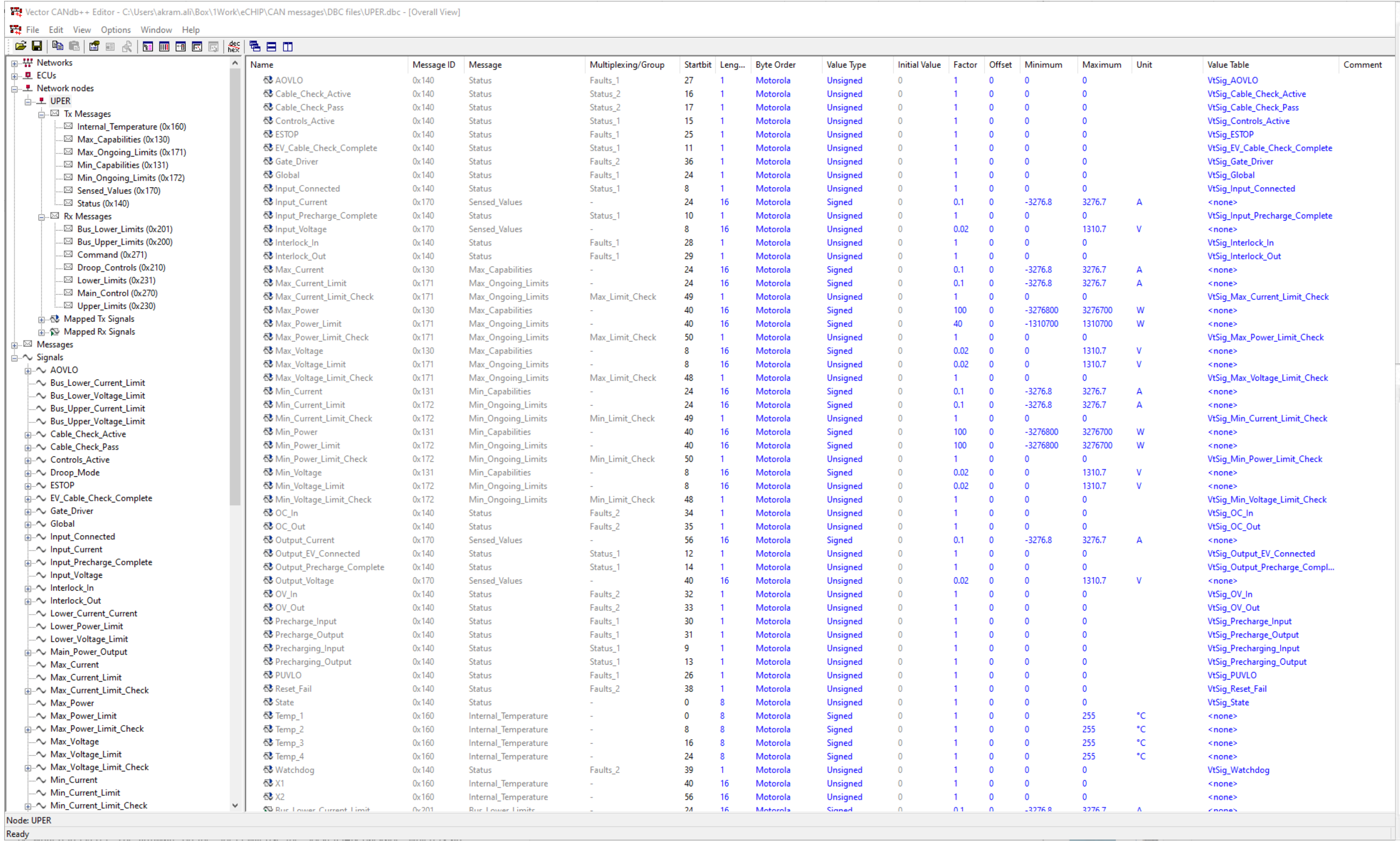
- The wiring interface between the SpEC and UPER controllers are identified in the integration document
- Specific components for power and communication are also described
  - CCS connector terminations to UPER and SpEC
  - CAN physical interface between UPER and SpEC using DE-9 connector



Communication Interface

eCHIP

All CAN messages are compiled by ANL into a CAN database file (.dbc) using Vector CANdb++ to be used for testing

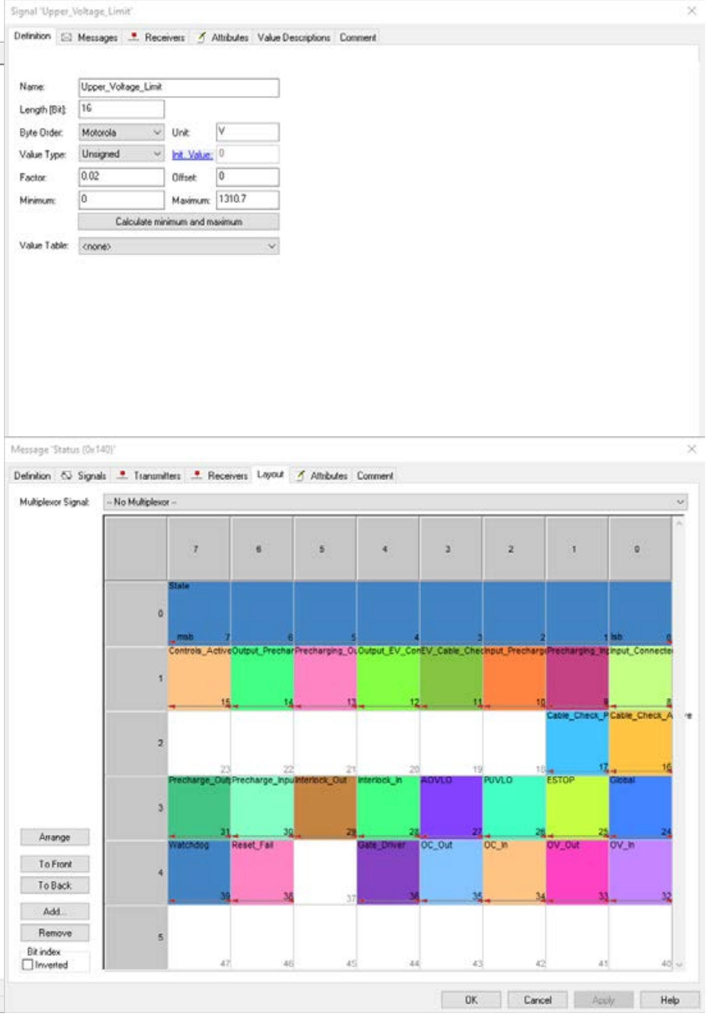


- Networks
- ECUs
- Network nodes
  - UPER
    - Tx Messages
      - Internal_Temperature (0x160)
      - Max_Capabilities (0x130)
      - Max_Ongoing_Limits (0x171)
      - Min_Capabilities (0x131)
      - Min_Ongoing_Limits (0x172)
      - Sensed_Values (0x170)
      - Status (0x140)
    - Rx Messages
      - Bus_Lower_Limits (0x201)
      - Bus_Upper_Limits (0x200)
      - Command (0x271)
      - Droop_Controls (0x210)
      - Lower_Limits (0x231)
      - Main_Control (0x270)
      - Upper_Limits (0x230)
    - Mapped Tx Signals
    - Mapped Rx Signals
- Messages
- Signals
  - AOVLO
  - Bus_Lower_Current_Limit
  - Bus_Lower_Voltage_Limit
  - Bus_Upper_Current_Limit
  - Bus_Upper_Voltage_Limit
  - Cable_Check_Active
  - Cable_Check_Pass
  - Controls_Active
  - Droop_Mode
  - ESTOP
  - EV_Cable_Check_Complete
  - Gate_Driver
  - Global
  - Input_Connected
  - Input_Current
  - Input_Precharge_Complete
  - Input_Voltage
  - Interlock_In
  - Interlock_Out
  - Lower_Current_Current
  - Lower_Power_Limit
  - Lower_Voltage_Limit
  - Main_Power_Output
  - Max_Current
  - Max_Current_Limit
  - Max_Current_Limit_Check
  - Max_Power
  - Max_Power_Limit
  - Max_Power_Limit_Check
  - Max_Voltage
  - Max_Voltage_Limit
  - Max_Voltage_Limit_Check
  - Min_Current
  - Min_Current_Limit
  - Min_Current_Limit_Check

Name	Message ID	Message	Multiplexing/Group	Startbit	Leng...	Byte Order	Value Type	Initial Value	Factor	Offset	Minimum	Maximum	Unit	Value Table	Comment
AOVLO	0x140	Status	Faults_1	27	1	Motorola	Unsigned	0	1	0	0	0		VtSig_AOVLO	
Cable_Check_Active	0x140	Status	Status_2	16	1	Motorola	Unsigned	0	1	0	0	0		VtSig_Cable_Check_Active	
Cable_Check_Pass	0x140	Status	Status_2	17	1	Motorola	Unsigned	0	1	0	0	0		VtSig_Cable_Check_Pass	
Controls_Active	0x140	Status	Status_1	15	1	Motorola	Unsigned	0	1	0	0	0		VtSig_Controls_Active	
ESTOP	0x140	Status	Faults_1	25	1	Motorola	Unsigned	0	1	0	0	0		VtSig_ESTOP	
EV_Cable_Check_Complete	0x140	Status	Status_1	11	1	Motorola	Unsigned	0	1	0	0	0		VtSig_EV_Cable_Check_Complete	
Gate_Driver	0x140	Status	Faults_2	36	1	Motorola	Unsigned	0	1	0	0	0		VtSig_Gate_Driver	
Global	0x140	Status	Faults_1	24	1	Motorola	Unsigned	0	1	0	0	0		VtSig_Global	
Input_Connected	0x140	Status	Status_1	8	1	Motorola	Unsigned	0	1	0	0	0		VtSig_Input_Connected	
Input_Current	0x170	Sensed_Values	-	24	16	Motorola	Signed	0	0.1	0	-3276.8	3276.7	A	<none>	
Input_Precharge_Complete	0x140	Status	Status_1	10	1	Motorola	Unsigned	0	1	0	0	0		VtSig_Input_Precharge_Complete	
Input_Voltage	0x170	Sensed_Values	-	8	16	Motorola	Unsigned	0	0.02	0	0	1310.7	V	<none>	
Interlock_In	0x140	Status	Faults_1	28	1	Motorola	Unsigned	0	1	0	0	0		VtSig_Interlock_In	
Interlock_Out	0x140	Status	Faults_1	29	1	Motorola	Unsigned	0	1	0	0	0		VtSig_Interlock_Out	
Max_Current	0x130	Max_Capabilities	-	24	16	Motorola	Signed	0	0.1	0	-3276.8	3276.7	A	<none>	
Max_Current_Limit	0x171	Max_Ongoing_Limits	-	24	16	Motorola	Signed	0	0.1	0	-3276.8	3276.7	A	<none>	
Max_Current_Limit_Check	0x171	Max_Ongoing_Limits	Max_Limit_Check	49	1	Motorola	Unsigned	0	1	0	0	0		VtSig_Max_Current_Limit_Check	
Max_Power	0x130	Max_Capabilities	-	40	16	Motorola	Signed	0	100	0	-3276800	3276700	W	<none>	
Max_Power_Limit	0x171	Max_Ongoing_Limits	-	40	16	Motorola	Signed	0	40	0	-1310700	1310700	W	<none>	
Max_Power_Limit_Check	0x171	Max_Ongoing_Limits	Max_Limit_Check	50	1	Motorola	Unsigned	0	1	0	0	0		VtSig_Max_Power_Limit_Check	
Max_Voltage	0x130	Max_Capabilities	-	8	16	Motorola	Signed	0	0.02	0	0	1310.7	V	<none>	
Max_Voltage_Limit	0x171	Max_Ongoing_Limits	-	8	16	Motorola	Unsigned	0	0.02	0	0	1310.7	V	<none>	
Max_Voltage_Limit_Check	0x171	Max_Ongoing_Limits	Max_Limit_Check	48	1	Motorola	Unsigned	0	1	0	0	0		VtSig_Max_Voltage_Limit_Check	
Min_Current	0x131	Min_Capabilities	-	24	16	Motorola	Signed	0	0.1	0	-3276.8	3276.7	A	<none>	
Min_Current_Limit	0x172	Min_Ongoing_Limits	-	24	16	Motorola	Signed	0	0.1	0	-3276.8	3276.7	A	<none>	
Min_Current_Limit_Check	0x172	Min_Ongoing_Limits	Min_Limit_Check	49	1	Motorola	Unsigned	0	1	0	0	0		VtSig_Min_Current_Limit_Check	
Min_Power	0x131	Min_Capabilities	-	40	16	Motorola	Signed	0	100	0	-3276800	3276700	W	<none>	
Min_Power_Limit	0x172	Min_Ongoing_Limits	-	40	16	Motorola	Signed	0	100	0	-3276800	3276700	W	<none>	
Min_Power_Limit_Check	0x172	Min_Ongoing_Limits	Min_Limit_Check	50	1	Motorola	Unsigned	0	1	0	0	0		VtSig_Min_Power_Limit_Check	
Min_Voltage	0x131	Min_Capabilities	-	8	16	Motorola	Signed	0	0.02	0	0	1310.7	V	<none>	
Min_Voltage_Limit	0x172	Min_Ongoing_Limits	-	8	16	Motorola	Unsigned	0	0.02	0	0	1310.7	V	<none>	
Min_Voltage_Limit_Check	0x172	Min_Ongoing_Limits	Min_Limit_Check	48	1	Motorola	Unsigned	0	1	0	0	0		VtSig_Min_Voltage_Limit_Check	
OC_In	0x140	Status	Faults_2	34	1	Motorola	Unsigned	0	1	0	0	0		VtSig_OC_In	
OC_Out	0x140	Status	Faults_2	35	1	Motorola	Unsigned	0	1	0	0	0		VtSig_OC_Out	
Output_Current	0x170	Sensed_Values	-	56	16	Motorola	Signed	0	0.1	0	-3276.8	3276.7	A	<none>	
Output_EV_Connected	0x140	Status	Status_1	12	1	Motorola	Unsigned	0	1	0	0	0		VtSig_Output_EV_Connected	
Output_Precharge_Complete	0x140	Status	Status_1	14	1	Motorola	Unsigned	0	1	0	0	0		VtSig_Output_Precharge_Compl...	
Output_Voltage	0x170	Sensed_Values	-	40	16	Motorola	Unsigned	0	0.02	0	0	1310.7	V	<none>	
OV_In	0x140	Status	Faults_2	32	1	Motorola	Unsigned	0	1	0	0	0		VtSig_OV_In	
OV_Out	0x140	Status	Faults_2	33	1	Motorola	Unsigned	0	1	0	0	0		VtSig_OV_Out	
Precharge_Input	0x140	Status	Faults_1	30	1	Motorola	Unsigned	0	1	0	0	0		VtSig_Precharge_Input	
Precharge_Output	0x140	Status	Faults_1	31	1	Motorola	Unsigned	0	1	0	0	0		VtSig_Precharge_Output	
Precharging_Input	0x140	Status	Status_1	9	1	Motorola	Unsigned	0	1	0	0	0		VtSig_Precharging_Input	
Precharging_Output	0x140	Status	Status_1	13	1	Motorola	Unsigned	0	1	0	0	0		VtSig_Precharging_Output	
PUVLO	0x140	Status	Faults_1	26	1	Motorola	Unsigned	0	1	0	0	0		VtSig_PUVLO	
Reset_Fail	0x140	Status	Faults_2	38	1	Motorola	Unsigned	0	1	0	0	0		VtSig_Reset_Fail	
State	0x140	Status	-	0	8	Motorola	Unsigned	0	1	0	0	0		VtSig_State	
Temp_1	0x160	Internal_Temperature	-	0	8	Motorola	Signed	0	1	0	0	255	°C	<none>	
Temp_2	0x160	Internal_Temperature	-	8	8	Motorola	Signed	0	1	0	0	255	°C	<none>	
Temp_3	0x160	Internal_Temperature	-	16	8	Motorola	Signed	0	1	0	0	255	°C	<none>	
Temp_4	0x160	Internal_Temperature	-	24	8	Motorola	Signed	0	1	0	0	255	°C	<none>	
Watchdog	0x140	Status	Faults_2	39	1	Motorola	Unsigned	0	1	0	0	0		VtSig_Watchdog	
X1	0x160	Internal_Temperature	-	40	16	Motorola	Unsigned	0	1	0	0	0		<none>	
X2	0x160	Internal_Temperature	-	56	16	Motorola	Unsigned	0	1	0	0	0		<none>	

