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

DE-EE0008361 **ELT241**

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Delta Electronics (Americas) Ltd
June, 2020

Project Overview

Timeline

- Start – December 1, 2018
- Finish – November 30, 2021
- 50% complete

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

Budget

- Total Budget: $7.0 million
  - DOE Cost Share: $3.5 million
  - Recipients Cost Share: $3.5 million
- 2020 Funding Planned: $2.1 million

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	Mile-stone #	Milestone	Achievement
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 ✓

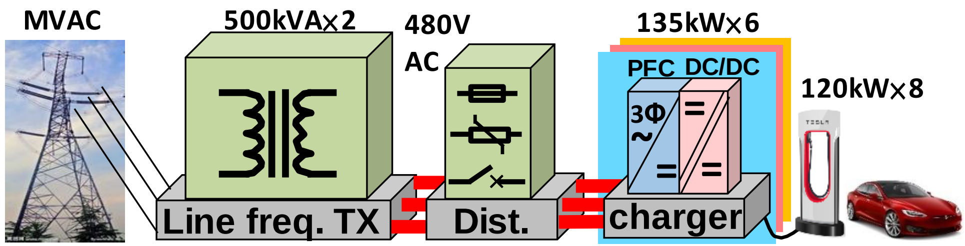
Budget Period 2 Milestones

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

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)

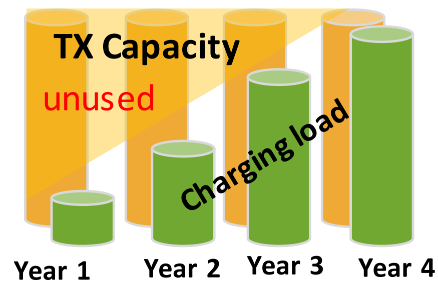
Conventional DC Fast Charger Solution



Efficiency: 99% × 99.3% × 95% = 93.4%

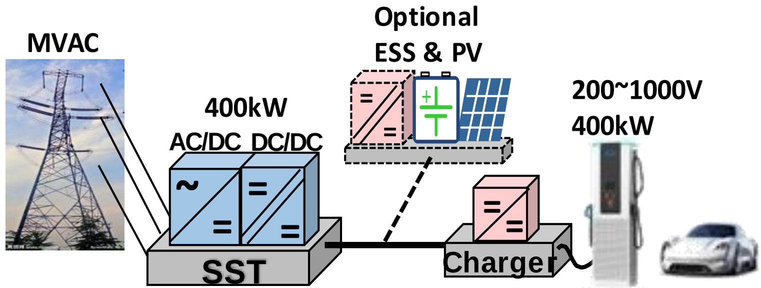
Footprint: 50 ft² + 40 ft² + 20 ft² = 110 ft²

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



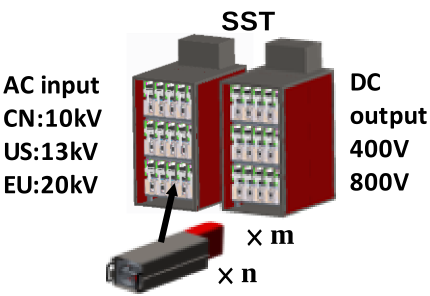
- **Bulky and heavy**
- **Fixed voltage & power**
- **Space consuming**
- **Labor intensive**
- **Non expandable capacity**
- **High initial investment**

Proposed Extreme Fast Charger Solution



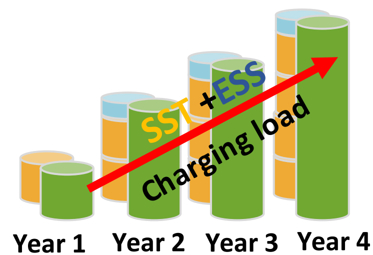
Efficiency: 97.5% × 99% = 96.5% **Increased by 3%**

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



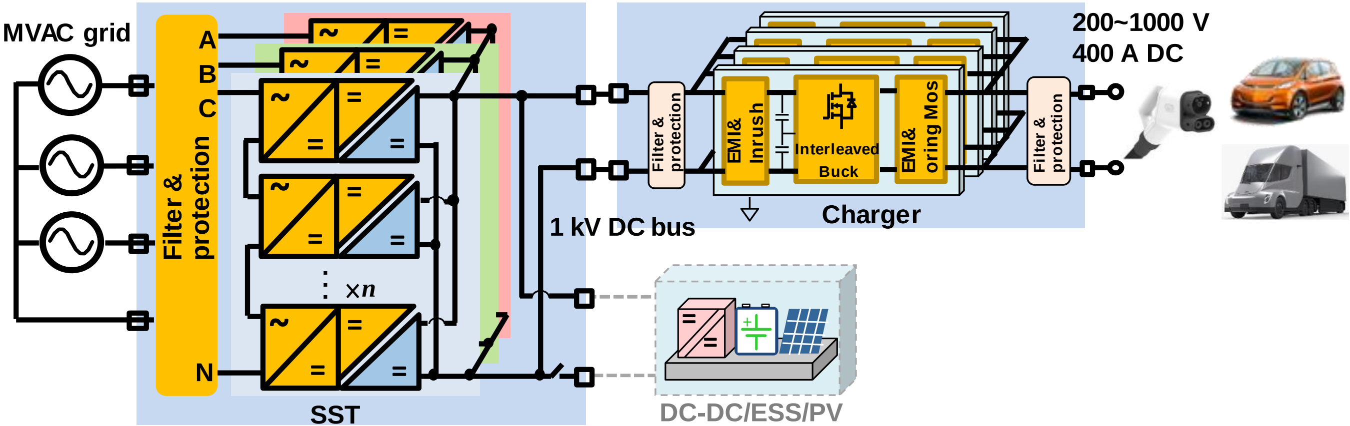
- **Modularized structure**
- **Scalable voltage/power**

