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Georgia World Congress Center

Addressing Insulation and Isolation Issues in the Solid-State Transformer

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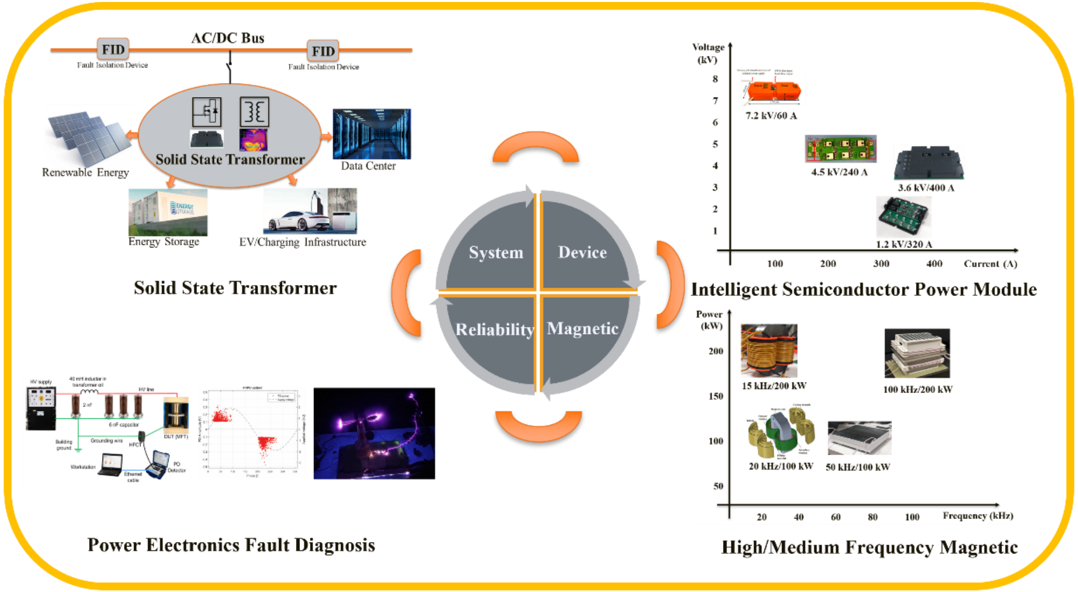
IS07.2

Power Electronics and Energy Conversion (PEEC) Lab



Research Area

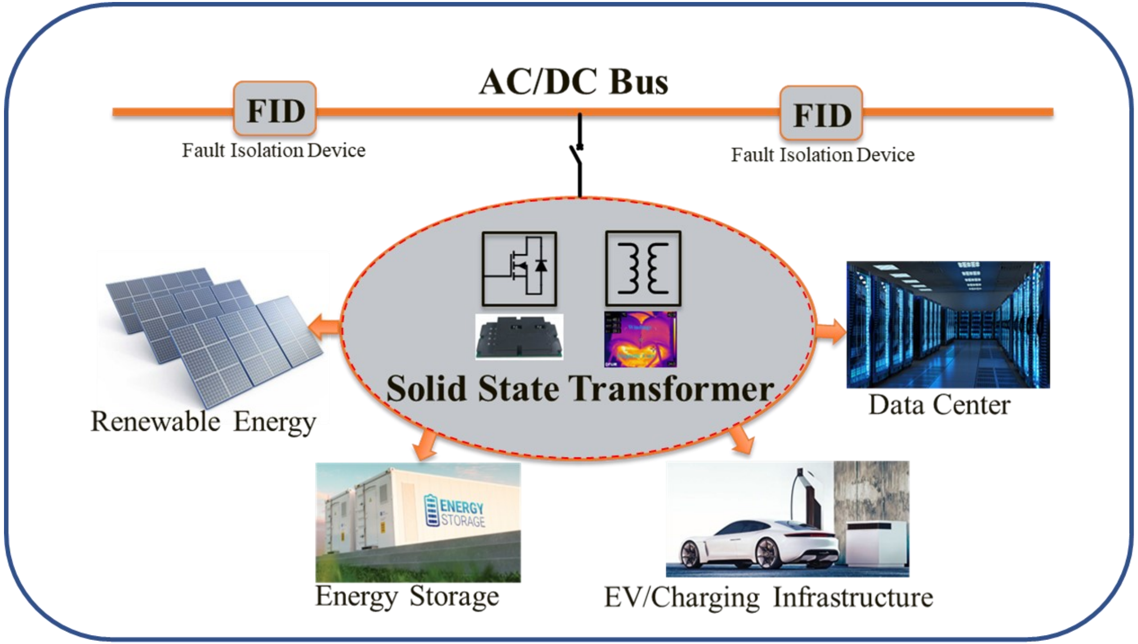
- Solid State Transformer
- High Frequency Magnetics
- Semiconductor Power Module
- Power Electronics Reliability

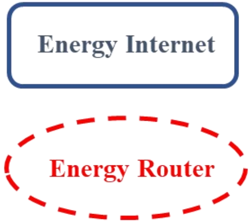
https://labs.engineering.asu.edu/zcguo/

Dr. Zhicheng Guo is an assistant professor at Arizona State University, director of Power Electronics and Energy Conversion (PEEC) Lab. Before he joined ASU, he was a postdoctoral fellow at the Semiconductor Power Electronics Center, UT Austin. Zhicheng Guo received his Ph.D. degree in power electronics and power systems from the University of Texas at Austin in 2023.