Node: UPER

Ready



Name: Upper_Voltage_Limit
Length [Bit]: 16
Byte Order: Motorola
Unit: V
Value Type: Unsigned
Init. Value: 0
Factor: 0.02
Offset: 0
Minimum: 0
Maximum: 1310.7
Value Table: <none>

Multiplexor Signal: -- No Multiplexor --

	7	6	5	4	3	2	1	0
0	State msb 7	6	5	4	3	2	1	lsb 0
1	Controls_Active 15	Output_Prechar 14	Precharging_Ou 13	Output_EV_Con 12	EV_Cable_Chec 11	Input_Precharg 10	Precharging_In 9	Input_Connecte 8
2	23	22	21	20	19	18	Cable_Check_P 17	Cable_Check_A 16
3	Precharge_Out 31	Precharge_Inpu 30	Interlock_Out 29	Interlock_In 28	AOVLO 27	PUVLO 26	ESTOP 25	Global 24
4	Watchdog 39	Reset_Fail 38	37	Gate_Driver 36	OC_Out 35	OC_In 34	OV_Out 33	OV_In 32
5	47	46	45	44	43	42	41	40

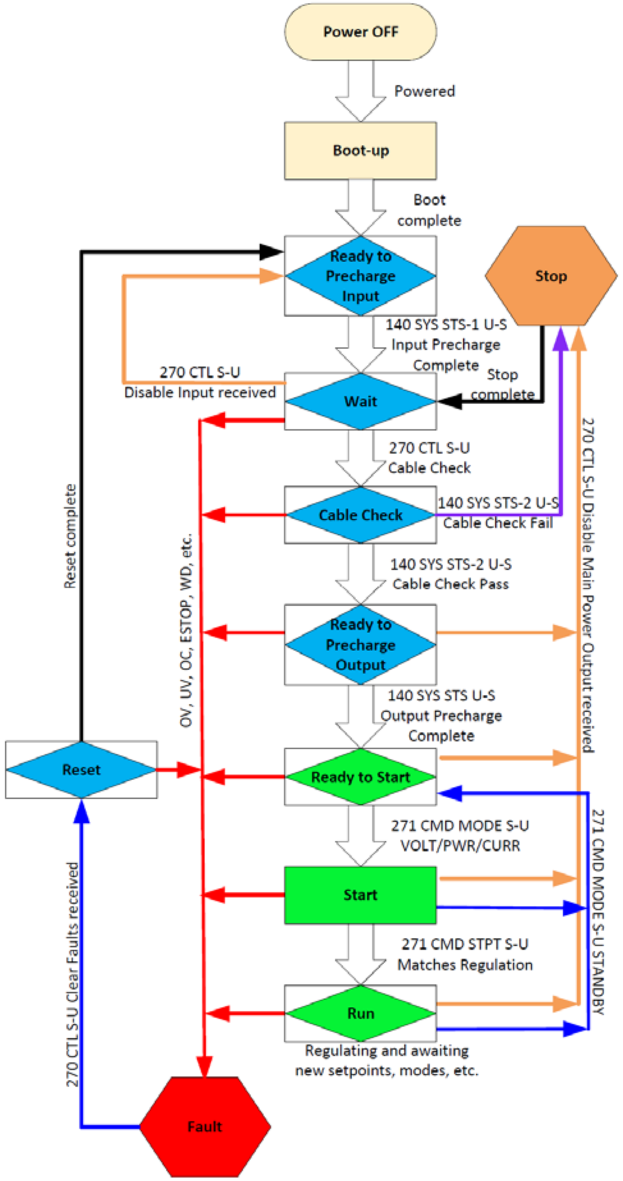
Bit index

☐ Inverted

UPER State machine

eCHIP

UPER State machine flow diagram provided by ORNL after discussions with ANL



Ready to Precharge Input: Waits for 270 CTL S-U Power Input to be enabled before any action is taken

Wait: Waits for 270 CTL S-U Disable Power Input or 270 CTL S-U Cable Check

Cable Check: Proceeds to do cable check and responds status when finished automatically moving to next state.

Ready to Precharge Output: Waits for 271 CMD Setpoint, Multiplier, and Voltage Mode and 270 CTL S-U Main Power Output to be enabled before any action is taken. Once voltage is within acceptable thresholds precharge finishes and main contactors close.

Ready to Start: Waits for 271 CMD Setpoint, Multiplier, and Mode other than Standby

Start: Waits for 271 CMD Setpoint to match the regulation target.

Run: Waits for new 271 CMD Setpoints, Multipliers, and Modes

Stop: Stops appropriately for given condition and then returns to the Wait state.

Fault: Occurs when any fault happens and opens all contactors and shuts down the converter. This stays in this state until cleared by the controller. The specific fault is sent up to the SPEC which can later be sent up to the SEM.

Reset: Automatically proceeds once faults are cleared

UPER Emulator

Development & Testing

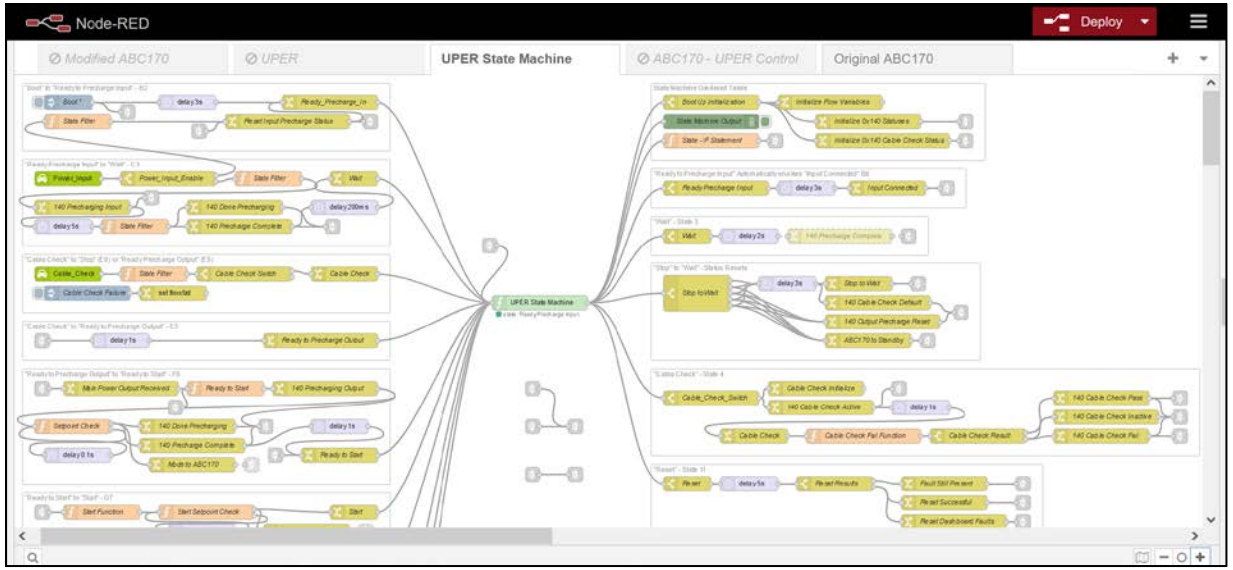
- **UPER emulator** was built using a *Raspberry Pi* single board computer
- All CAN communication with the UPER Emulator is done using a *PiCAN2 Duo CAN-Bus Board* for the Raspberry Pi
- Important communication interfaces (CAN and Ethernet) are broken out of enclosure for quick and easy testing

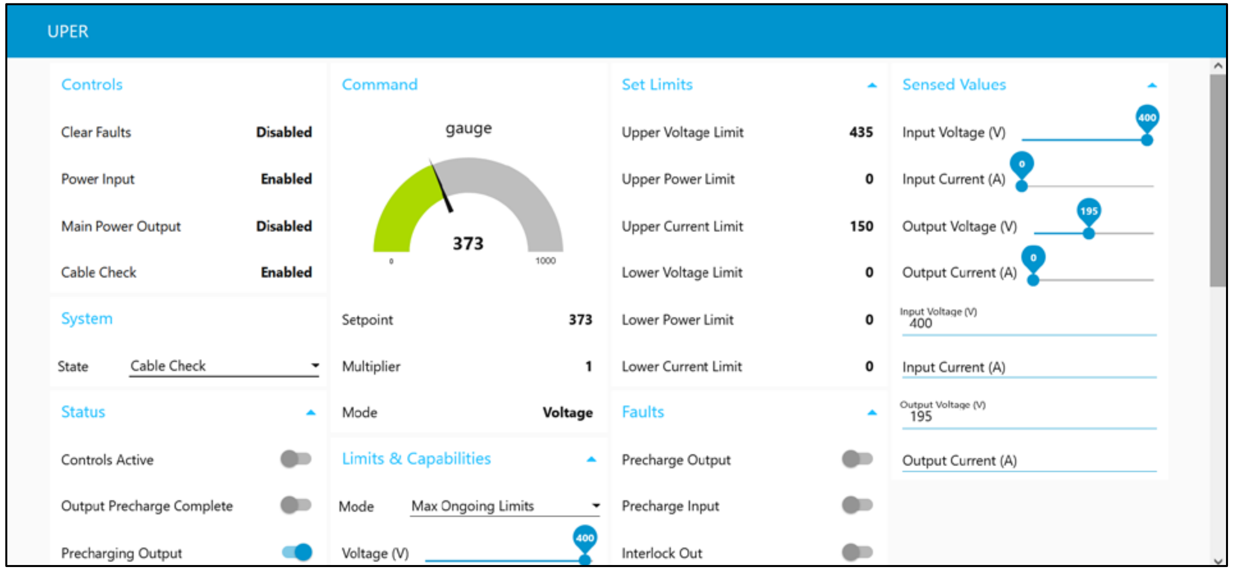
Emulation Software

Development

Node-RED

- **Node-RED** used as platform of choice for emulating UPER's controller
  - Browser-based programming tool for wiring hardware devices and APIs
  - Lightweight, built on Node.js, can run easily on Raspberry Pi
- *node-red-contrib-can* package developed by ANL to handle CAN messages
- Custom flow to simulate UPER state machine
- Dashboard to provide easy access to read and control UPER settings




UPER

Controls
Clear Faults Disabled
Power Input Enabled
Main Power Output Disabled
Cable Check Enabled

System
State Cable Check

Status
Controls Active
Output Precharge Complete
Precharging Output

Command
gauge
373
0
1000
Setpoint 373
Multiplier 1
Mode Voltage

Limits & Capabilities
Mode Max Ongoing Limits
Voltage (V) 400

Set Limits
Upper Voltage Limit 435
Upper Power Limit 0
Upper Current Limit 150
Lower Voltage Limit 0
Lower Power Limit 0
Lower Current Limit 0