Conceptual SST based extreme fast charging station



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

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

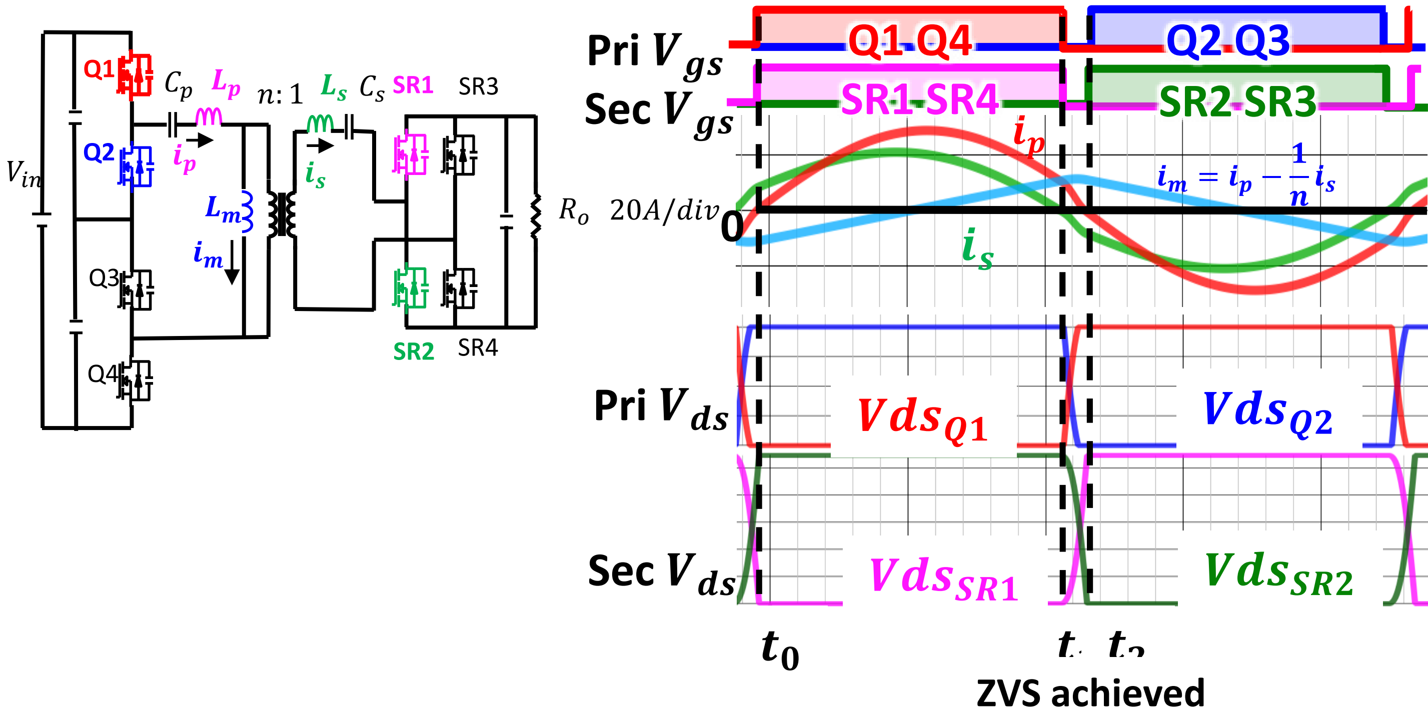
Charger output:
- 200V~1000VDC
- 400A max current
- SAE J1772 charging interface CCS1

XFC Specification

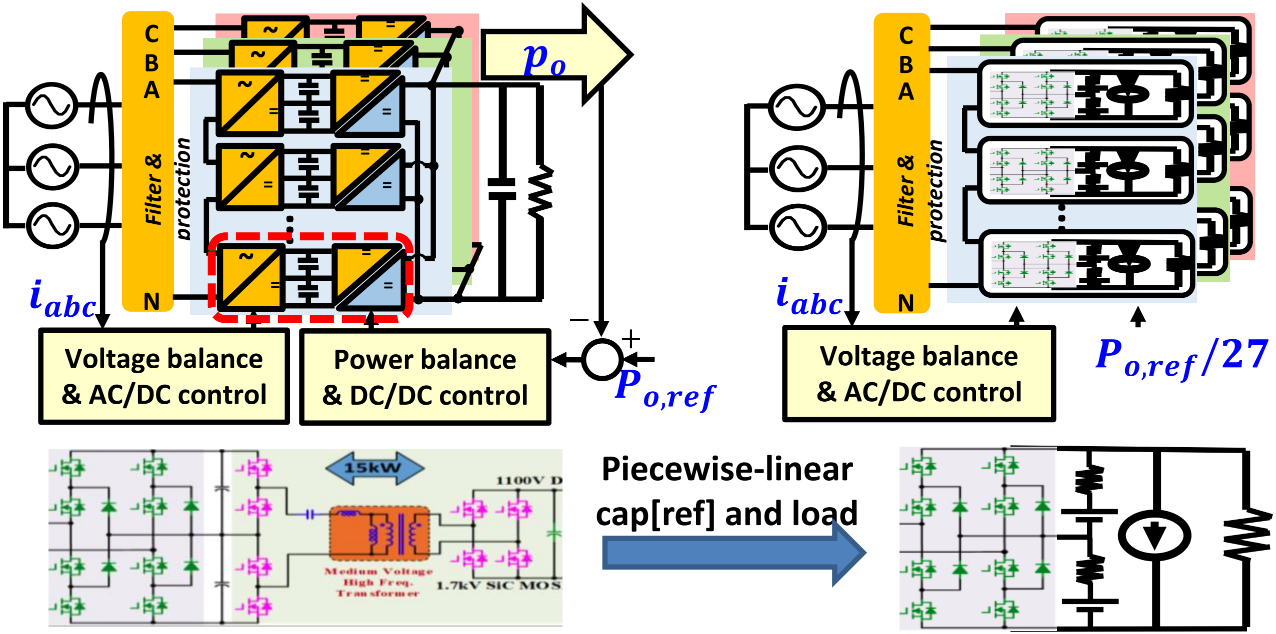
Power Rating	400 kW
Input AC Voltage	4.8 kV and 13.2 kV, 3-Phase, line-to-line
AC Line Frequency	60 Hz
HV Battery Voltage Range	200-1000 VDC
Maximum Output Current	400ADC
Efficiency	96.5% peak
Charge Interface	J1772 CCS1
Operational Ambient Temperature Range	-25 to 50°C
Environmental Protection	NEMA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

