High-Efficiency, Medium-Voltage Input, Solid-State, Transformer-Based 400-kW/1000-V/400-A Extreme Fast Charger for Electric Vehicles

DE-EE0008361 **ELT241**

Dr. Charles Zhu, Principal Investigator
Delta Electronics (Americas) Ltd
June, 2021

Project Overview

Timeline

- Start – December 1, 2018
- Finish – November 30, 2021
- 75% complete

Budget

- Total Budget: $7.0 million
  - DOE Cost Share: $3.5 million
  - Recipients Cost Share: $3.5 million
- 2021 Funding Planned: $1.7 million

Barriers

- System architecture and control for solid state transformer
- Medium-voltage isolation
- Power cell topology and control for high efficiency
- SiC semiconductor devices with high dv/dt and noise

Team

Lead: Delta Electronics Americas Ltd

Partners:

- General Motors
- DTE Energy
- CPES at Virginia Tech
- NextEnergy
- Michigan Energy Office
- City of Detroit

Relevance Project Objectives

- **AREA OF INTEREST (AOI) 1: Extreme Fast Charging (XFC) Systems for Electric Vehicles**
- **Delta Electronics aims to achieve objectives by the end of program**
  - To design and test a high-efficiency, medium-voltage-input, solid-state-transformer-based 400-kW Extreme Fast Charger (XFC) for electric vehicles, achieving better than 96.5 percent efficiency.
  - To demonstrate extreme fast charging with a retrofitted General Motors' light-duty battery electric vehicle at 3C or higher charging rate for at least 50 percent increase of SOC.
  - To achieve a 180-mile charge within 10 minutes.

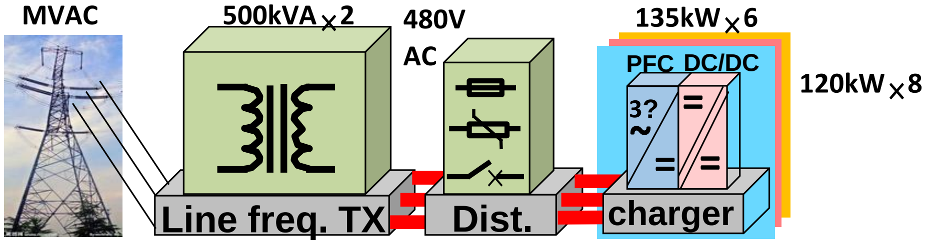
Budget Period 2 Milestones

BP2: 12/1/2019 - 11/30/2020				
Planned Date	Mile-stone #	Milestone	Achievement	
2/28/2020	M2.1	HVDS/RESS Build and Functional Test Complete	HVDS/RESS Build and Functional Test demonstrates compliance with specifications	✓
5/31/2020	M2.2	3-Phase 135kW Charger Integration and Test Complete	3-Phase 135kW Charger Test demonstrates compliance with specifications	✓
8/31/2020	M2.3	4.8kV 400kW XFC mechanical design complete	4.8kV/13.2kV 400kW XFC mechanical design complete for system prototype making	✓
11/30/2020	M2.4	4.8kV 400kW XFC Lab Test Complete	4.8kV 400kW XFC Lab Test Results demonstrate compliance at partial power	✓ 13.2kV 400kW
11/30/2020	BP2	4.8kV 400kW XFC Build Complete	The 4.8kV 400kW XFC system build is complete and fully functional with at least 96% efficiency	✓

Approaches

- Medium-voltage AC input, 4.8-kV and 13.2-kV
- Solid state transformer (SST)-based technology to reduce the size and weight, and to increase scalability and flexibility
- Cascaded multilevel converter topology as medium voltage interface to reduce the total number of power cell
- Multilevel resonant converter for medium voltage isolation, operated at high frequency with soft switching
- SiC MOSFET devices for high voltage and lower loss
- Interface to an Energy Storage System (ESS) and/or a renewable energy generation system (e.g. PV)

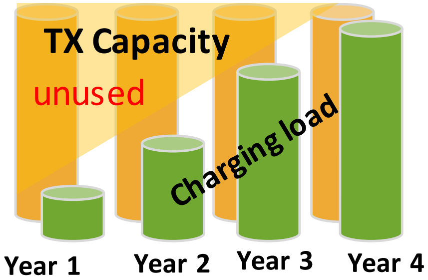
Conventional DC Fast Charger



Efficiency: 99% × 99.3% × 95% = 93.4%

Footprint: 50 ft^2 + 40 ft^2 + 20 ft^2 = 110 ft^2

Installation site for Tesla Super Charger in U.S.A

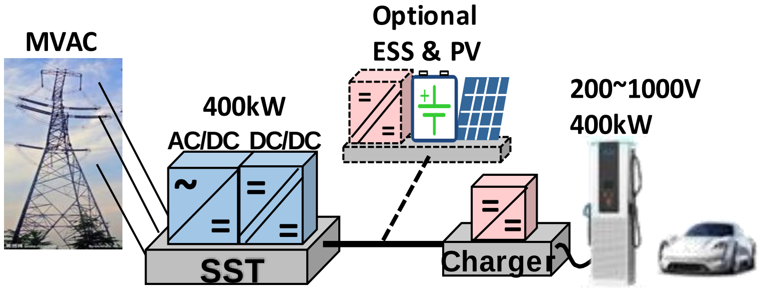


- **Bulky and heavy**
- **Fixed voltage & power**

- **Space consuming**
- **Labor intensive**

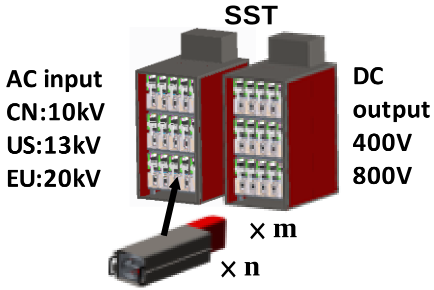
- **Non expandable capacity**
- **High initial investment**

Proposed Extreme Fast Charger

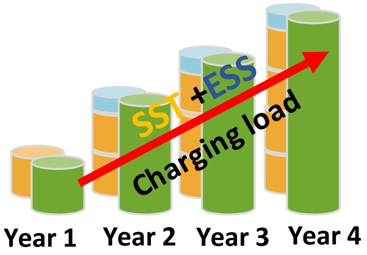


Efficiency: 97.5% × 99% = 96.5% **Increased by 3%**

Footprint: 28 ft^2 + 10 ft^2 = 38 ft^2 **Reduced by 50%**



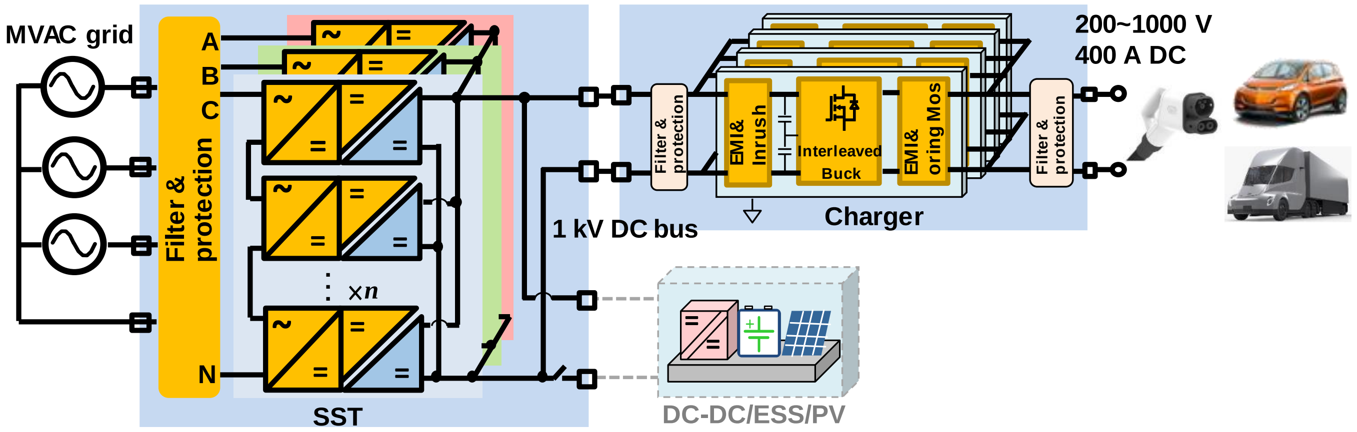
Conceptual SST based extreme fast charging station