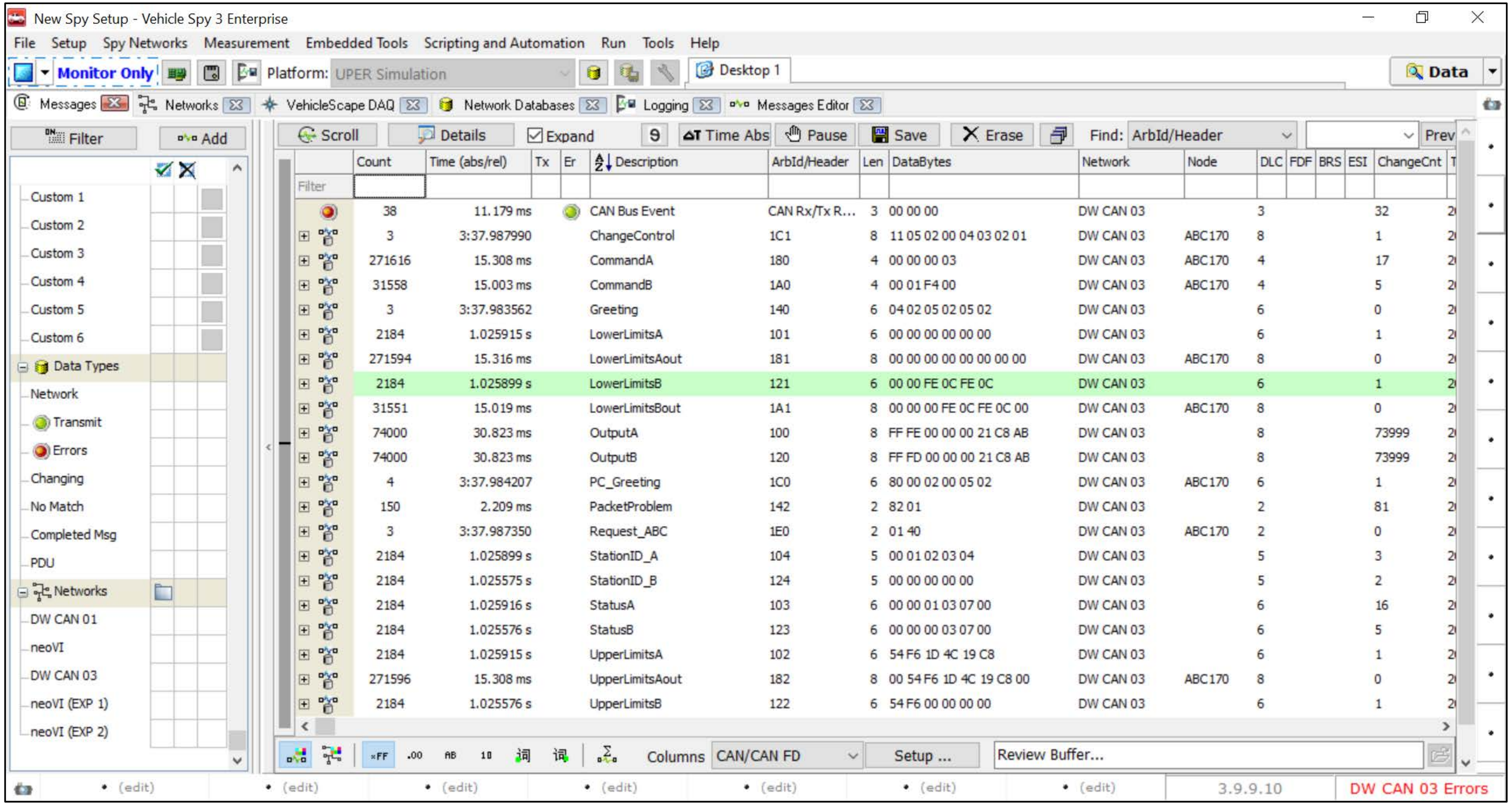
Faults
Precharge Output
Precharge Input
Interlock Out

Sensed Values
Input Voltage (V) 400
Input Current (A) 0
Output Voltage (V) 195
Output Current (A) 0
Input Voltage (V) 400
Input Current (A)
Output Voltage (V) 195
Output Current (A)

Data logging

Debugging

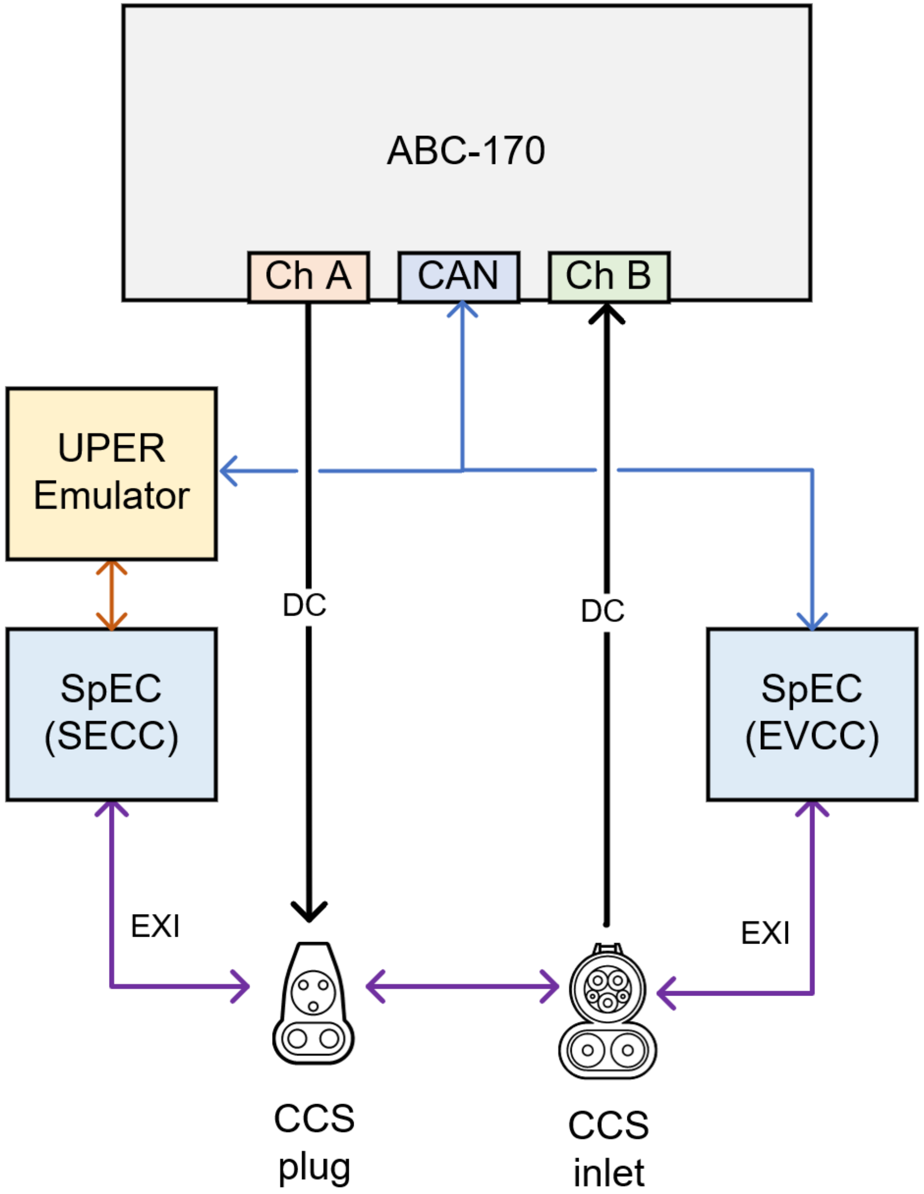
neoVI FIRE 2 used along with **Vehicle Spy Enterprise** for data logging and debugging during development



Count	Time (abs/rel)	Tx	Er	Description	ArbId/Header	Len	DataBytes	Network	Node	DLC	FDF	BRS	ESI	ChangeCnt
38	11.179 ms			CAN Bus Event	CAN Rx/Tx R...	3	00 00 00	DW CAN 03		3				32
3	3:37.987990			ChangeControl	1C1	8	11 05 02 00 04 03 02 01	DW CAN 03	ABC170	8				1
271616	15.308 ms			CommandA	180	4	00 00 00 03	DW CAN 03	ABC170	4				17
31558	15.003 ms			CommandB	1A0	4	00 01 F4 00	DW CAN 03	ABC170	4				5
3	3:37.983562			Greeting	140	6	04 02 05 02 05 02	DW CAN 03		6				0
2184	1.025915 s			LowerLimitsA	101	6	00 00 00 00 00 00	DW CAN 03		6				1
271594	15.316 ms			LowerLimitsAout	181	8	00 00 00 00 00 00 00 00	DW CAN 03	ABC170	8				0
2184	1.025899 s			LowerLimitsB	121	6	00 00 FE 0C FE 0C	DW CAN 03		6				1
31551	15.019 ms			LowerLimitsBout	1A1	8	00 00 00 FE 0C FE 0C 00	DW CAN 03	ABC170	8				0
74000	30.823 ms			OutputA	100	8	FF FE 00 00 00 21 C8 AB	DW CAN 03		8				73999
74000	30.823 ms			OutputB	120	8	FF FD 00 00 00 21 C8 AB	DW CAN 03		8				73999
4	3:37.984207			PC_Greeting	1C0	6	80 00 02 00 05 02	DW CAN 03	ABC170	6				1
150	2.209 ms			PacketProblem	142	2	82 01	DW CAN 03		2				81
3	3:37.987350			Request_ABC	1E0	2	01 40	DW CAN 03	ABC170	2				0
2184	1.025899 s			StationID_A	104	5	00 01 02 03 04	DW CAN 03		5				3
2184	1.025575 s			StationID_B	124	5	00 00 00 00 00	DW CAN 03		5				2
2184	1.025916 s			StatusA	103	6	00 00 01 03 07 00	DW CAN 03		6				16
2184	1.025576 s			StatusB	123	6	00 00 00 03 07 00	DW CAN 03		6				5
2184	1.025915 s			UpperLimitsA	102	6	54 F6 1D 4C 19 C8	DW CAN 03		6				1
271596	15.308 ms			UpperLimitsAout	182	8	00 54 F6 1D 4C 19 C8 00	DW CAN 03	ABC170	8				0
2184	1.025576 s			UpperLimitsB	122	6	54 F6 00 00 00 00	DW CAN 03		6				1

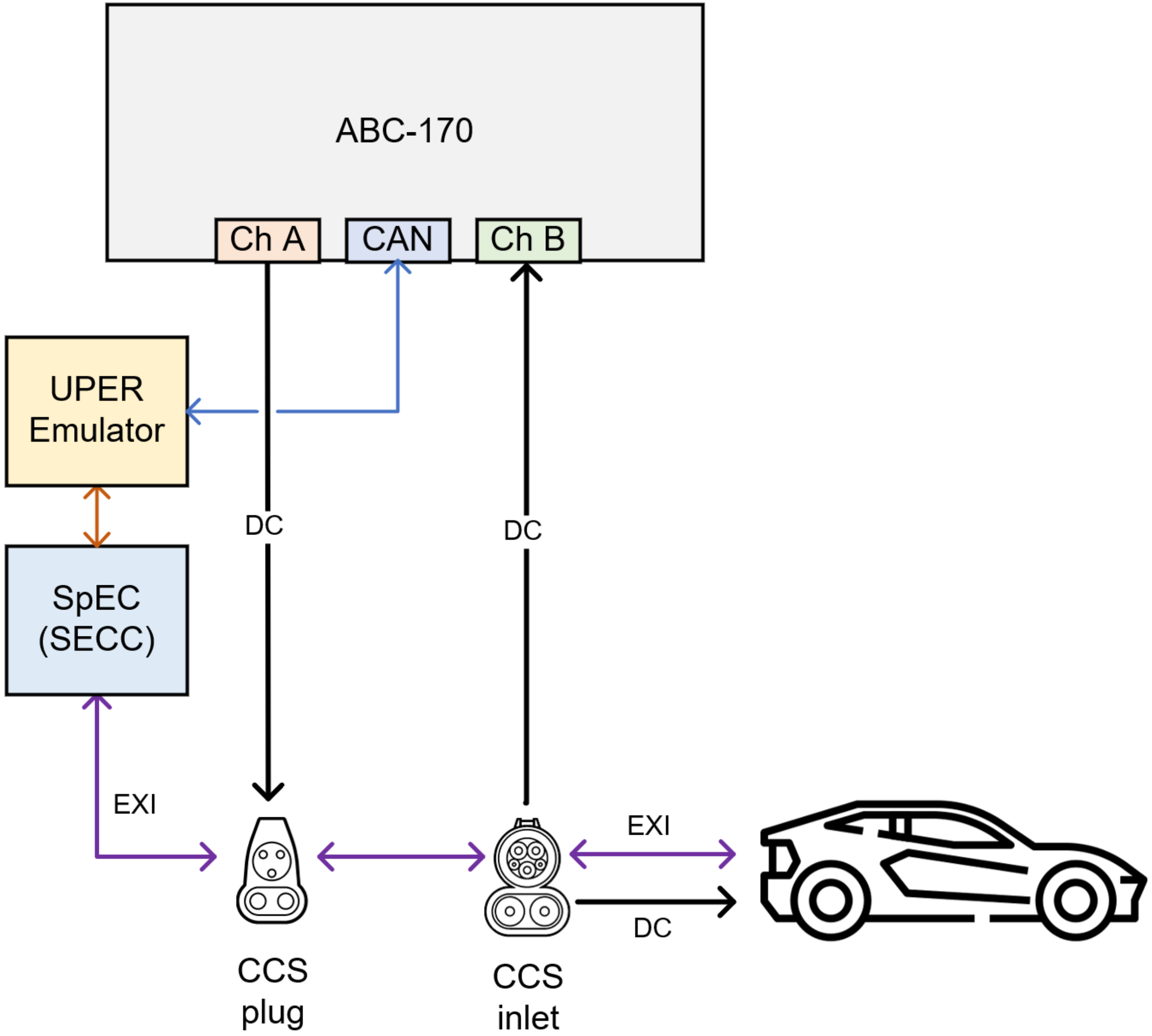
Testing

- Setup the **UPER emulator** to communicate with the SpEC SECC and ABC-170
- All CAN commands *translated* from UPER to ABC-170 (Channel A)
- ABC-170 is only used to test power delivery
- Setup automatically able to go through each state of UPER while following J1772 charging sequence
- Successfully performed a full DIN 70121 charge session



Testing

- The same test was repeated with actual EV instead of emulated EVCC
- Successfully demonstrated SpEC + UPER performing an actual charge session with Ford F-150 Lightning
- For final deployment in eCHIP project, the UPER emulator will be replaced with an actual UPER module when ready



Testing

- Successfully demonstrated SpEC + UPER performing an actual charge session with **Keysight CDS** acting as emulated EV

- The Keysight CDS will be used for testing future implementations of ISO 15118-20 bidirectional charging, since no EV is available as of today that implements this standard

Site Energy Management System (SEMS)

