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Evolution of the Solid-State Transformer for Different Applications

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- **Work Experience and Degrees:**
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  - BS and MS: RF Power Electronics, adv. J.S. Modzelewski, Warsaw University of Technology, WAW, PL, 202009
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- Acknowledgments

Solid State Transformer for Different Applications

Site-level integration of High-Power Charging

- Charging applications
- Renewables
- Grid interface converters
- Local loads

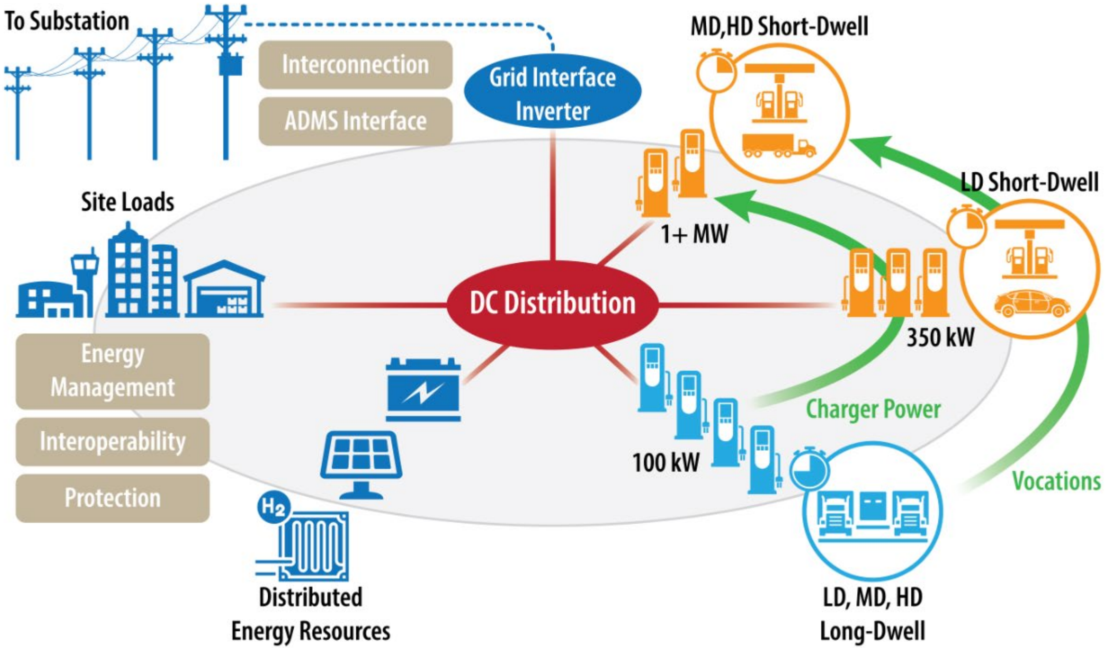
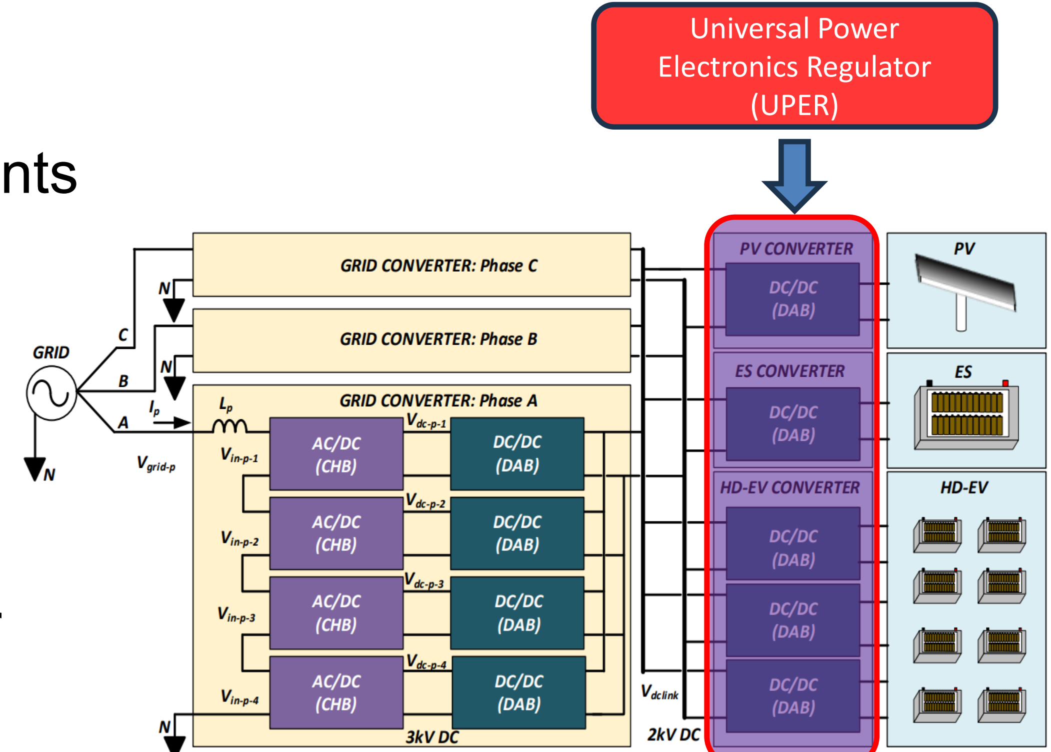