Technical Progress

DC/DC Resonant Converter



Simplification of AC-DC Stage Simulation

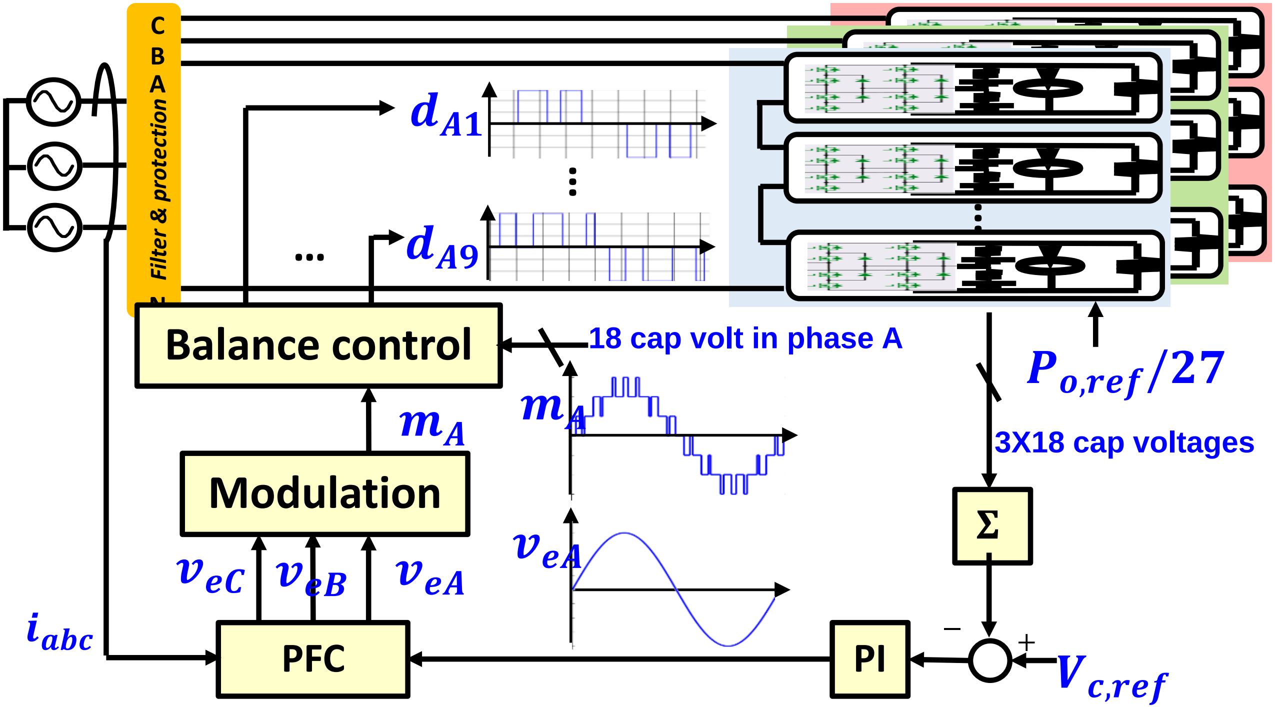


System order: $\underset{(L)}{3} + 3 \times \underset{(N)}{9} \times [\underset{(C)}{2} + \underset{(CLLLC)}{5}\ ] + \underset{(C)}{1} + \underset{(L)}{X} = 193 + X$

System order: 0

Reference: U. N. Gnanarathna, A. M. Gole, and R. P. Jayasinghe, "Efficient Modeling of Modular Multilevel HVDC Converters (MMC) on Electromagnetic Transient Simulation Programs," *IEEE Trans. On Power Delivery*, vol. 26, no. 1, pp 316-324, Jan. 2011