- Modularized structure
- Scalable voltage/power

- Expandable capacity
- Lower initial cost

SST based XFC System Architecture



3-Φ MVAC input:
- 4.8kV/13.2kV
- iTHD<5%, PF≥0.98
- 60Hz±10%

SST DC output:
- 1050V±3%
- 400kW power
- Interface for ESS/PV

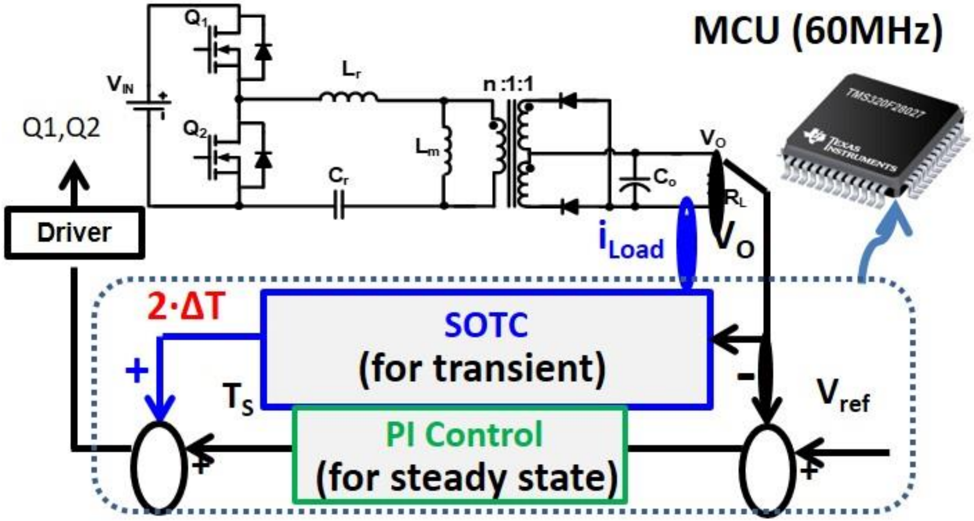
Charger output:
- 200V~1000VDC
- 400A max current
- SAE J1772 charging interface CCS1

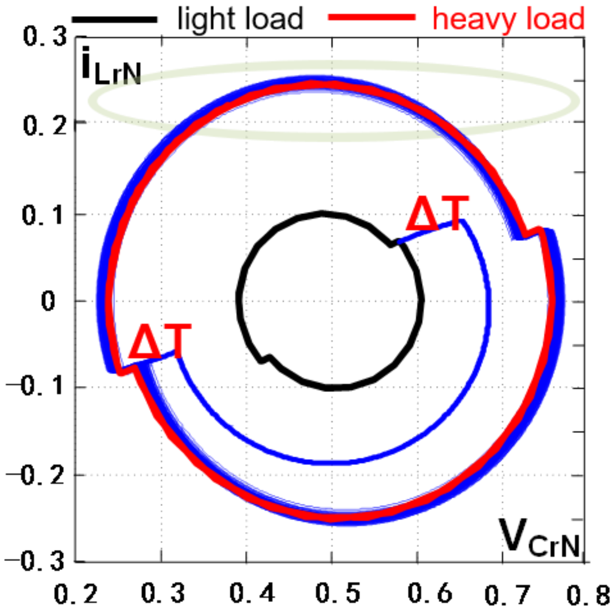
XFC Specification

Power Rating	400 kW
Input AC Voltage	4.8 kV and 13.2 kV, 3-Phase, line-to-line
AC Line Frequency	60 Hz
HV Battery Voltage Range	200-1000 VDC
Maximum Output Current	Continuous 400ADC, peak 500ADC
Efficiency	Target 96.5% peak. Test result 97.5% peak.
Charge Interface	J1772 CCS1
Operational Ambient Temperature Range	-25 to 50°C
Environmental Protection	NEMA 3R (outdoor)
Additional Interface	HVDC interface (to ESS/renewable energy source)

Technical Progress

Simplified Optimal Trajectory Control (SOTC) for Resonant Converter

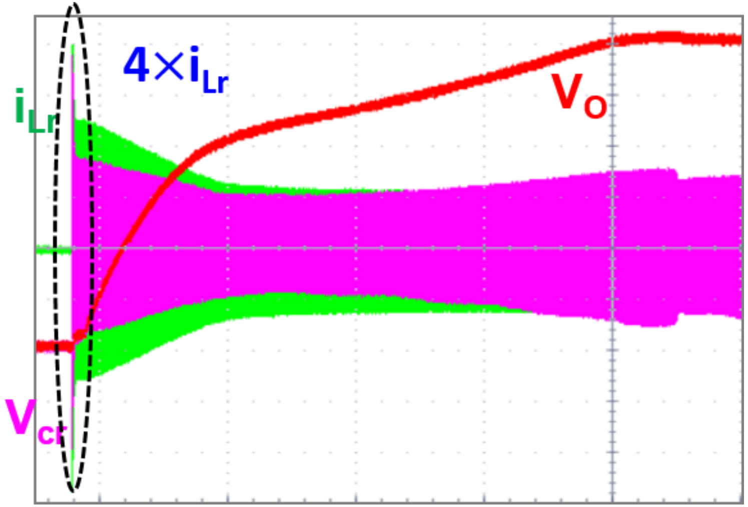


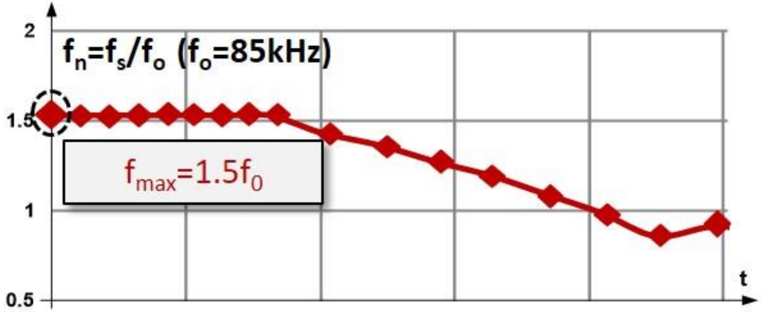


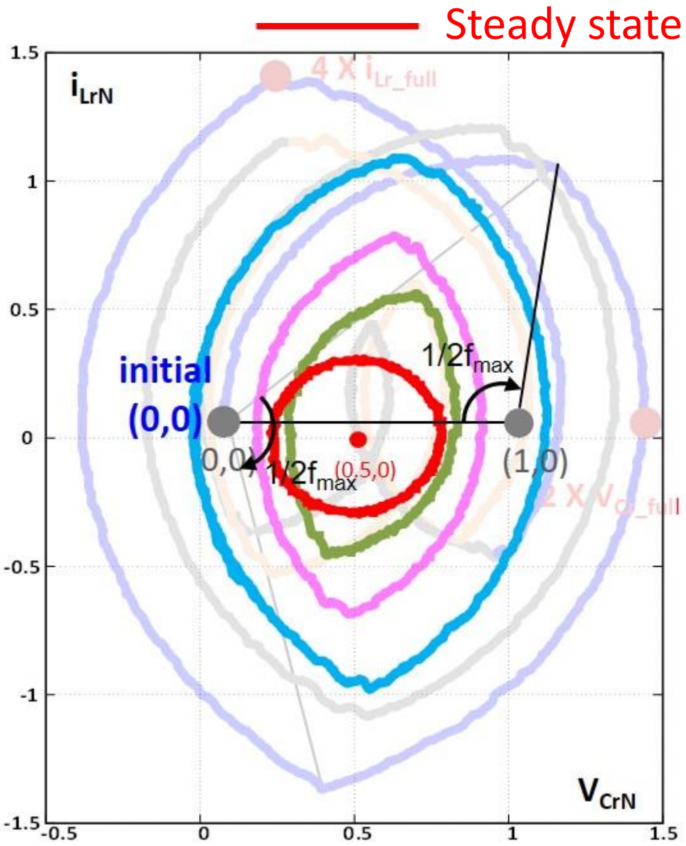
- SOTC settles resonant tank to around the optimal point
- PI control eliminates the small steady-state error
- Applied into load transient, start-up and short circuit protection, and burst mode