Figure courtesy: Electric Vehicles at Scale Consortium High-Power Charging
https://www.energy.gov/eere/vehicles/electric-vehicles-scale-consortium-high-power-charging

UPER Requirements for EV Charging

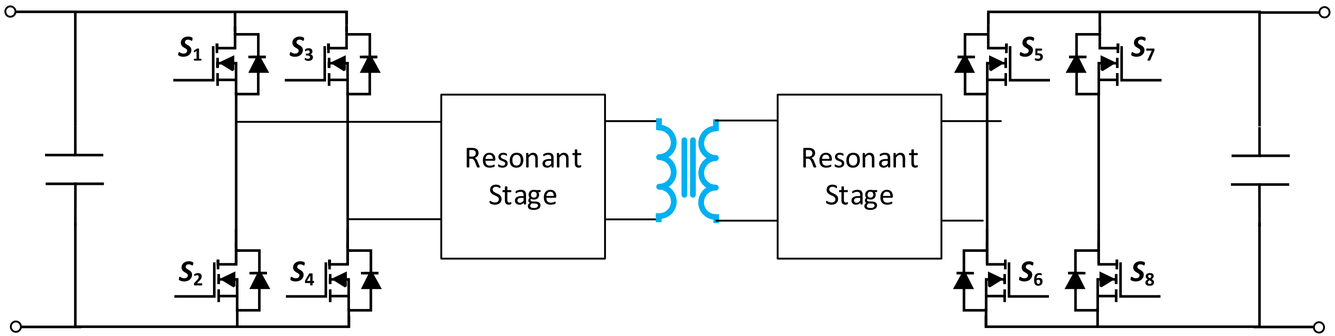
EV Charging Requirements

- Isolation
- Bidirectionality
- Wide voltage range
- Small output current ripple
- Adaptability for higher voltage classes



M. Starke et al., “A MW scale charging for supporting extreme fast charging of heavy-duty electric vehicles, “ 2022 IEEE ITEC, [10.1109/ITEC53557.2022.9813825](https://doi.org/10.1109/ITEC53557.2022.9813825)