Control Block Diagram for AC/DC Stage

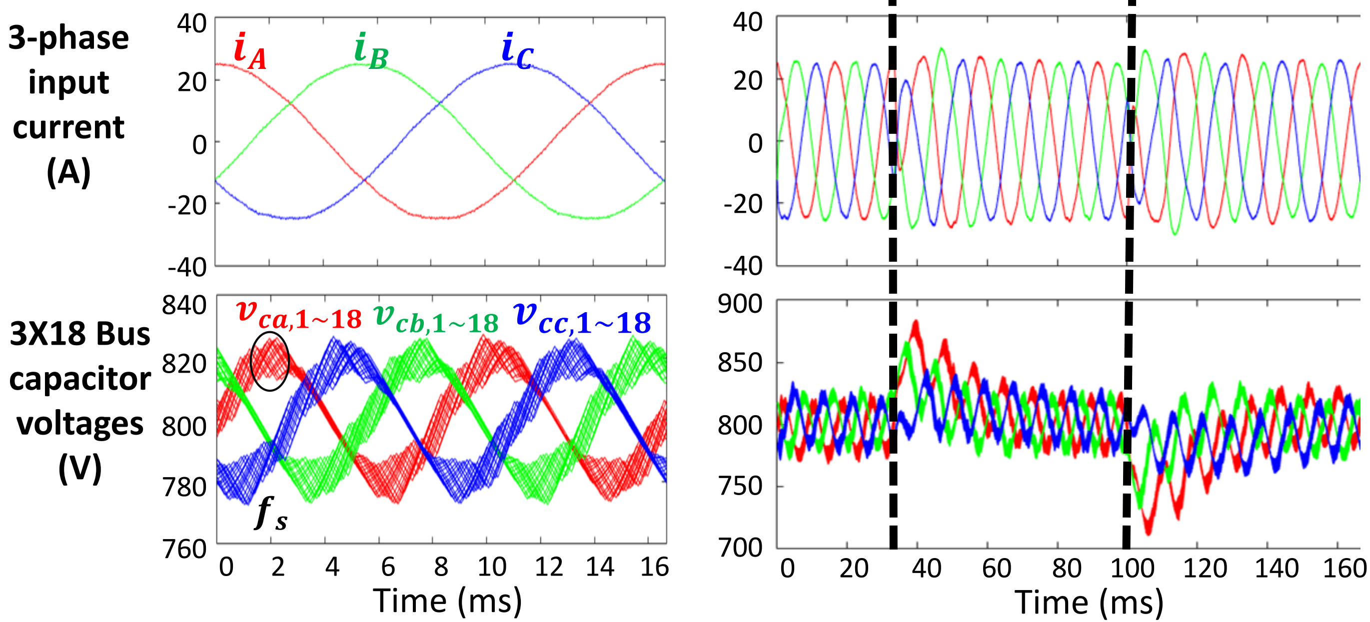


Hossein Iman-Eini, Jean-Luc Schanen, Shahrokh Farhangi, James Roudet, "A Modular Strategy for Control and Voltage Balancing of Cascaded H-Bridge Rectifiers," *IEEE Trans. on Power Electronics*, vol. 23, pp. 2428-2442, 2008

Simulation of Load Power Step Response

$$Device\ switching\ f_s = 600Hz$$
$$Ripple\ effective\ f_e = 18f_s = 10.8kHz$$

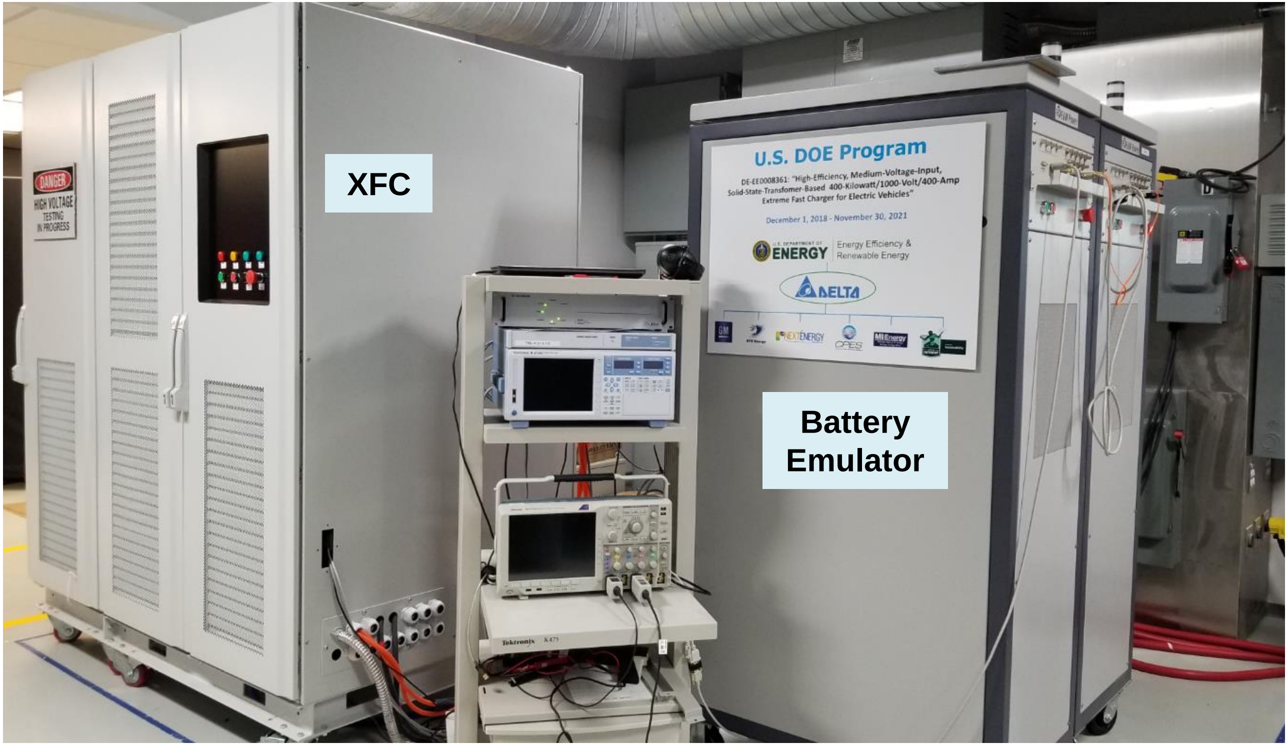
$$Output\ power\ changes$$
$$400kW \rightarrow -400kW \mapsto +400kW$$