Ref: Choao Fei. "Optimization of LLC Resonant Converters: State-trajectory Control and PCB based Magnetics ." PhD dissertation, Virginia Polytechnic Institute and State University, 2018.

Resonant Converter Start-up without SOTC

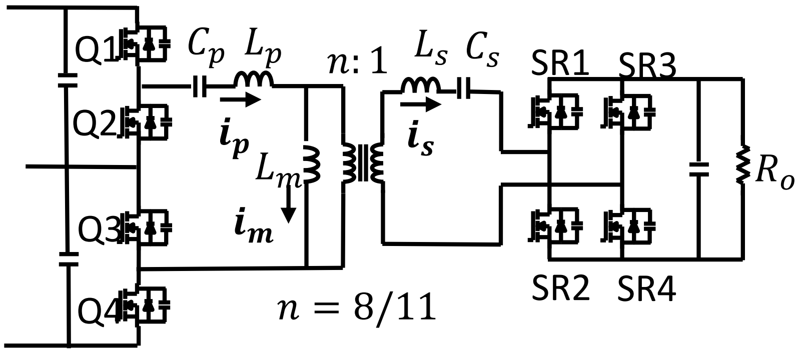


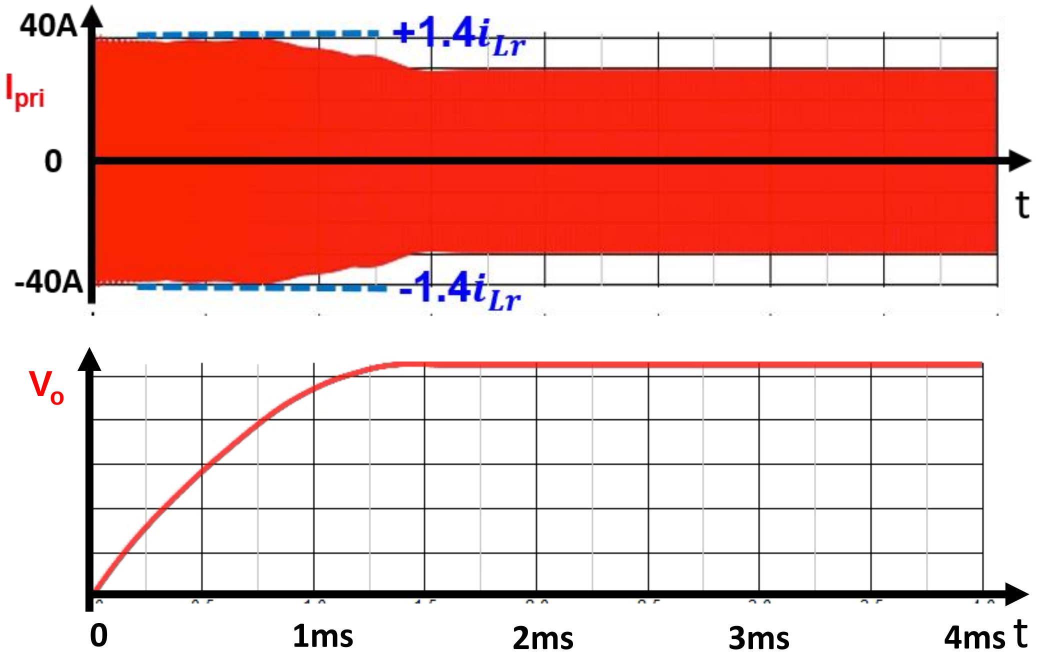




i_{Lr} stresses = 4 × full load stress

CLLC Start-up with SOTC

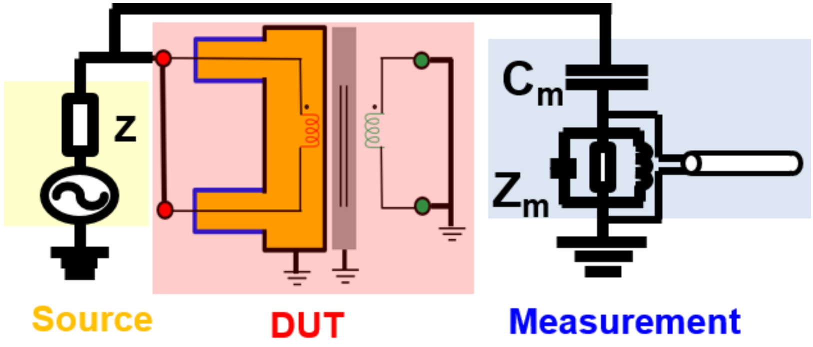




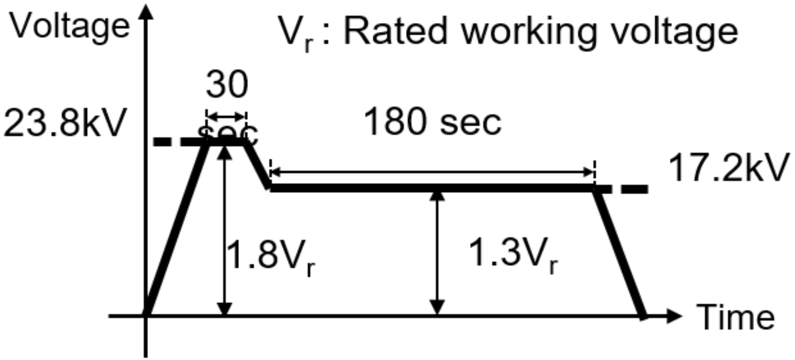
i_{Lr} **stresses < 1.4 × full load stress.**

Transformer Insulation

Partial discharge (PD) test equivalent circuit



Partial discharge (PD) test source waveform



IEC60076-3 Requirement: partial discharge < 50pC @ 17.2kV

Litz wire jacketed in Teflon sleeve
Blocks material penetration and air escape.

$PD > 50pC\ @8.2kV$ **Fail the test**

Litz wire wrapped in yarn
Allows material penetration and air escape.

