Components, Systems, and Grid Interface Challenges Related to Solid-State Transformers in Emerging Applications

CURENT 2024 Industry Conference

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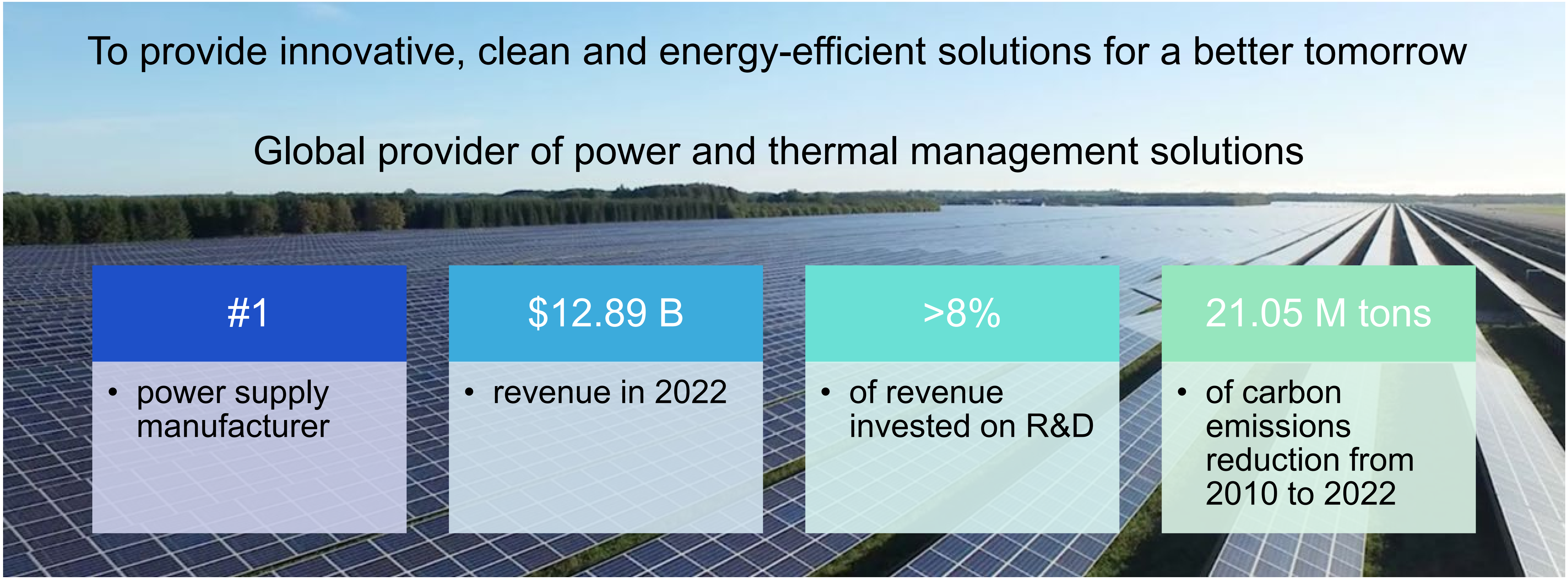
Outline

- Delta-at-a-Glance
- Solid-State-Transformers for Emerging Applications
    - DOE DC Fast Charging Demonstration
    - Datacenter Power Distribution
- Key Component: MV Transformer
- Take Aways

Delta Electronics at-a-Glance

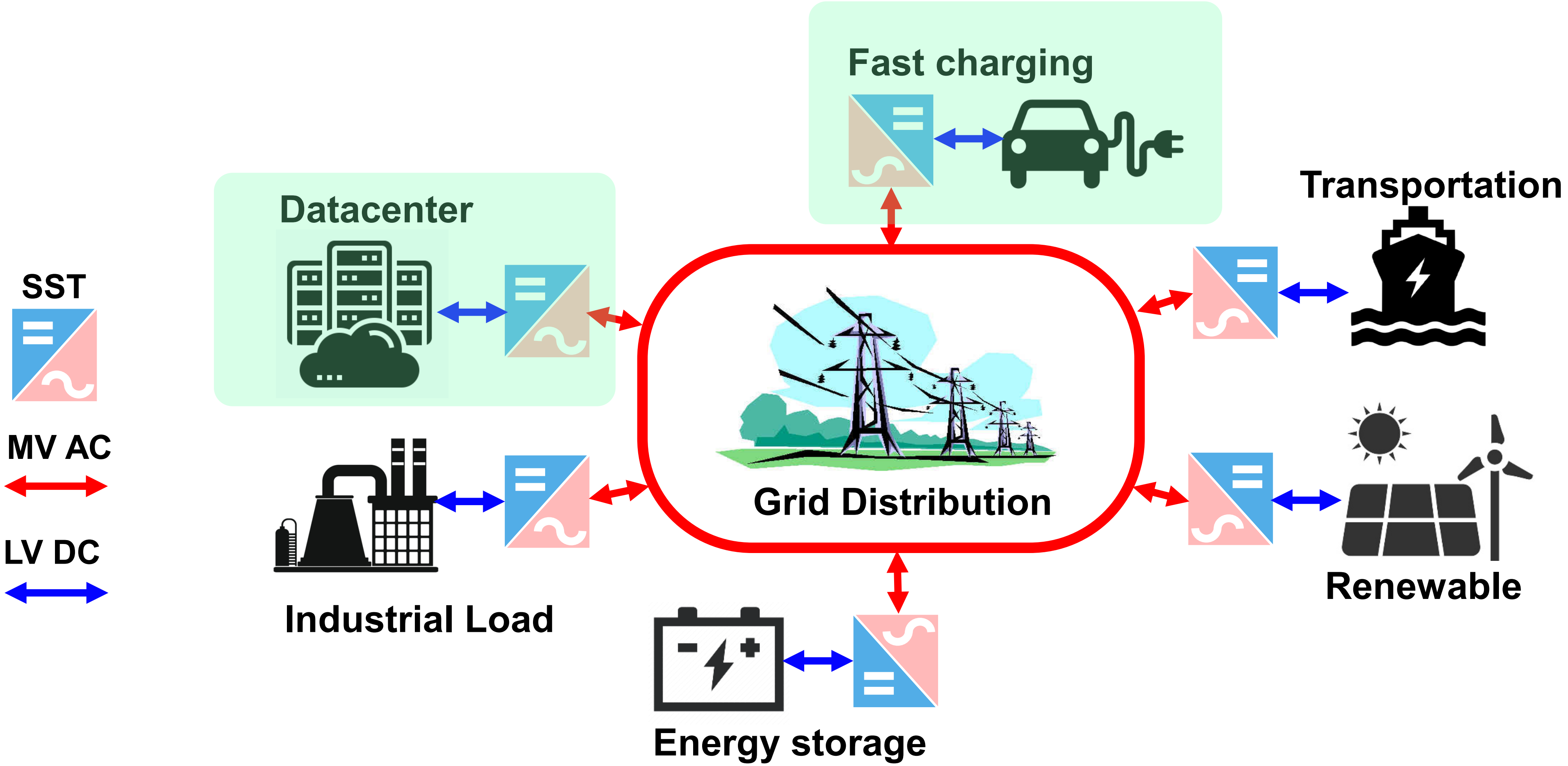


To provide innovative, clean and energy-efficient solutions for a better tomorrow

Global provider of power and thermal management solutions

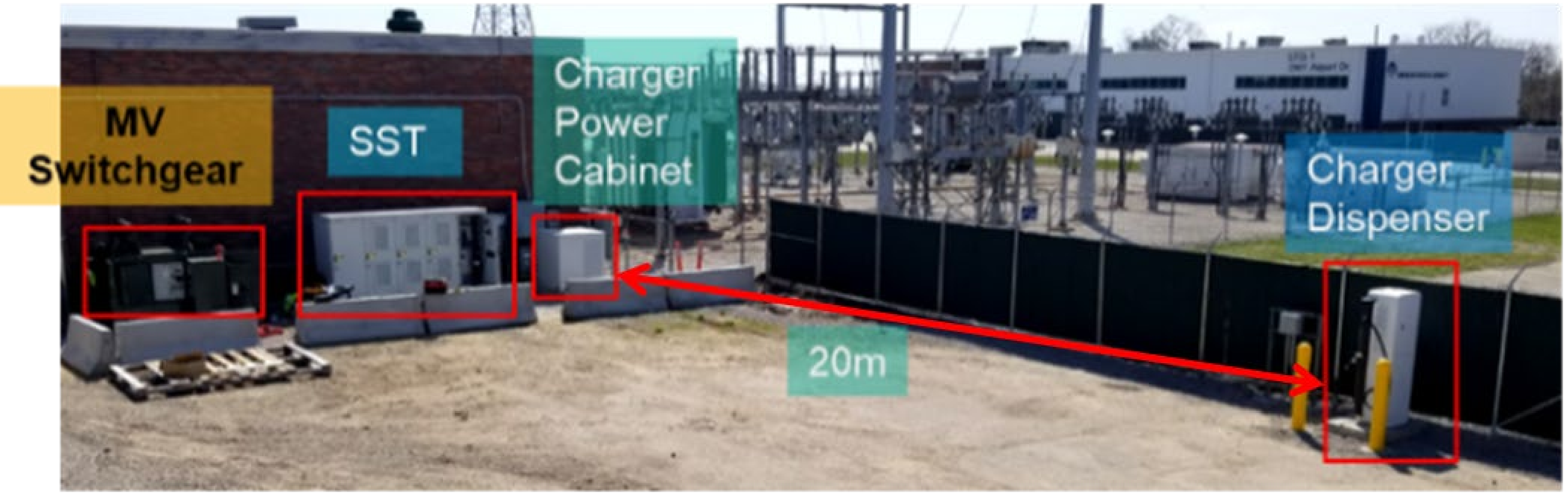
#1	$12.89 B	>8%	21.05 M tons
• power supply manufacturer	• revenue in 2022	• of revenue invested on R&D	• of carbon emissions reduction from 2010 to 2022