Bi-directional Charging Classes



1 kV Class

Input: 800 V – 1200 V

Output: 250 V - 900 V

Current: 450 A

Efficiency: > 98.5 %

2 kV Class

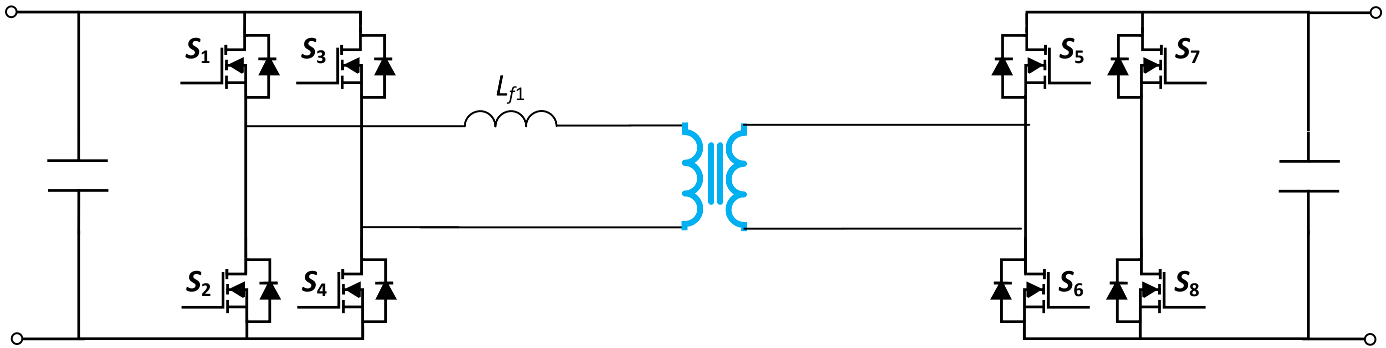
Input: 1500 V – 2000 V

Output: 500 V - 1500 V

Current: 150 A

Efficiency: > 99 %

Dual Active Bridge for EV Charging



Disadvantages

- **Transformer voltages are square wave**
- DC Bias currents are control based

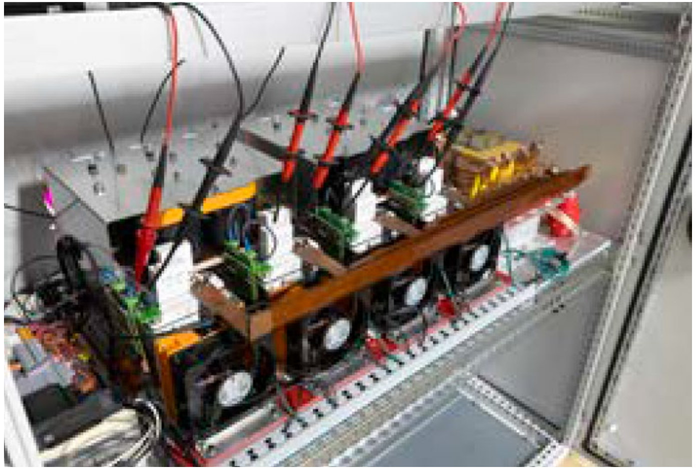
Advantages

- **Low current ripple**
- Light load regulation
- Low voltage current stress

1kV Class Charger

- 3 x 175 kW DAB modules
- Input Voltage 900 ± 5%
- Maximum current 200 A

- 500 kW Charger
- Nominal current 350 A

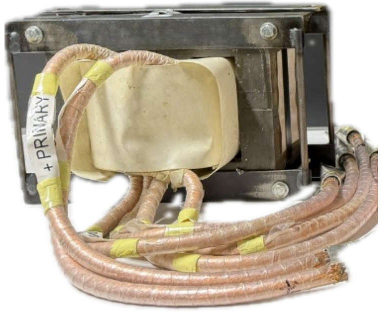


1kV 175+ kW Module
24 x 36 x 25 inch

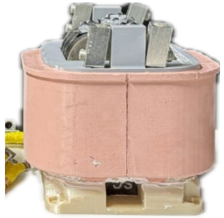
1kV 500+ kW charger

Components and Materials

- Finmet FT3M Cores (CC 1000/150)
- 40AWG Copper Litz-Wire Windings
  - CTI 1: Biaxially-oriented PET (Class B: 130°C)
  - CTI 3: Polyimide resin (Class H: 180°C)
- 3D printed bobbins
  - Polyethermide
  - Carbon nylon fiber
  - Epoxy
- VPI printed bobbins
  - Thermal conductive silicone
  - Dielectric Gel

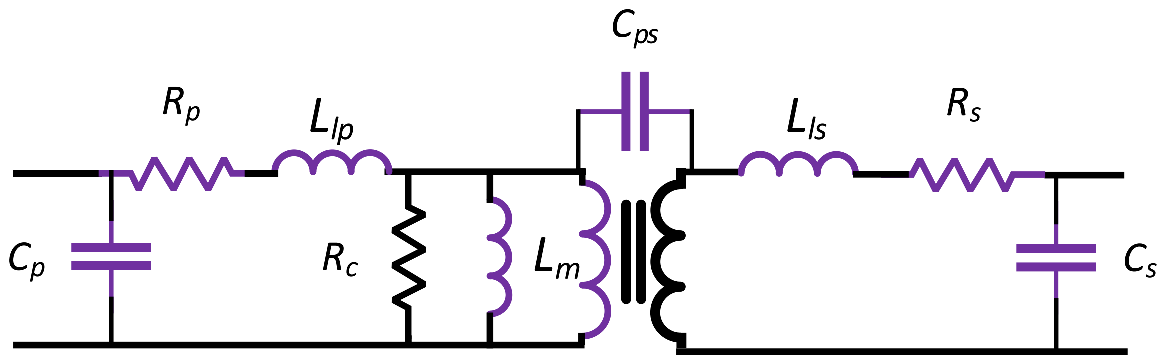


1 KV CLASS
NATURAL
CONVECTION



2 KV CLASS
VPI

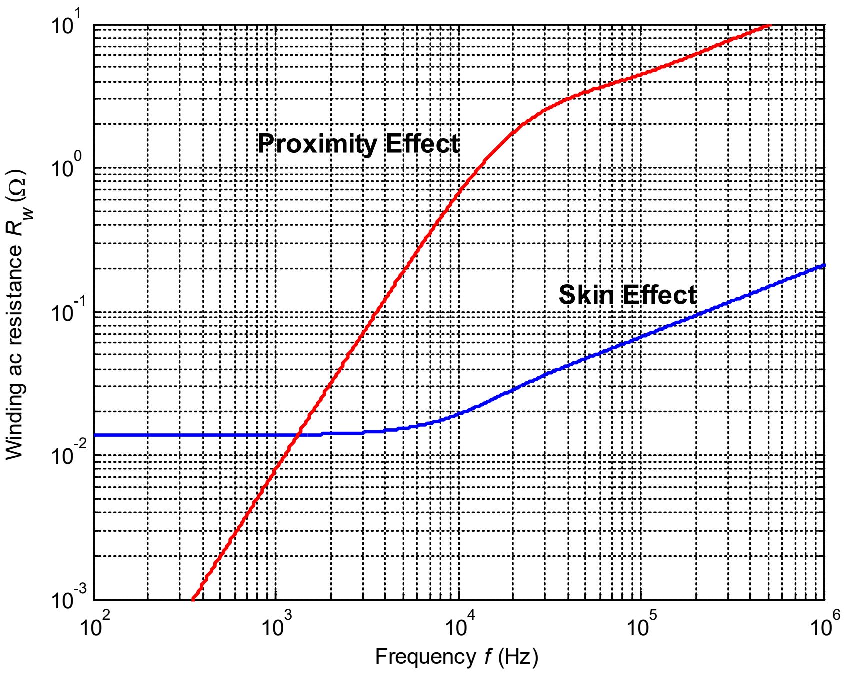
1 kV Class Transformer Challenges
Equivalent model