$PD = 12pC\ @17.2kV$ **Pass the test !**

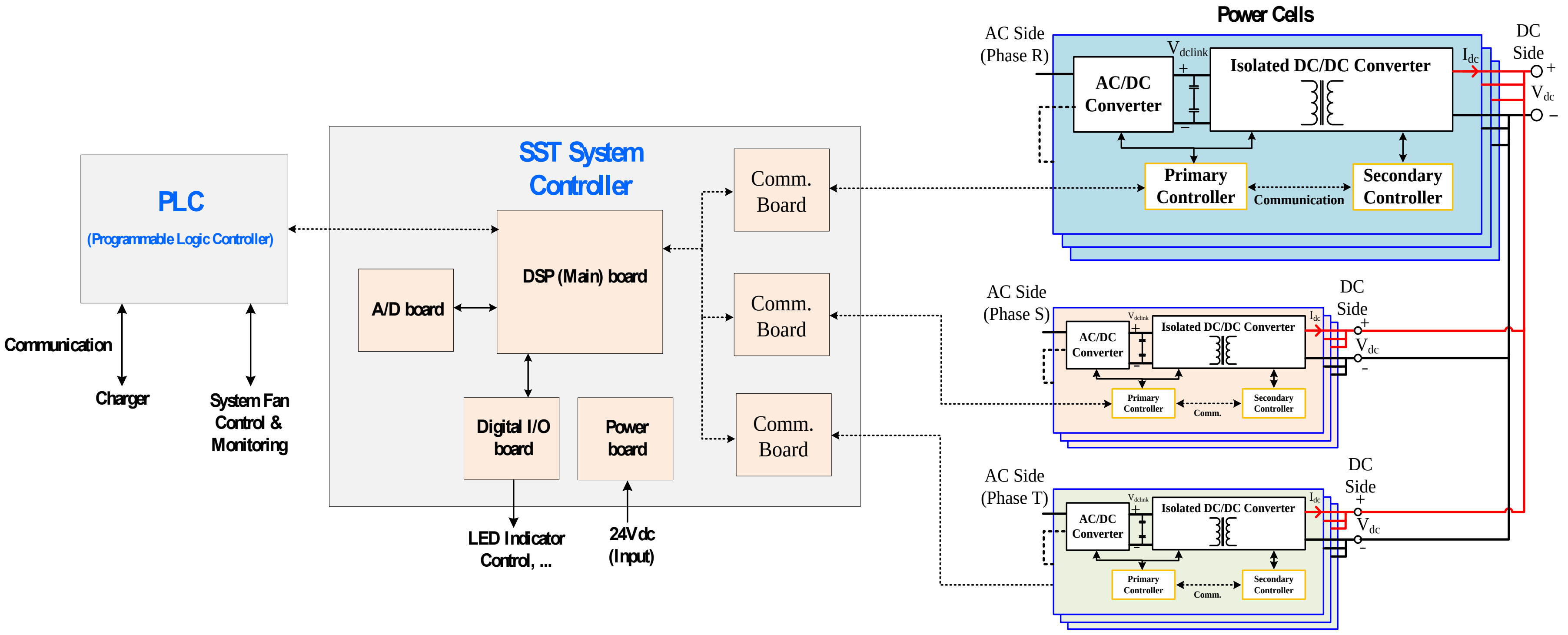
13.2kV 400kW System Test Setup

Charge Dispenser User Interface

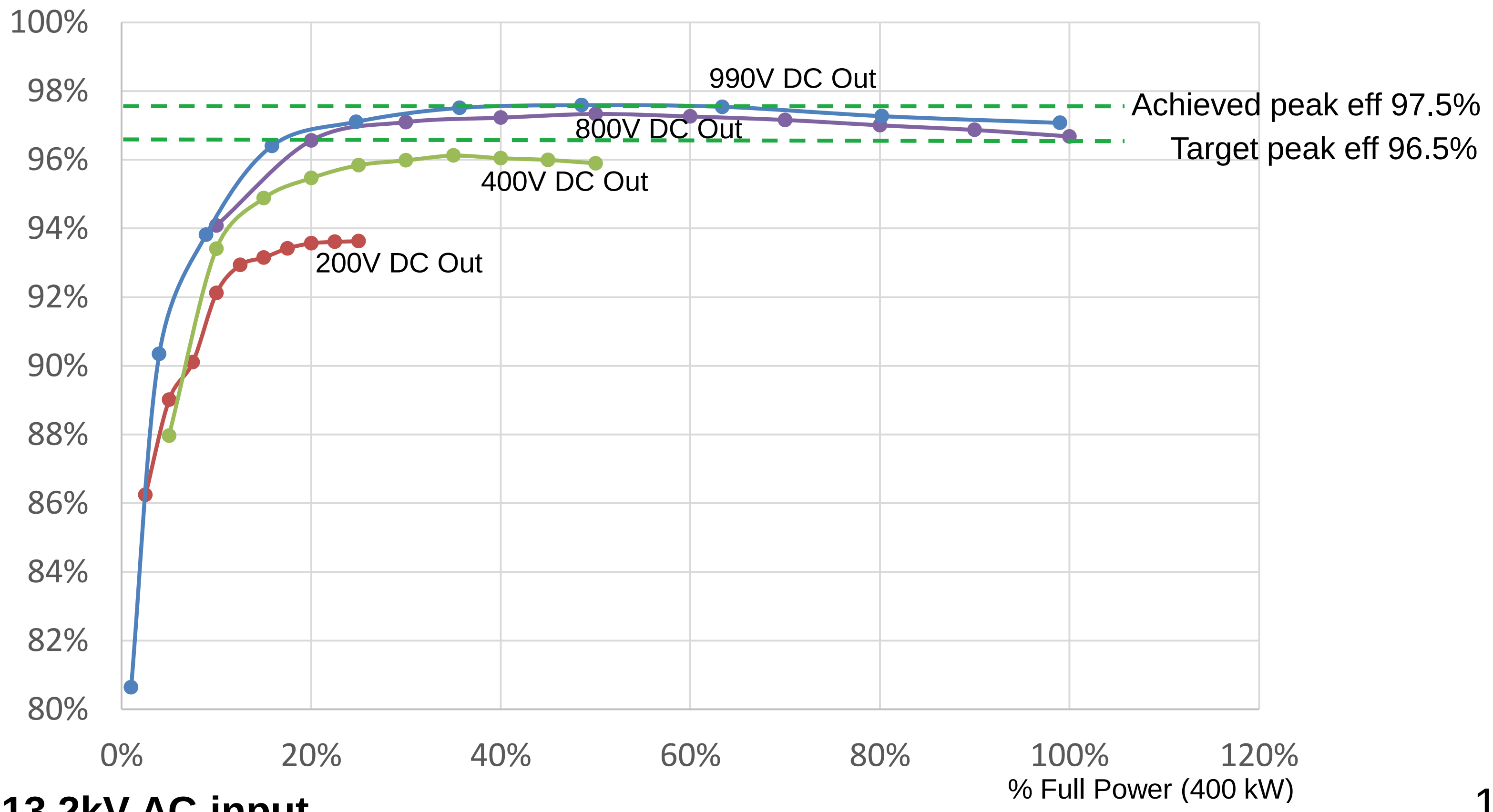
Test with battery emulator
- Input 13.2kVac,
- Output 200V-990V, up to 500A;
- Full range up to 400kW

Charge test with Chevy Bolt.
Up to 400V/100A, limited by the vehicle.