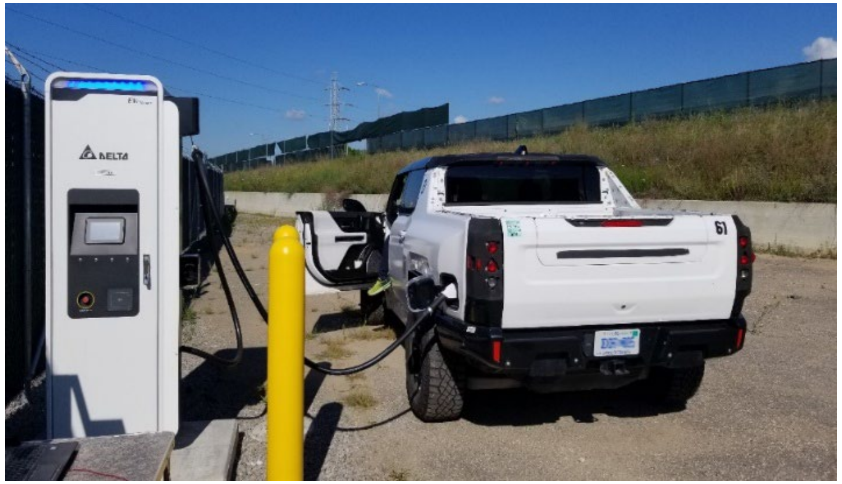
Solid-State-Transformers (SST) Applications

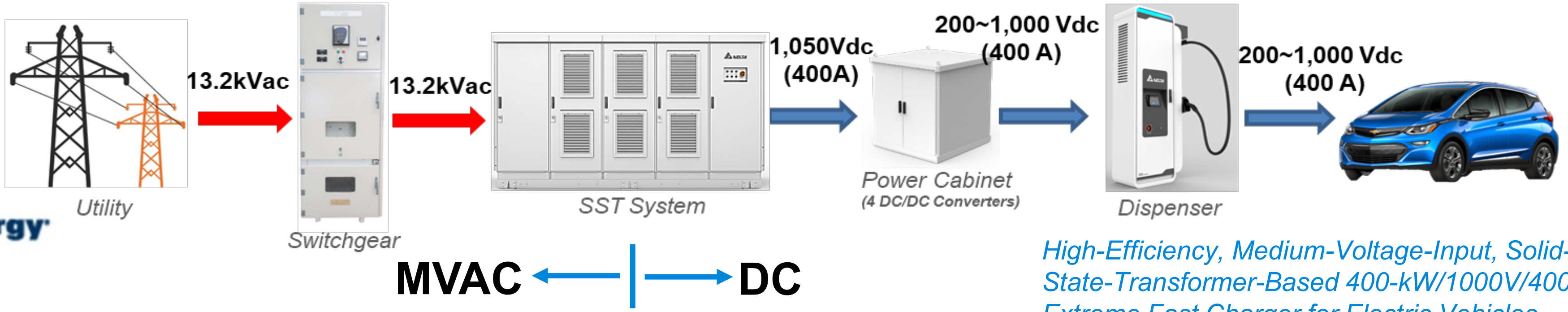


SST is an enabling technology for emerging applications

SST for EV Charging Applications



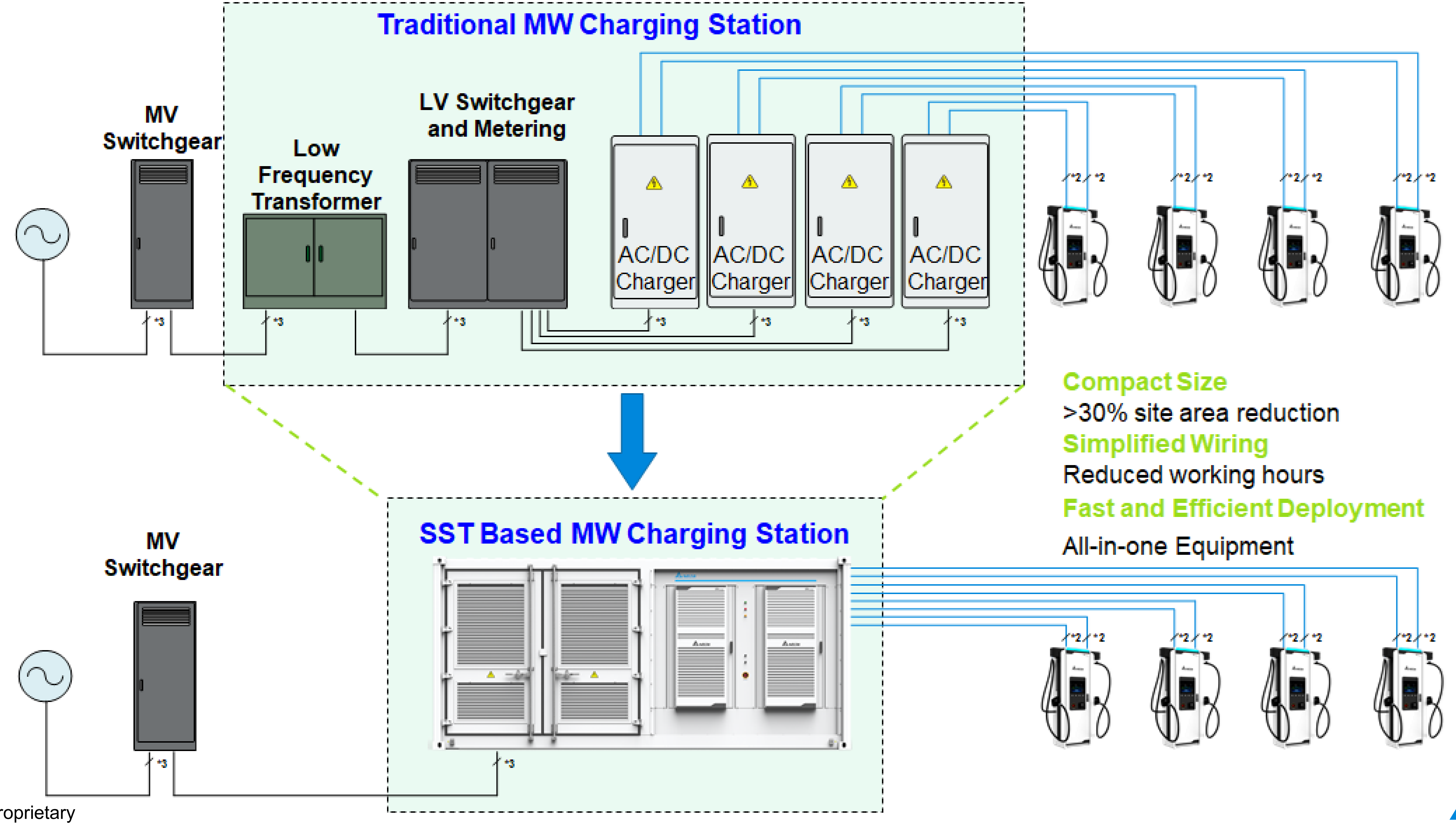




High-Efficiency, Medium-Voltage-Input, Solid-State-Transformer-Based 400-kW/1000V/400A Extreme Fast Charger for Electric Vehicles DE-EE0008361

- **Successfully commissioned a DOE-sponsored project in Detroit in cooperation with our partners on a 13.8 kV$_{ac}$, 400 kW, 400 A$_{dc}$ single point charging station, November 2022**