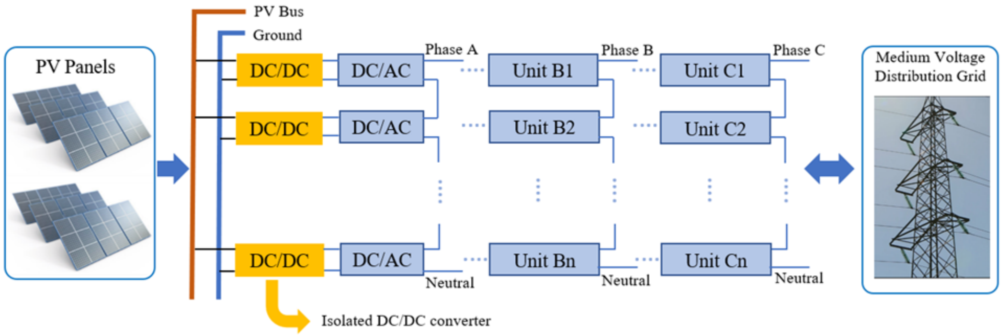
His research interests include Solid-state transformers, high-frequency magnetic, WBG intelligent power modules, 60 Hz/HF partial discharge, and insulation design of modern power electronics systems. Dr. Zhicheng Guo is the recipient of U.S. Department of Energy (DOE) 2023 Electricity / Large Power Transformers Bonus Prize Winner, the 2022 Transformer Association (TTA) Award, 4 times Cockrell School of Engineering fellowship, the University of Texas at Austin. He serves as a member of the IEEE standard committee P3105 working group, and Technical Program Committee of multiple IEEE journals and technical conferences.

Medium Voltage Energy Conversion

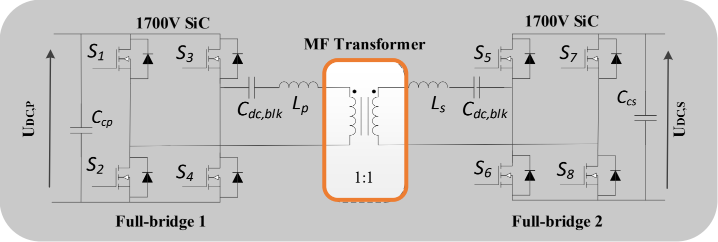




Medium Voltage Energy Conversion



Wolfspeed 1.7 kV SiC Module

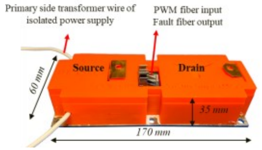


DOE DE-EE0008348 Award Amount: $3 million, PI: Dr. Alex Q. Huang

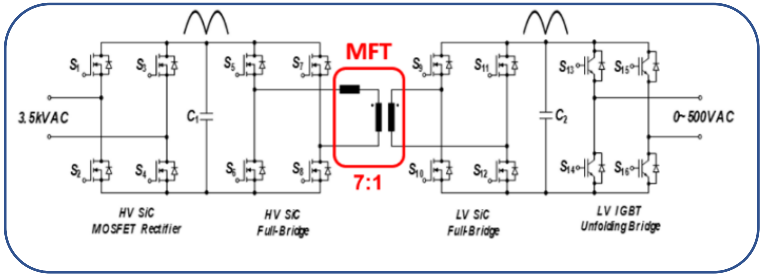
- 1MW Medium Voltage PV Inverter

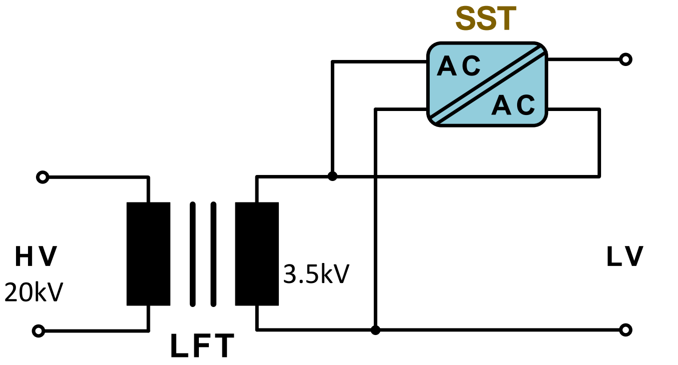
W. Xu, Z. Guo, A. Vetrivelan, R. Yu and A. Q. Huang, "Hardware Design of a 13.8-kV/3-MVA PV Plus Storage Solid-State Transformer (PVS-SST)," in *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 10, no. 4, pp. 3571-3586, Aug. 2022, doi: 10.1109/JESTPE.2021.3082033.

Medium Voltage Energy Conversion



7.2-kV SiC Austin SuperMOS





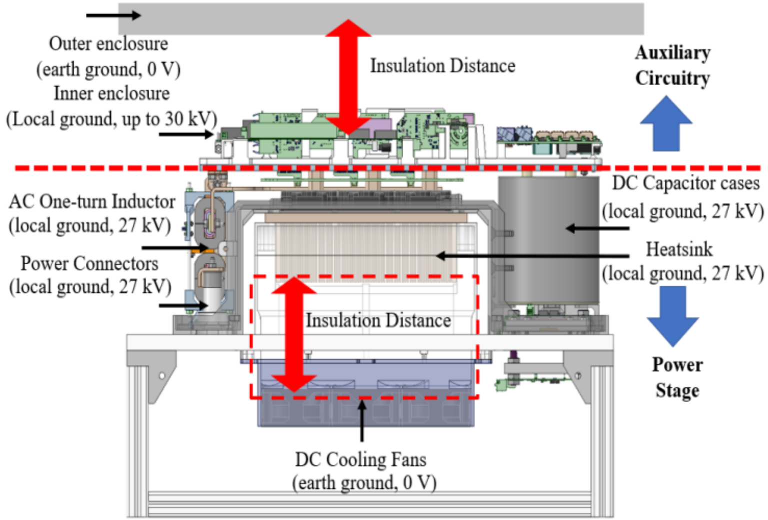
Secondary Side Input Parallel and Output Series