3-Phase SST Control Architecture

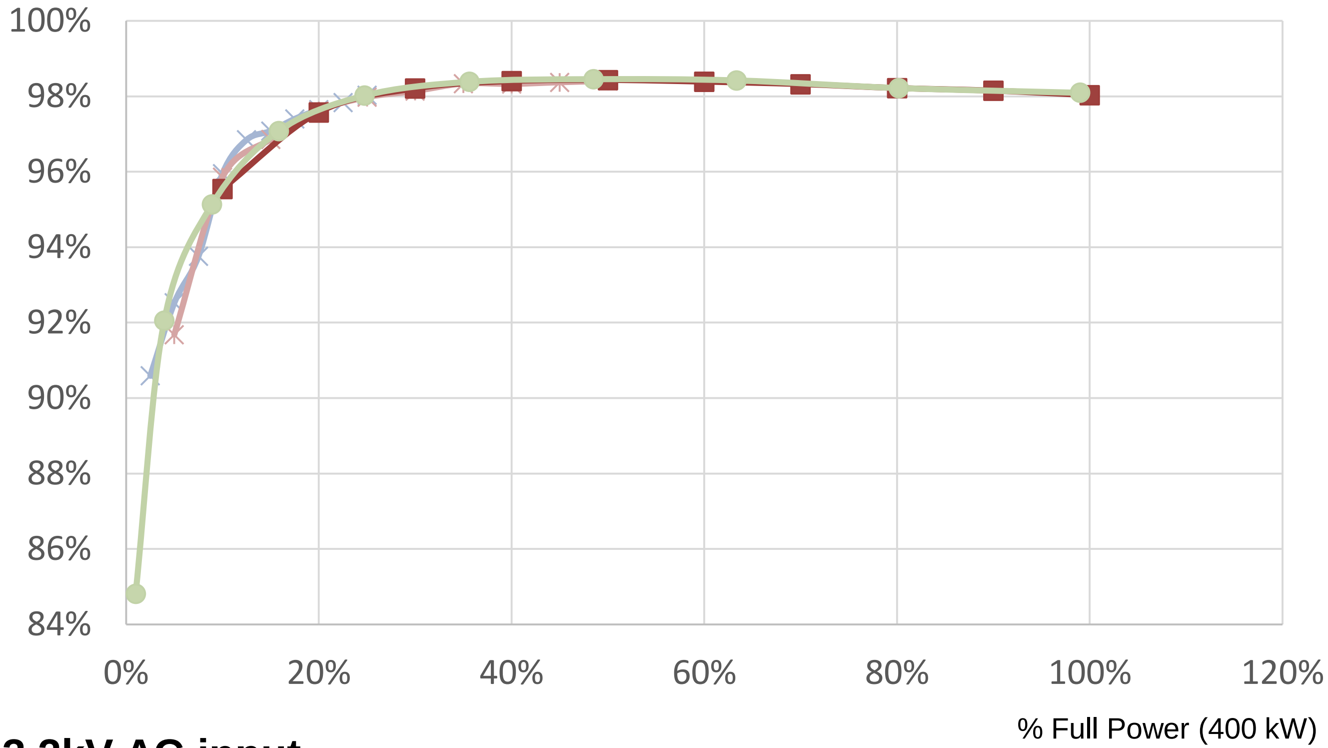


400kW XFC Total System Efficiency



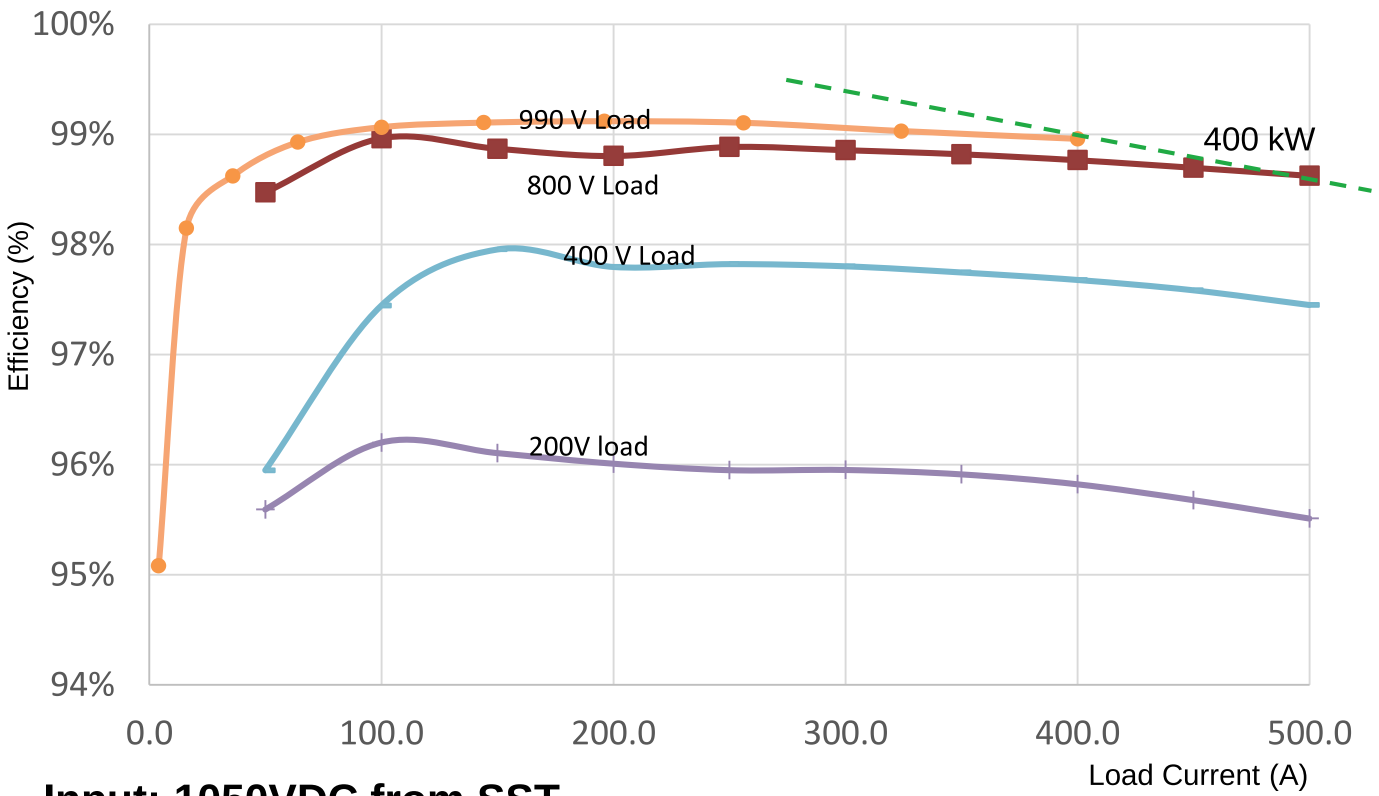
13.2kV AC input

400kW SST Efficiency



13.2kV AC input

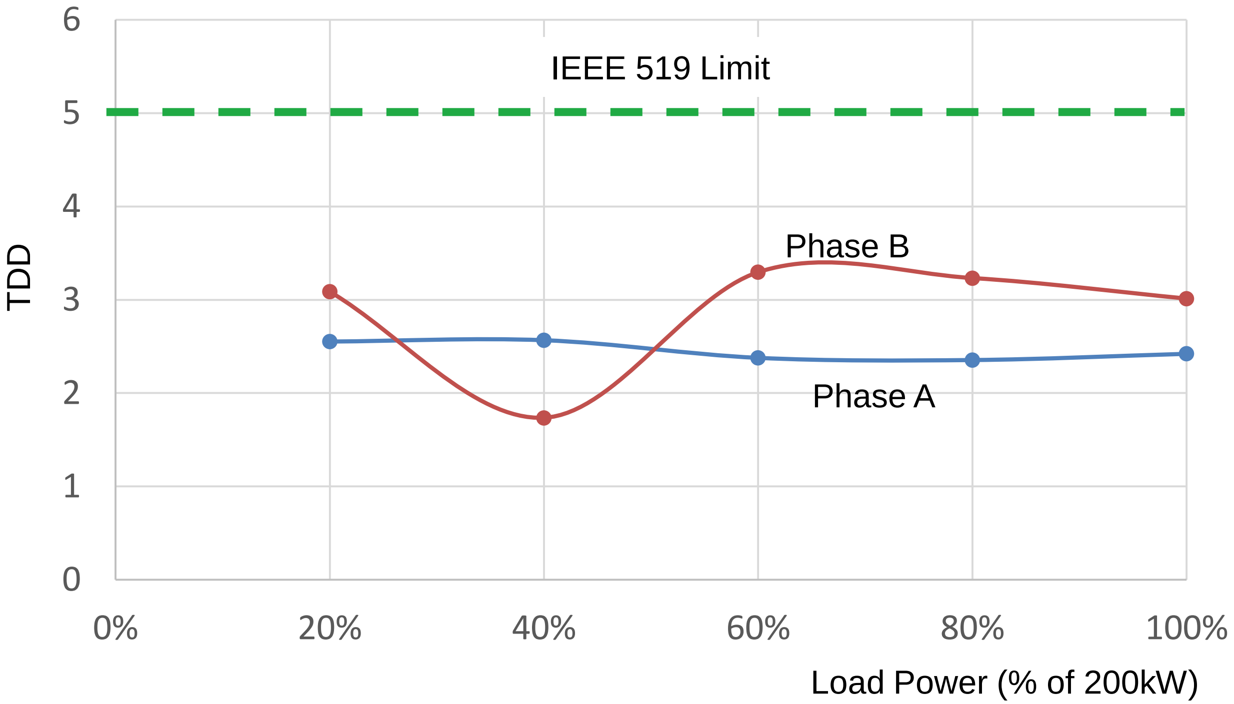
400kW Buck Converter Efficiency



Input: 1050VDC from SST

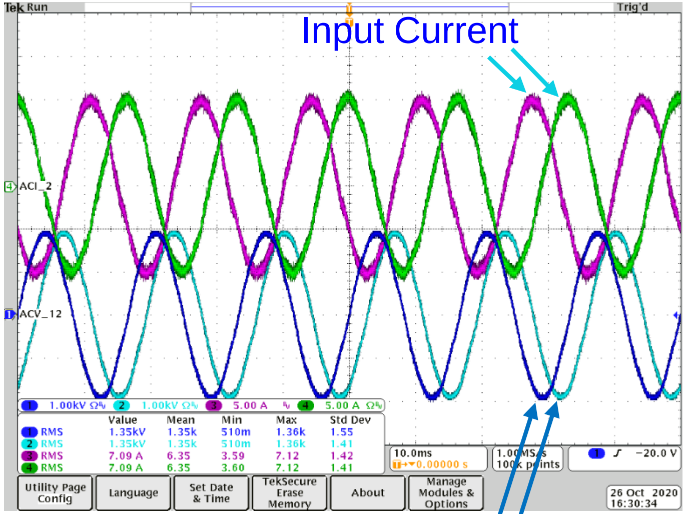
SST Input Current TDD

TDD = Total Demand Distortion

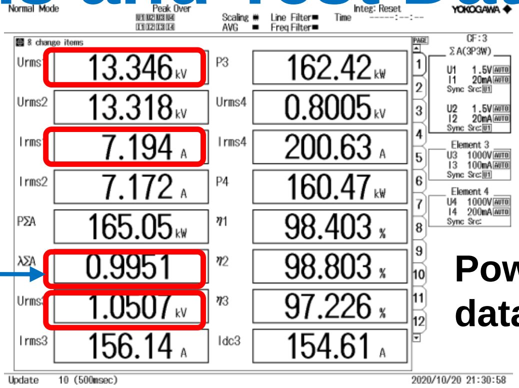