Value Proposition - SST Charging Station



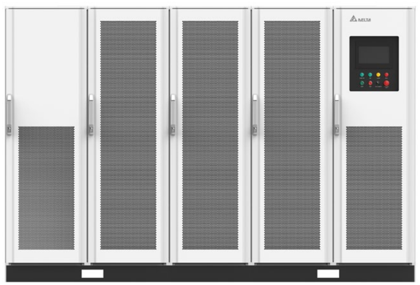
Compact Size
>30% site area reduction

Simplified Wiring
Reduced working hours

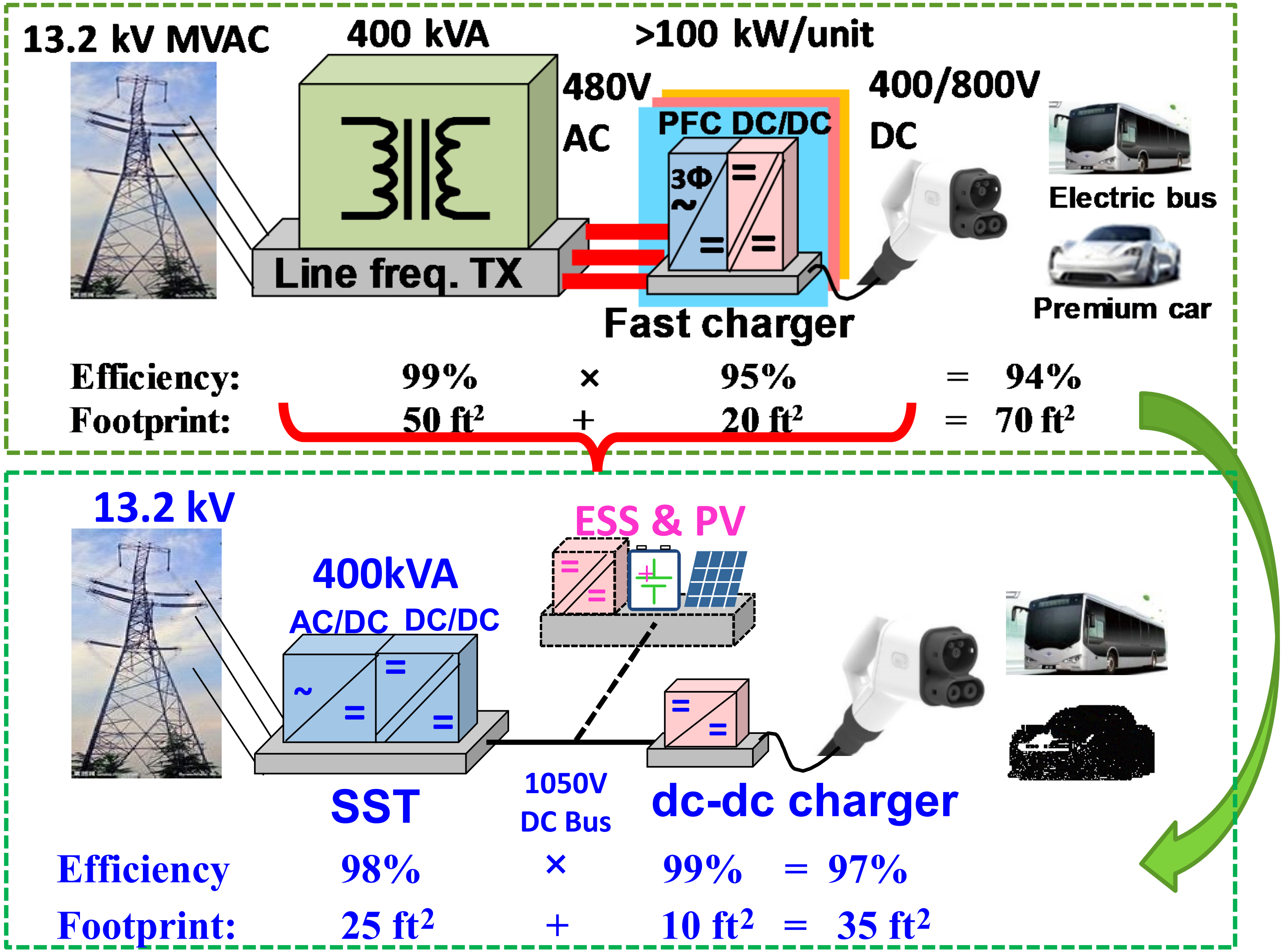
Fast and Efficient Deployment
All-in-one Equipment

Line Frequency Transformer vs SST

Line Freq. Transformer



SST

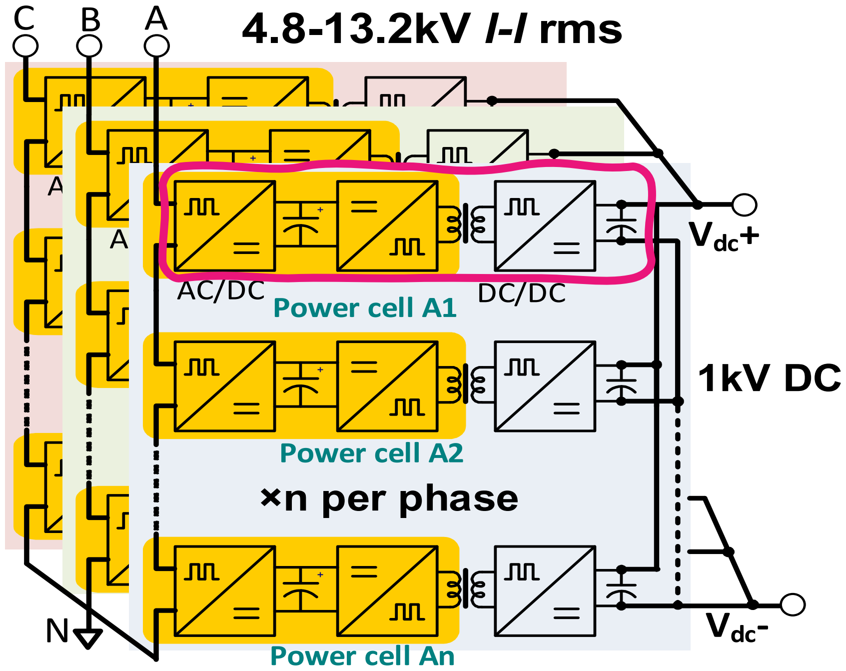


3% Eff. Improved

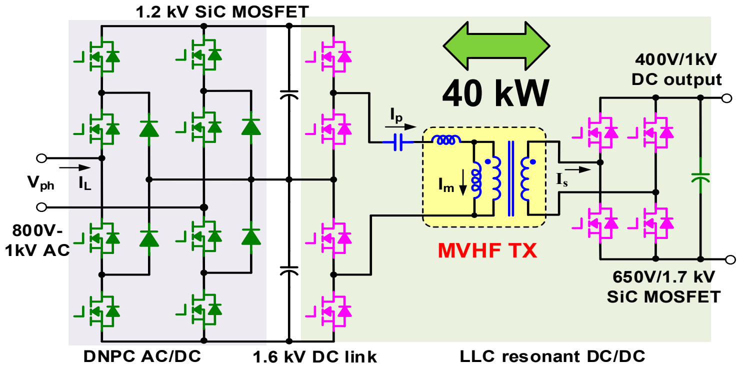
Up to 50% Space Saving

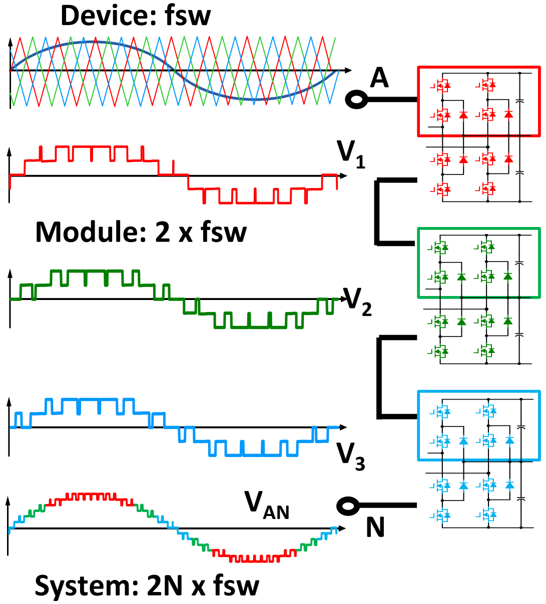
SST Architecture

SYSTEM



MODULE (POWER CELL)