DOE DE-OE0000905 Award Amount: $2.2 million, PI: Dr. Alex Q. Huang

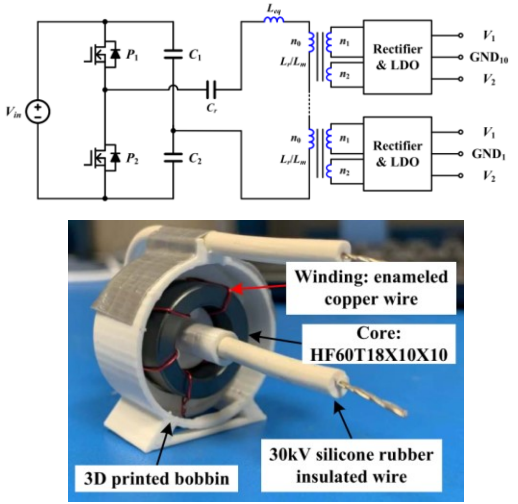
- **500 kVA Hybrid Solid State Transformer**

S. Rajendran, S. Sen, L. Zhang, Z. Guo, Q. Huang and A. Q. Huang, "500kVA Hybrid Solid State Transformer (HSST): Design and Implementation of the SST," *2020 IEEE Energy Conversion Congress and Exposition (ECCE)*, Detroit, MI, USA, 2020, pp. 1642-1649, doi: 10.1109/ECCE44975.2020.9235804.

Medium Voltage Energy Conversion



❑ **MV submodule**



❑ **MV auxiliary power supply**

Y. Xu *et al*., "High Power Density Medium-Voltage Converter Integration via Electric Field Management," in *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 10, no. 1, pp. 895-905, Feb. 2022,
W. Xu and A. Q. Huang, "15-kV/50-A SiC AC Switch Based on Series Connection of 1.7-kV MOSFETs," in *IEEE Transactions on Industry Applications*, vol. 59, no. 5, pp. 6543-6555, Sept.-Oct. 2023,

High Power MFTs

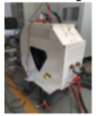
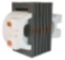
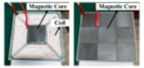
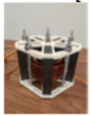
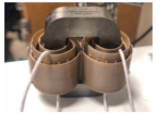
❑ Challenges

➢ **Efficiency:**
system expectations

➢ **Power density:**
volume/weight limitations

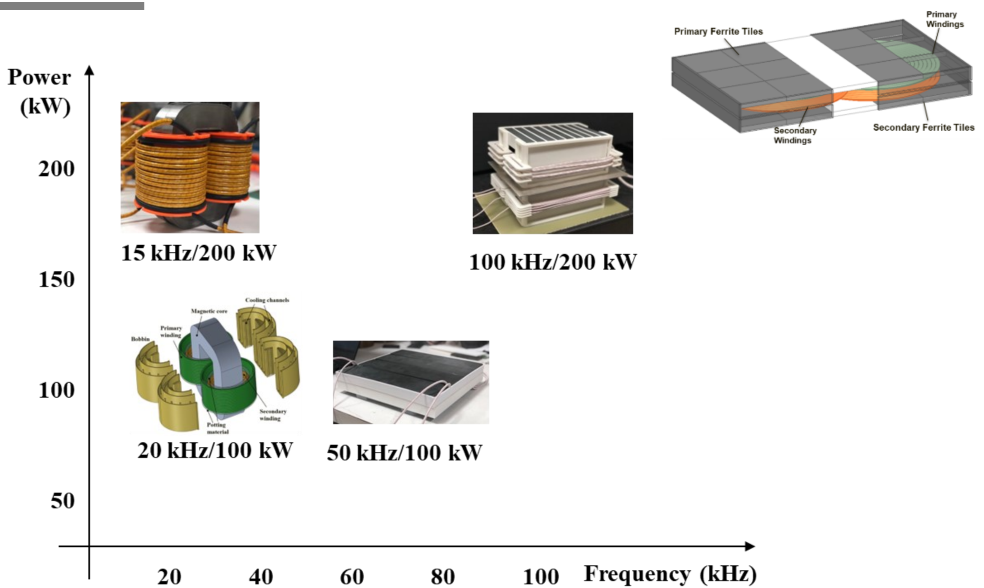
➢ **Thermal management:**
materials limitations

➢ **Insulation design**
Increasing electric insulation/reliability requirements

	Power Rating (kW)	Frequency (kHz)	Core Material	Cooling Method	Insulation Voltage (kV)	Efficiency %	Power Density (kW/L)	Hot Spot Temperature (°C)
UT Austin 2021[10] 	200	15	Nanocrystalline	Air	5.3 kV (**)	99.84	19.23	55
SEU 2021[11] 	250	10	Nanocrystalline	Air	18 kV (**)	99.76	4.9	62.6
ETH 2022 [12] 	166	77.4	Air-core	Air	> 6.36 kV (*)	99.5	7.8	106@225 kW
		40	Ferrite			99.7	12.2	>94.2@250 kW
KMUST 2022 [13] 	80	43	Ferrite	Air	42 kV (*)	N/A	21.1	102.1
University of Arkansas [14] 	100	50	Ferrite	Air	N/A	99.62	17.7	106
This work 	100	20	Nanocrystalline	Air	14 kV (**)	99.73	10.6	64.2

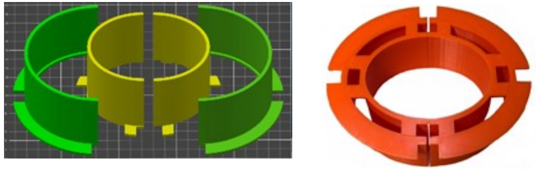
* Applied voltage insulation test. ** Partial discharge insulation test.

