Solid-State-Transformer Technology Implemented Medium Voltage Input Extreme Fast Charger for EV Charging Applications

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Key Objectives of the DOE 400 kW XFC Program

- Medium-voltage-input, MVAC at 4.8 kVac or 13.2 kVac
- Solid state transformer (SST)-based 400 kW/1000 Vdc/400 Adc EV extreme fast charger
- Local energy storage systems and/or renewable energy integration
- Charging speeds of 3C, or above
- To achieve a 180 mile charge within 10 minutes

DOE Program #: DE-EE0008361
Conventional DC Fast Charger System

Efficiency: $99\% \times 99.3\% \times 95\% = 93.4\%$

Footprint: $50 \text{ sqft} + 40 \text{ sqft} + 20 \text{ sqft} = 110 \text{ sqft}$
Conventional DC Fast Charger System

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

Installation site for Tesla Super Charger in US

TX Capacity

Year 1
Year 2
Year 3
Year 4

Unused
Charging load

13 kVac
480 Vac

1 MVA
Proposed Extreme Fast Charger Solution

Efficiency: 97.5% × 99% = 96.5%  Increased efficiency by 3%
Footprint: 28 sqft + 10 sqft = 38 sqft  Reduced footprint by 50%

MVAC

AC/DC  DC/DC

400 kW

SST

Optional ESS & PV

200 ~ 1000 Vdc
400 kW

Charger

MVAC

Optional ESS & PV

200 ~ 1000 Vdc
400 kW

Proposed Extreme Fast Charger Solution
Proposed Extreme Fast Charger Solution

- Smaller footprint
- Easier installation & deployment
- ESS and renewable energy
- Less impact to grid

Conceptual SST based extreme fast charging station

- Modularized structure
- Scalable voltage/power
- Smaller footprint
- Easier installation & deployment
- ESS and renewable energy
- Less impact to grid
- Expandable capacity
- Lower initial cost
# 400 kW XFC Specification

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power Rating</td>
<td>400 kW</td>
</tr>
<tr>
<td>Input AC Voltage</td>
<td>4.8 kVac and 13.2 kVac, 3-Phase, line-to-line</td>
</tr>
<tr>
<td>AC Line Frequency</td>
<td>60 Hz</td>
</tr>
<tr>
<td>HV Battery Voltage Range</td>
<td>200-1000 Vdc</td>
</tr>
<tr>
<td>Maximum Output Current</td>
<td>400 Adc</td>
</tr>
<tr>
<td>Efficiency</td>
<td>96.5% peak</td>
</tr>
<tr>
<td>Charge Interface</td>
<td>J1772 CCS1</td>
</tr>
<tr>
<td>Operational Ambient</td>
<td>-25 to 50°C</td>
</tr>
<tr>
<td>Temperature Range</td>
<td></td>
</tr>
<tr>
<td>Environmental Protection</td>
<td>NEMA 3R (outdoor)</td>
</tr>
<tr>
<td>Additional Interface</td>
<td>HVDC interface to Energy Storage System(ESS) / Renewable Energy Source</td>
</tr>
</tbody>
</table>
SST based XFC System Structure

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

- **SST DC output:**
  - 400 kW power
  - Interface for ESS/PV

- **Charger output:**
  - 200 ~ 1000 Vdc
  - 400 Adc max current
  - SAE J1772 charging interface CCS1
**System Level Topology and Control**

- Scalable structure
- Redundant operation

4.8 kVac, 3×3 cells per phase
13.2 kVac, 1×9 cells per phase

3-level Diode Neutral Point Clamped (DNPC) AC/DC
- Fewer isolation components
- Simpler system structure

- fsw multiplied by 2N. N stands for number of modules
- Better THD, smaller filter
- Lower fsw for higher η

Series input paralleled output (SIPO) structure

Filter & protection

MVAC Grid

AC/DC

DC/DC

SST

To charger

To ESS

Phase-shifted modulation

Device: 5kHz

Module: 10kHz

System: 30kHz

V1

V2

V3

VAN
Technical Challenges for SST

System
- Scalable design
- MV grid fault tolerance
- Balance for multiple cells

Power module
- High efficiency, high frequency
- Noise & dv/dt with SiC

Insulation
- Concentrated E-field
- Partial discharge

Si IGBT
- $f_{sw} < 40$ kHz
- $dv/dt < 10$ kV/μs
- 480 Vac input

SiC MOSFET
- $f_{sw} > 100$ kHz
- $dv/dt > 50$ kV/μs
- 13.2 kVac input

60 Hz
- E < 1 kV/mm

60 Hz + 200 kHz
- E > 4 kV/mm

MVAC

LVDC

A2D

LFT based

SST

2-level

Multi-level

Scalable design
MV grid fault tolerance
Balance for multiple cells

High efficiency, high frequency
Noise & dv/dt with SiC

Concentrated E-field
Partial discharge
High Voltage/High Frequency Switching

Property of SiC vs. Si Device

- Low conduction loss
- Low switching energy
High Voltage/High Frequency Switching