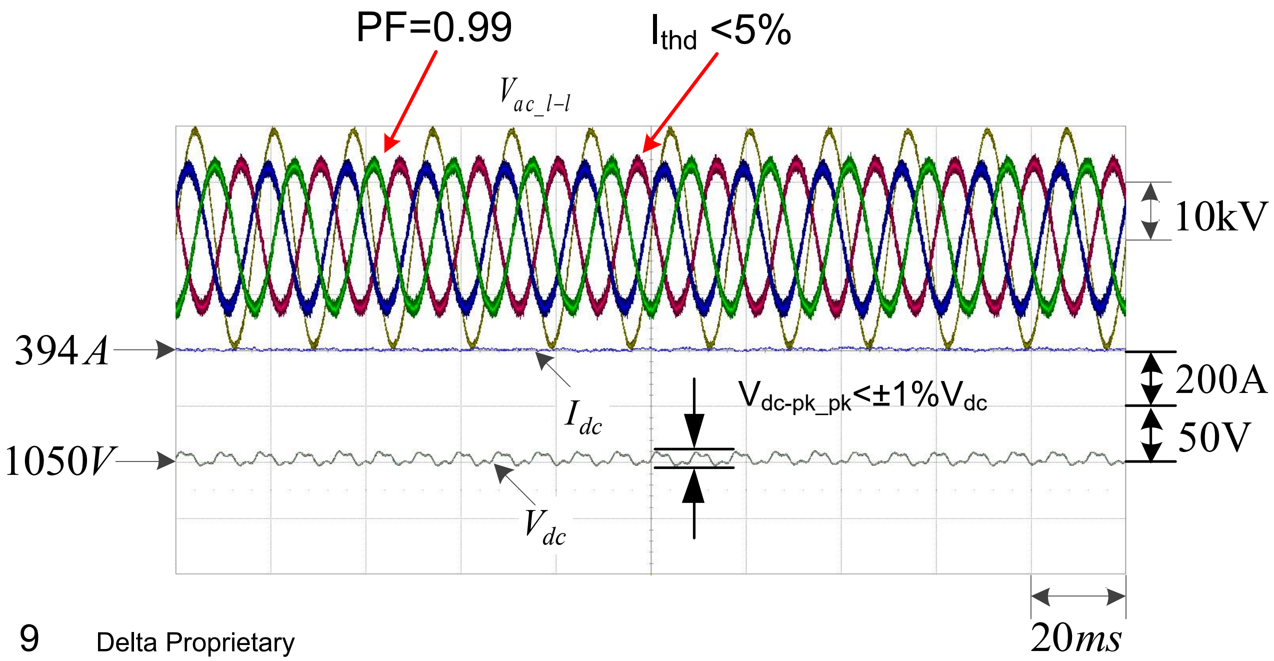
Interleaved Input Operation

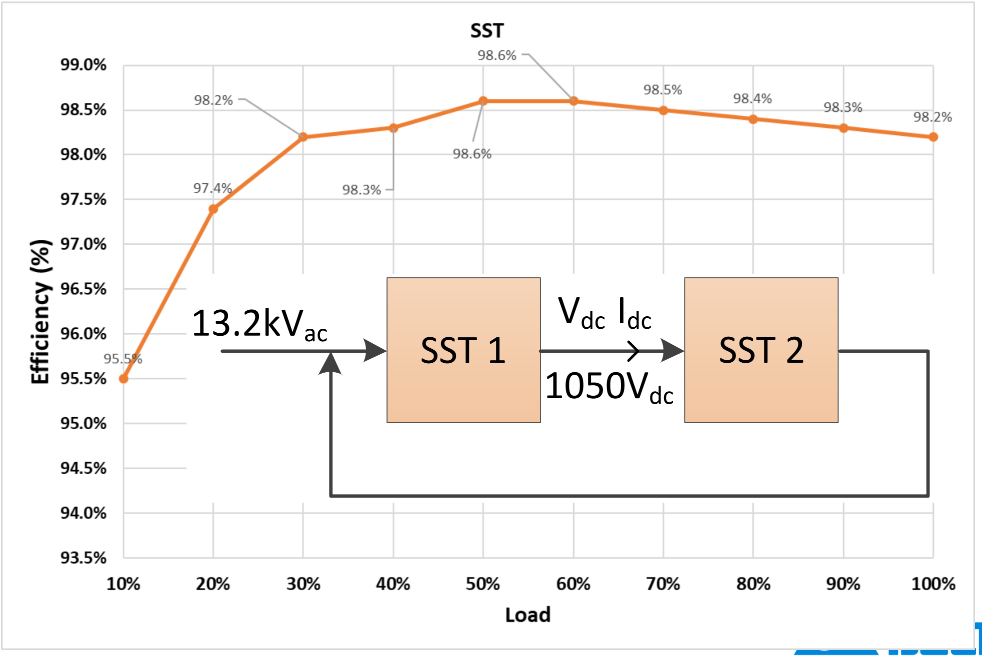
Cascaded multilevel topology:

- Modular architecture and scalable
- Series-input, parallel-output (SIPO) module connection
- Interleaved input operation
  - Increases effective frequency and lowers THD
- Redundant operation possibility

SST System Integration Test

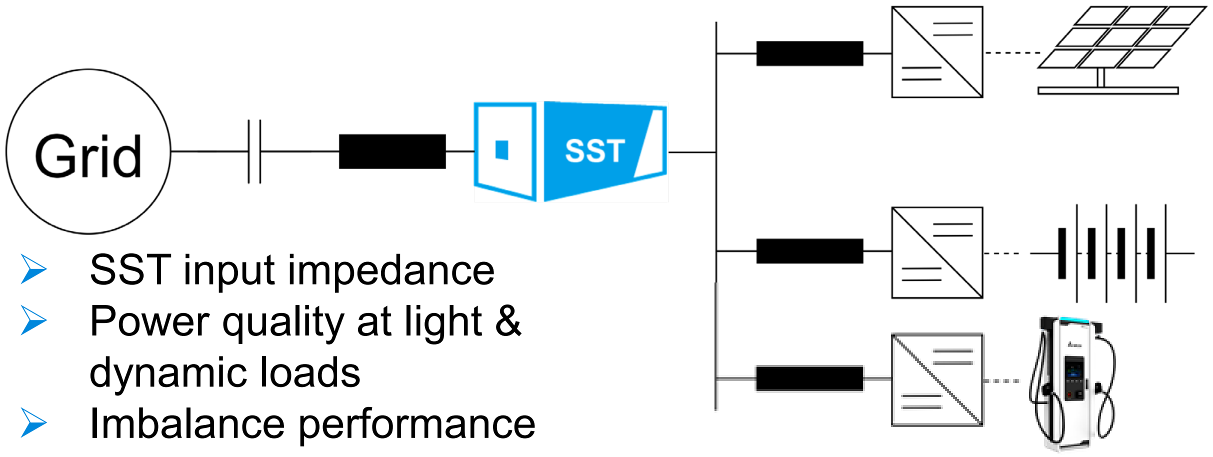
- Back-to-Back Test Setup
  - Bidirectional Power Flow
- AC Input 13.2 kV / 410kW
  - PF: ±0.99 @ 50%~100% Load
  - THDi < 5% @ 50%~100% Load
  - Efficiency: 98.6% @ 50% Load
    98.2% @ 100% Load



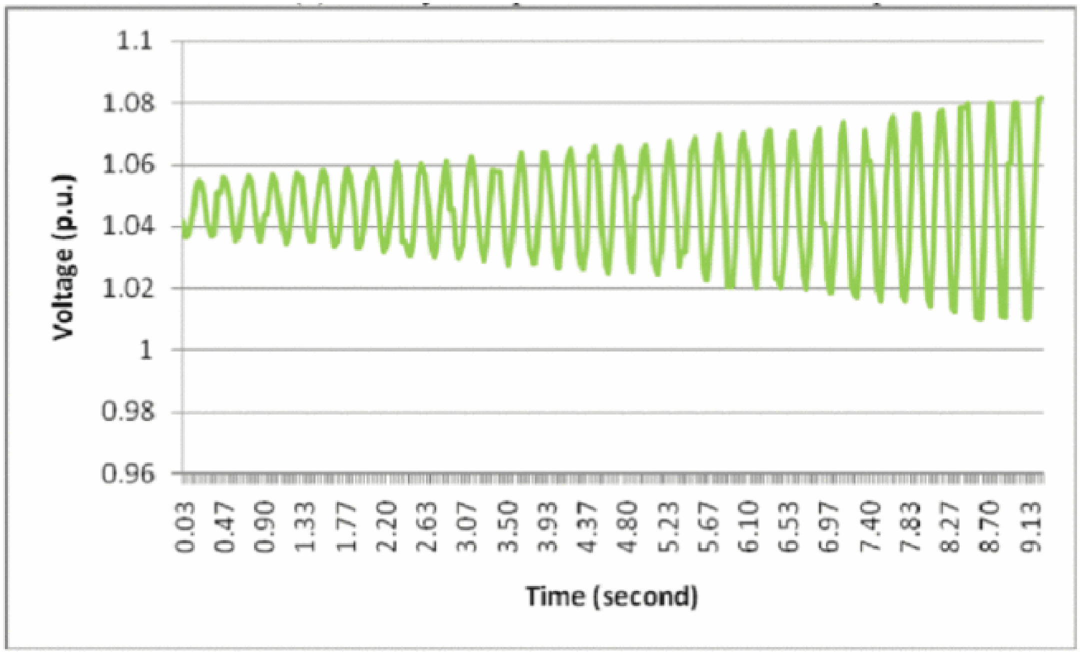


Sub-Synchronous Oscillations

DC-Coupled PV and BESS Hybrid Power Plant

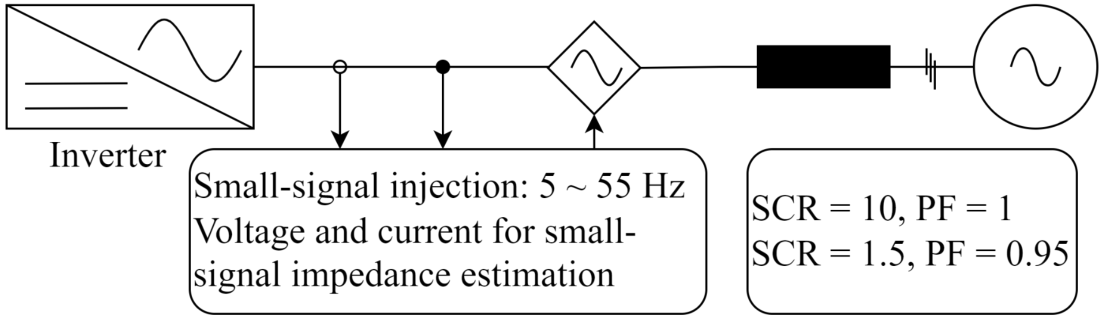


- SST input impedance
- Power quality at light & dynamic loads
- Imbalance performance



