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

DE-EE0008361

Dr. Charles Zhu, Principal Investigator
Delta Electronics (Americas) Ltd
June 13, 2019

ELT241

Project Overview

Timeline

- Start – December 1, 2018
- Finish – November 30, 2021
- 17% complete

Budget

- Total Budget: $7.0 million
  - DOE Cost Share: $3.5 million
  - Recipients Cost Share: $3.5 million
- 2019 Funding Planned: $3.2 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.

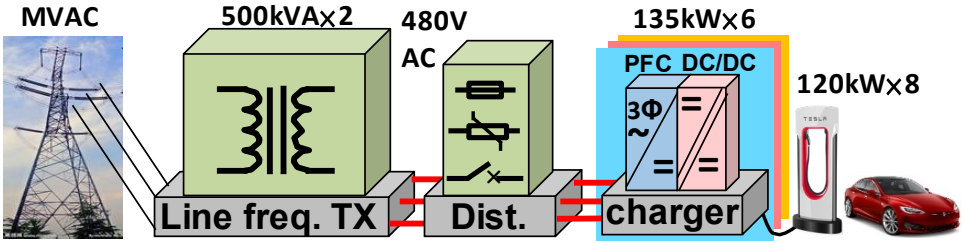
Budget Period 1 Milestones

BP1: 12/1/2018 - 11/30/2019			
Planned Date	Milestone #	Milestone	Milestone Description
2/28/2019	M1.1	Charge Interface Specification	Complete the charge interface documentation and have specification review
5/31/2019	M1.2	SST Cells Built and 1-Phase Serial Integration complete	1-phase SST module built
8/31/2019	M1.3	1-phase series SST and Buck cell Integrated test complete	1-phase SST cell and buck cell test results demonstrate compliance with cell specifications
11/30/2019	M1.4	3-phase 135kW charger integration complete	3-phase SST module built

Approaches

- Medium-voltage AC input, 4.8-kV or 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)

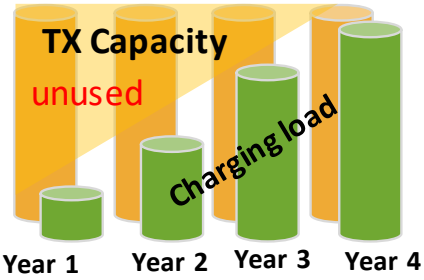
Conventional DC Fast Charger Solution



Efficiency: 99% × 99.3% × 95% = 93.4%

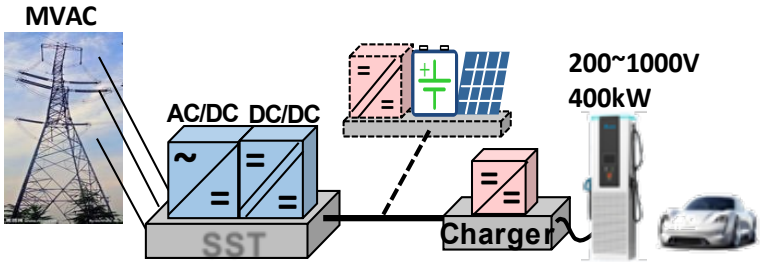
Footprint: 50 ft² + 40 ft² + 20 ft² = 110 ft²

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



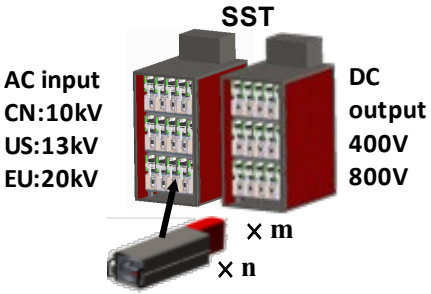
- Bulky and heavy
- Fixed voltage & power
- Space consuming
- Labor intensive
- Non expandable capacity
- High initial investment

Proposed Extreme Fast Charger Solution



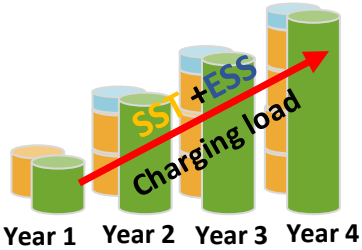
Efficiency: 97.5% × 99% = 96.5% **Increased by 3%**