- Controlled EMI propagation path
- Higher CM noise immunity

SiC gate driver design

Problem w/ SiC Device

- High dv/dt and EMI noise

SiC driver w/ SiC device

- Improved switching transient
- Reduced false triggering risk
Experimental Waveforms

AC/DC stage waveforms (Line Cycle)

- Good THD and power factor at AC grid side

Input Phase Currents
Input Line Voltages

Isolation Probe attenuation is 10,000:1 (DP30-10k-LVC)

DC/DC stage waveforms (Switching Cycle)

- Soft Switching for high efficiency at high switching frequency

V gs
V ds
I Lr
V Cr
Retrofit Vehicle RESS/HVDS System

Battery Cells / Modules

Retrofit BEV Vehicle in Progress

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

- Courtesy of DOE Program partner General Motors
Vehicle Charging Profile Analysis Result

SOC increased by 57.3% and 62.4% respectively in 10 minutes. The target is 50%.
400 kW SST XFC System Testing

- Completed full power test
- Input 13.2 kVac,
- Output 200 - 1000 Vdc, 400 kW,
- Peak efficiency 97.5%

- Courtesy of DOE Program partner NextEnergy Test Site
System Efficiency (SST + Buck Converter)
### System Efficiency (SST + Buck Converter)

<table>
<thead>
<tr>
<th>Item</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Urms1</td>
<td>13.311 kV</td>
<td></td>
</tr>
<tr>
<td>Urms2</td>
<td>13.277 kV</td>
<td></td>
</tr>
<tr>
<td>Irms1</td>
<td>17.835 A</td>
<td></td>
</tr>
<tr>
<td>Irms2</td>
<td>17.809 A</td>
<td></td>
</tr>
<tr>
<td>P3</td>
<td>402.11 kW</td>
<td></td>
</tr>
<tr>
<td>ψ3</td>
<td>409.91 kW</td>
<td></td>
</tr>
<tr>
<td>η1</td>
<td>0.9989</td>
<td></td>
</tr>
<tr>
<td>η2</td>
<td>98.095 %</td>
<td></td>
</tr>
<tr>
<td>η3</td>
<td>98.958 %</td>
<td></td>
</tr>
<tr>
<td>Ul</td>
<td>1.0498 kV</td>
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</tr>
<tr>
<td>Ic</td>
<td>383.06 A</td>
<td></td>
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<tr>
<td>Ic</td>
<td>383.03 A</td>
<td></td>
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<tr>
<td>SST output V</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SST output Ic</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Buck Iout</td>
<td>0.4012 kA</td>
<td></td>
</tr>
<tr>
<td>Buck Pout</td>
<td>0.3979 MW</td>
<td></td>
</tr>
<tr>
<td>SST off</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Buck off</td>
<td></td>
<td></td>
</tr>
<tr>
<td>XFC: system off</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- Power Analyzer Measurement
- Yokogawa WT-1800
DCFC Vehicle Charging Test with Chevy Bolt

- Completed vehicle charging communication test

- Courtesy of DOE Program partner General Motors Bolt Vehicle
Future XFC System Application

Utility side
- AC input
- Power cell rack
- Control & DC output

SST
- Optional ESS chiller
- HMI
- 150~1000 Vdc
- 400 kW

User side
- Charging port
- 4.8 kVac/13.2 kVac

MVAC grid
- 1 kVac
A solid state transformer (SST) technology has been introduced for XFC
- Input 13.2 kVac,
- Output 200 – 1000 Vdc, 400 kW/400 Adc
- SST enabled 50% footprint reduction and reached 97.5% peak efficiency
- EMI issues has been resolved with novel gate drive design
- SiC device has been utilized in the design with soft switching technology
- Vehicle charging test has been completed
Acknowledgement to the DOE Program Partners

DOE Program #: DE-EE0008361
Thank you!