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, 2021

“This presentation does not contain any proprietary, confidential, or otherwise restricted information”
Timeline
• Start – December 1, 2018
• Finish – November 30, 2021
• 75% complete

Budget
• Total Budget: $7.0 million
  o DOE Cost Share: $3.5 million
  o 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
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

<table>
<thead>
<tr>
<th>Planned Date</th>
<th>Milestone #</th>
<th>Milestone</th>
<th>Achievement</th>
</tr>
</thead>
<tbody>
<tr>
<td>2/28/2020</td>
<td>M2.1</td>
<td>HVDS/RESS Build and Functional Test Complete</td>
<td>HVDS/RESS Build and Functional Test demonstrates compliance with specifications</td>
</tr>
<tr>
<td>5/31/2020</td>
<td>M2.2</td>
<td>3-Phase 135kW Charger Integration and Test Complete</td>
<td>3-Phase 135kW Charger Test demonstrates compliance with specifications</td>
</tr>
<tr>
<td>8/31/2020</td>
<td>M2.3</td>
<td>4.8kV 400kW XFC mechanical design complete</td>
<td>4.8kV/13.2kV 400kW XFC mechanical design complete for system prototype making</td>
</tr>
<tr>
<td>11/30/2020</td>
<td>M2.4</td>
<td>4.8kV 400kW XFC Lab Test Complete</td>
<td>4.8kV 400kW XFC Lab Test Results demonstrate compliance at partial power</td>
</tr>
<tr>
<td>11/30/2020</td>
<td>BP2</td>
<td>4.8kV 400kW XFC Build Complete</td>
<td>The 4.8kV 400kW XFC system build is complete and fully functional with at least 96% efficiency</td>
</tr>
</tbody>
</table>
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:** $99\% \times 99.3\% \times 95\% = 93.4\%$
- **Footprint:** $50 \text{ ft}^2 + 40 \text{ ft}^2 + 20 \text{ ft}^2 = 110 \text{ ft}^2$

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

Installation site for Tesla Super Charger in U.S.A.
Proposed Extreme Fast Charger

- Efficiency: 97.5% × 99% = 96.5% Increased by 3%
- Footprint: 28 ft² + 10 ft² = 38 ft² Reduced by 50%

- Modularized structure
- Scalable voltage/power
- Expandable capacity
- Lower initial cost

Conceptual SST based extreme fast charging station

AC input
CN: 10kV
US: 13kV
EU: 20kV

DC output
400V
800V

Optional ESS & PV
200~1000V
400kW

SST
× n
× m

Charging load

Year 1
Year 2
Year 3
Year 4
SST based XFC System Architecture

MVAC grid

Filter & protection

SST

1 kV DC bus

Charger

200~1000 V
400 A DC

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

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

Resonant Converter Start-up without SOTC

\[ 4 \times i_{Lr} \]

Steady state

\[ f_n = f_s / f_o \quad (f_o = 85\text{kHz}) \]

\[ f_{\text{max}} = 1.5f_0 \]

\[ i_{Lr} \text{ stresses} = 4 \times \text{full load stress} \]
CLLC Start-up with SOTC

i_{LR} stresses < 1.4 \times \text{full load stress.}
Transformer Insulation

Partial discharge (PD) test equivalent circuit

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

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

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

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

$PD = 12pC @ 17.2kV$ Pass the test!
13.2kV 400kW System Test Setup

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

- 400V DC Out
- 800V DC Out
- 990V DC Out

Achieved peak eff 97.5%
Target peak eff 96.5%

13.2kV AC input

% Full Power (400 kW)
400kW SST Efficiency

13.2kV AC input

% Full Power (400 kW)
400kW Buck Converter Efficiency

Input: 1050VDC from SST
**SST Input Current TDD**

TDD = Total Demand Distortion

IEEE 519 Limit

Load Power (% of 200kW)

- Phase A
- Phase B

13.2kV AC input
XFC Waveforms and Test Data

SST AC input voltage and current

Buck converter voltage and current

Input Voltage

Input Current

Output Voltage

Output Current

Output Current Ripple ≈ 1%

Power analyzer data

PF

50A/div

200V/div

13.346
13.318
7.194
7.172
165.05
0.9951
1.0507
156.14
162.42
0.8005
200.63
160.47
98.403
98.803
97.226
154.61
RESS Build

RESS: Rechargeable Energy Storage System (battery pack)

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

Quad RESS in Vehicle

Completed Quad RESS
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
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
American Center for Mobility, Ypsilanti, MI
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.

To learn more about Delta, please visit www.deltaww.com or scan the QR code.

English  Traditional Chinese  Simplified Chinese