Footprint: 28 ft² + 10 ft² = 38 ft² **Reduced by 50%**



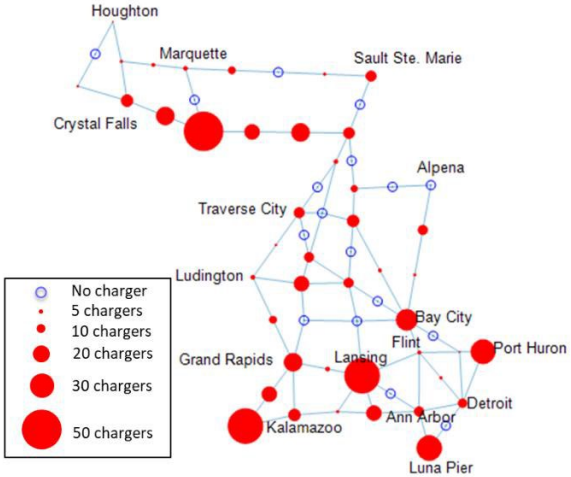
- **Modularized structure**
- **Scalable voltage/power**

Conceptual SST based extreme fast charging station

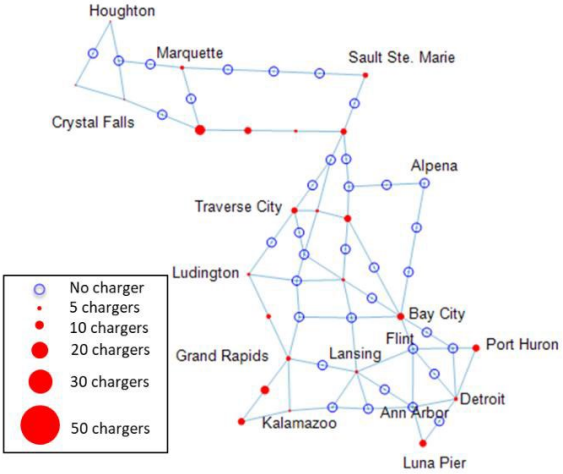


- **Expandable capacity**
- **Lower initial cost**

Michigan EV Placement Optimization



2030 Low Tech Scenario
70kWh battery, 50kW charger



2030 High Tech Scenario
100kWh battery, 150kW charger

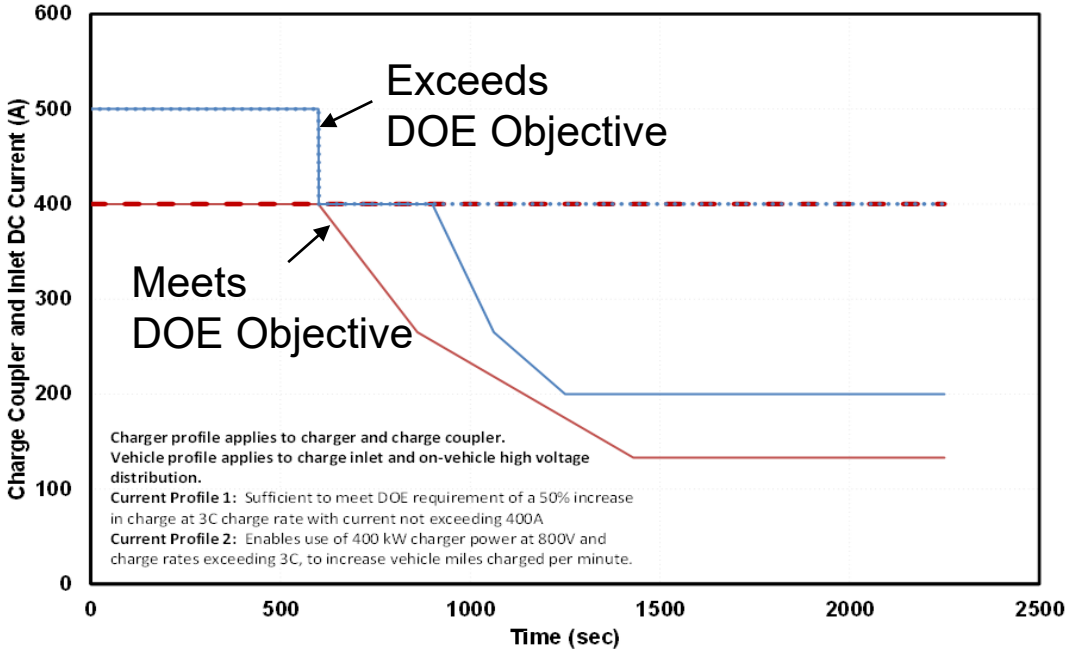
Conclusion: High-tech scenario (high power charge, large battery) has lower cost with less EV user delay.