- The SEMS will provide **real-time monitoring and control** for all sub-systems in a charging plaza

- There is no de facto SEMS implementation in the industry today

Choice of Commercial vs Open-Source:

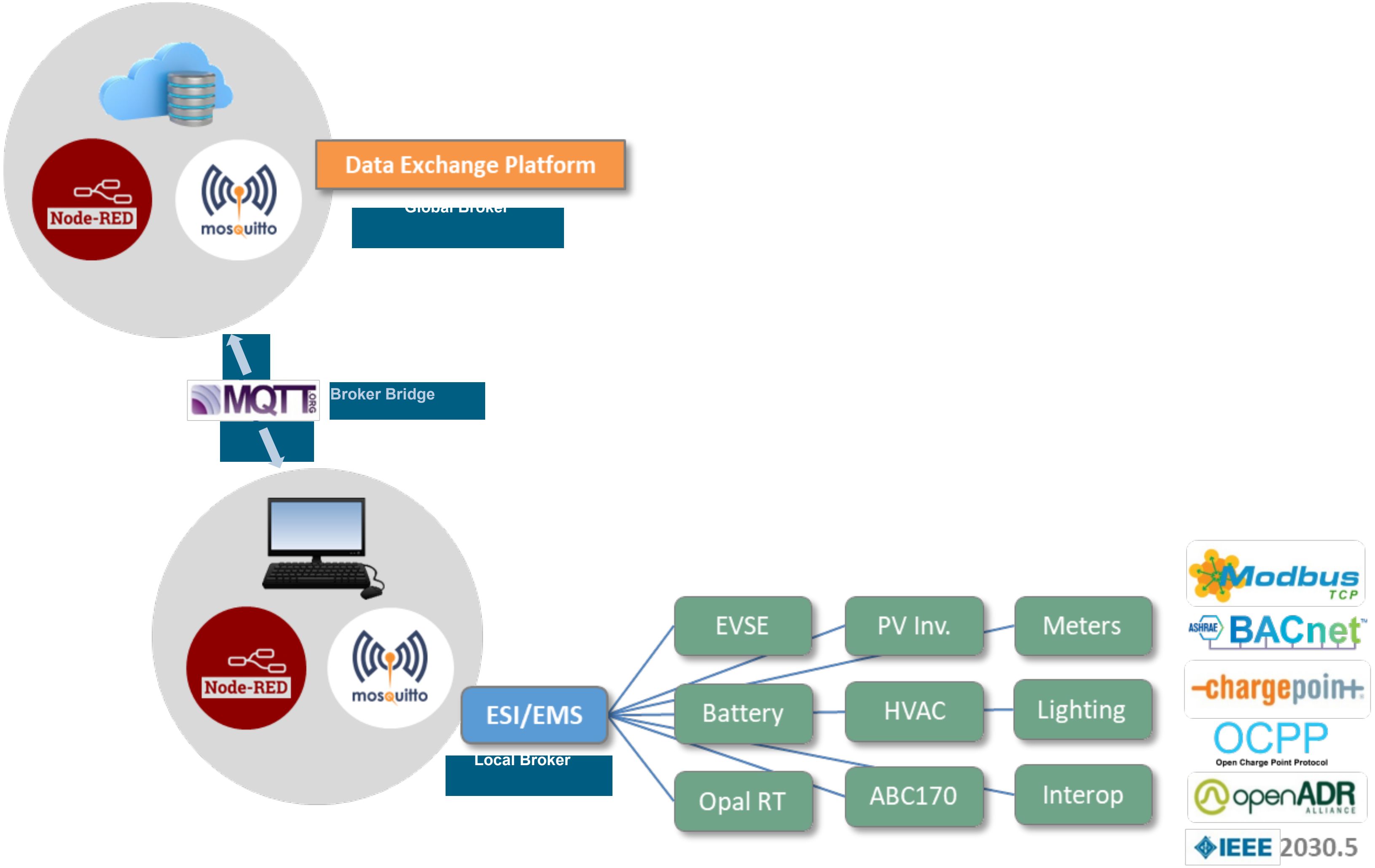
- OSS Advantages:
  - Potential for cost savings due to free or low-cost open-source software
  - High customizability and ability to tailor software to specific needs
  - Potential for collaboration and innovation with a community of contributors
- OSS Disadvantages:
  - Lack of vendor support and reliance on community forums and documentation for troubleshooting
  - Limitations in integration with proprietary software, reducing functionality in certain situation

- Typical communication protocols: OCPP, Modbus, BACnet, MQTT, OpenADR, etc.

- **OCPP** is the most widely used protocol for station to CSMS communication

Common Integration Platform

CIP.io



Data Exchange Platform

Global Broker

Broker Bridge

Local Broker

ESI/EMS

EVSE

PV Inv.

Meters

Battery

HVAC

Lighting

Opal RT

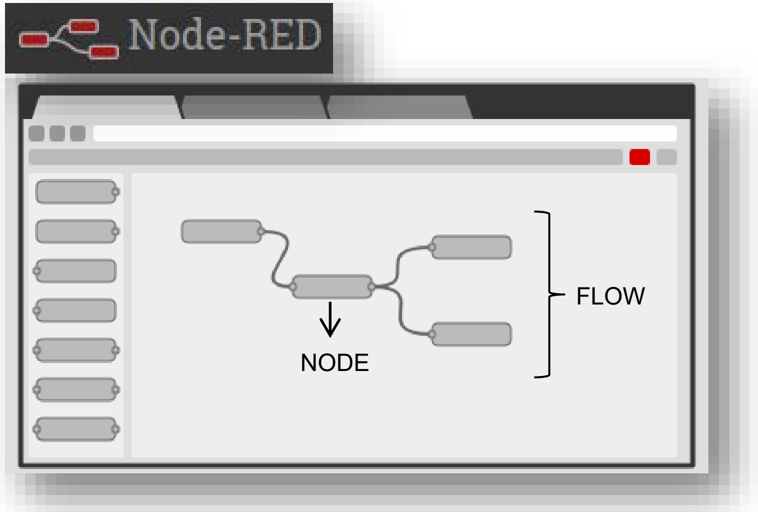
ABC170

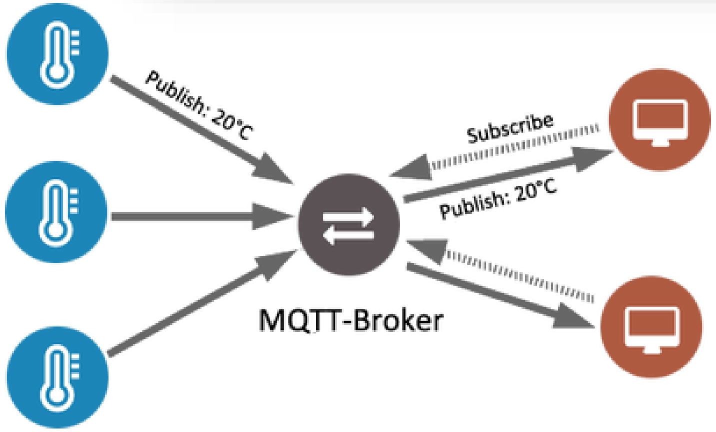
Interop

Common Integration Platform

Containerized for Deployment

- **SEMS controller with built-in capabilities:**
  - Mosquitto (MQTT)
  - Influxdb (time-series database)
  - Node-Red (logic)
  - Grafana (plotting and dashboards)
- Common language distributed over **MQTT Broker(s)**
- **Open-source** - runs on single board computer
- Customizable via **Node-RED** flows; example flows provided
- **Auto-loads Argonne custom nodes**
  - OCPP
  - OpenADR
  - Modbus





mongoDB

mosquitto

influxdb

Node-RED

Grafana

Common Integration Platform

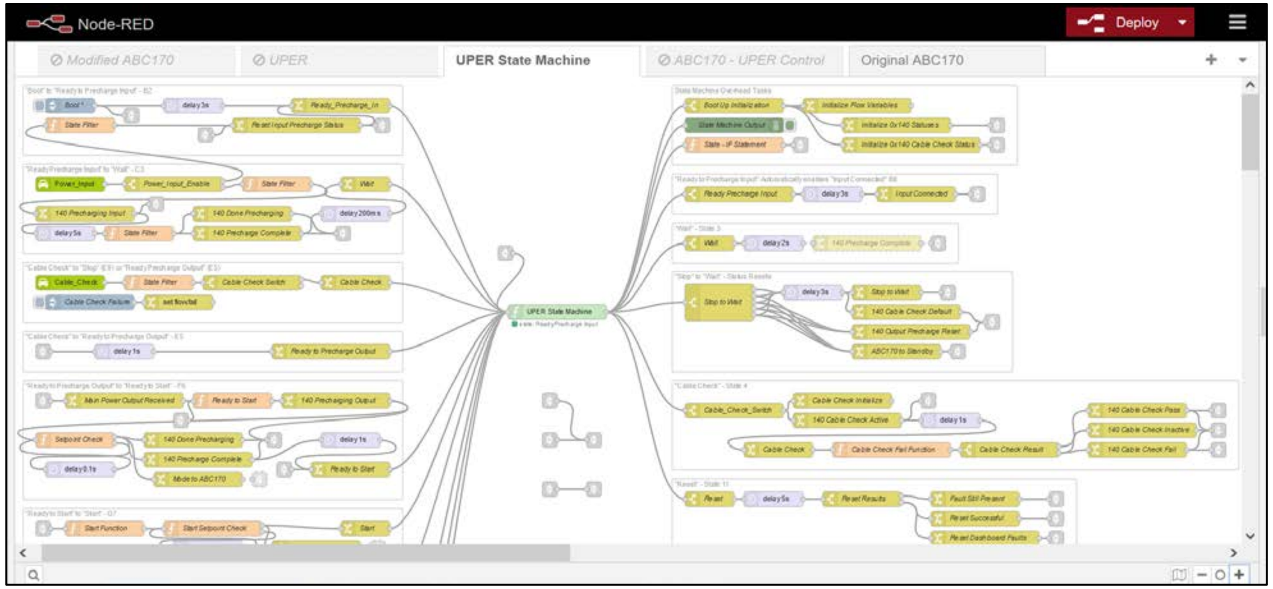
Containerized for Deployment

- CIP.io supports multiple **databases** (InfluxDB, MongoDB, etc.) to store real-time data and access control information

- Custom **control applications** are created in Node-RED, Python and C/C++ where needed

- The historical and real-time data can be visualized on dashboards using the open-source platform **Grafana**

- CIP.io will be used in **eCHIP** due to the high degree of customization required as well as the researchers vast experience with open-source IoT projects that require similar setups



Site Energy Management System (SEM)

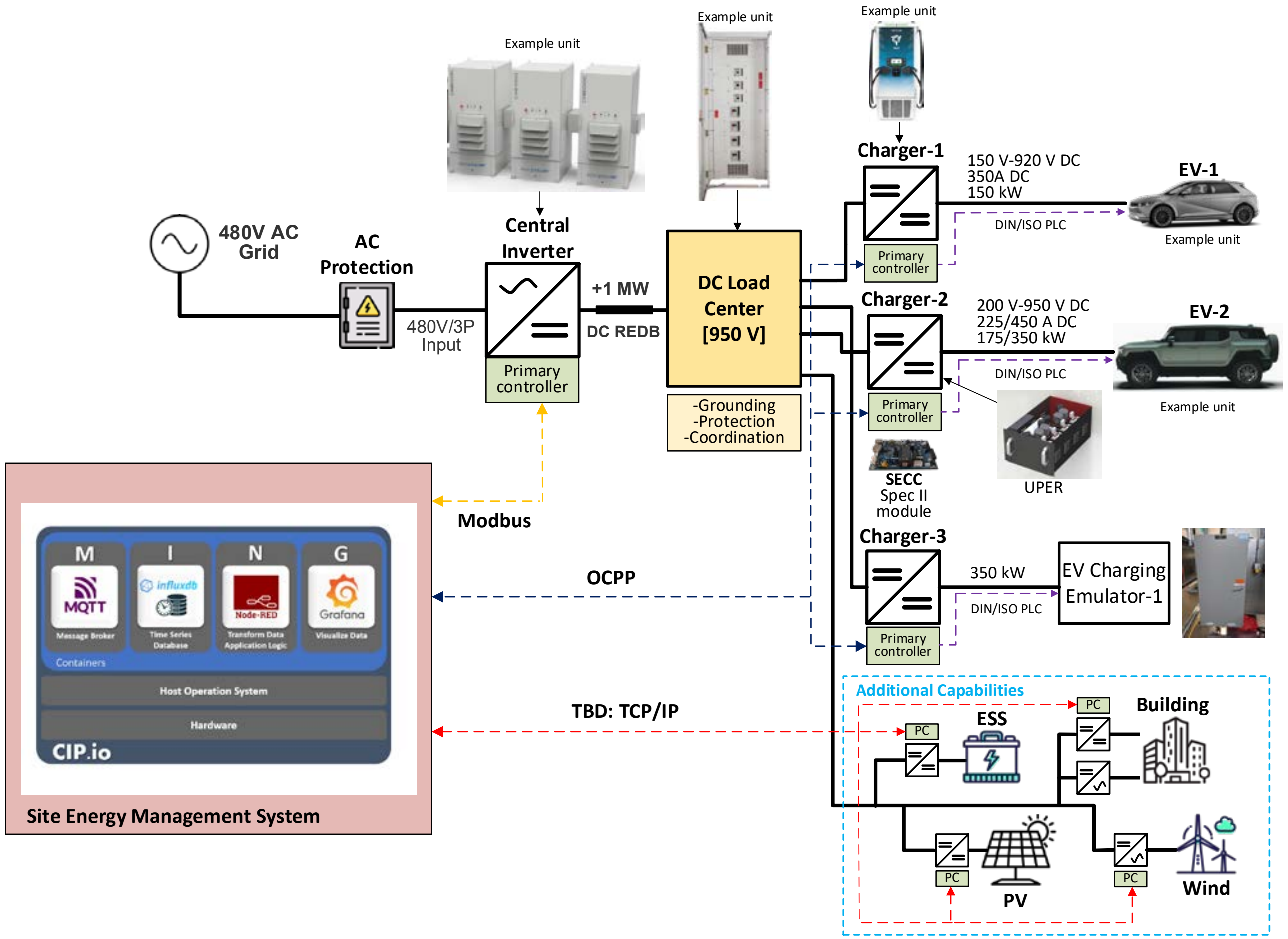
eCHIP

- For eCHIP, the DC-coupled charger will integrate into SEM via Open Charge Point Protocol (**OCPP**) and **MQTT**

- OCPP will be used to handle monitoring and control of EV charging, while MQTT will be used to implement non-standardized DC hub integration monitoring and control (ramp rate, droop control, etc.)