13.2kV AC input

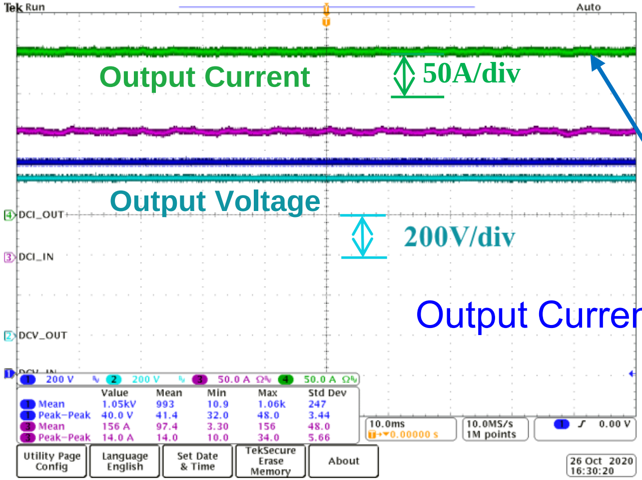
XFC Waveforms and Test Data



SST AC input voltage and current



Power analyzer data



Buck converter voltage and current

RESS Build

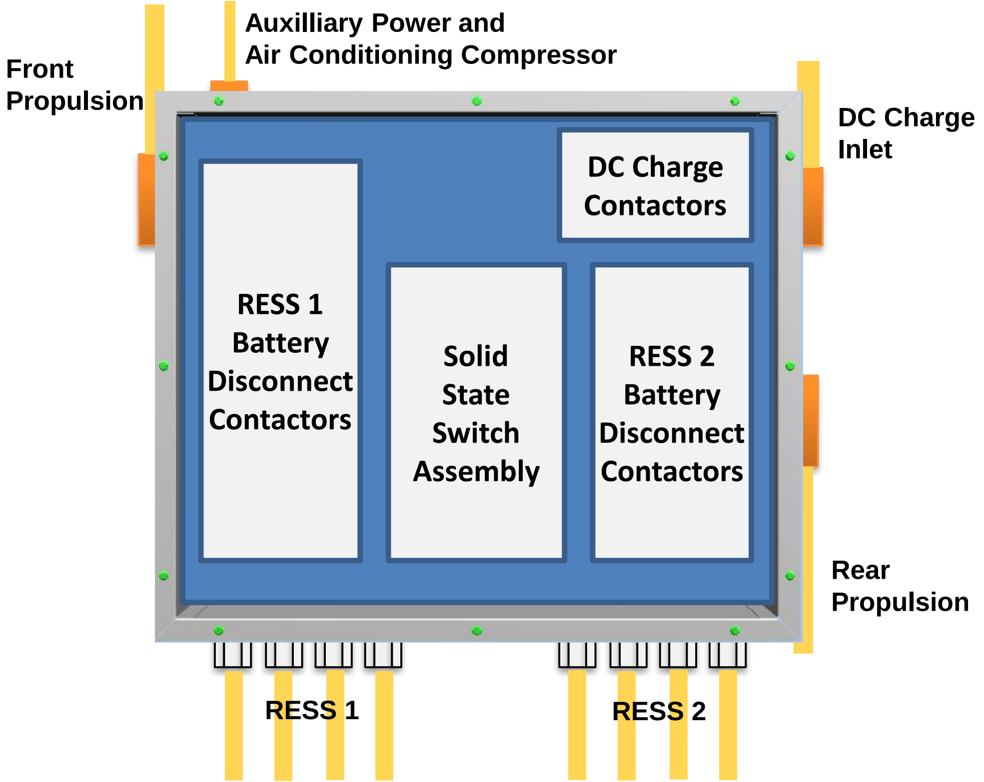
Quad RESS in Vehicle

Completed Quad RESS

RESS: Rechargeable Energy Storage System (battery pack)

- 768 Volt cells to achieve >3C charge rate
- 192 series, 4 parallel string configuration for 800V charging