Research conducted by Michigan State University, funded by Michigan Energy Office, 2019

Technical Progress

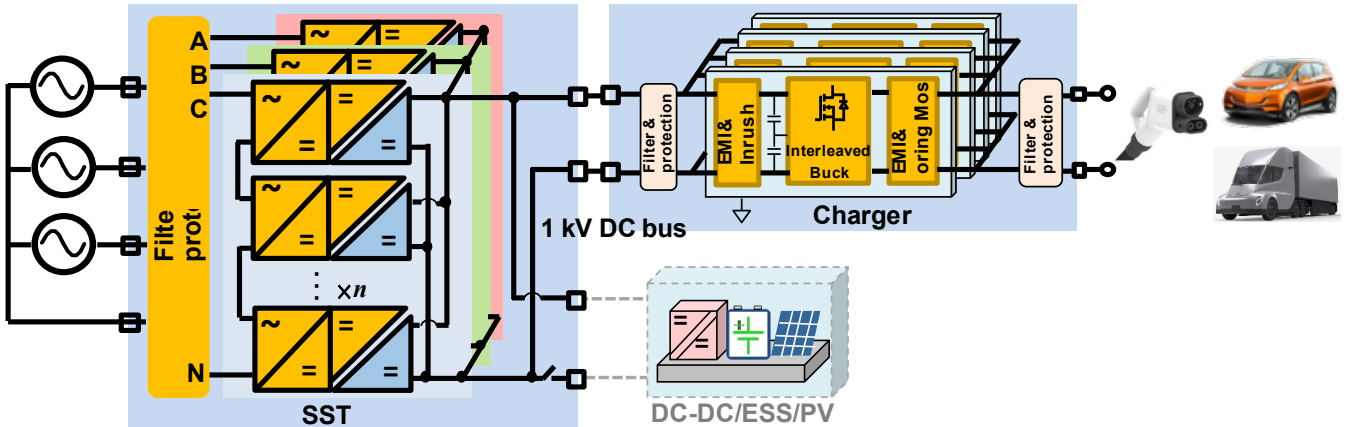
Charge Interface Specification

GM and Delta created the charge interface specification. Milestone 1.1 was completed in time.



Charge Current - Time Profile

SST based XFC System Structure



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

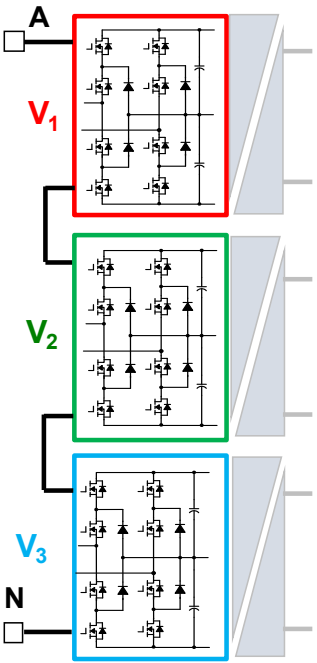
Charger output:

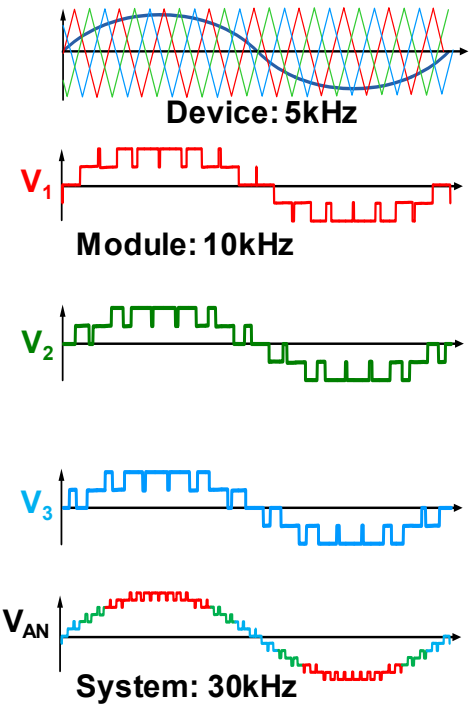
- 200V~1000VDC
- 400A max current
- SAE J1772 charging interface CCS1

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	400ADC
Efficiency	96.5% 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)
SST Unit Dimensions	3000mm (W) x 1100mm (D) x 2100mm (H), estimated
Charger Unit Dimensions	1100mm (W) x 600mm (D) x 2100mm (H), estimated

Cascaded Multilevel AC/DC Stage

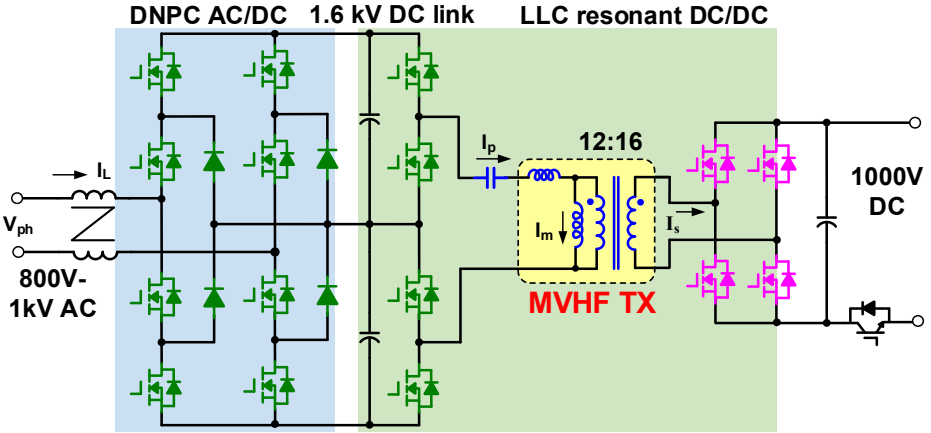




- Fewer isolation components
- Simple structure, lower cost

- f_{sw} multiplied by 2N
- Better THD, smaller filter
- Lower fsw for higher η

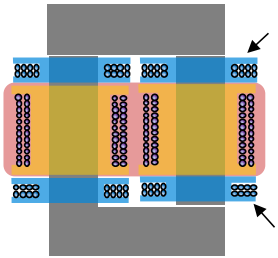
SST Power Cell Topology

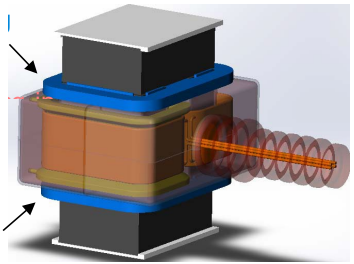


	AC/DC	DC/DC Pri. side	DC/DC Sec. side
Topology	3-level DNPC	4-switch SHB	Full bridge
Operation	CCM, hard switching	ZVS soft switching	
f_{sw}	5~8kHz	100~200kHz	
Switching devices	1.2kV/40mΩ SiC MOSFET	1.2kV/22mΩ SiC MOSFET	1.7kV/45mΩ SiC MOSFET