Steady-State

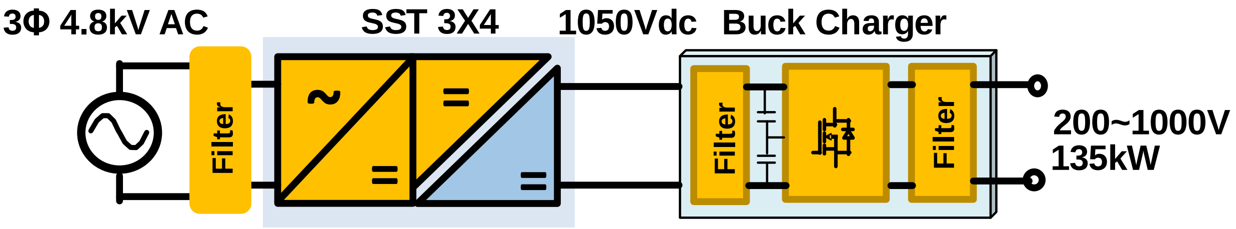
Transient

135kW System Test



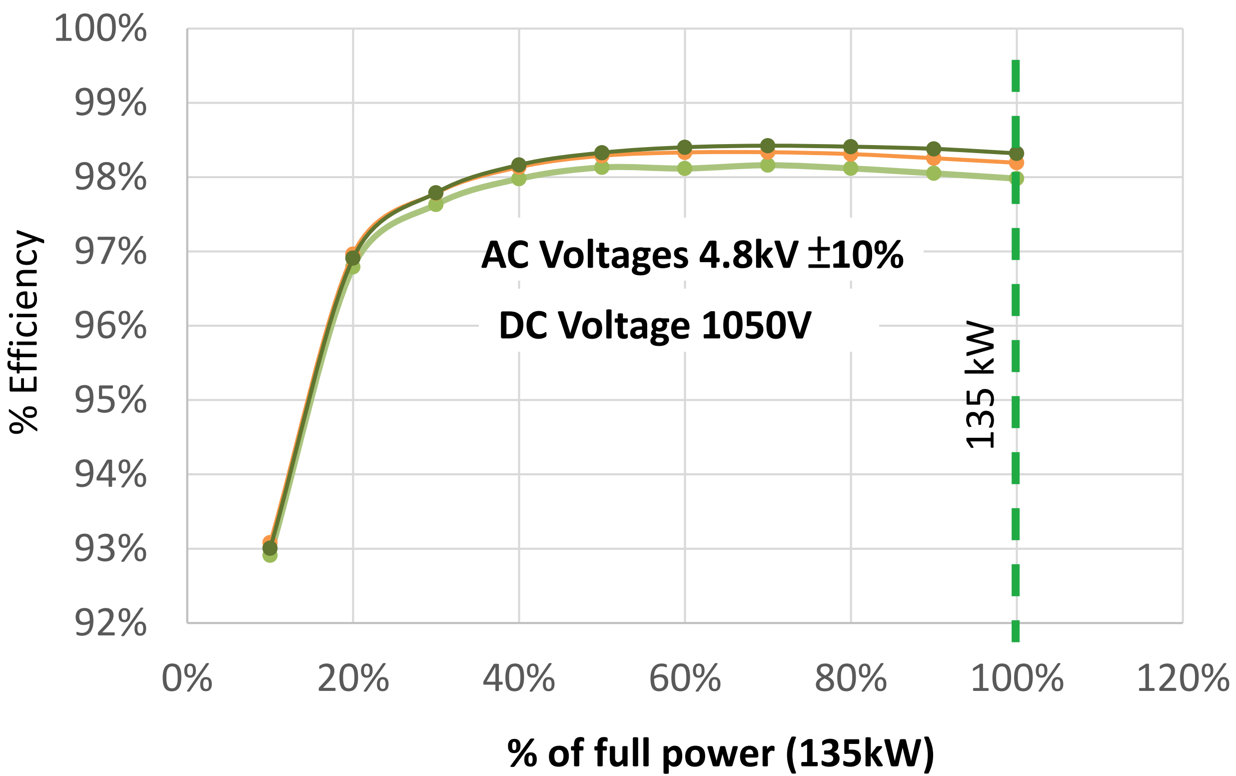
Delta Livonia Automotive Lab

135kW System Test Conditions

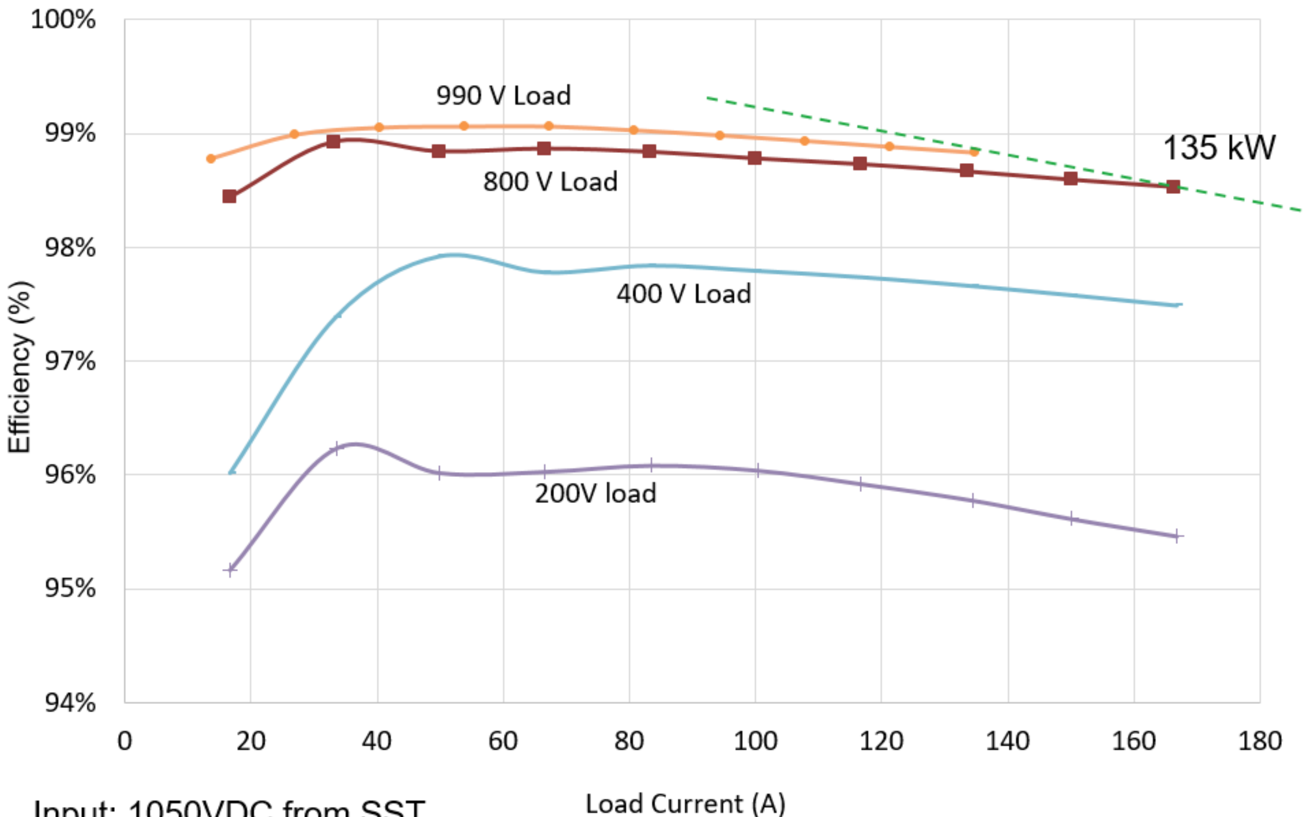


- Input: 4.8kV +/- 10% 3-phase AC
- SST output: 1050Vdc
- Buck Charger output: 200V, 400V, 800V, 990V
- Power: 10%~100% of 135kW