(b) Un-damped oscillations at high output

ERCOT PGRR-08, Sub-synchronous Frequency Scan Test

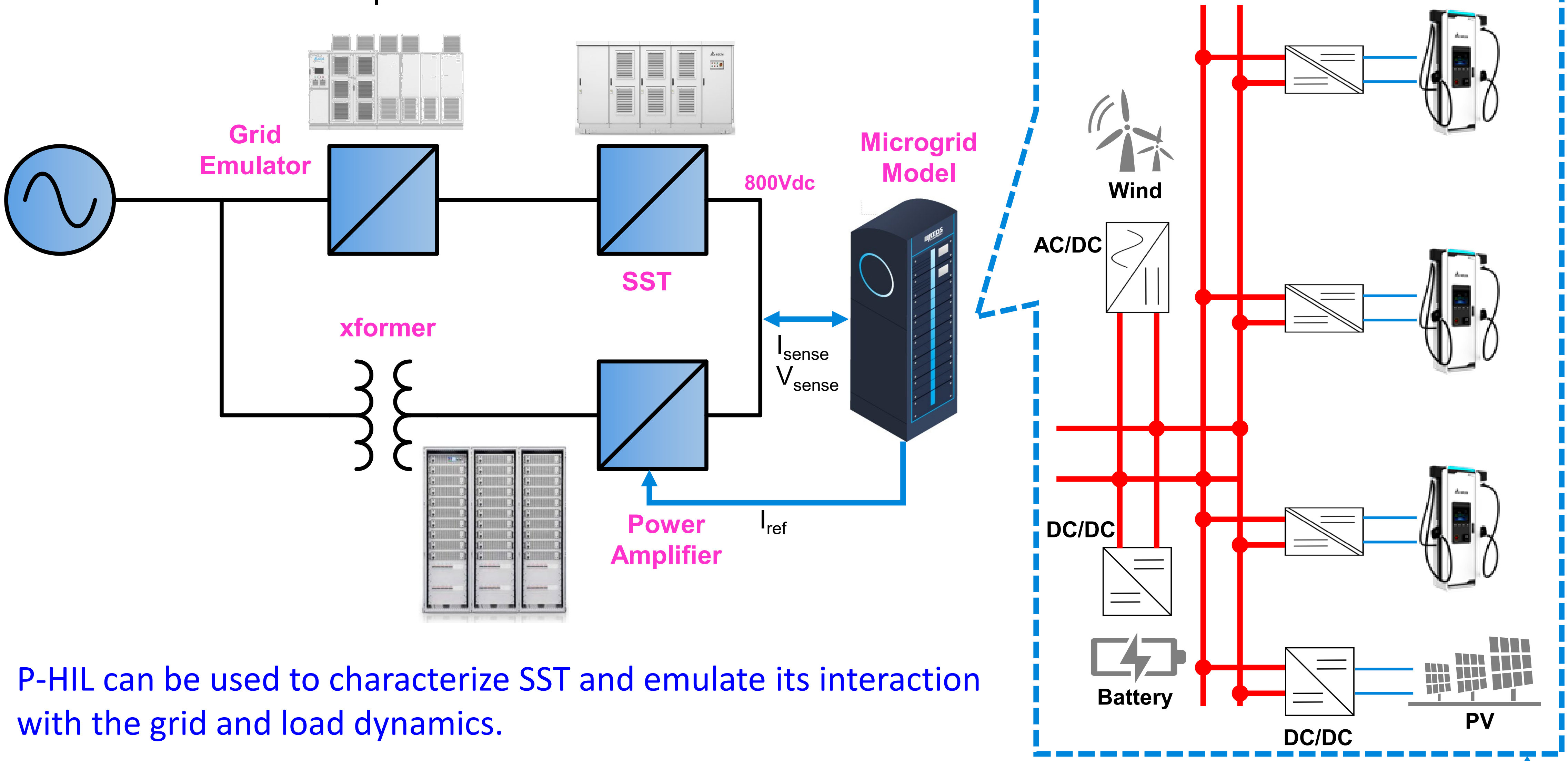


*Texas **4-Hz weak grid oscillations**: recorded voltage measurement at a WPP's point of interconnection.*

1. *Y. Cheng et al., "Real-World Sub-synchronous Oscillation Events in Power Grids With High Penetrations of Inverter-Based Resources," in IEEE Transactions on Power Systems, Jan. 2023.*

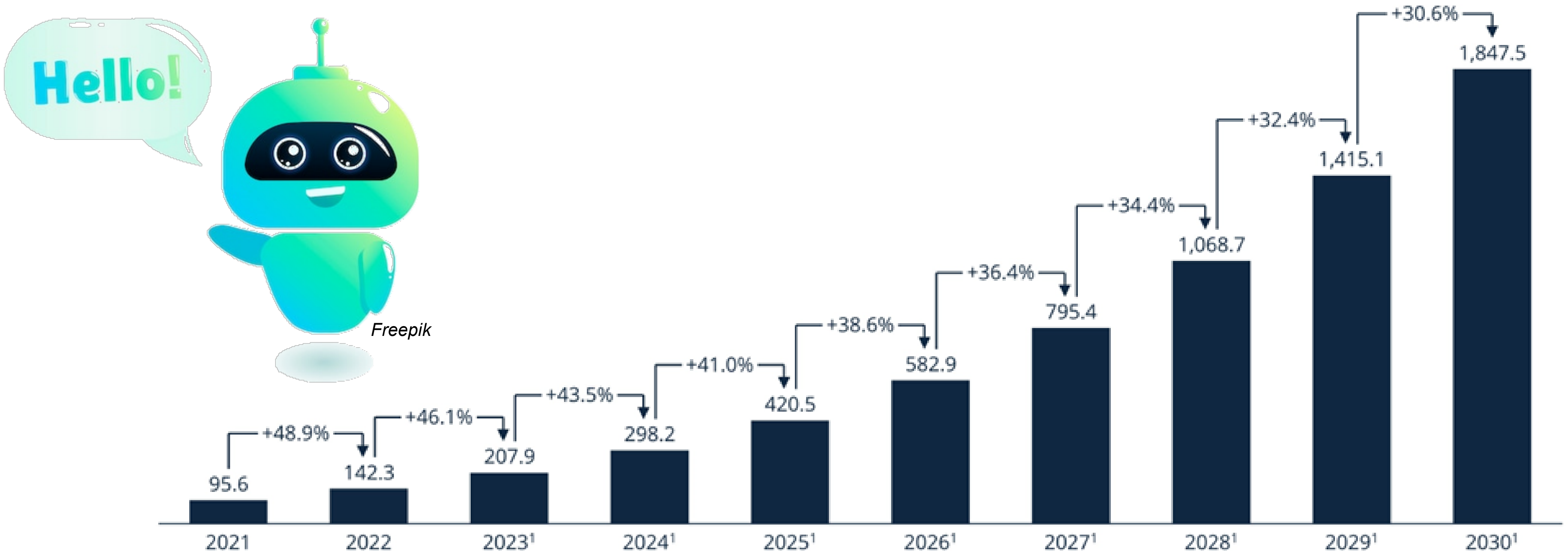
SST P-HIL Microgrid Simulation

Power Hardware in Loop SST Verification



- P-HIL can be used to characterize SST and emulate its interaction with the grid and load dynamics.

Global Artificial Intelligence Market



Freepik

BUSD

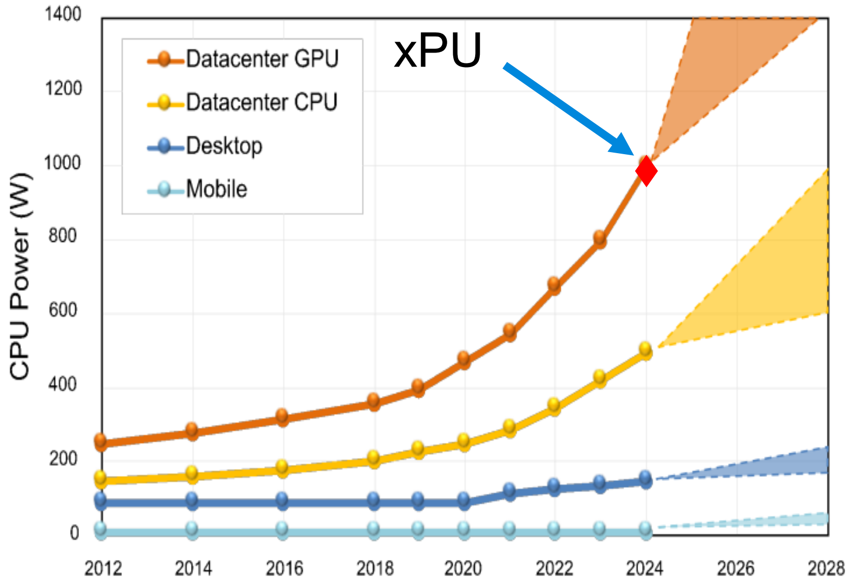
(1) Forecast
Sources: Next Move Strategy Consulting

ecommerceDB

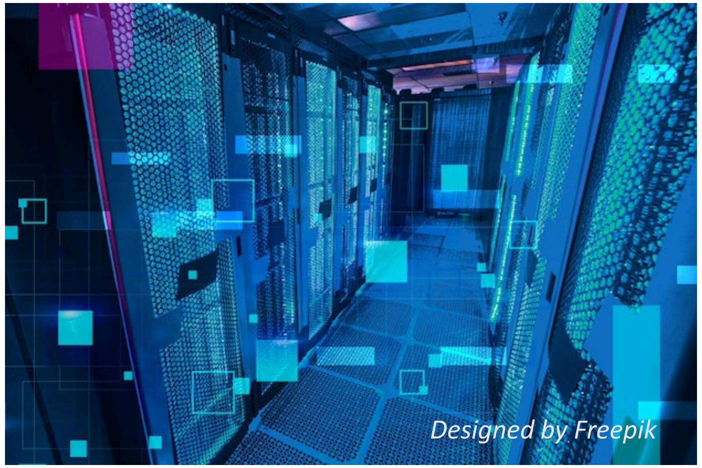
The AI market is projected to reach US$1.8 trillion by 2030