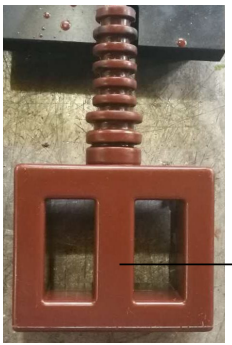
Medium Voltage Transformer Design

Transformer Structure

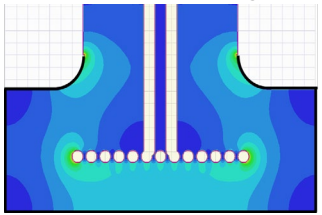




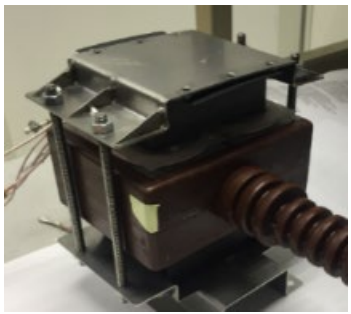
Winding Isolation Design



Electric field distribution on MV winding



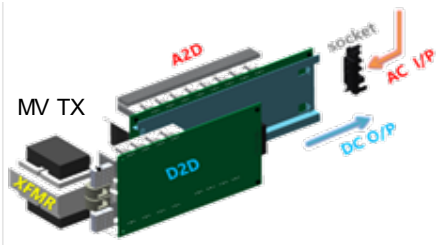
- **Weight: 13.2 lb**
- **Size: 5.1”×4.1”×5.2”**
- **Efficiency: 99.3%**
- **N=12:16**
- **L_m≈150μH, L_k≈12μH**



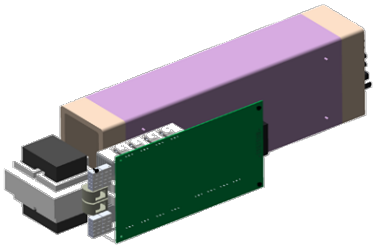
- **Shielded winding w/ epoxy**
- **30kV insulation > 1min**
- **PD<10pC @ 12kV**

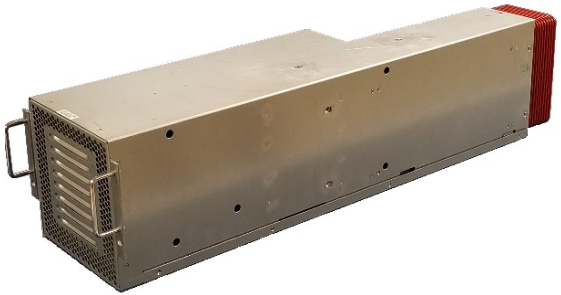
SST Power Cell Hardware

Circuit only



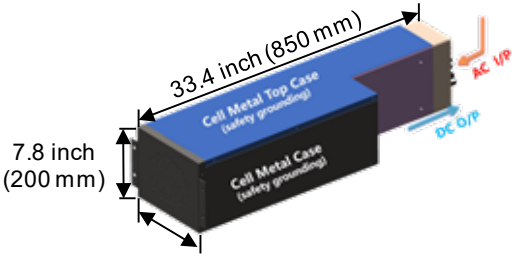
With isolation case





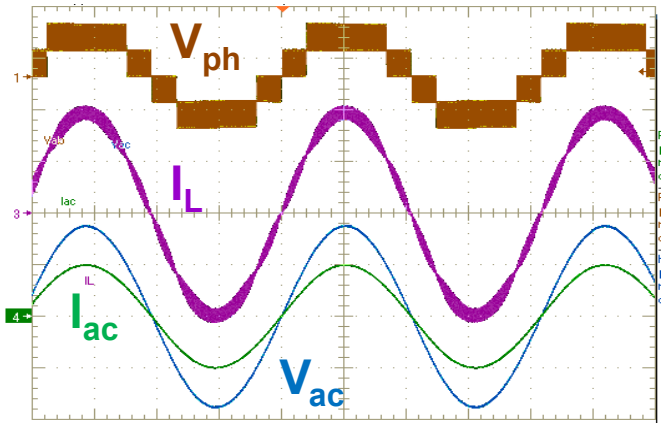
- **Size:33.4”x7.8”x7.8”**
- **Weight: 51 lb**