High Power MFTs



1. **Z. Guo** et al., "*A Novel High Insulation 100 kW Medium Frequency Transformer,*" in IEEE Transactions on Power Electronics, 2022, doi: 10.1109/TPEL.2022.3205646.
2. **Z. Guo**, R. Yu, W. Xu, X. Feng and A. Q. Huang, "*Design and Optimization of a 200-kW Medium-Frequency Transformer for Medium-Voltage SiC PV Inverters*," in IEEE Transactions on Power Electronics, vol. 36, no. 9, pp. 10548-10560, Sept. 2021, doi: 10.1109/TPEL.2021.3059879.
3. **Z. Guo**, W. Xu, A. Vetrivelan and A. Q. Huang, "Magnetic Design of a 4.16 kV/1 MW Medium Voltage PV Plus Storage Solid State Transformer (PVS-SST)," 2023 IEEE Applied Power Electronics Conference and Exposition (APEC), Orlando, FL, USA, 2023, pp. 1-5, doi: 10.1109/APEC43580.2023.10131543.
4. **Z. Guo**, C. Chen, Z. Chen and A. Q. Huang, "A High Power High Isolation Medium Frequency Transformer With A Planar Matrix Structure," 2023 IEEE Energy Conversion C nd Exposition (ECCE), Nashville, TN, USA, 2023, pp. 5827-5830, doi: 10.1109/ECCE53617.2023.10362495.
5. **Z. Guo**, C. Chen, R. Yu and A. Q. Huang, "A High Power 200kW Medium Frequency Transformer With Improved Thermal Management," 2023 IEEE Energy Conversion C d Exposition (ECCE), Nashville, TN, USA, 2023, pp. 5587-5591, doi: 10.1109/ECCE53617.2023.10362391.

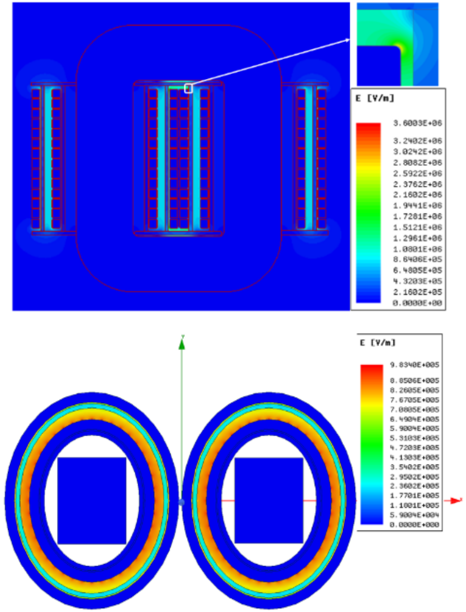
High Power MFTs-Insulation Design



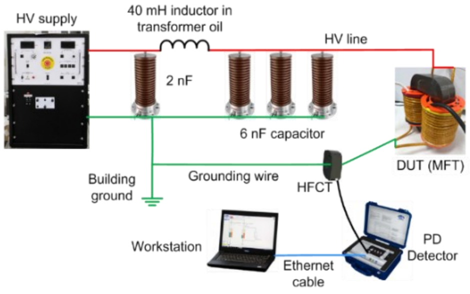
❖ 3D printed bobbin

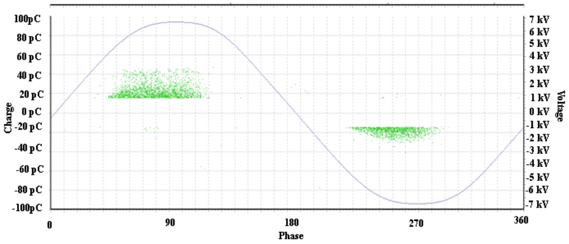
	Thickness (mm)	Material	Dielectric Strength@25 °C	Dielectric Constant	Thermal conductivity
Bobbin	3	Acrylonitrile Butadiene Styrene (ABS)	16.7 kV/mm	2.87	0.17 W/mK
Insulation tape	0.05	polyimide	102 kV/mm	3.5	0.12 W/mK

❖ Insulation structure and materials



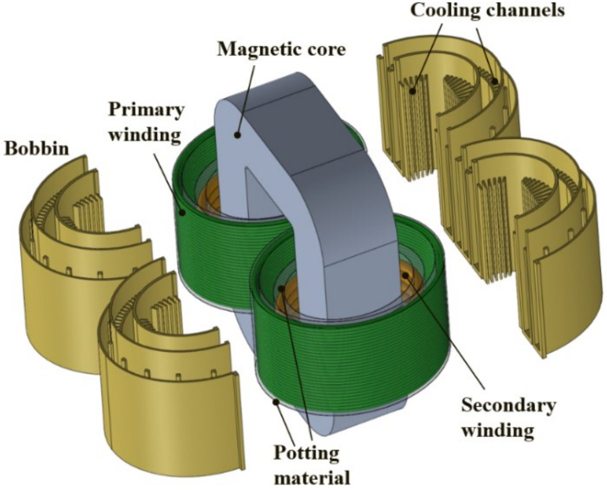
❖ Maxwell electrostatic simulation under applied voltage of 7.5 kV



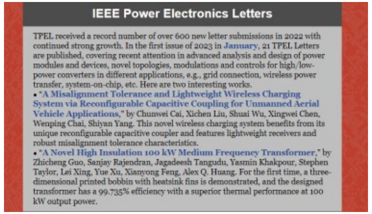


❖ Partial discharge test

High Power MFTs-Insulation Design



- **Novel MFT insulation/cooling structure:**
  - **Potted windings**
  - **Two layers 3D printed** bobbin with **heatsink fins**