HVDS Build



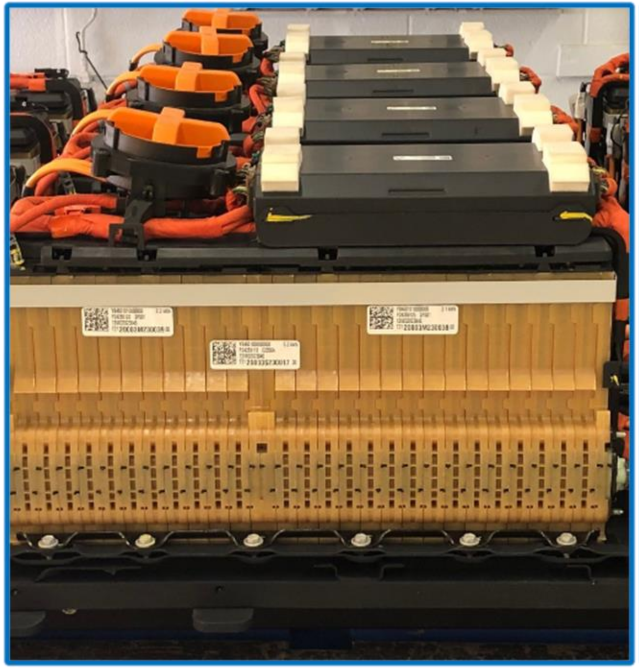
High Voltage Junction Box

HVDS: High Voltage Distribution System

Controls power flow among

- 4 battery packs
- 2 traction inverters
- DC fast charge connector
- HV accessories including auxiliary power and air conditioning compressor

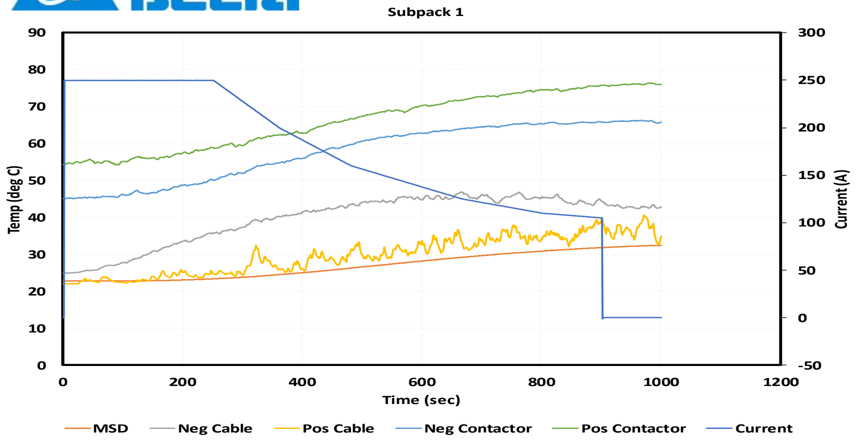
Full RESS Thermal Test

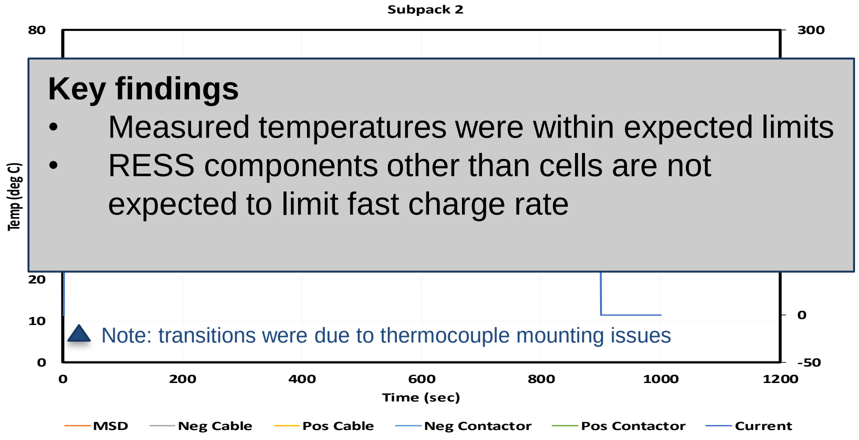


Functional test

- Discharge and charge
- Verify on board electronics
- Balance cells
- Use ABC170 to cycle dual-subpack at up to 250A
- Measure V, I, T from on-board sensors
- 15 minute profile based on simulation profile
- Coolant temperature: 25C

RESS Thermal Test Result

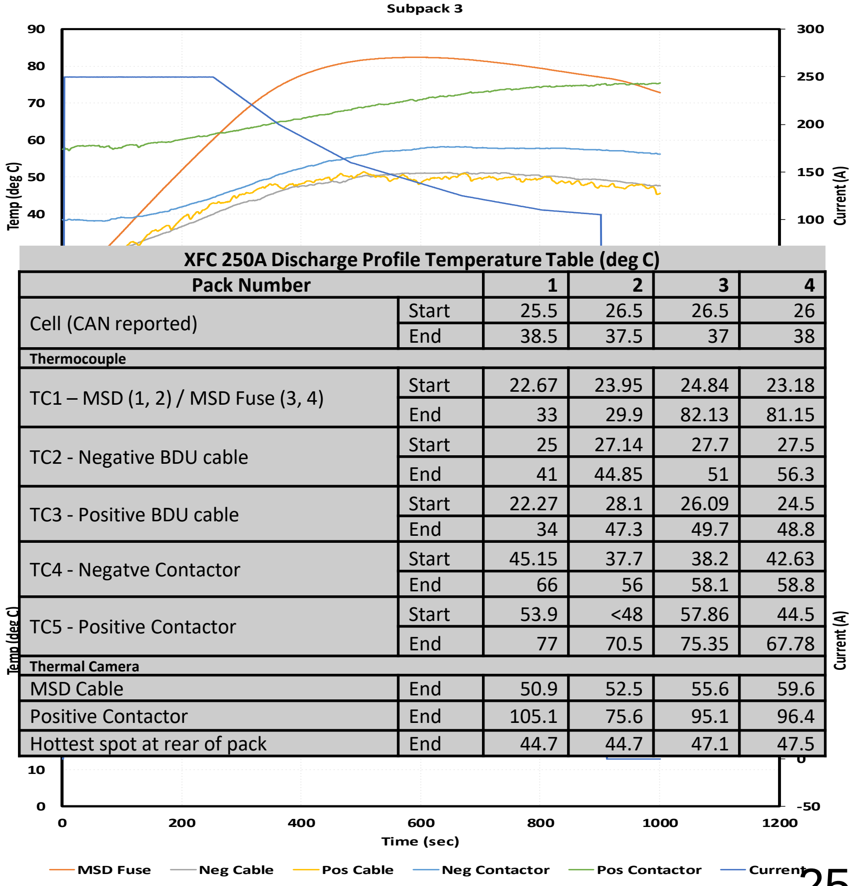




Key findings

- Measured temperatures were within expected limits
- RESS components other than cells are not expected to limit fast charge rate

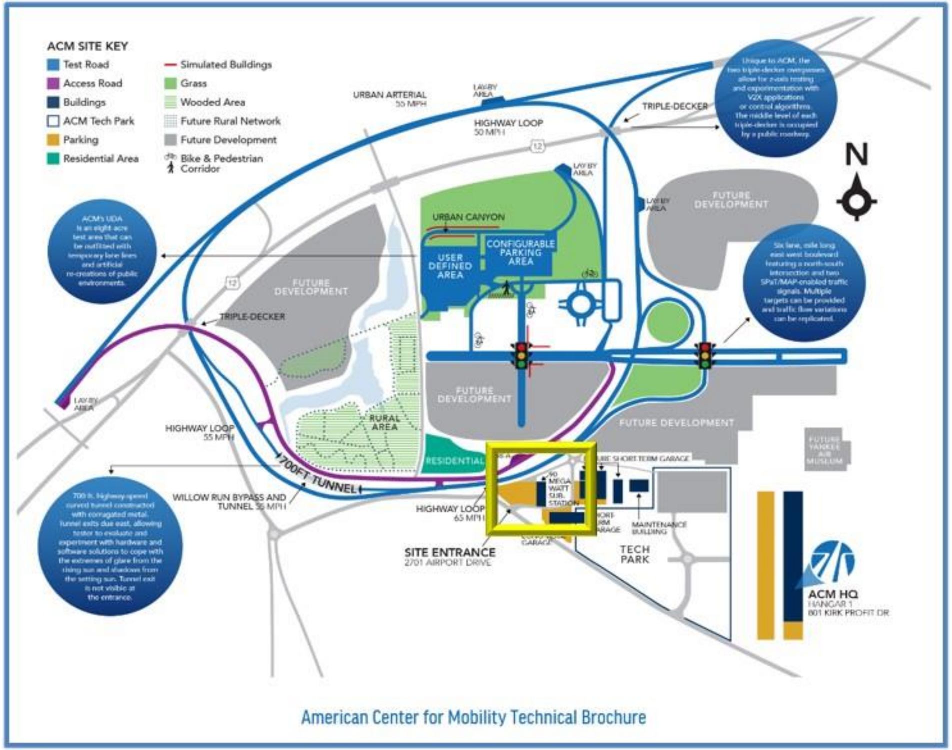
Note: transitions were due to thermocouple mounting issues