With power cell case



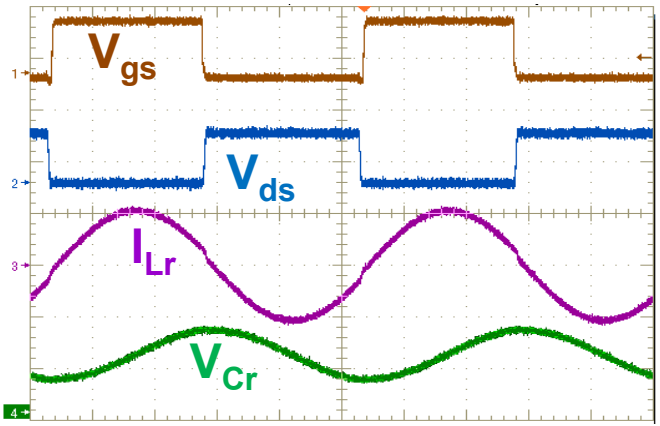
SST Power Cell Experimental Waveforms

AC/DC stage waveforms (Line Cycle)



- **Good THD and power factor at AC grid side**

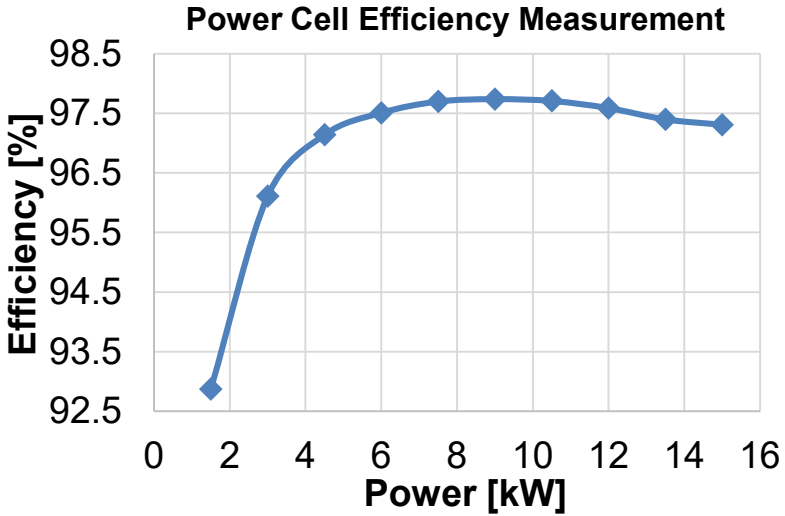
DC/DC stage waveforms (Switching Cycle)

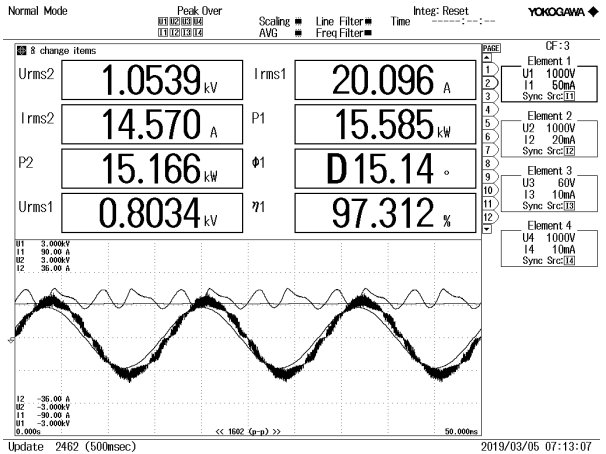


- **Soft Switching for high efficiency at high switching frequency**

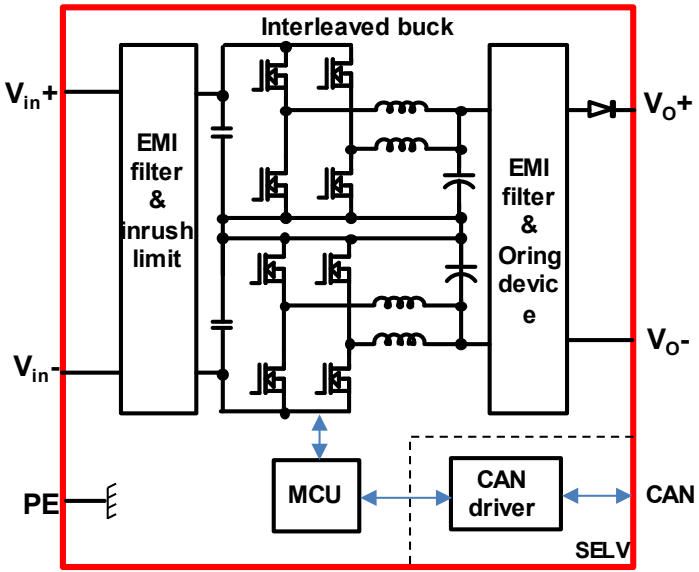
SST Power Cell Test Results

Test Condition: forced air cooling, 25℃ ambient.
800Vac input and 1kVdc output. 100% load at 15kW