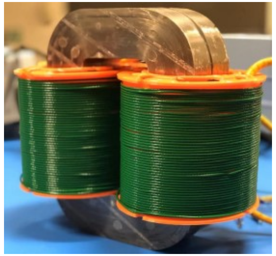


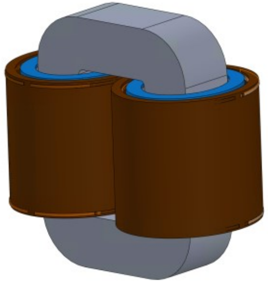
IEEE Power Electronics Letters

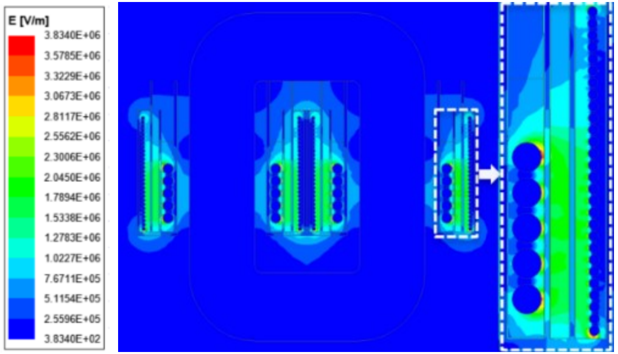
TPEL received a record number of over 600 new letter submissions in 2022 with continued strong growth. In the first issue of 2023 in January, 21 TPEL Letters are published, covering recent attention in advanced analysis and design of power modules and devices, novel topologies, modulations and controls for high/low-power converters in different applications, e.g., grid connection, wireless power transfer, system-on-chip, etc. Here are two interesting works.

- "A Misalignment Tolerance and Lightweight Wireless Charging System via Reconfigurable Capacitive Coupling for Unmanned Aerial Vehicle Applications," by Chunwei Cai, Xichen Liu, Shuai Wu, Xingwei Chen, Wenping Chai, Shiyan Yang. This novel wireless charging system benefits from its unique reconfigurable capacitive coupler and features lightweight receivers and robust misalignment tolerance characteristics.
- "A Novel High Insulation 100 kW Medium Frequency Transformer," by Zhicheng Guo, Sanjay Rajendran, Jagadeesh Tangudu, Yasmin Khakpour, Stephen Taylor, Lei Xing, Yue Xu, Xianyong Feng, Alex Q. Huang. For the first time, a three-dimensional printed bobbin with heatsink fins is demonstrated, and the designed transformer has a 99.735% efficiency with a superior thermal performance at 100 kW output power.

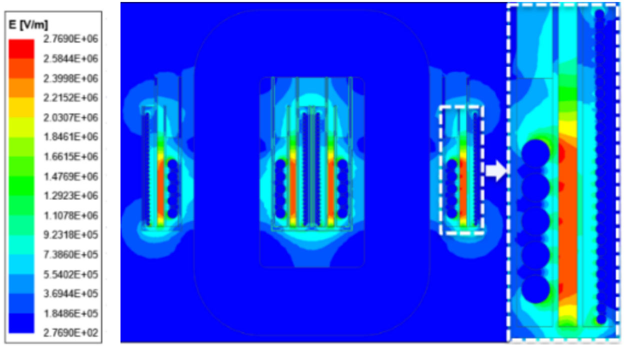
High Power MFTs-Insulation Design





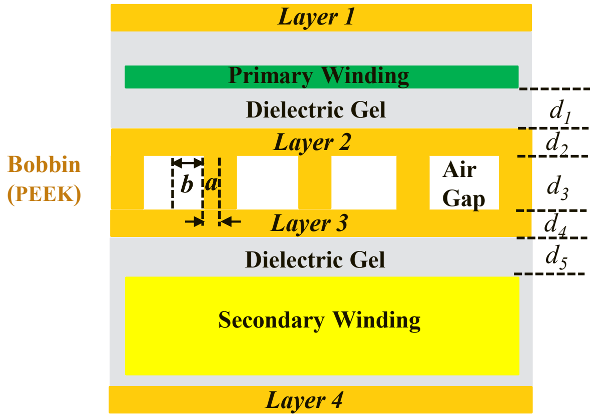


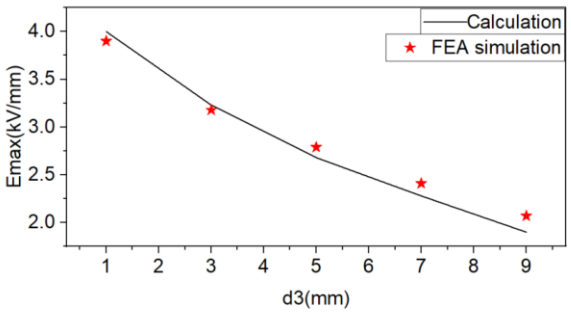
Peak E-field **3.83 kV/mm**



Peak E-field **2.77 kV/mm**

High Power MFTs-Insulation Design





3D Printed Filament Candidates

Material	Glass Transition Temperature* - Tg (° C)	Dielectric Strength@25 ° C (kV/mm)	Dielectric Constant	Thermal Conductivity (W/mK)
PLA	60-65	13.4	3.1	0.13
ABS	105	16.7	2.87	0.17
PEEK	**143**	**23**	**3**	**0.29**

*The temperature where the material begins to lose the ability to hold its shape

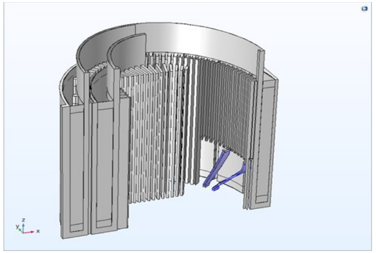
Polyether ether ketone (**PEEK**) filament is one of the best materials on the market. Exceptional mechanical, thermal, and electric properties make this an ideal material for this application.