XFC 250A Discharge Profile Temperature Table (deg C)

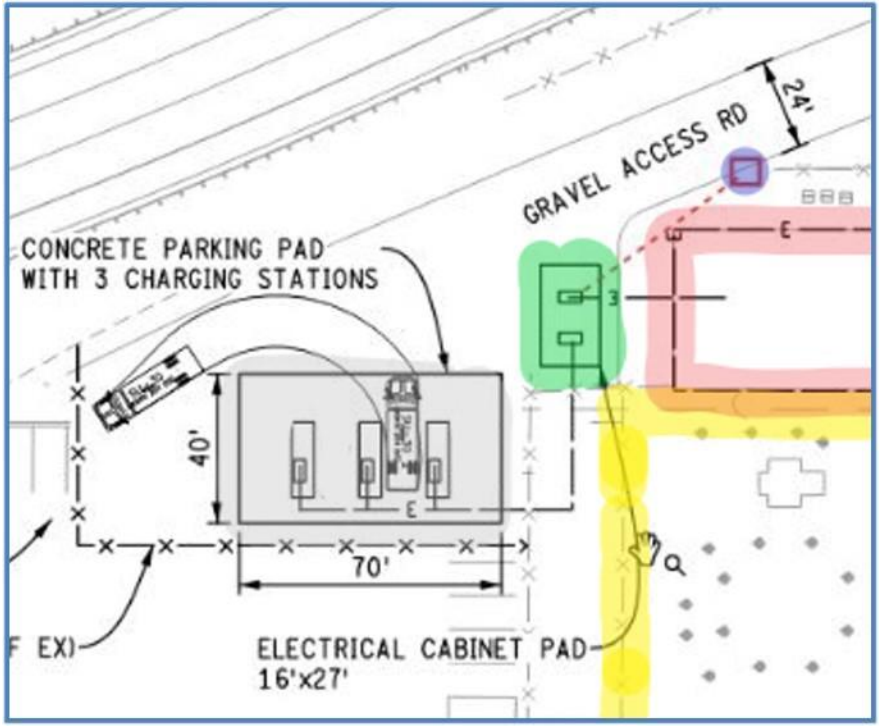
Pack Number		1	2	3	4
Cell (CAN reported)	Start	25.5	26.5	26.5	26
	End	38.5	37.5	37	38
Thermocouple					
TC1 – MSD (1, 2) / MSD Fuse (3, 4)	Start	22.67	23.95	24.84	23.18
	End	33	29.9	82.13	81.15
TC2 - Negative BDU cable	Start	25	27.14	27.7	27.5
	End	41	44.85	51	56.3
TC3 - Positive BDU cable	Start	22.27	28.1	26.09	24.5
	End	34	47.3	49.7	48.8
TC4 - Negatve Contactor	Start	45.15	37.7	38.2	42.63
	End	66	56	58.1	58.8
TC5 - Positive Contactor	Start	53.9	<48	57.86	44.5
	End	77	70.5	75.35	67.78
Thermal Camera					
MSD Cable	End	50.9	52.5	55.6	59.6
Positive Contactor	End	105.1	75.6	95.1	96.4
Hottest spot at rear of pack	End	44.7	44.7	47.1	47.5

Final Test and Demo Site Planning

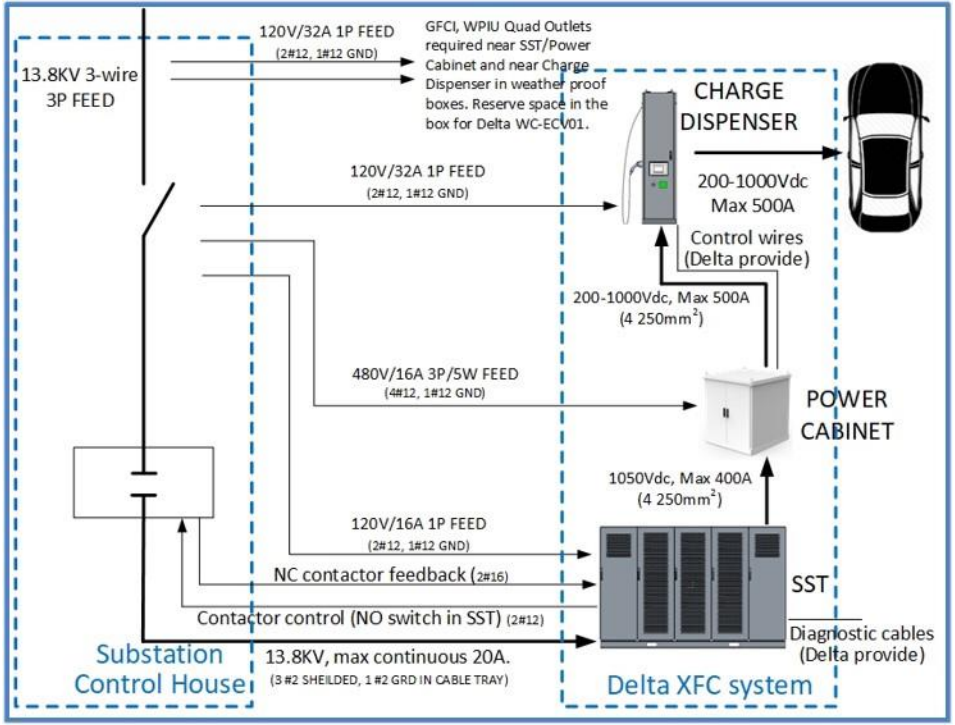


American Center for Mobility, Ypsilanti, MI

Final Test and Demo Site Planning



Site Plan



Test Setup Electric Diagram

Collaboration and Coordination

Delta Electronics (Americas) Ltd. -Primary Recipient

- Administrative responsible to DOE, single point of contact.
- Technical direction and program management (timing, deliverables, budget).
- XFC prototypes development, testing, and system integration
- Commercialization.

General Motors

- Provide a retrofit BEV capable of XFC at 800-V or higher at 3C charging

CPES at Virginia Tech

- Conduct advanced research of power stage topology for the XFC.
- Conduct advanced research of the system level control for both AC/DC and DC/DC stages.

DTE Energy

- Contribute the use of a test facility for XFC testing, vehicle charging test and demonstration.
- Consult on grid impact and operation safety, voltage specifications, standards conformance and certification.

NextEnergy

- Support XFC installation, integration, testing with battery emulator and EV, demonstration within its medium-voltage Microgrid Power Pavilion Platform.

Michigan Energy Office

- Engage state-level public sector stakeholders supporting XFC deployment.

City of Detroit

- Strengthen coordination and fostering partnerships among business, neighborhood and municipal departments.

Future Works

Remainder of FY 2021

- Test site construction and equipment installation.
- Build and verify retrofit vehicle.
- Test 400kW XFC system with Chevy Bolt.
- Test 400kW XFC system with retrofit vehicle.
- Final operation demonstration.

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