- The current plan is to use an **optimized centralized control architecture** as shown, with plans to explore other architectures later

- The **SpEC module** will handle all site energy management communication for the DC coupled charger, along with communicating with the electric vehicle



Thank You

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OCPP for Smart Charging

- As of 2023, most OCPP-based charge stations have been deployed with **OCPP 1.6-J** (2015)
- Disadvantage of OCPP 1.6-J "charging profiles" is that it does not take into account the needs of the typical EV driver who will likely need the **fastest charging** in the **least amount of time**.
- Using a standard charging profile will deliver only the power *allowed* by the profile at that given time, potentially slowing down a fast charge session.
- Due to this, the deployment of standard charging profiles for high-power DC charging may not always be useful optimal for the EV driver for most fast-charging sessions

OCPP for Smart Charging

- The **ISO 15118-2** and **ISO 15118-20** message stack implemented with **OCPP 2.0.1** address this issue with the use of smarter optimized charging.

- It enables **dynamic demand response** based on the grid's demand, load balancing that adjusts charging rate based on grid capacity and prioritized charging for EVs that need it most.

- Other applications include grid frequency regulation and vehicle-to-grid (V2G) capabilities where EVs can provide energy back to the grid during periods of high demand. A charge scheduler application/logic must be added to the OCPP 2.0.1 CSMS in order to receive the maximum power (Pmax) profiles from the grid operator.

- These will be implemented as **a charge scheduler application**, and on the SEMS.

- The charge scheduler must handle initial charge schedules, initiate renegotiations and handle EV initiated renegotiations. A successfully negotiated charge schedule meets the needs of the EV driver, while the aggregate charge schedules of all EVs managed by the charge scheduler do not exceed the maximum power profile provided by the grid operator.

EVs@Scale

U.S. Department of Energy

eCHIP

Modeling and Control of DC Charging Hub

Emin Ucer, NREL

May 2, 2023

Presentation Outline

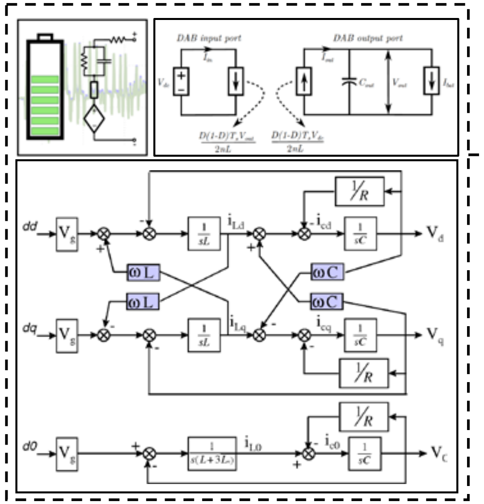
- **Modeling of DC charging hub for C-HIL simulation**
  - Need for Controller-Hardware-in-the-loop environment
  - CHIL Development Progress
- **Development of Site Energy Management Systems (SEMS)**
  - Objectives of SEMS
  - Performance metrics
  - SEMS architectures and their pros/cons
  - SEMS implementation results
    - Centralized architecture
    - Decentralized architecture
- **Conclusions**
- **Q&A**

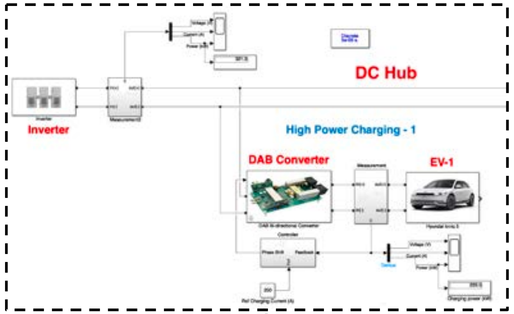
Why do we need a C-HIL platform?

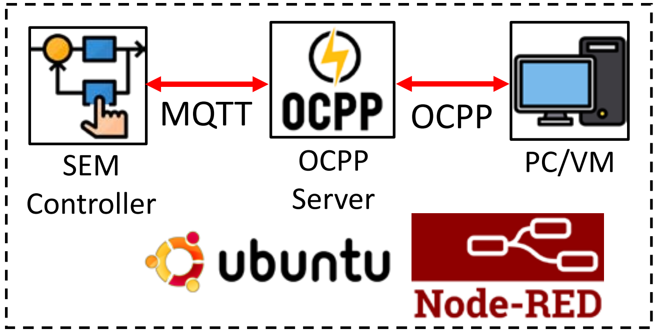
- **C-HIL is a non-destructive platform** for quickly developing, scaling, testing, and verifying any DC hub operation, controller, and SEMS architecture as well as strategy development before the real-world deployment and implementation.

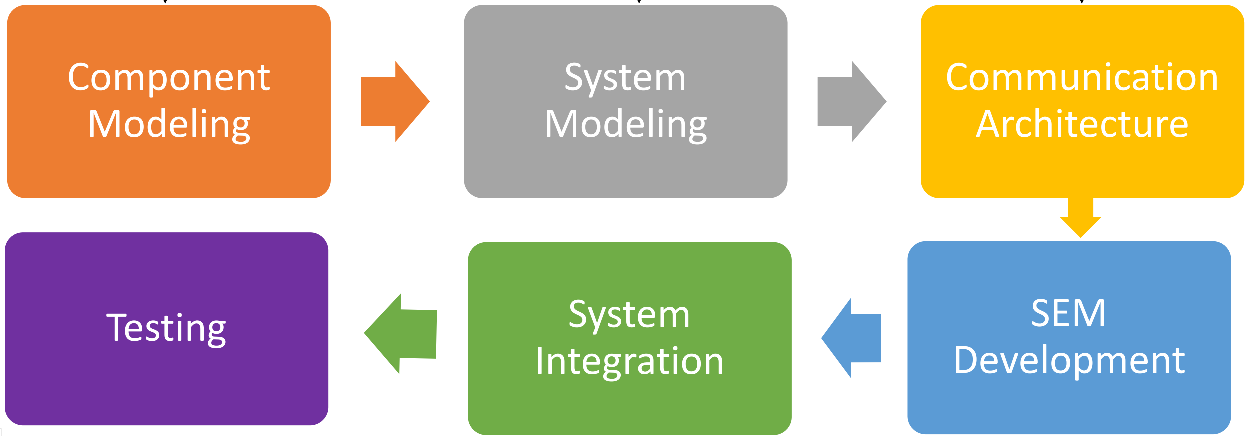
- **To overcome challenges such as**
  - Scalability
  - Safe operation
  - Testing and verification duration
  - Protocol and standard implementation

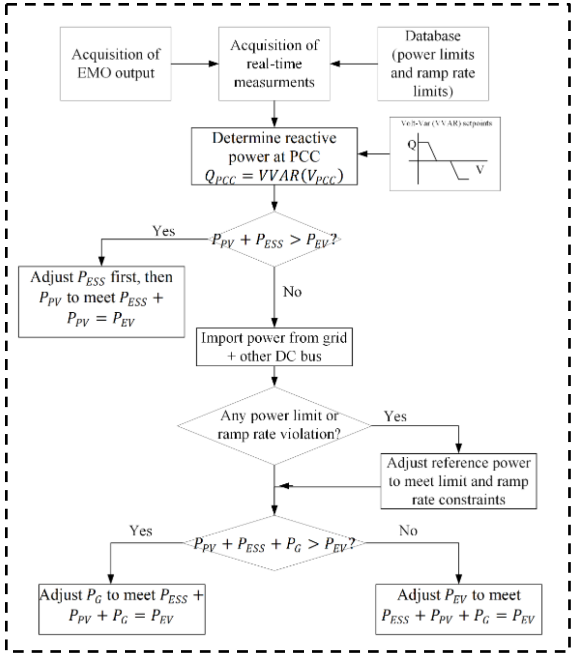
Modeling of DC charging hub for C-HIL simulation

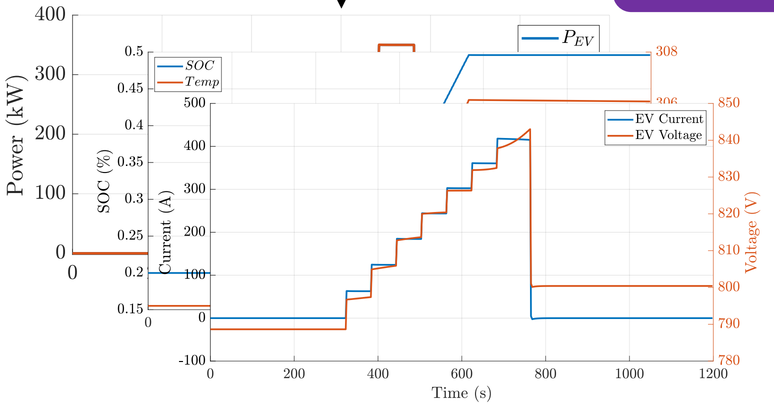


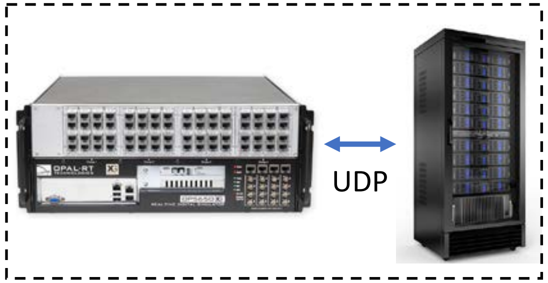






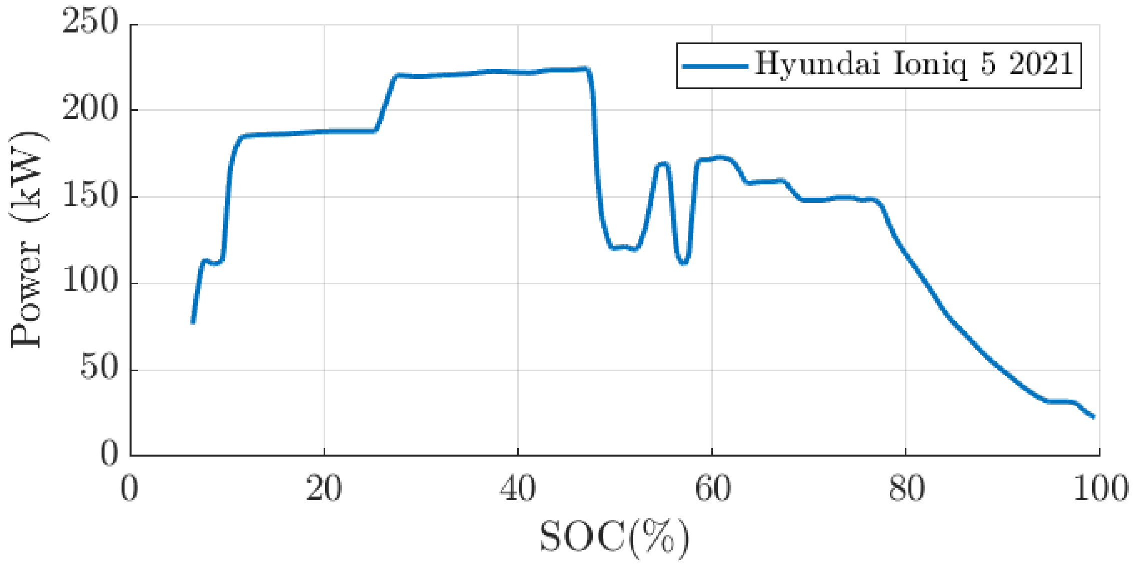




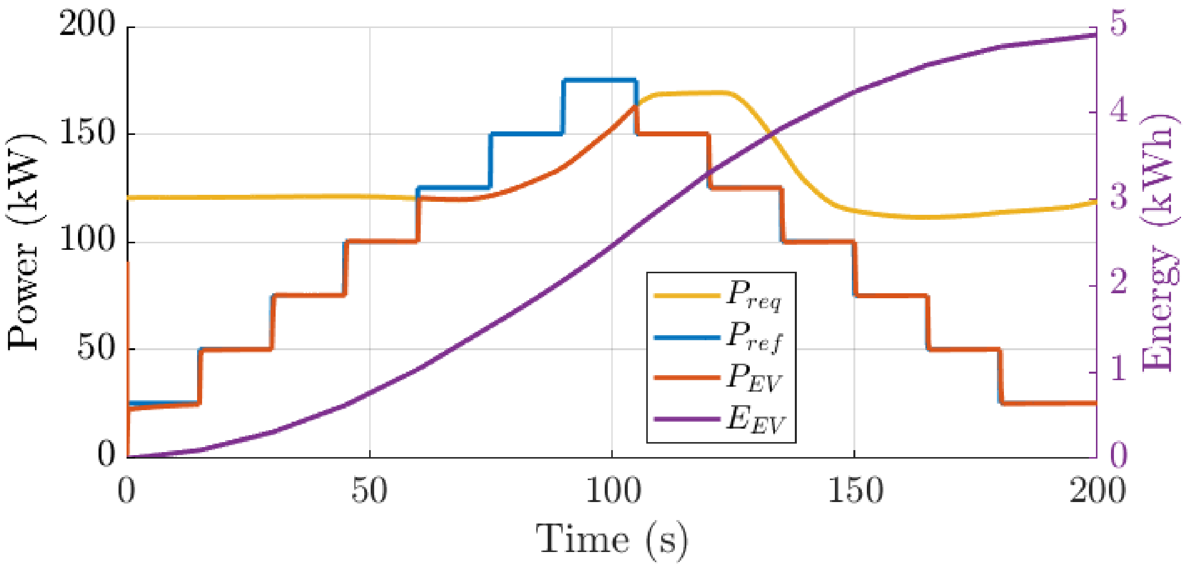


BMS Charge Acceptance

- **BMS charge acceptance** refers to the requested power of the EV battery.
- Depends on physical factors such as battery and ambient temperature and SOC.
- Can significantly limit the decision domain of a SEMS strategy.
- Full charging tests are performed to extract charge acceptance profiles.