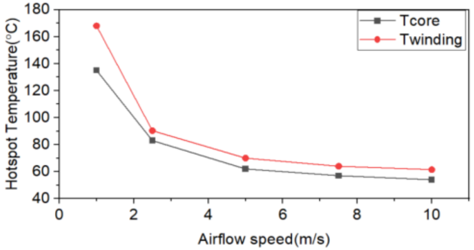
Potting Material Candidates

Material	Viscosity (mPa·s)	Dielectric Strength@25 ° C (kV/mm)	Dielectric Constant	Thermal Conductivity (W/mK)	Pot Life (min)
CoolTherm® SC-309	3600	23.6	4	1	30
DOWSIL™ CN-8760	2850	33	2.7	0.66	120
WACKER SilGel® 612	**1000**	**23**	**2.8**	**0.2**	150

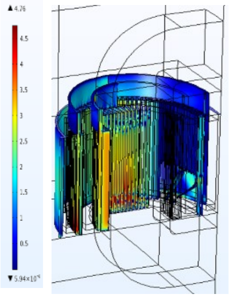
SilGel® 612 was selected due to the lowest viscosity, longest pot life v helps to remove air bobbles during the vacuum fabrication process.

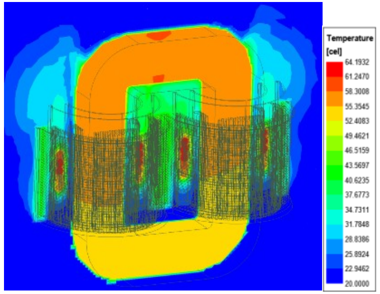
High Power MFTs-Insulation Design

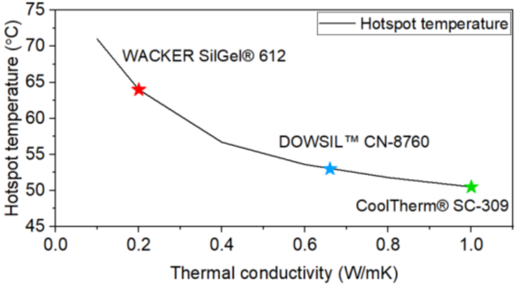




❖ **Effect of inlet airflow speed on core / windings hotspot temperature**





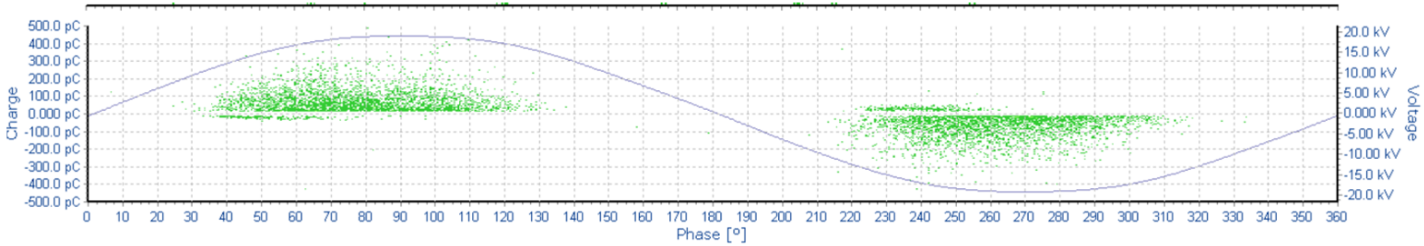


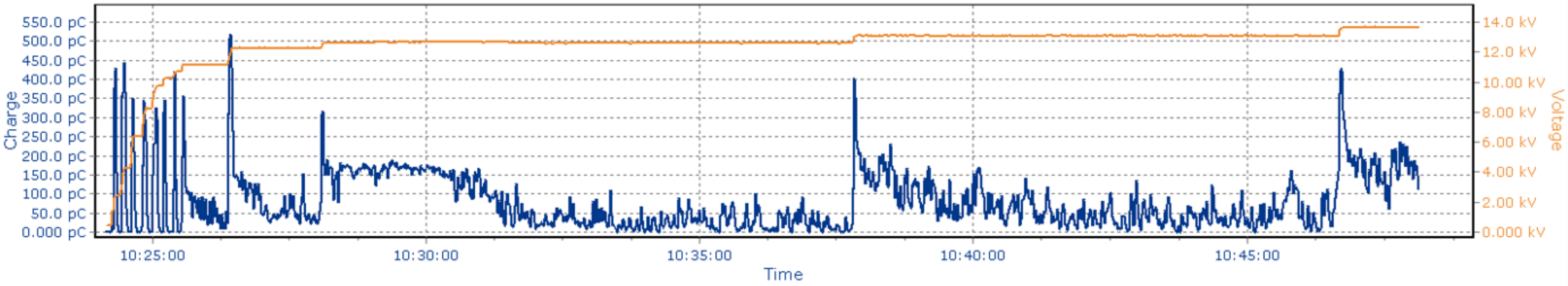
❖ **Airflow speed passing through the bobbin air channels**

❖ **MFT temperature distribution**

❖ **Effect of encapsulant thermal conductivity on hotspot temperature**

High Power MFTs-Insulation Design





❖**Partial discharge insulation test (20 kV peak)**

IEEE Standards for LFT Insulation

IEEE Std C57.12.00	IEEE Standard for General Requirements for Liquid-Immersed Distribution, Power, and Regulating Transformers
IEEE Std C57.12.90	IEEE Standard Test Code for Liquid-Immersed Distribution, Power, and Regulating Transformers
IEEE Std C57.113	IEEE Recommended Practice for **Partial Discharge** Measurement in Liquid-Filled Power Transformers and Shunt Reactors
IEEE Std C57.98	IEEE Guide for Transformer Impulse Tests

IEEE Std C57.12.01	IEEE Standard for General Requirements for Dry-Type Distribution and Power Transformers
IEEE Std C57.12.60	IEEE Standard for Thermal Evaluation of Insulation Systems for Dry-Type Power and Distribution Transformers
IEEE Std C57.12.91	IEEE Standard Test Code for Dry-Type Distribution and Power Transformers
IEEE Std C57.124	IEEE Recommended Practice for the Detection of **Partial Discharge** and the Measurement of Apparent Charge in Dry-Type Transformers

IEEE Standards for LFT Insulation

Purpose

The purpose of dielectric tests in the factory is to demonstrate that the transformer has been designed and constructed to withstand the imposition of voltages associated with the specified insulation levels of the transformer.