DELTA

Datacenter Power Demand



1. *K. Radhakrishnan, "Recent Advances in IVR Solutions for High Power Microprocessors," APEC2024*



Current Scenario

- 7 ~ 18 kW average enterprise rack power
- 30 kW ~ > 100 kW AI workloads rack power

AI Workloads (2023)

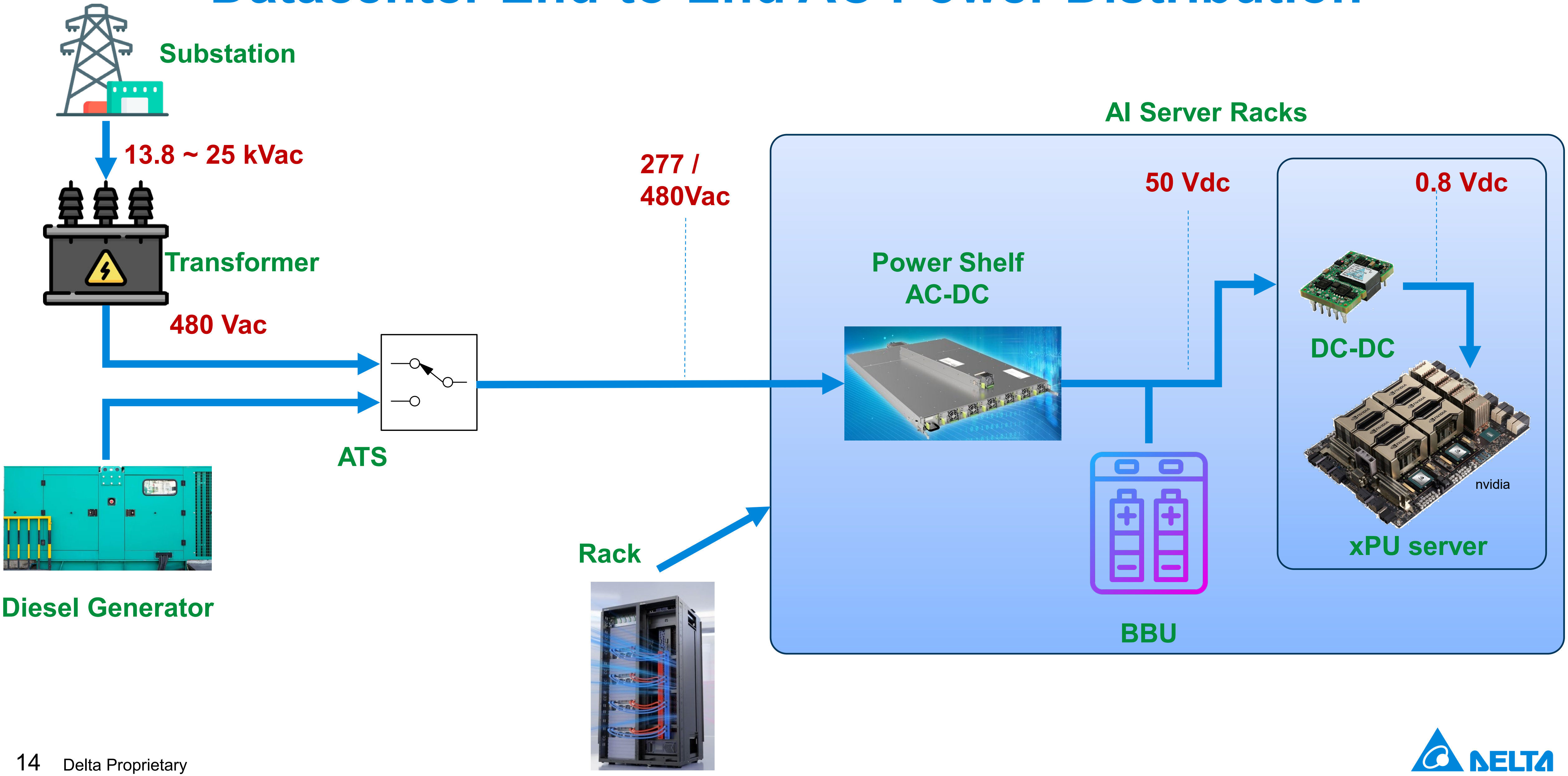
- 54 GW total datacenter capacity (US ~ 19 GW)
- ~8% or 4.3 GW for AI workloads
  - 20% for training; 80% for inference

Projections for 2028

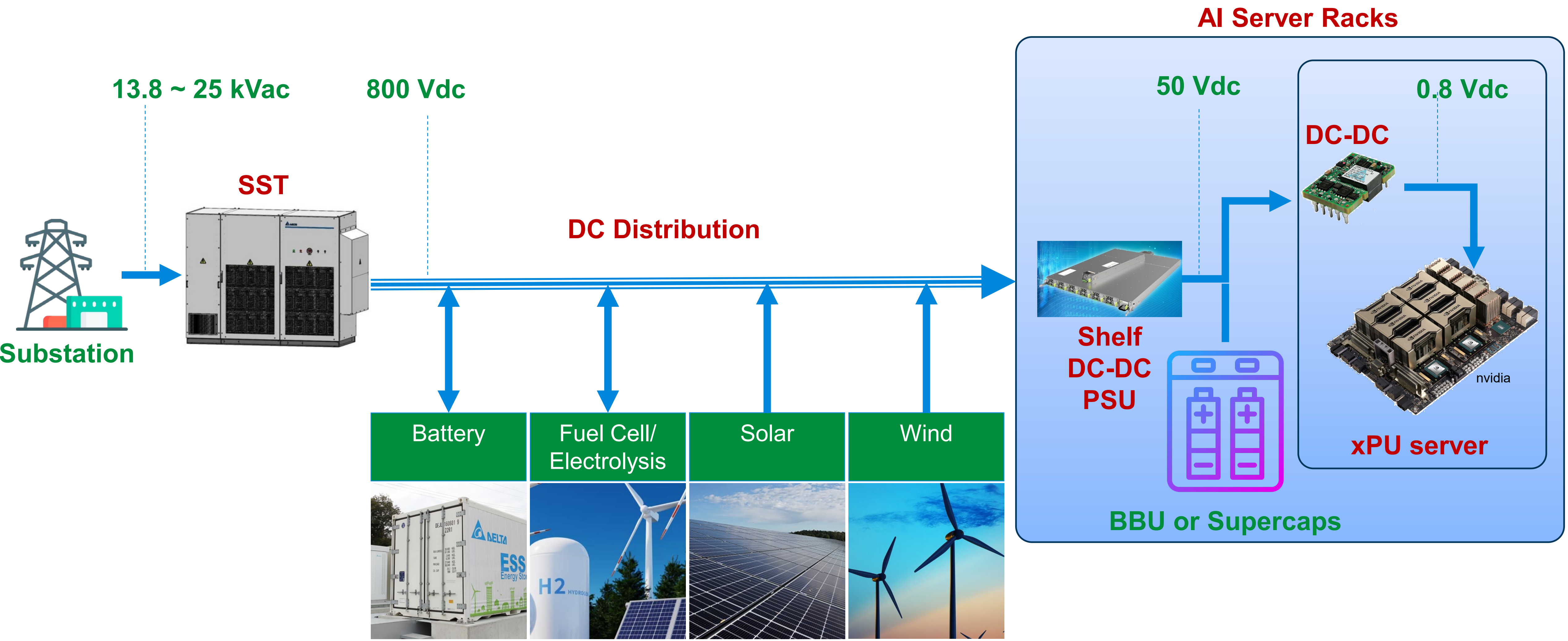
- 90 GW total datacenter capacity (US ~ 35 GW)
- 20 GW for AI workloads (20% data center consumption)
  - 15% for training; 85% for inference

1. *The AI Disruption Challenges and Guidance for Data Center Design, Schneider Electric*