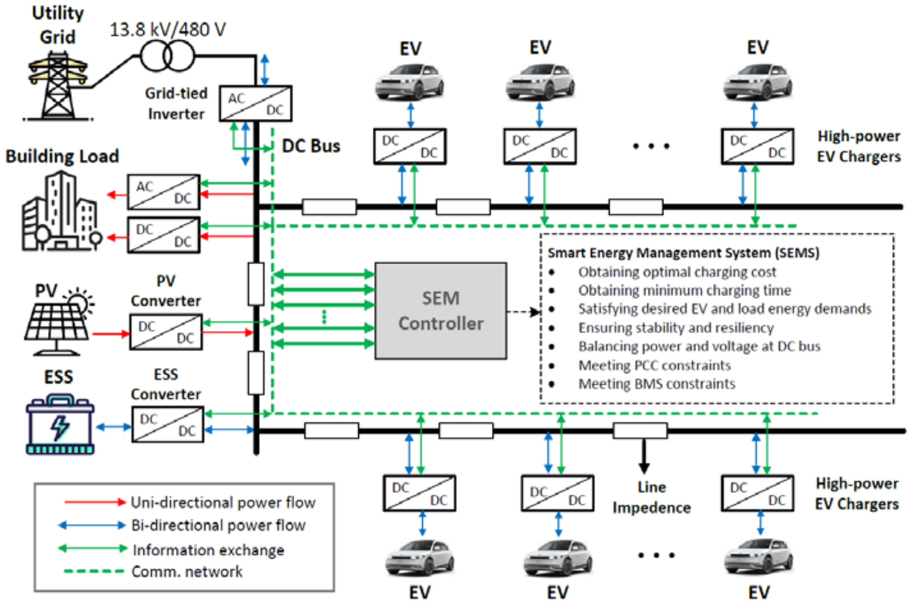
Hyundai Ioniq Charge acceptance curve



EV Charging Power and Energy

Site Energy Management System (SEMS) Development

- **Goal of SEMS** is to coordinate, optimize and monitor hub operations while minimizing its impact on the electricity grid.
- **This involves** coordinating charging of multiple EVs in a way that maximizes the use of distributed energy sources, reduces the cost of electricity, and minimizes the risk of grid overloading or other disruptions.
- **Role and architecture of SEMS** are determined based on operational objectives, design preferences and performance criteria.



Smart Energy Management System (SEMS)
- Obtaining optimal charging cost
- Obtaining minimum charging time
- Satisfying desired EV and load energy demands
- Ensuring stability and resiliency
- Balancing power and voltage at DC bus
- Meeting PCC constraints
- Meeting BMS constraints

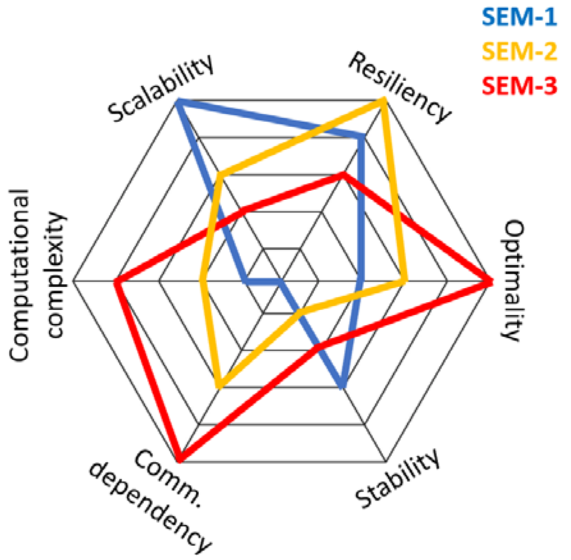
DC hub architecture

Centralized

Decentralized/Distributed

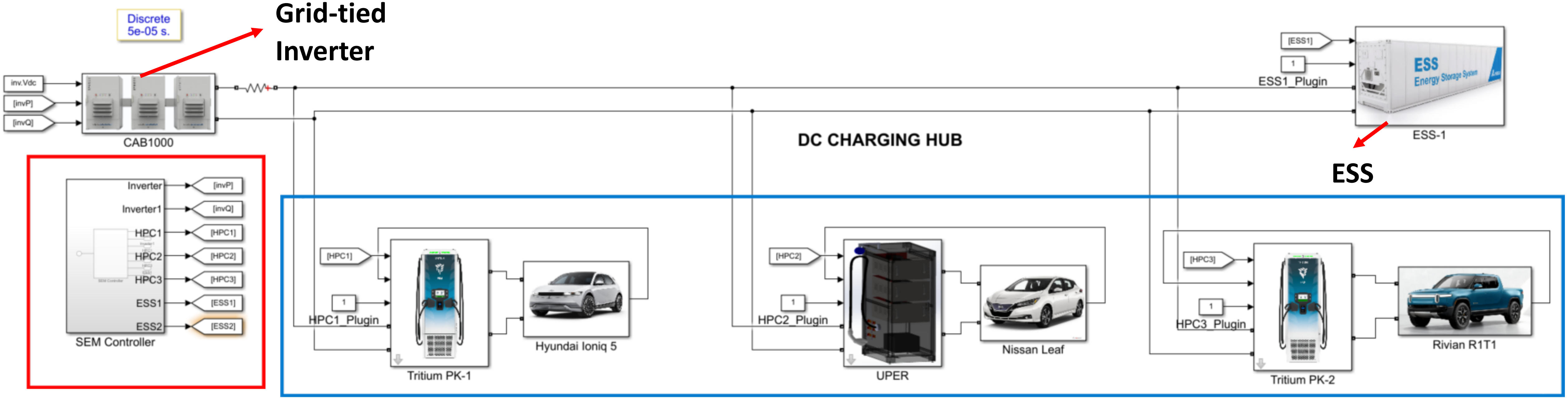
Hybrid

SEMS architecture



SEMS performance

HPC DC Hub Model



Grid-tied Inverter

ESS

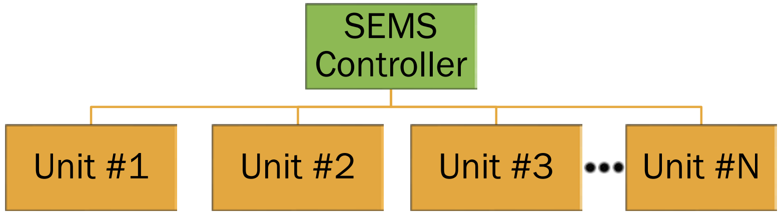
SEMS Controller

HPCs and EVs

- Developed SEMS controller will be demonstrated in this model
- HPC and EV models were developed based on actual hardware/equipment specs and tests
- Extension and scaling of DC hub will continue to include more units (EV, ESS, and PV, etc.)

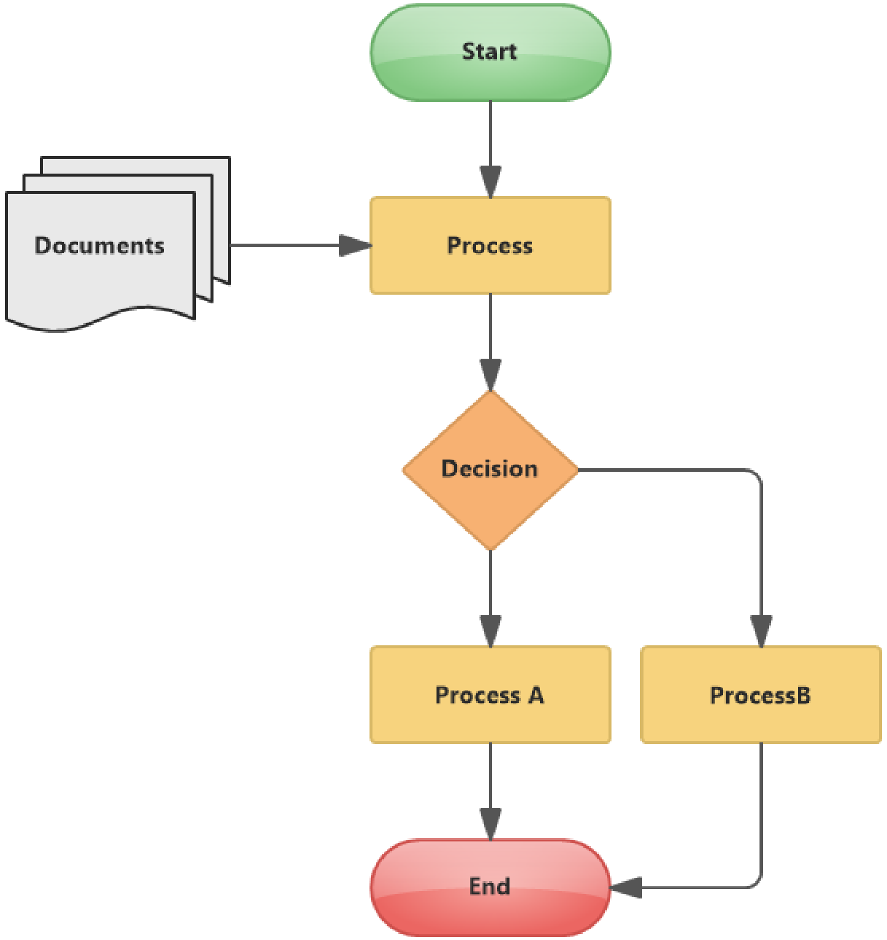
Centralized Architectures

- Pros
  - More optimal operation
  - More complex objective definition
  - More advanced controller development
- Cons
  - Communication dependency
  - High computational complexity
  - Suffer from scalability
  - Vulnerable to single-point failure



- Common objectives
  - Optimizing charging time (customer satisfaction and quality of service (QoS))
    - Prioritizes satisfying EVs' energy demand within dwell time
  - Optimizing operational costs
    - Prioritizes charging EVs at low cost within dwell time
    - Prioritizes using of ESS and PV to reduce costs
  - Providing grid-services
    - Responding to grid-side demand management requests
- Conflicting objectives
  - Trying to achieve all these objectives result in multi-objective optimization with conflicting objectives
  - Pareto solution can be found by using different techniques to solve multi-objective problems
  - Prioritization of objectives can be made based on needs and interests

Centralized Architecture : Rule Based SEMS

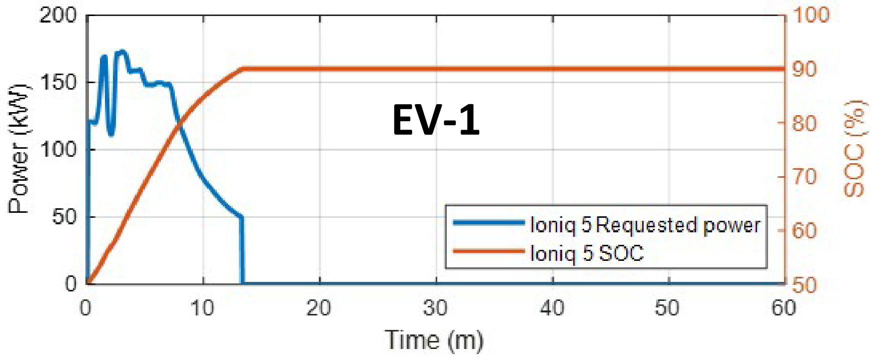


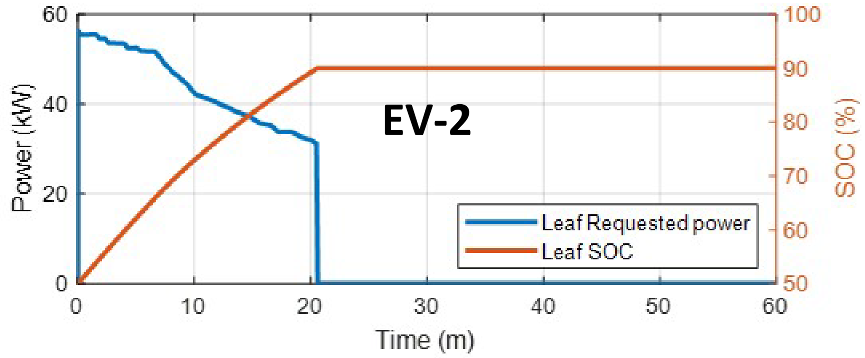
- ✓ Pre-defined, heuristic rules
- ✓ No optimization necessary
- ✓ Fast and simple implementation
- ✓ Power, SOC, and BMS response used
- ✓ Direct power setpoint dispatch

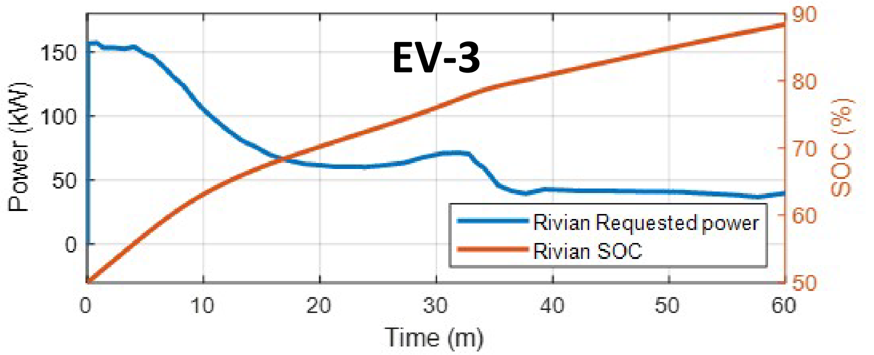
AN EXAMPLE OF RULE-BASED SEMS

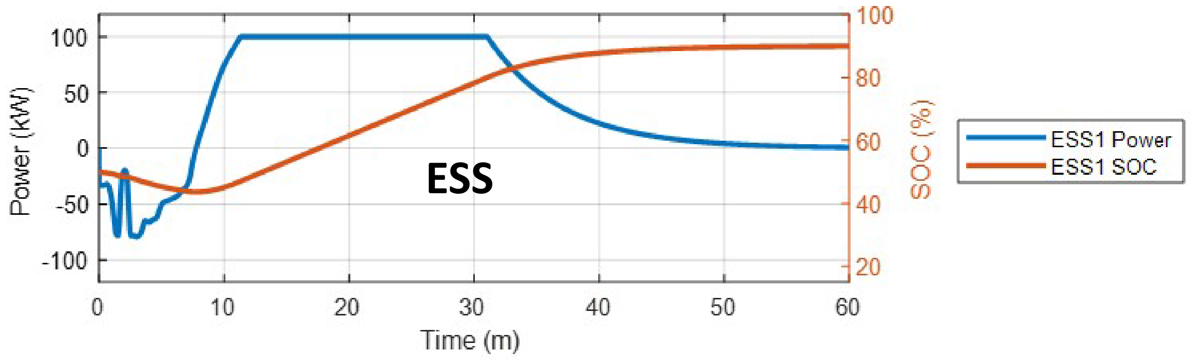
- Charge EVs as soon as possible
- Inverter will try to supply EV load first
- If inverter supply is not enough, ESS will provide remaining power
- If both inverter and ESS are not sufficient to meet load, then EV charging powers will be reduced
- If there is net generation on hub, it will be offered to ESS first, then inverter will supply it back to the grid if necessary.