Test sequence

The dielectric tests should be performed in the following preferred sequence:

a) Lightning impulse tests

b) Applied voltage test

c) Induced voltage test

d) Partial discharge test

Partial Discharge Test

Partial discharge (PD) tests are intended to verify that the internal insulation is free from damaging discharges .

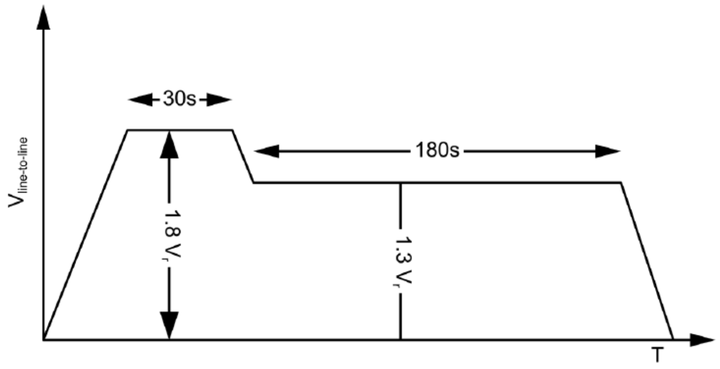
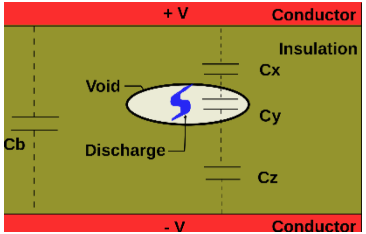


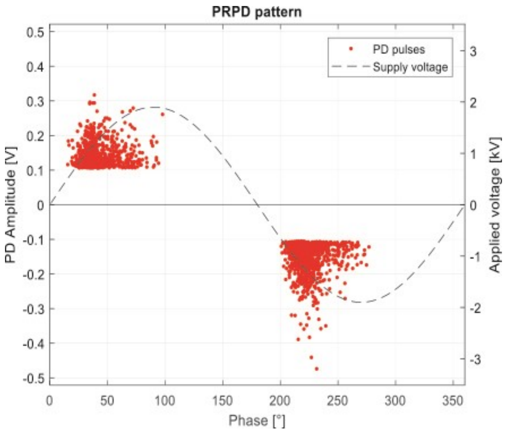
Figure 27 —Partial discharge test voltage application

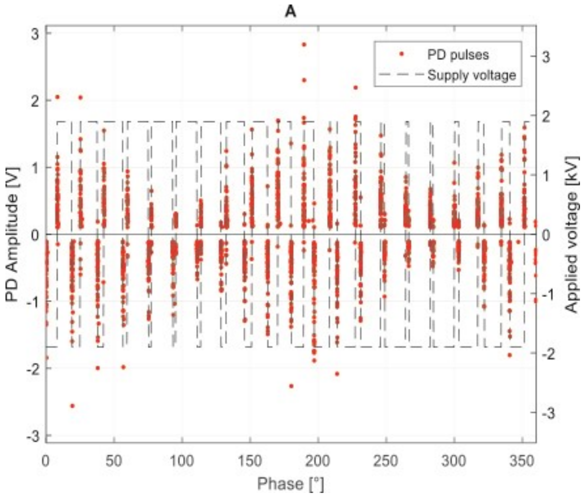


Liquid-Immersed: 10 pC

Dry type: 50 pC

Partial Discharge Test





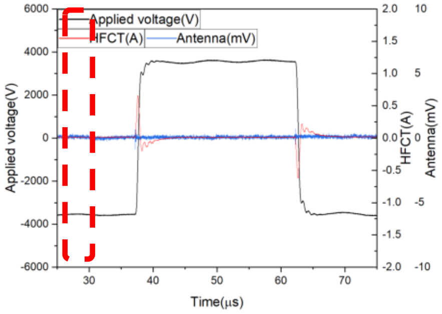
- ❑ **Working waveform Partial discharge(PD) test?**
- ❖ **Different voltage**
- ❖ **Different dv/dt**
- ❖ **Different frequencies**

IEEE SA STANDARDS ASSOCIATION

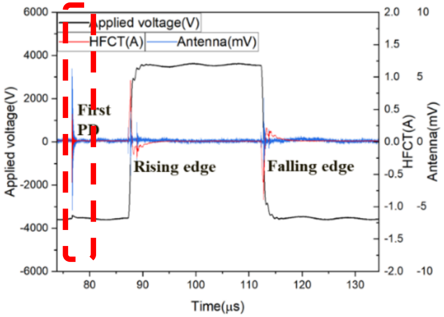
IEEE P3105 (Recommended Practice for Design and Integration of Solid-State Transformers in Electric Grid)

IEEE Standard for General Requirements for Dry-Type Distribution and Power Transformers, IEEE Standard C57.12.01-2015 (Revision of IEEE Standard C57.12.01-2005), 2015.