Transformer is a system of mutually coupled two or more coils usually wound on a common magnetic core. Its components are:

- Core resistance
- **Winding resistance (proximity effect)**
- **Leakage and magnetizing inductances**
- **Parasitic intra- and inter-winding capacitances**

Winding Resistance:
Skin and Proximity Effects

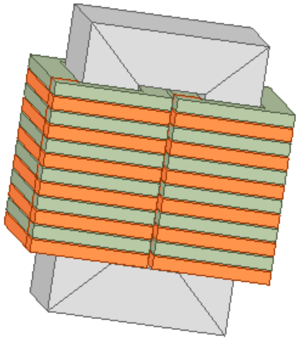


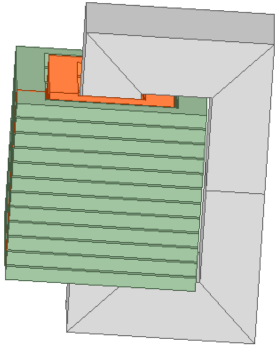
For multiple-layer transformers, the AC winding resistance is higher than the DC resistance due to the skin and proximity effects , the **current flows in both directions** in higher order winding layers, significantly **increasing the rms currents** and copper loss. Proximity effect loss in multiple-layer windings dominates over the skin-effect loss.

AC-to-DC resistance ratio depends on:

- Number of strands
- Strand size
- **Winding configuration**

1 kV Class Transformer Challenges
Proximity Effect Reduction



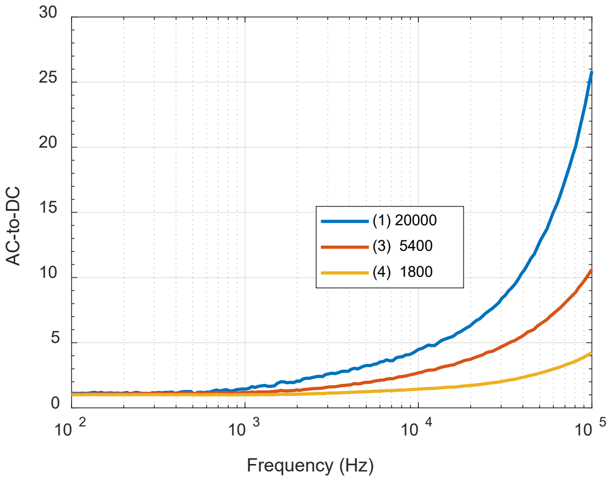


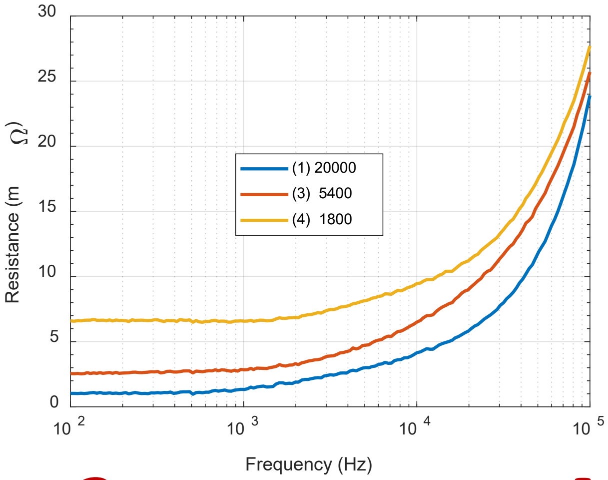
- Interleaving windings reduce the copper loss caused by proximity
- Reducing the number of winding layers
- Increasing the clearance between conductors in the same layer and between layers
- Increasing the winding width

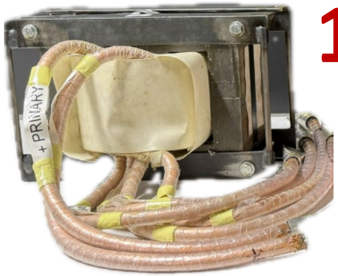
Litz wire increases the effective conduction area and thereby reduces the copper loss **BUT** at high frequencies smaller† parallel branches may offer better performance