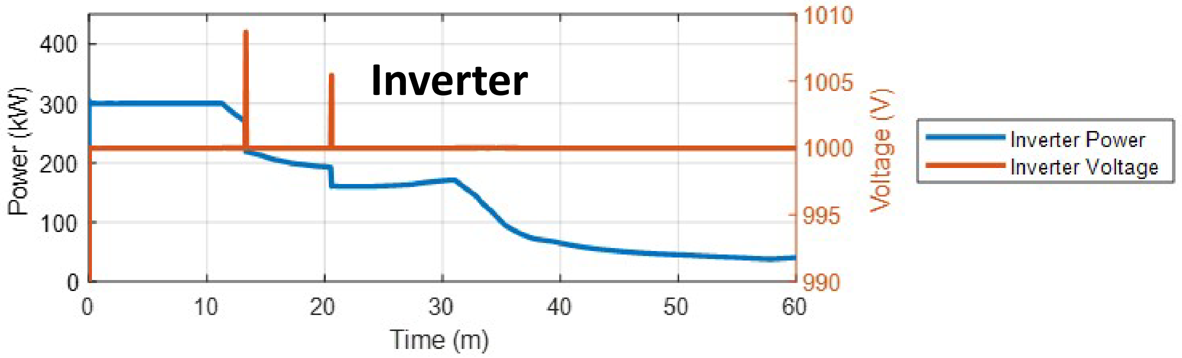
Centralized Architecture : Rule Based SEMS











Remarks

- EVs are charged as soon as possible
- Inverter supplies to loads (EVs) up to 300kW
- Rest of the load is compensated by ESS
- ESS recovers its SOC whenever there is available power in inverter

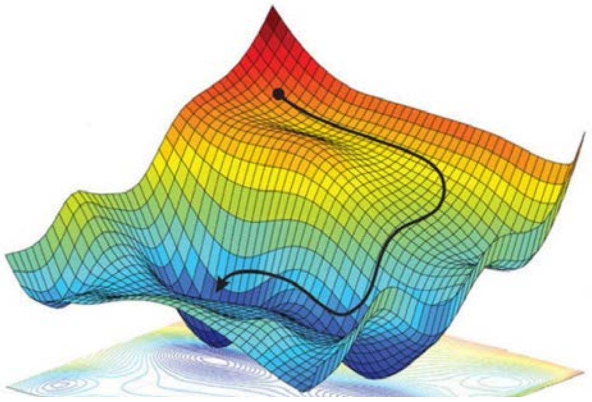
Centralized Architecture : Optimized SEMS

min ʎ(Charging Time) + (1- ʎ)(Charging Cost)

subject to:

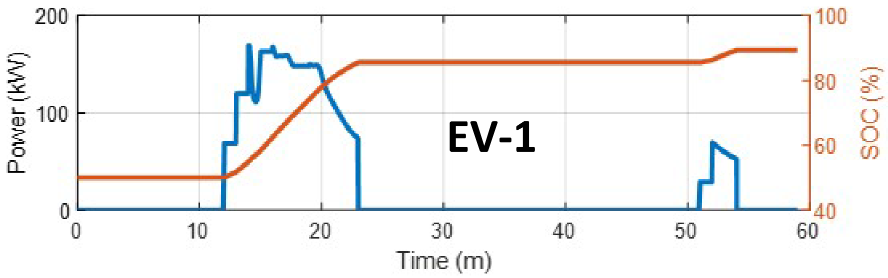
i) Satisfy EV energy demands
ii) Maintain minimum SOC in ESS
iii) Maintain min and max EV powers
iv) Maintain hub power balance
v) Impose ramp-up/down rates

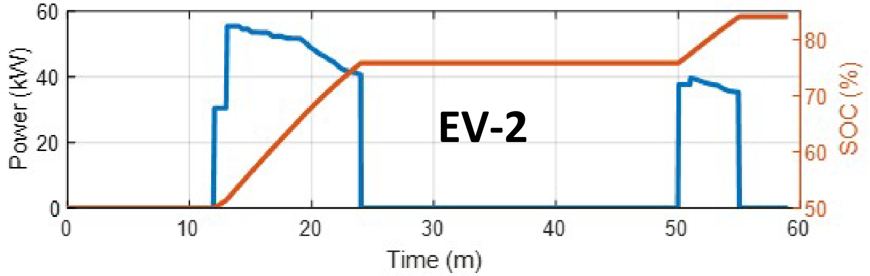
$$\left.\begin{aligned}
\mathbf{P} &:= [\mathbf{P}_{\mathbf{EV}_1}\ \mathbf{P}_{\mathbf{EV}_2}\ \mathbf{P}_{\mathbf{EV}_3}\ \mathbf{P}_{\mathbf{ESS}}]^\top \\
\mathbf{P}_{\mathbf{EV}_1} &:= [P_{EV_1}[0] \cdots P_{EV_1}[N-1]]^\top \\
\mathbf{P}_{\mathbf{EV}_2} &:= [P_{EV_2}[0] \cdots P_{EV_2}[N-1]]^\top \\
\mathbf{P}_{\mathbf{EV}_3} &:= [P_{EV_3}[0] \cdots P_{EV_3}[N-1]]^\top \\
\mathbf{P}_{\mathbf{ESS}} &:= [P_{ESS}[0] \cdots P_{ESS}[N-1]]^\top
\end{aligned}\right\}\ \text{Decision variables}$$

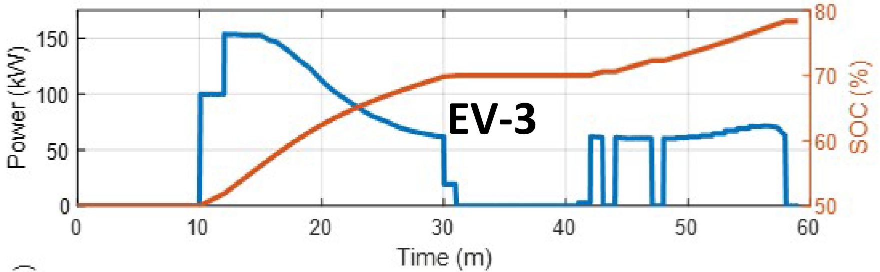


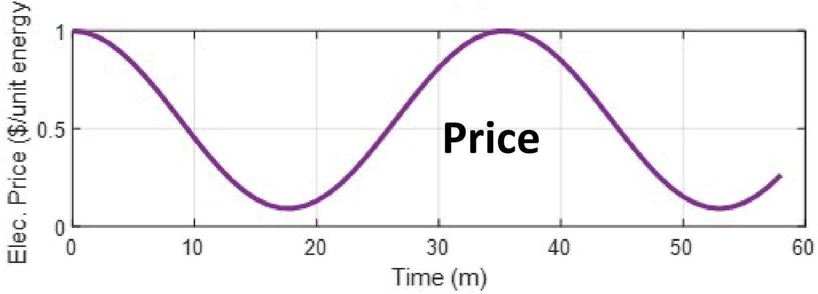
- Objectives are minimizing charging time and charging cost
- Constraints are satisfying EV energy demands, maintaining a minimum SOC in ESSs, ensuring power balance in DC hub
- Ramp-up/down rates can be used to cap power increase/decrease
- BMS response can be used to determine bounds of decision variables
- Prioritization variable can be defined for each objective and unit separately
- Not easy to scale. Each unit and longer time horizons add non-linear complexity
- Can suffer from infeasible regions due to physical constraints
- Relaxations may be frequently required for uninterrupted operation

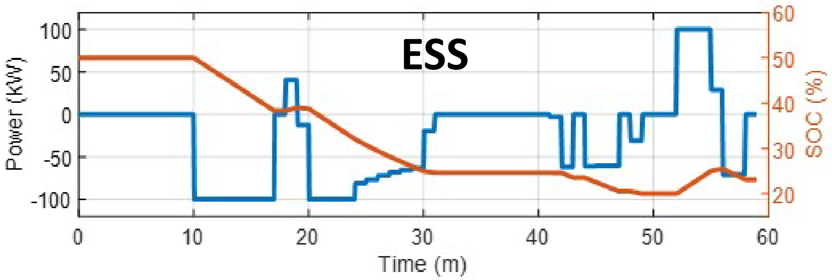
Centralized Architecture : Optimized SEMS

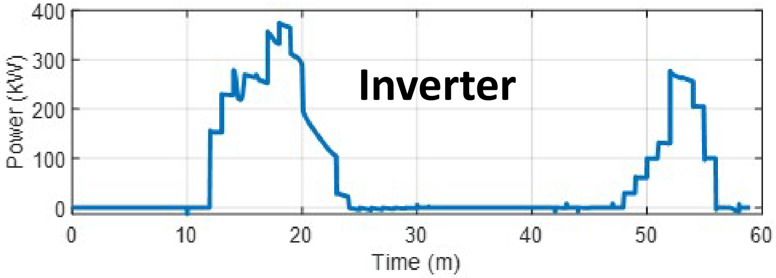










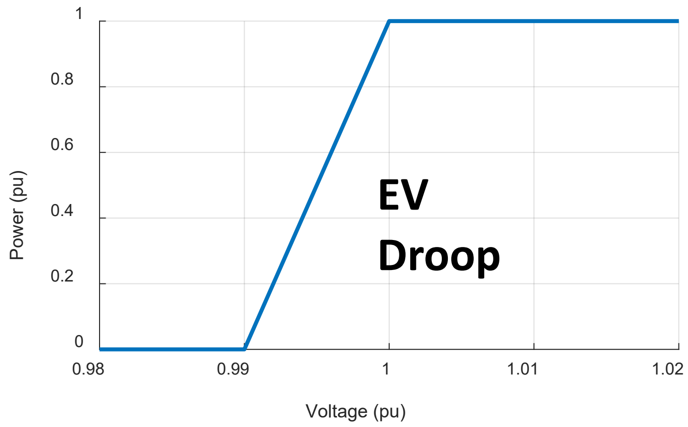


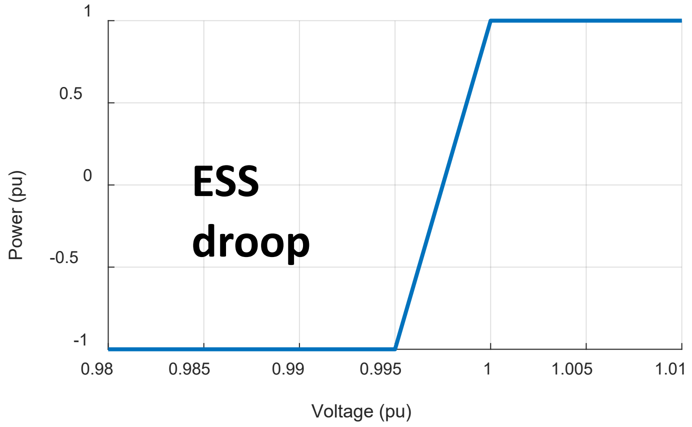
Remarks

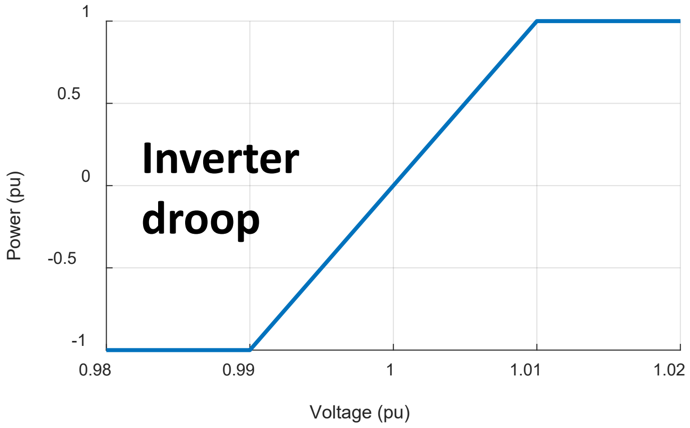
- SEMS prioritizes low-cost charging
- EVs and ESS are charged when the price is low
- ESS SOC is maintained between 20% and 80%
- EV BMS response significantly affects charging decisions