Datacenter End-to-End AC Power Distribution



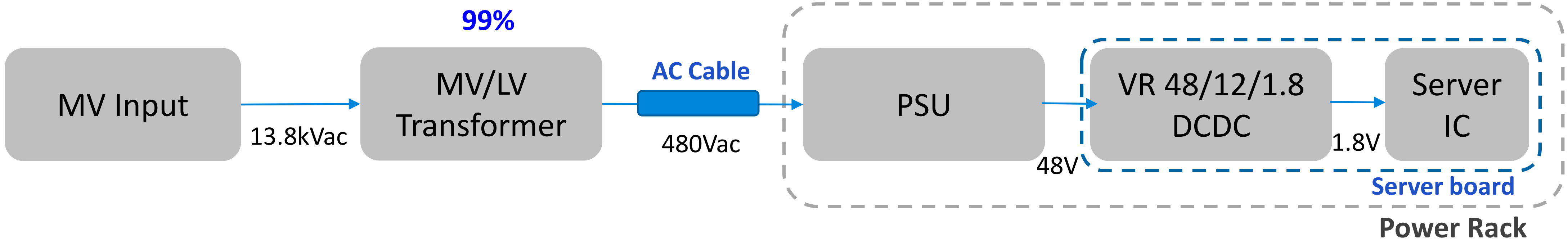
Next Generation Power Distribution



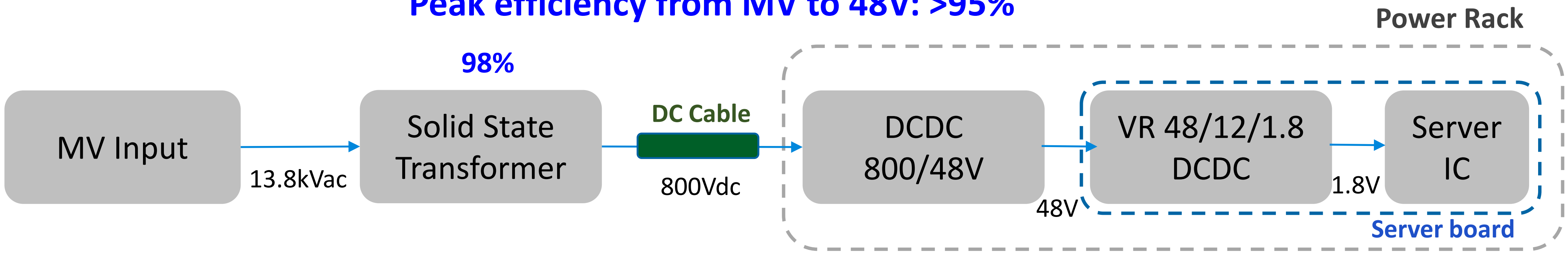
Distributed Energy Resources and Backup Power

Datacenter Power Architecture Comparison

Peak efficiency from MV to 48V: 95%

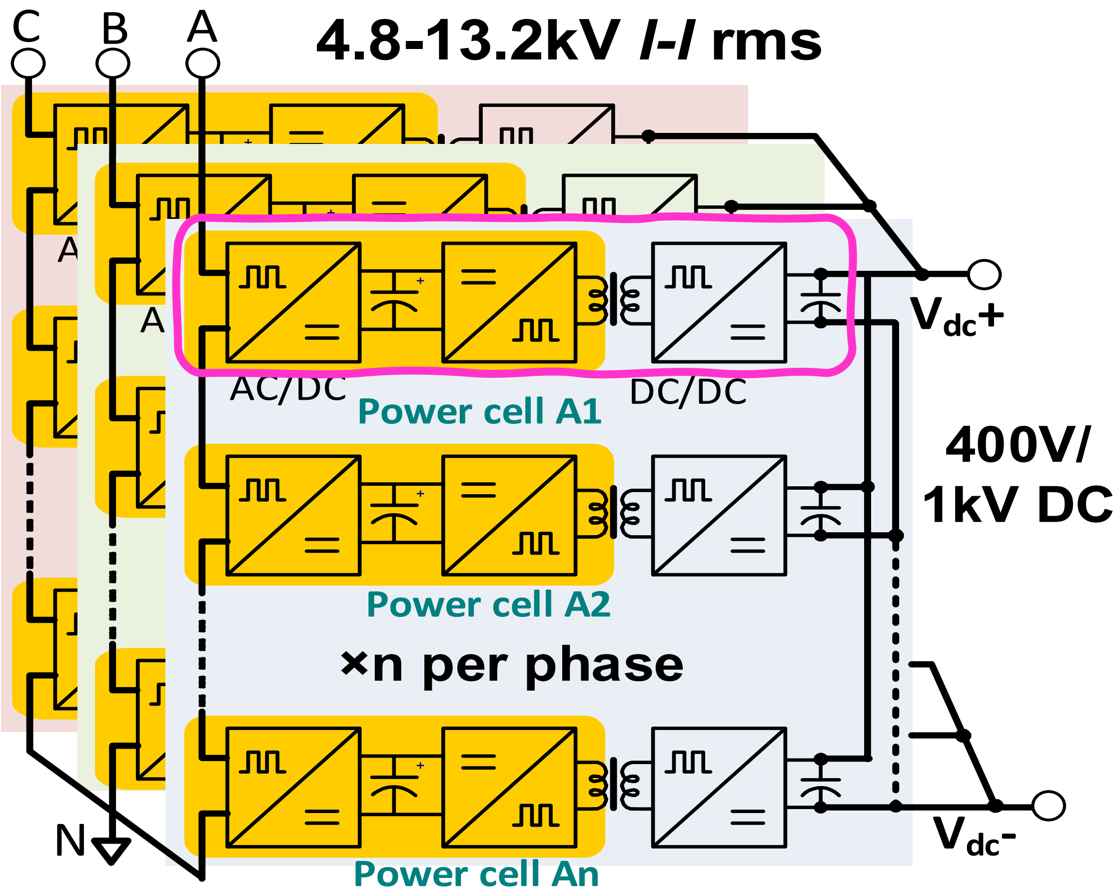


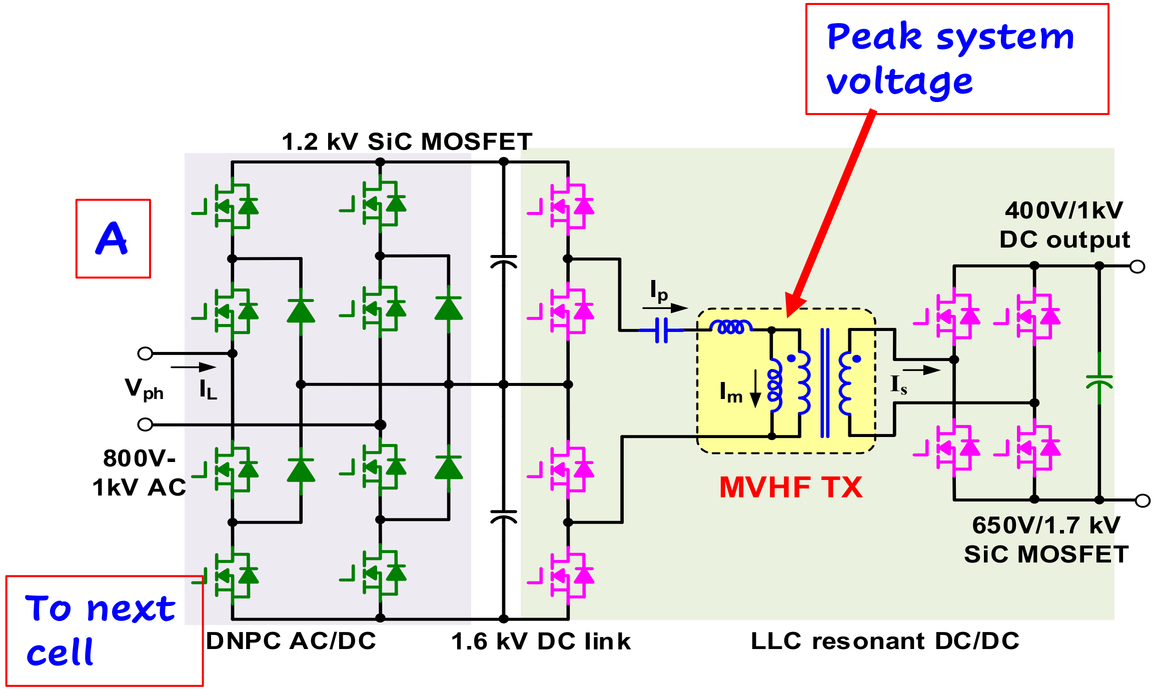
Peak efficiency from MV to 48V: >95%



- Smaller footprint and lighter weight will save infrastructure capex
- The cost trend will favor more SST vs LFT in the long run
- Higher efficiency SST + DC distribution saves opex
- Modular & scalable without large LFT
- DC Bus provides RE/ESS integration capability
- SST also provides grid support functions

Key Component: MV Transformer

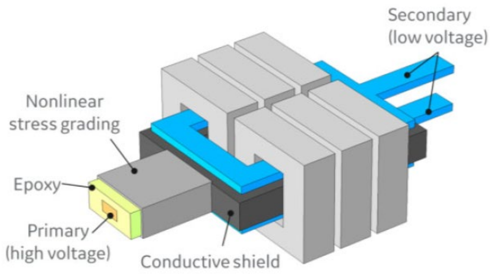




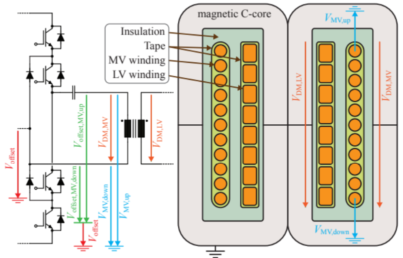
- High frequency transformer is key for insulation and power density (contradiction!)
- Challenges: concentrated e-fields, partial discharge, thermal handling, and manufacturing consistency

Medium-Voltage High-Frequency Transformer Technologies

Epoxy Filled HV or (HV and LV) winding



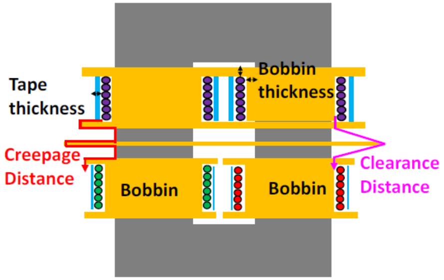
General Electric, 2018



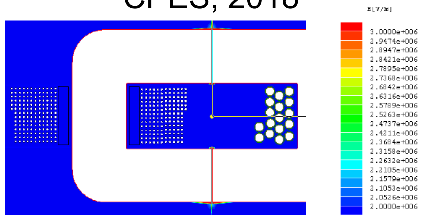
ETH, 2014

- Litz wire and epoxy combination defect
- Low turn to turn insulation capability