† **DOI:** 10.1109/TIA.2018.2821647 **(Fig. 7)**

ESR Windings Measurement







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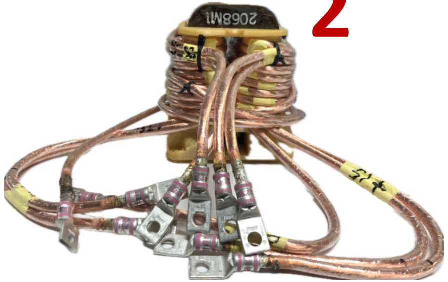

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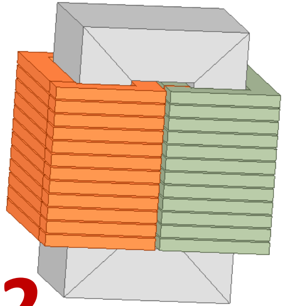
Magnetizing and Leakage Inductances

Low magnetizing inductance:

- Increases ZVS region
- Increases current peaks

Low leakage inductance increases switching frequency bandwidth

$$L_{lp} = L_1 - L_m \qquad L_{ls} = L_2 - L_{ms}$$



2

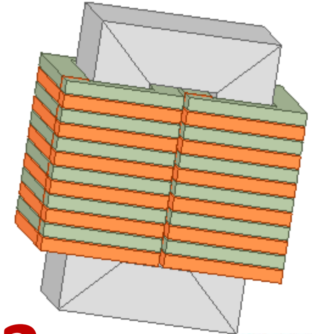
The leakage inductance is **increased** as the

- winding-core
- winding-winding

clearances increase

The leakage reduction is achieved by:

- Interleaving primary with the secondary winding
- twisting the primary and secondary winding wires before winding them on the core



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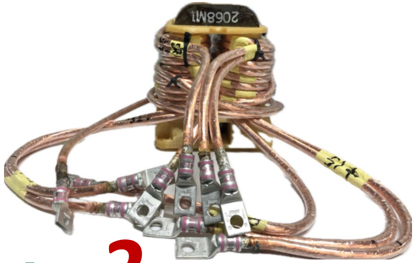

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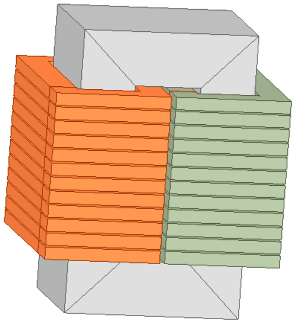
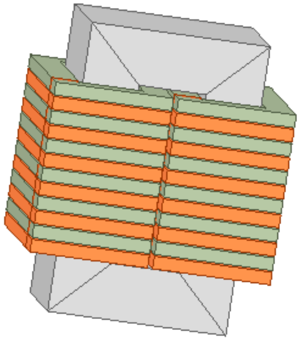
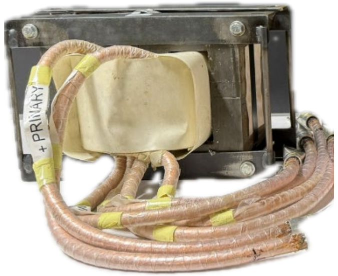
Capacitance


vs.


- The useful operating frequency range is determined by their self-resonant frequency

$$C_s \ (f_r = 1/\sqrt{L_s C_s})$$

- The capacitance is proportional to length turn
- The insulation coating causes the turn-to-turn capacitance of a single-layer inductor to increase



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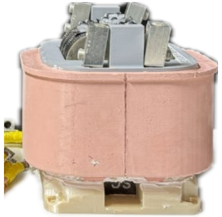
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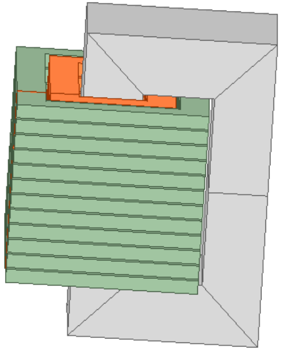
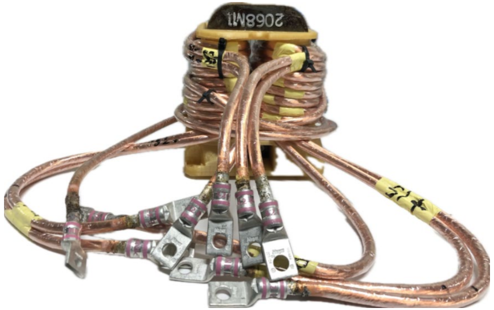
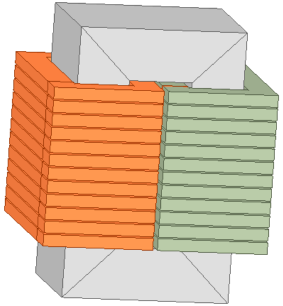
1 kV Class Transformer Challenges
Parasitic Capacitance, Leakage, and Resistance



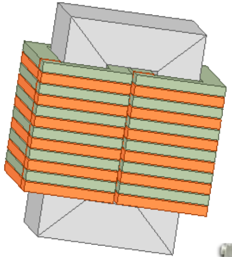
Stray capacitance: 60pF
Leakage inductance: 2 uH
AC-to-DC Resistance: **6.5**