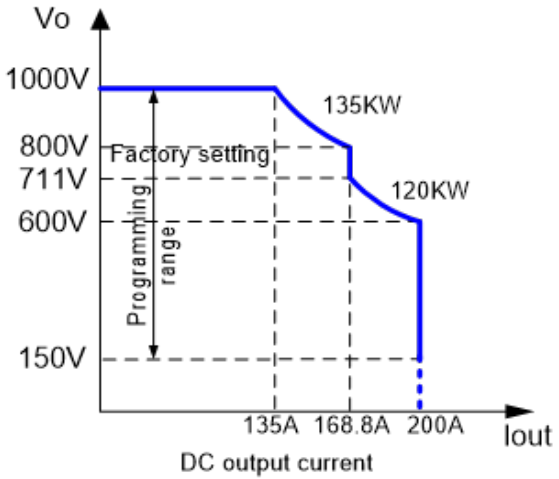




Charger Module Topology

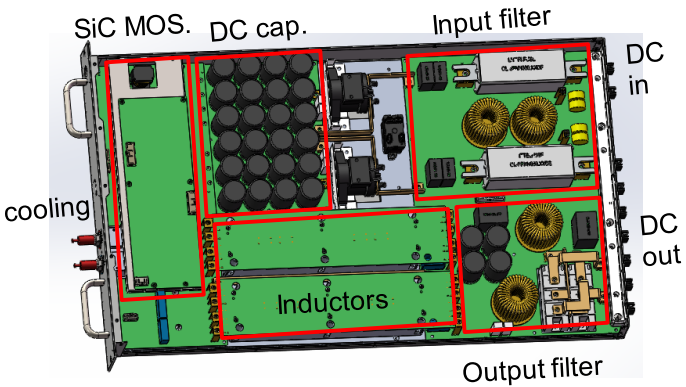


Charger module output profile



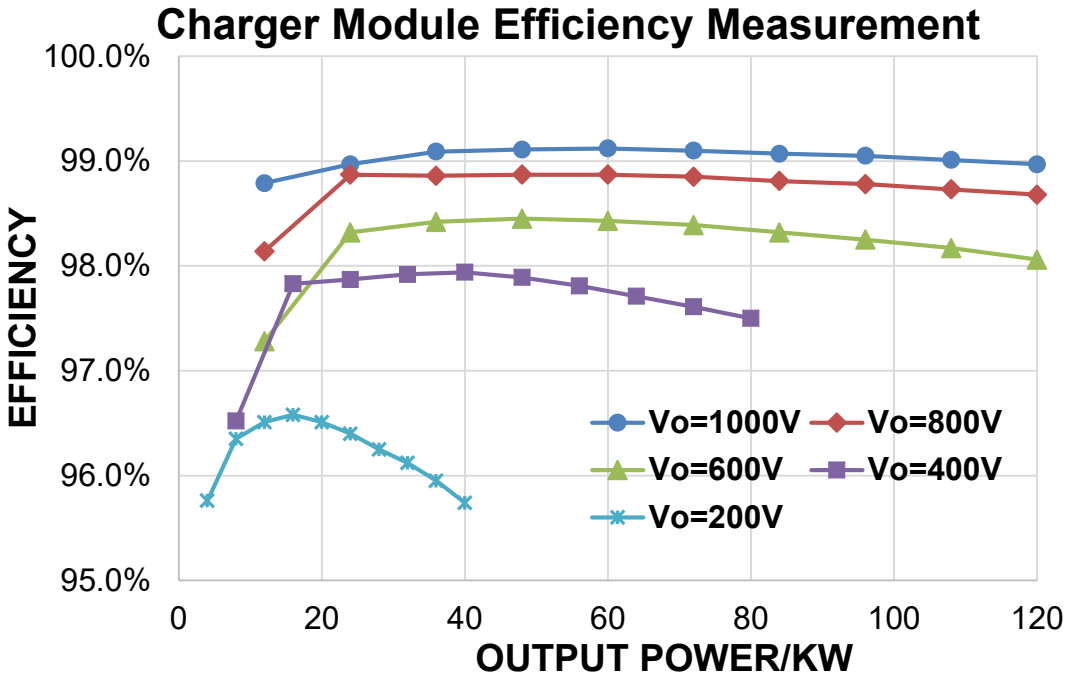
- 135-kW, 200-A $I_{max,}$ 150V~1000V
- 1.2-kV/50-A FB SiC module
- CCM with 50-kHz f_{sw}
- Liquid cooling system