135kW SST Efficiency Measurement

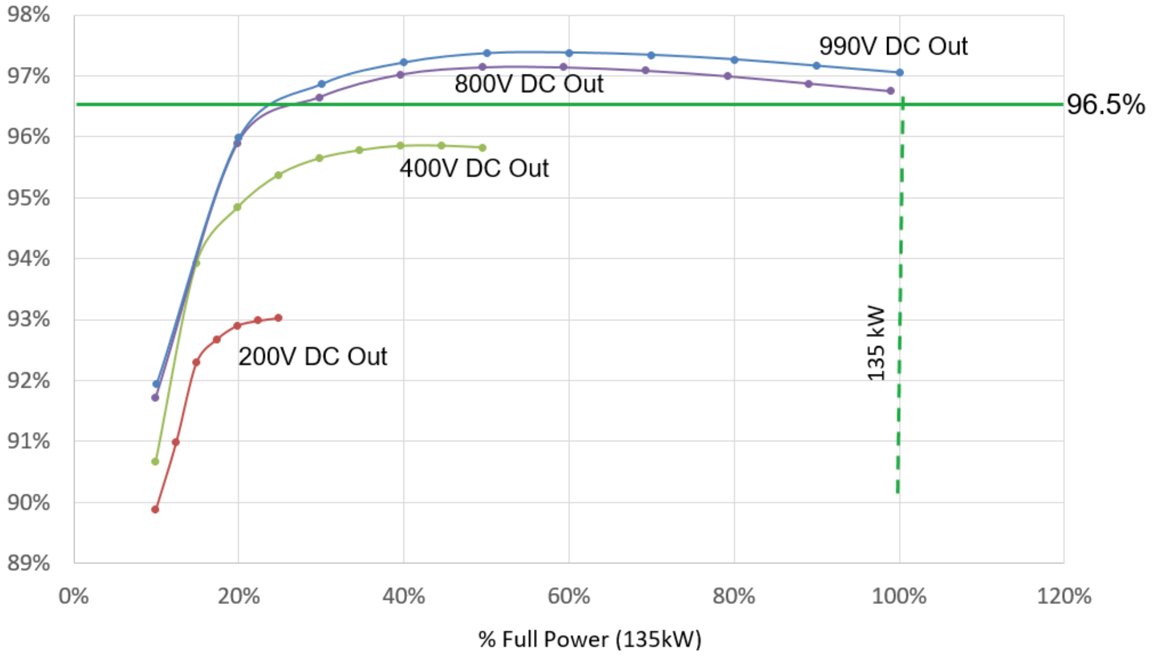


Buck Converter Efficiency



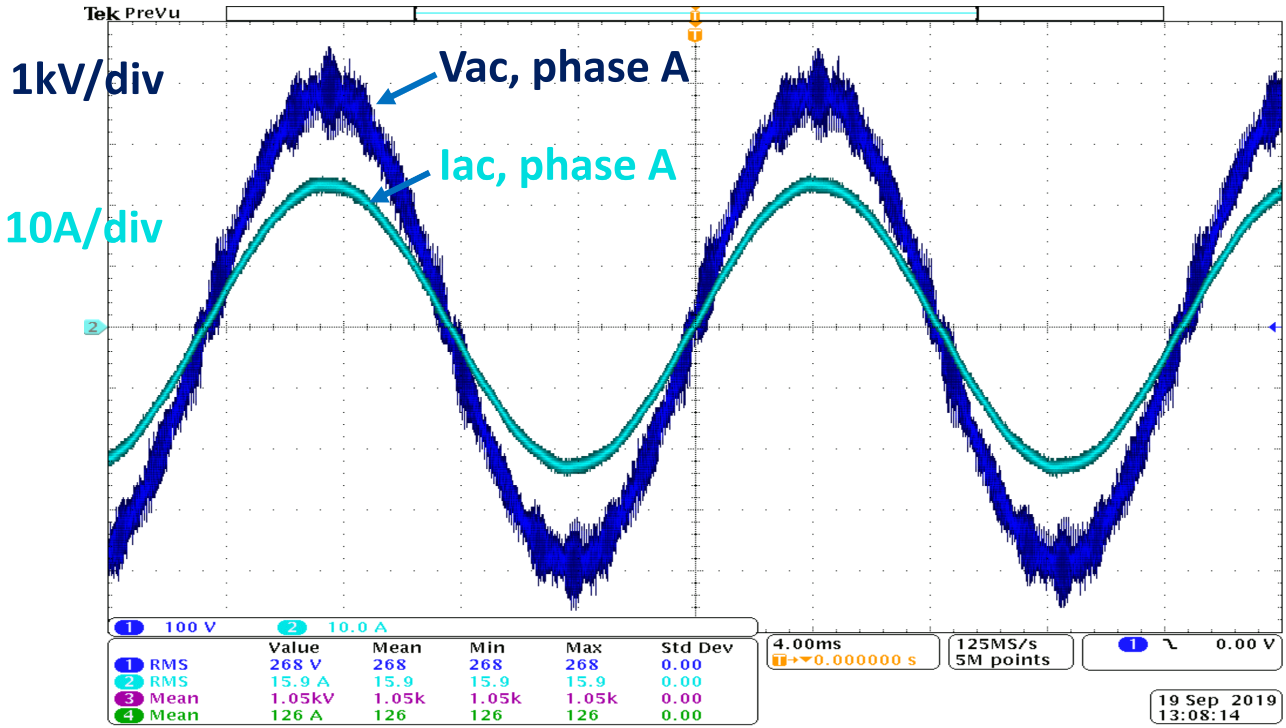
Input: 1050VDC from SST

135kW XFC System Efficiency



The peak efficiency reached 97.37%, which over achieve the target of 96.5%.

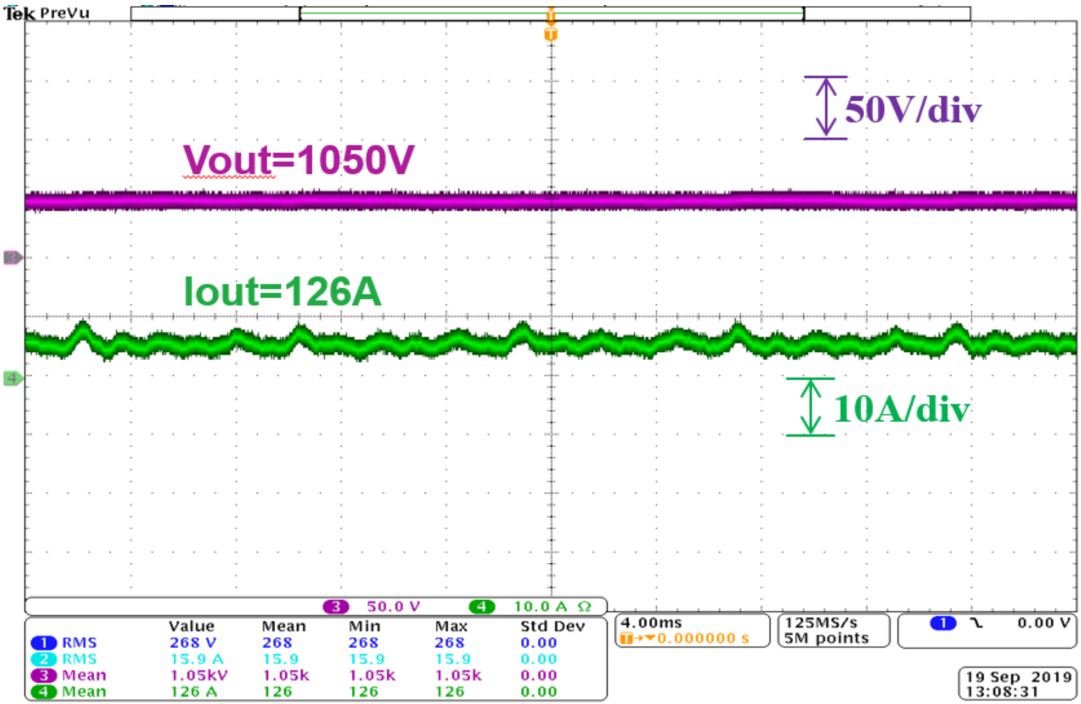
4.8kV/135kW SST AC Input Waveforms (full load)



Vin = 4.8kVac 3-phase, Pout=135kW

THD of AC current is only 0.80%

135kW SST DC Output Waveforms (full load)



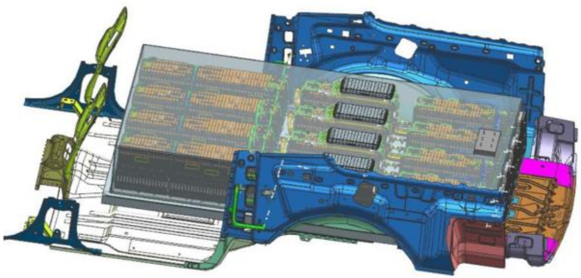
The voltage ripple is 5Vp-p, or 0.5% of the DC voltage.
The current ripple is 5Ap-p, or 4% of the DC current.