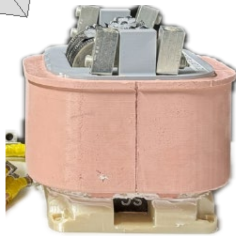




Stray capacitance: 3 pF
Leakage inductance: 23 uH
AC-to-DC Resistance: **4.8**

Stray capacitance: 571 pF
Leakage inductance: 2.5 uH
AC-to-DC Resistance: **3.8 - 1.7**





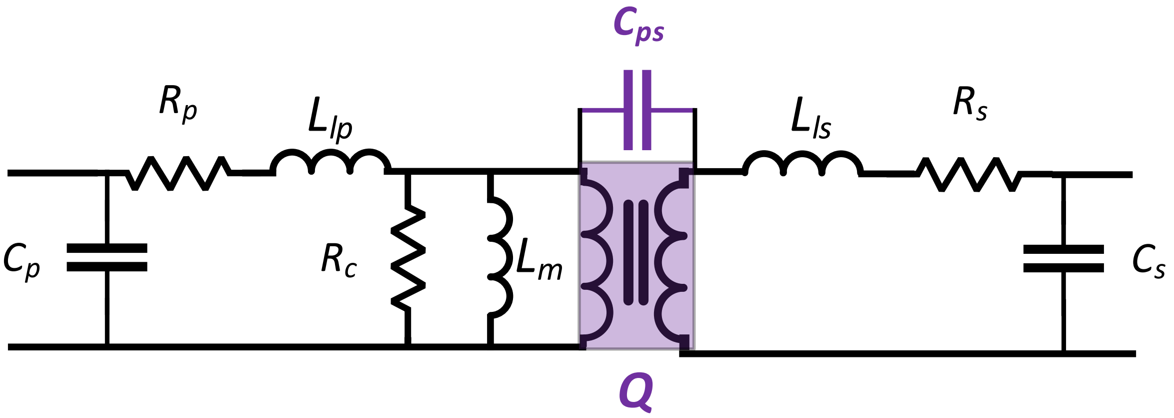
Smallest 175 kW DAB Transformer (as of Feb. 2025)

1 kV Transformer Class Parameters Summary

Parameters	1	2	3	4	5
Voltage Class	1 kV	1 kV	1 kV	1 kV	2 kV
DC/AC Winding Resistance (mΩ)	0.9/6 **(6.5)**	2.5 / 12 **(4.8)**	2.4/9 **(3.8)**	6/13 **(1.7)**	20 / 28 **(1.4)**
Leakage Inductance (μH)	2.57	23	**2.5**	**2**	1.5
Capacitance (pF)	60	**3**	512	530	409
Size (mm)	280x175x181	160x160x176	160x160x176	162x162x179	125x94x137
Mass (kg)	23	13	**12**	**15.6**	2.77

2 kV Class Transformer Challenges

Equivalent model

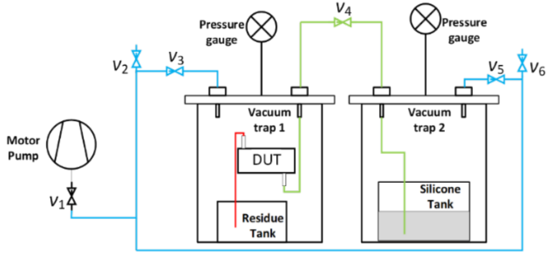


Significant emphasis on the following parameter for 2 kV class:

- **Interwinding charge**
- Parasitic interwinding capacitance

Vacuum Pressure Impregnation (VPI)

VPI is crucial for HV applications reliability as partial discharges in the transformer deteriorates insulation over the time and leads to insulation failure



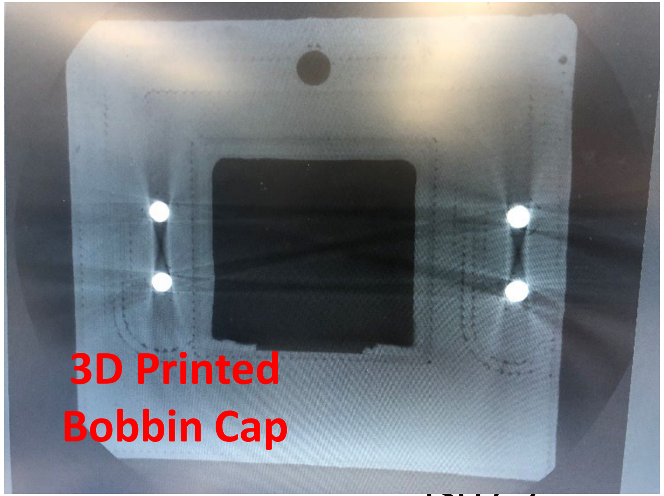
2 kV Class Transformer:

- Silicon gel and conductive silicon
- 20-10 Torr (30 - 10 mBar)

D. Rothmund, T. Guillod, D. Boritis, J. W. Kolar, "99% Efficient 10 kV SiC-Based 7 kV/400 V DC Transformer for Future Data Centers," *IEEE Journal of Emerging and Selected Topics in Power Electronics,* vol. 7, no. 2, June 2019.