Charger Module Hardware

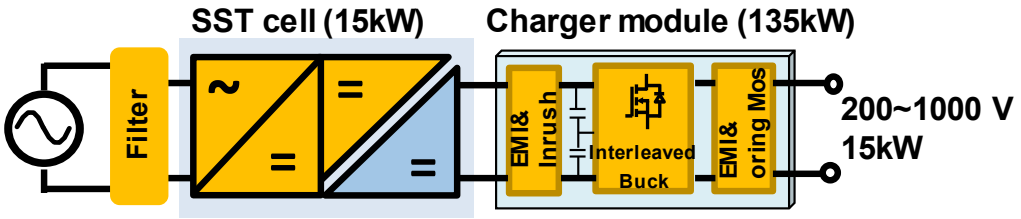


- **Size:16.5”x3.1”x30”**
- **Weight: 79 lb**
- **Power density: 77W/in^3**

Charger Module Efficiency Measurement



SST Cell + Charger Module Test

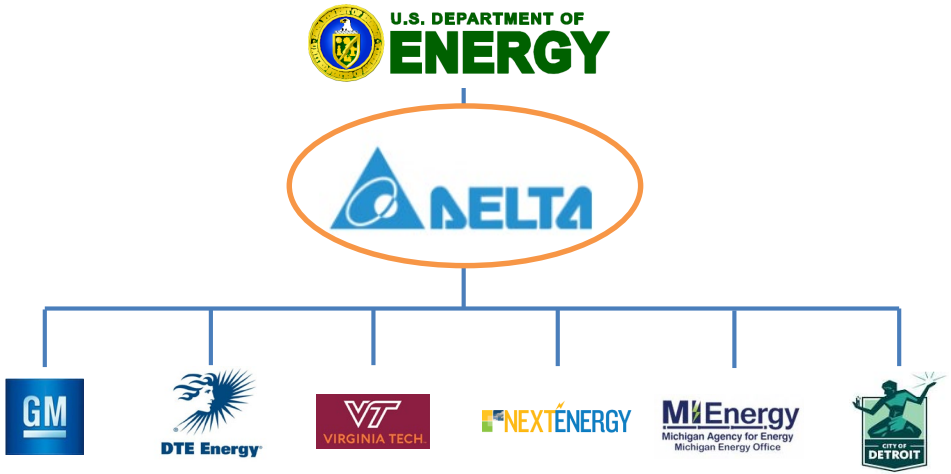


Delta Livonia Automotive Lab

Test conditions:

- **AC input: 623V, 800V, 931V**
- **SST cell output: 1050V**
- **Charger output: 200V, 600V, 950V**
- **Tested power: 10%~100% load (15kW)**

Partners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VIRGINIA TECH
NEXTENERGY
MiEnergy
Michigan Agency for Energy
Michigan Energy Office
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Activities

DOE XFC Program Kick-off Meeting at Delta Livonia Office, August 16th, 2018

Technical Meeting at Future Test Site at NextEnergy, November 26th, 2018

Proposed Future Works

- Remainder of FY 2019
  - Test 1-phase 45kW charger integrated.
  - Build 3-phase 135kW charger.
- FY 2020
  - Test vehicle HVDS/RESS.
  - Test integrated 3-phase 135kW charger.
  - Test 4.8kV XFC system in lab.
- FY 2021
  - Build test vehicle.
  - Test 4.8kV XFC charging test with vehicle.
  - Test 13.2kV XFC charging test with vehicle.

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English

Traditional Chinese

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