400kW SST Cabinet Design

AC Input Cabinet   Converter Cabinets   Control Cabinet

Dimension (W*D*H)	3100*1300*2100mm
Weight (System)	3000kgs
Cooling	Forced air

Retrofit Vehicle RESS/HVDS System



Cells/Modules

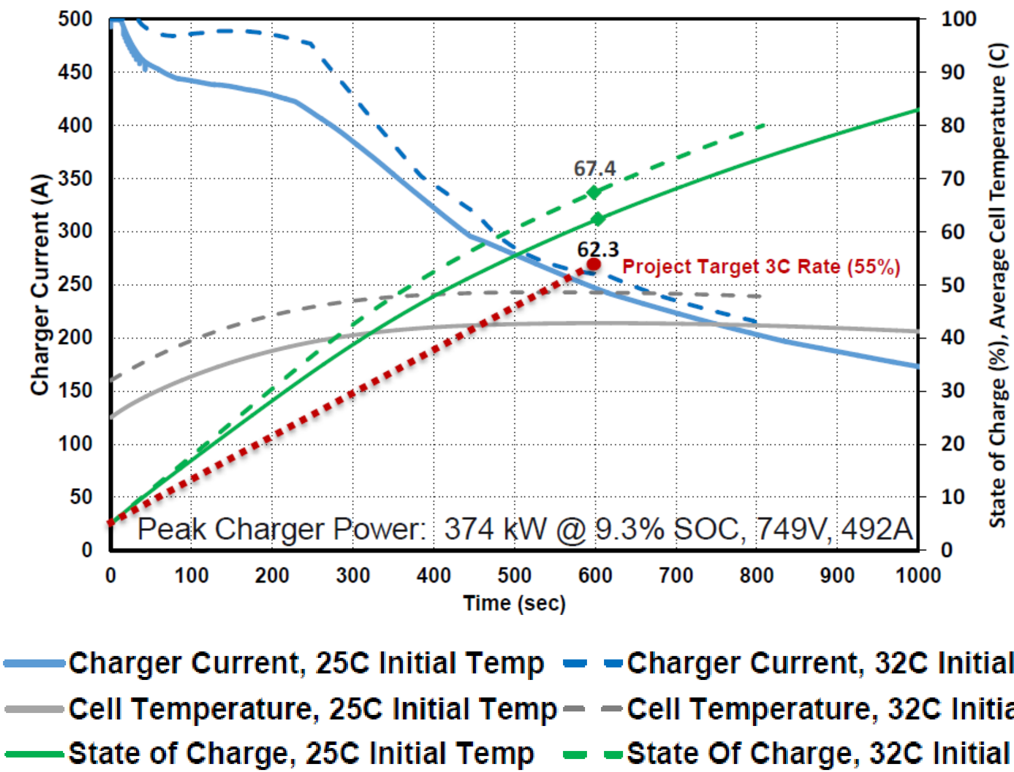
Retrofit vehicle in Progress

Battery Module Configuration

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

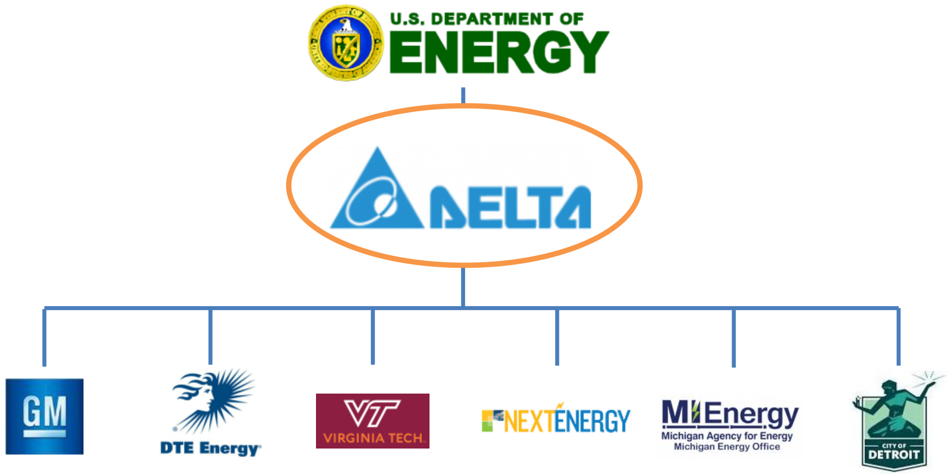
RESS: Rechargeable Energy Storage System (battery pack)
HVDS: High Voltage Distribution System

Vehicle Charging Profile Analysis Result



SOC increased by 57.3% and 62.4% respectively in 10minutes. The target is 50%.

Acknowledgement to Partners



Activities

BP1 Year-End Review
Delta Livonia Office
December 12th, 2019

Proposed Future Works

- Remainder of FY 2020
  - Test vehicle HVDS/RESS.
  - Test 400kW XFC system with vehicle emulator.
  - Test 400kW XFC system with Chevy Bolt car.

- FY 2021
  - Build test vehicle.
  - Test 400kW XFC system with 800V retrofit vehicle.

“Any proposed future work is subject to change based on funding levels.”

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