Computer Tomography Evaluation of VPI

- High precision metrology
- Pores, cracks detection
- Assembly control
- Joining technology control (glue, solder, joints quality check)



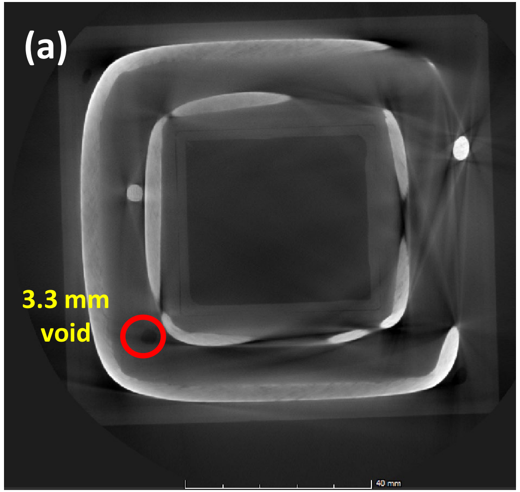
CT Scan Results

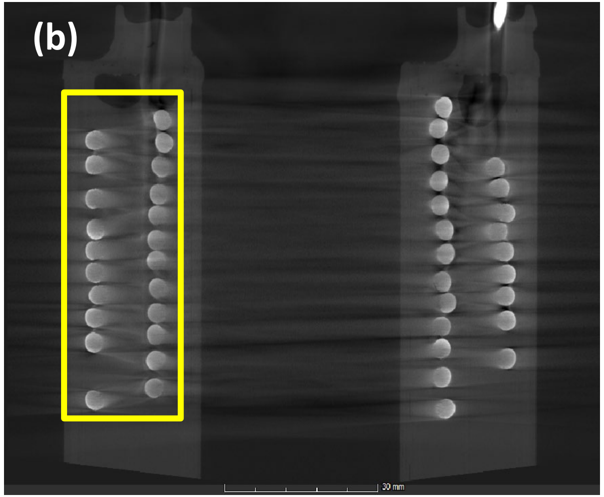
Evaluation of vacuum pressure impregnation:

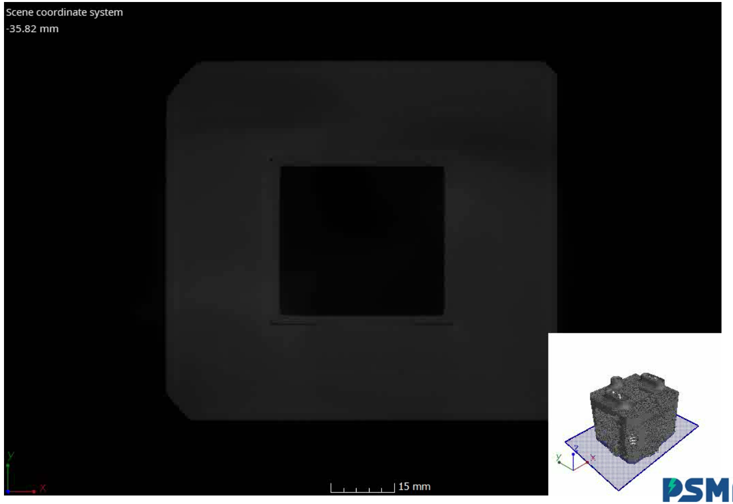
a) Voids detected

b) Overlapping of turns and shifted secondary windings

c) CT artifacts prevent identification of the litz wire impregnation



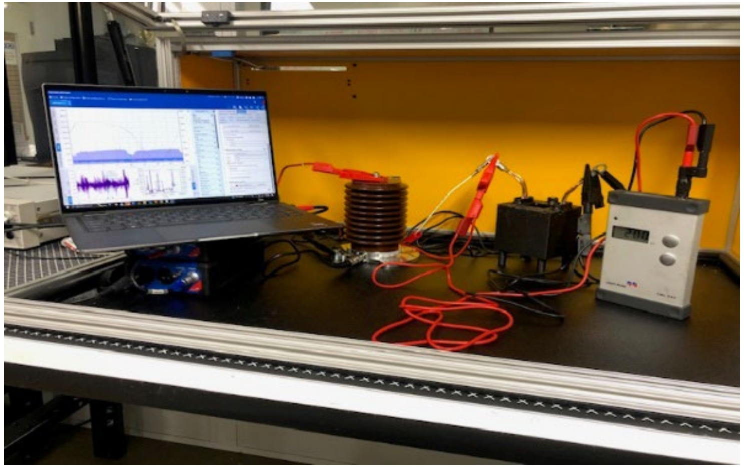




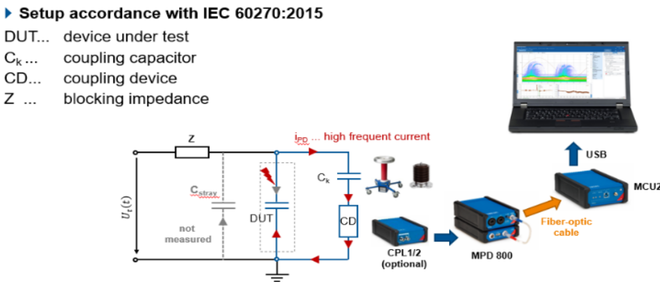
Partial Discharge Measurements

Partial discharge measurements play a crucial role in diagnosing insulation defects and early-stage faults in high-voltage systems. They enable:

- The detection of insulation degradation resulting from contamination, aging, moisture ingress, and mechanical stress
- Facilitate the identification of electrical faults such as voids, cracks, and electrical treeing within insulation
- Enhancing the reliability and performance of electrical components and systems



Measurement Setup

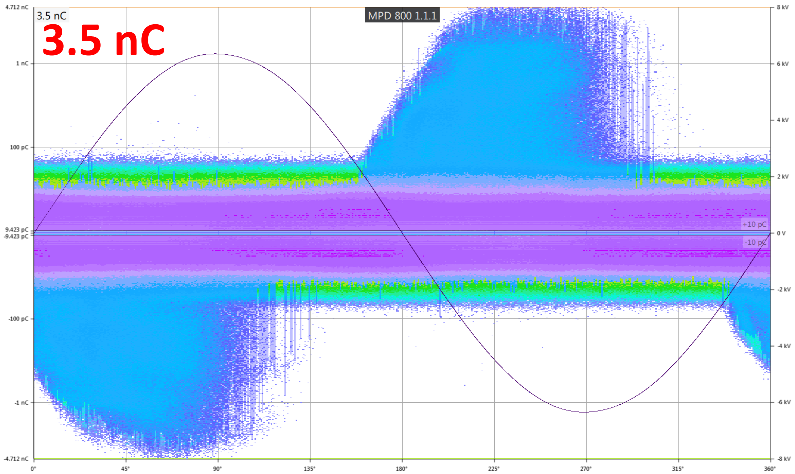


PD test setup Figure courtesy: Omicron

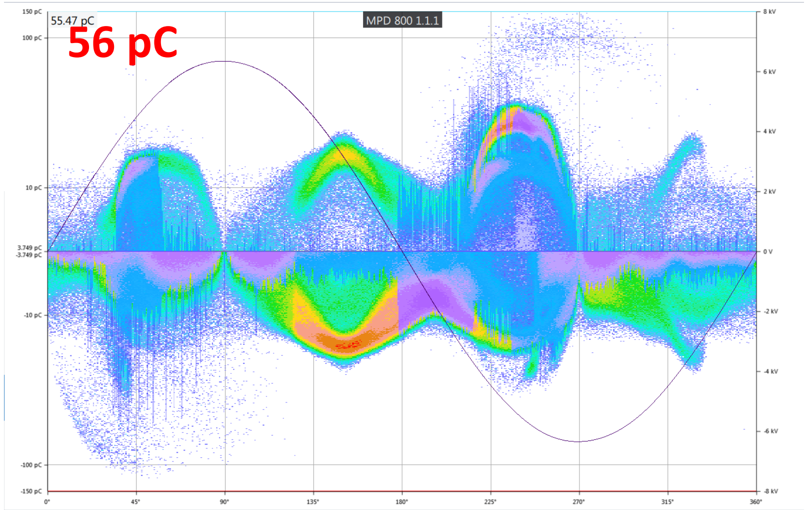
Partial Discharge Patterns

Tests, were performed for line frequency 4 kV_{RMS} air and vacuum impregnated windings

Non VPI



VPI



- Parasitic capacitance 13 nF
- Non-conducting material without contact to winding (polyester film)

- Parasitic capacitance 409 pF
- Micro void discharge (litz wire)

Transformer Evolution for EV Charging Summary

- Multiple transformer design iterations has been performed to achieve zero voltage switching (ZVS) across the entire (voltage and current) operating range of the charger
- Converter peak efficiency was 98.5%
- As of February 2025, we have achieved to design, build, and test **the smallest in dimension fully working 175 kW DAB transformer (as of February 2025)**
- Computer tomography confirmed later PD measurements associated with VPI procedure
- VPI Bobbin structure needs specific design
- Wrapped insulation litz wires for 2 kV class still sufficient

Acknowledgments

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- **Christian Boone**, Technical Professional, Electric Drive Research
- **Ethan Crisp**, Grid Systems Hardware Technician
- **Jonathan Harter**, Grid Systems Hardware Technical Professional
- **Andres Marquez Rossy**, T/A for Process and Characterization of Materials
- **Dr. Madhu Chinthavali**, Electrical Systems Integration Program Manager

Thank you all for your collaboration and support !!!

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