Separate HV and LV side through gap



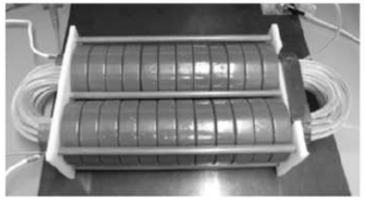
CPES, 2018



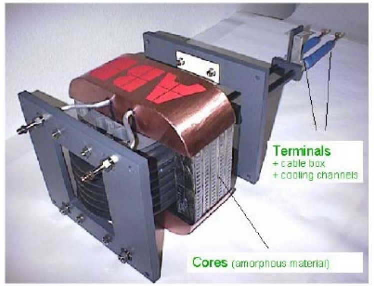
NCSU, 2010

- Magnetic inductance coupled with insulation

Coaxial type transformer



NCSU, 2011



ABB, 2002

- Limited to 1:1 turns ratio

Oil Insulated Transformer

ABB, 2014

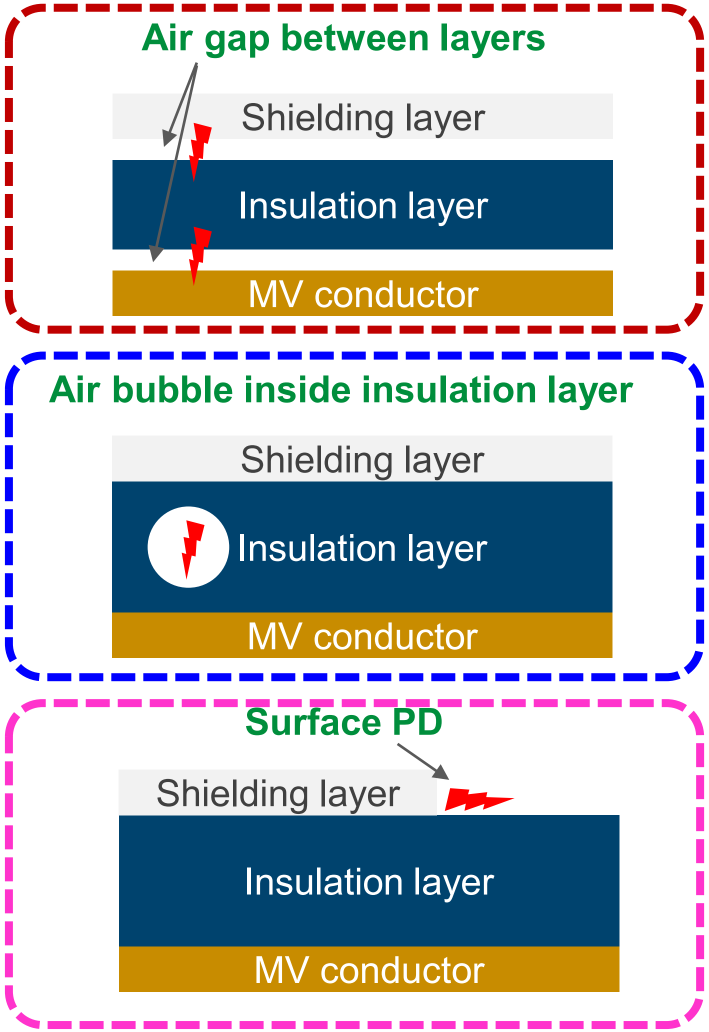
Aachen, 2014

- Dry type MV transformer preferred

R. Wang, Z. Shen, C. Zhang, B. Zhang and P. Barbosa, "Planar Structure High-Frequency Transformer Design for Medium Voltage Applications," 2022 IEEE ECCE.

Partial Discharge & Design Goals

Typical partial discharge defects



Air gap or air bubble defects can be well controlled through PCB process

Stress grading or terminal treatment is needed to reduce the surface PD

Property	Epoxy		PCB
	SilGel 612	**50-3182NC**	**FR4-TG180**
Dielectric Strength (kV/mm)	22	22	45
Thermal Conductivity (W/(m·K))	0.2	1.7	0.35
Viscosity (cps)	1000	15000	/

Dielectric selection & breakdown field strength

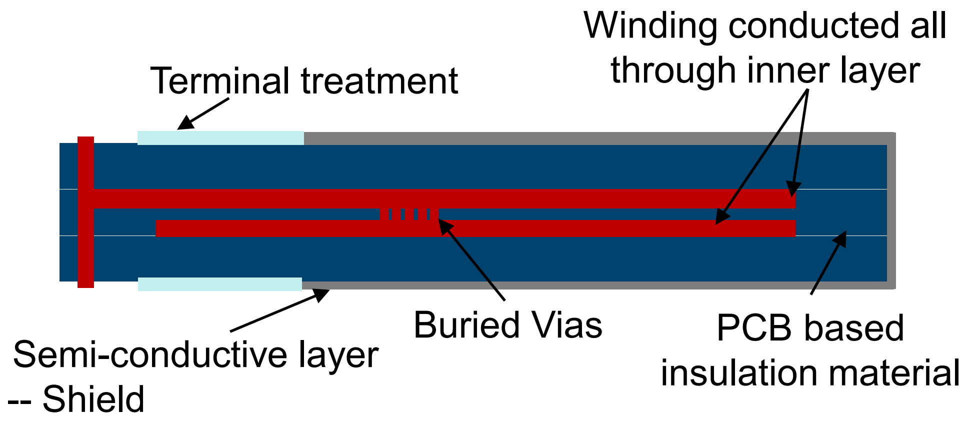
- Internal peak e-field **< 20kV/mm**
- Air peak e-field **< 2kV/mm**

Goals

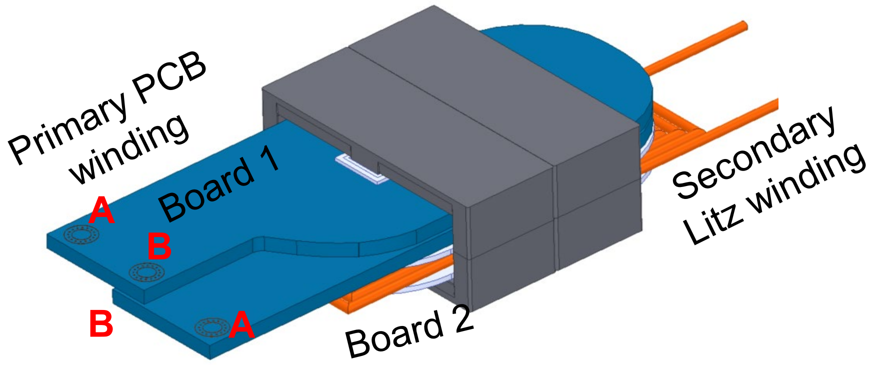
- No partial discharge in the operation range
- High efficiency and power density
- Easy manufacturing

R. Wang, Z. Shen, C. Zhang, B. Zhang and P. Barbosa, "Planar Structure High-Frequency Transformer Design for Medium Voltage Applications," 2022 IEEE ECCE.

Planar Structure MV Transformer Solution



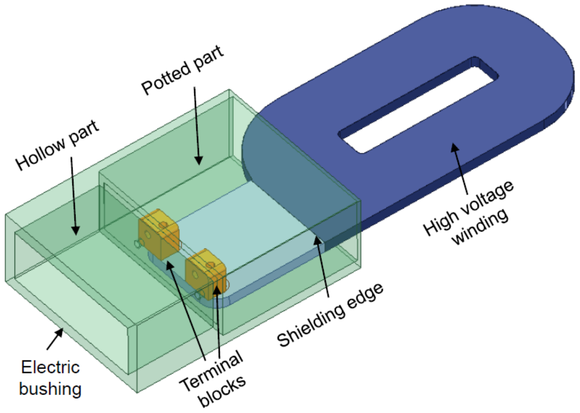
Cross-section View of High Voltage Winding Structure



Conceptual view of transformer prototype

- Inner layer for the HV conduction
- PCB based material (FR4) for insulation
- Buried vias (epoxy filled) for connect between inner layers
- Semi-conductive layer for shielding
- Stacked up windings for more turns
- Terminal treatment for surface PD and creepage requirement

- **Proposed solution constrains the e-field within the high voltage PCB winding. Winding and core area can be PD free**



Terminal potted with SilGel (Wacker 612)

R. Wang, Z. Shen, C. Zhang, B. Zhang and P. Barbosa, "Planar Structure High-Frequency Transformer Design for Medium Voltage Applications," 2022 IEEE ECCE.

Take Aways

SST is a key technology for emerging applications

Key components

HV WBG (>10 kV SiC) and UWBG power semiconductors

Passive components (inductors and capacitors)

High frequency transformers for MV insulation

Reliability

High operating temperatures and thermal cycling stresses

Failure mechanisms

Lifetime prediction and power device packaging

Harsh electrical and thermal stress on power and control circuits

Challenges

Cost

Limited power capability

Complex control requirements

Thermal management

Insulation

DC distribution fault, protection, grounding

Smarter. Greener. Together.

Thank You!