Decentralized Architectures

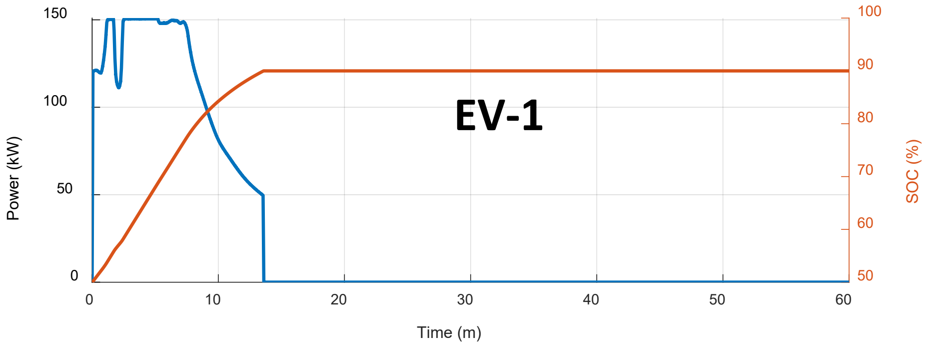
- Pros
  - More autonomous (plug & play) operation
  - No or limited real-time communication
  - More scalable
  - Higher resiliency
- Cons
  - Sub-optimal operation
  - Limited ability for high-level operational objectives
  - Requires voltage-based control
- Common methods
  - Droop control
    - Static droop
    - Adaptive droop
  - Voltage signaling
  - Other action functions P=f(V_{bus})

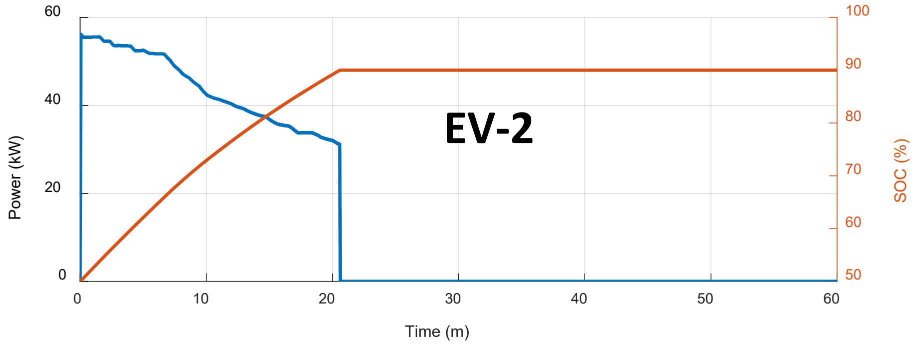


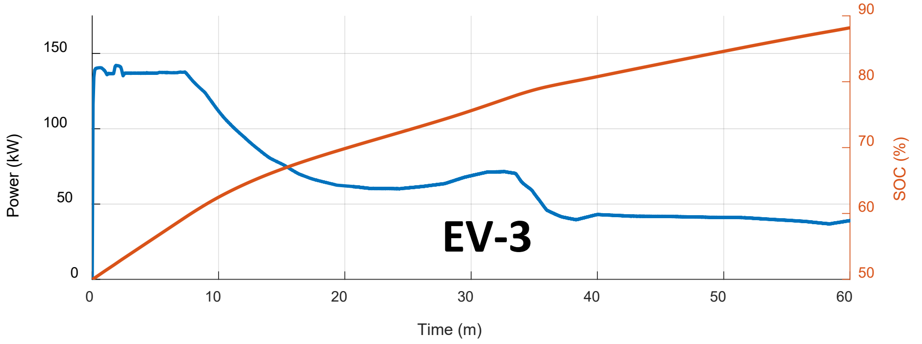


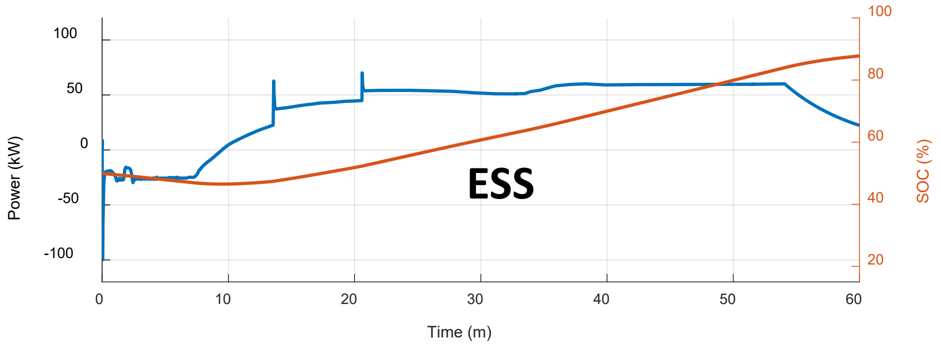


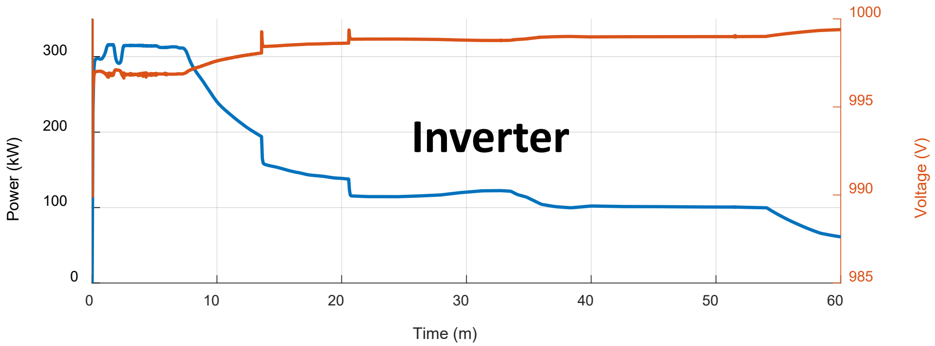
Decentralized Architectures: Static Droop











Remarks

- Each unit follows its droop curve
- ESS helps inverter meet EV demand and
- Power share is proportional droop parameters
- No comm. is required. All autonomous.

Conclusion and Next Steps

- **C-HIL platform** is an important enabler in quickly developing, scaling, testing, and verifying any DC hub operation, controller, and SEMS architecture and strategy development before the real-world deployment and implementation.
- **Defining SEMS** architecture and strategy depends on operational objectives as well as performance metrics.
- **Hybrid SEMS** solutions could be key to taking advantage of both worlds and eliminating risks associated with each solution.
- **Implementation** of developed SEMS solutions through existing protocols and chargers/units will be performed to verify their applicability and evaluate their performances.
- **Use case development** will be critical to explore vocation-specific potential barriers, challenges, and strategies.

Thank You

Questions and Comments

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Centralized Architecture : Optimized SEMS

$$
\begin{aligned}
\underset{\mathbf{P}}{\arg\min} \quad & \lambda \mathbf{c}^\top \mathbf{P} + (1-\lambda) \textstyle\sum_{i=1}^{M} \sum_{k=1}^{N-1} E_{EV_i}[k] \\
\text{s.t.} \quad & E_{EV_i}[k] = P_{EV_i}[k-1] \cdot \Delta k \quad \forall i \in \{1,\cdots,M\} \\
& E_{ESS}[k] = P_{ESS}[k-1] \cdot \Delta k \\
& P_{EV_i}[k+1] \leq P_{EV_i}[k] + R_{up} \\
& P_{EV_i}[k+1] \geq P_{EV_i}[k] - R_{down} \\
& P_{ESS}[k+1] \leq P_{ESS}[k] + R_{up} \\
& P_{ESS}[k+1] \geq P_{ESS}[k] - R_{down} \\
& \textstyle\sum_{k=1}^{N-1} P_{EV_i}[N-1] \cdot \Delta k = E_{EV_i}^{demand} \\
& SOC_{ESS}^{min} \leq SOC_{ESS}[k] \leq SOC_{ESS}^{max} \\
& P_{EV_i}^{min} \leq P_{EV_i}[k] \leq P_{EV_i}^{max} \\
& P_{ESS}^{min} \leq P_{ESS}[k] \leq P_{ESS}^{max} \\
& 0 \leq \textstyle\sum_{i=1}^{M} P_{EV_i}[k] + P_{ESS}[k] \leq P_{inv}^{rated}
\end{aligned}
$$

$R_{up} > 0$: Ramp rate (up)
$R_{down} > 0$: Ramp rate (down)
$0 \leq \lambda \leq 1$: Prioritization coefficient
$N-1$: Time horizon

$$
\left.
\begin{aligned}
\mathbf{P} &:= \left[\mathbf{P_{EV_1}}\ \mathbf{P_{EV_2}}\ \mathbf{P_{EV_3}}\ \mathbf{P_{ESS}}\right]^\top \\
\mathbf{P_{EV_1}} &:= \left[P_{EV_1}[0] \cdots P_{EV_1}[N-1]\right]^\top \\
\mathbf{P_{EV_2}} &:= \left[P_{EV_2}[0] \cdots P_{EV_2}[N-1]\right]^\top \\
\mathbf{P_{EV_3}} &:= \left[P_{EV_3}[0] \cdots P_{EV_3}[N-1]\right]^\top \\
\mathbf{P_{ESS}} &:= \left[P_{ESS}[0] \cdots P_{ESS}[N-1]\right]^\top
\end{aligned}
\right\} \text{Decision variables}
$$

- A model predictive control (MPC) approach
- Objectives are minimizing charging time and charging cost
- Constraints are satisfying EV energy demands, maintaining a minimum SOC in ESSs, ensuring power balance in DC hub
- Ramp up/down rates can be used to cap power increase/decrease
- BMS response can be used to determine bounds of decision variables
- Prioritization variable can be defined for each objective and unit separately
- Not easy to scale. Each unit and longer time horizons add non-linear complexity
- Can suffer from infeasible regions due to physical constraints
- Relaxations may be frequently required for uninterrupted operation

Breakout Session Notes
HPC Ecosystem

No	Topic Discussed	Feedback / Takeaways
1	User Charging Experience / Standard Ratings	1. Focus on peak power ratings can lead to end user dissatisfaction because those power levels are only attained under a narrow set of conditions. 2. End users should be provided with additional information explaining what factors are determining their instantaneous charge power and overall charge time. 3. Potential for standardized charge speed ratings (e.g. miles per minute) to allow comparison between vehicles but a rating need to be selected and more definition is needed on how to consistently determine that rating. 4. SAE J2954 committee has had conversations around standardizing charge rate reporting.
2	Industry Participation	1. Partners receive access to the timeseries data for their own asset and anonymized timeseries data of the other partners. 2. With enough participation, the public facing report can help inform end user expectations on charging speeds under different conditions.
3	Grid Interconnection for Charging Stations	1. EVSPs intending to utilize BESS or smart charge management tend to be required to go through a full interconnection process. Otherwise, you get a basic service feed. 2. More research is needed to simplify the interconnection process for EV charging stations utilizing these technologies. 3. Additional clarification needed here on where research can impact this challenge vs process / policy development. 4. Potential for research on how to size interconnects, incorporating expected utilization, charge curves, BESS, etc.

Notes
Design and Implementation Approach of DC Charging Hub

No	Topic Discussed	Feedback / Takeaways
1	What is driving the DC hub bus voltage selection?	1. The available grid-connection inverters are one limit on the DC bus voltage. 2. Semiconductor module voltage ratings also constrain the DC bus voltage. 1200 and 1700 V switching modules are available, which can support up to 800 and 1100 V, respectively.
2	EVSE DC-DC topology selection	1. Since DAB, LLC, and CLLC topologies have similar number of semiconductor devices and similar high-frequency transformers, their differences in power density and cost are minimal. Therefore, DAB was selected for the UPER module due to its greater controllability. 2. Another question related to the UPER DAB's efficiency over the full load cycle, and if the ZVS can be maintained over such a wide range. It was explained that UPER has uses a modified modulation strategy to enable ZVS over a very wide operating region. 3. There was discussion around the expected vehicle battery voltage ranges that an EVSE DC-DC (and specifically UPER) must operate with. Considering the range of vehicle voltage levels, 200 – 900 V range is expected. Since around 4:1 conversation ratio is necessary, it was asked if it was still reasonable to achieve this with a single DAB converter as opposed to two conversion ranges. The advanced modulation scheme in the DAB was said to enable ZVS even at large step-down ratios. Multiple transformer taps can be used to switch between 2:1 and 4:1 conversion ratios.
3	DC distribution approach	1. Participants were generally supportive of a DC distribution approach for vehicle charging. 2. However, there were some concerns over some aspects of DC distribution. The lack of standardization was discussed, with one participant suggesting that NEC code, specifically article 625, is lacking for DC distribution. IEC standards for EVSEs were also mentioned. However, it was suggested that their uptake in the US may be limited. 3. Additionally, DC protection remained a concern for some participants with the challenges of DC breakers and circuit interruption being highlighted. 4. Prior feedback from the consortium biannual meeting was referenced, in which survey respondents selected the lack of product maturity for DC/DC charging systems as the largest barrier to implementation of a DC hub system (ranked choice of 5 options)

Breakout Session Notes

Modeling and Control of DC Charging Hub

EVs@Scale
U.S. Department of Energy

No	Topic Discussed	Feedback / Takeaways
1	Thoughts on publicly accessible DC charging?	1. From utility grid perspective, it's inevitable that it will be curtailed, just not in a way that prevents fast DC charging. 2. It is a scheduling problem that takes advantage of locations, times, prices, communication with vehicle, etc. 3. Controlled service point – facility gets a maximum block of power to operate within and needs to follow the load schedule. Can use storage to compensate for changing schedule, but sites will not be allowed to exceed the cap, otherwise there may be penalties instead of directly affecting operation 4. In VGI – important to elevate driver to #1 priority, and fleet or grid managers need to figure out how to serve. Site managers using DERMs can provide service using storage even if grid is impacted
2	What about tariffs in future when EVs are more common?	1. Unsure how effective timing and tariffs are at this time – maybe around 20-30%. Studies are being done to verify. 2. In CA, project to implement dynamic pricing, project with price calculators with pricing sent to customers and they make decisions 3. Generally, this is way too complex for customers. Involves too much hand waving, and someone has to operate a computer to act on the receiving signals. It should be a system automatically managing all of this
3	What other common objectives of SEMS should researchers investigate in eCHIP project?	1. Industry is looking to learn as well. Several projects lined up to understand DC service at distribution level. Benefits of AC vs DC hubs need to be demonstrated clearly. 2. Need to have solid use cases for DC hubs from business perspective as well as control perspective, i.e. how can it be managed and how are protections done with minimal impact 3. Interested in stitching together a vision for future by working together with labs to build and test it out, along with building new technical and business use cases.