High Frequency PWM PD Test

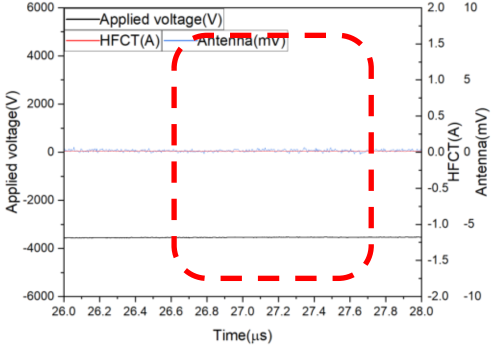


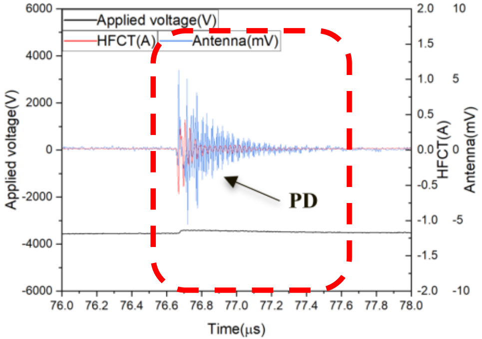
Without PD



PD

Global waveform

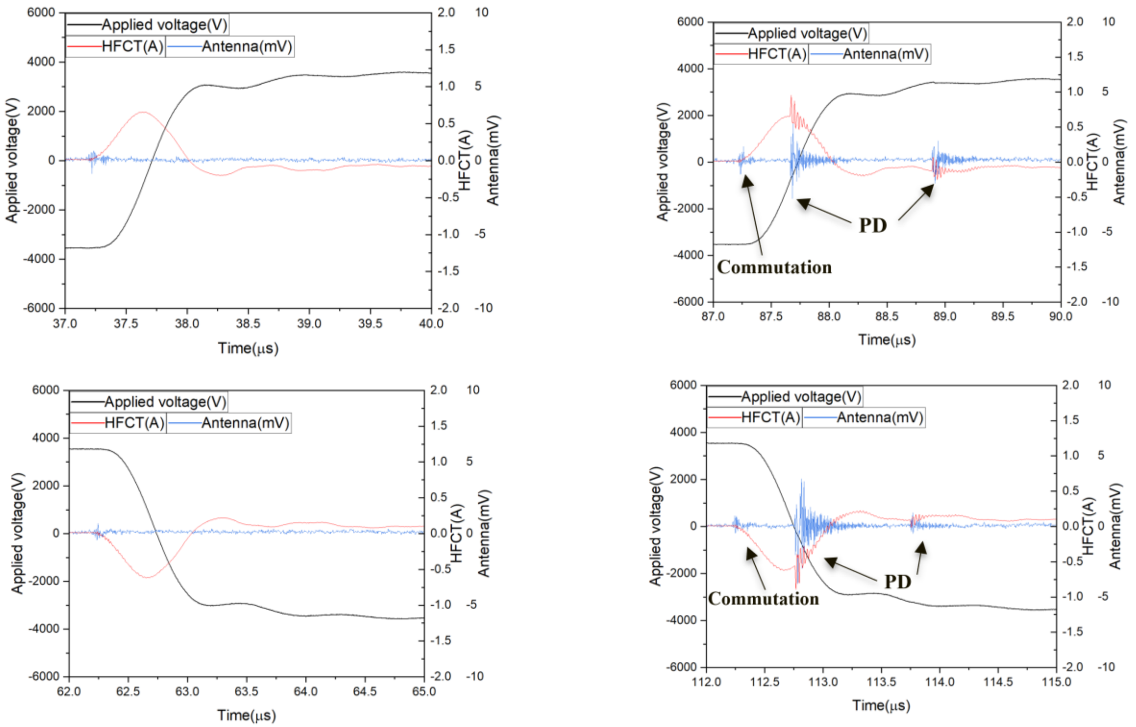




First PD signal

- Test waveforms under 20 kHz peak-to-peak 7 kV PWM pulses

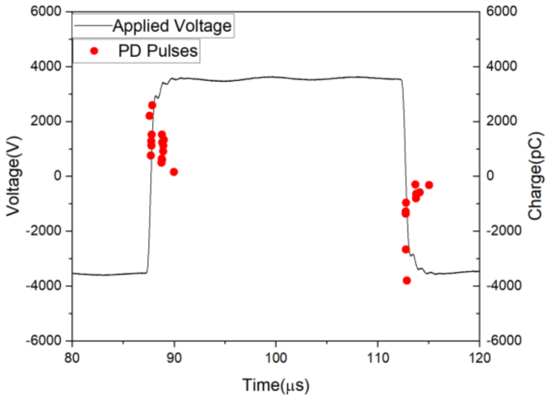
High Frequency PWM PD Test



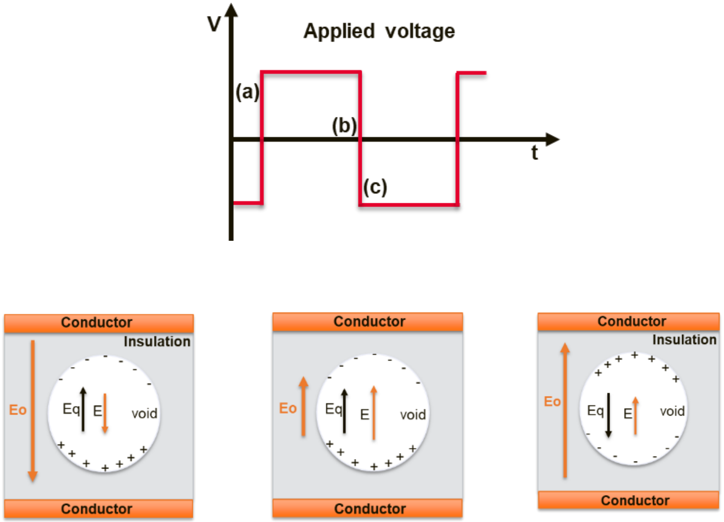
Rising edge

Falling edge

High Frequency PWM PD Test



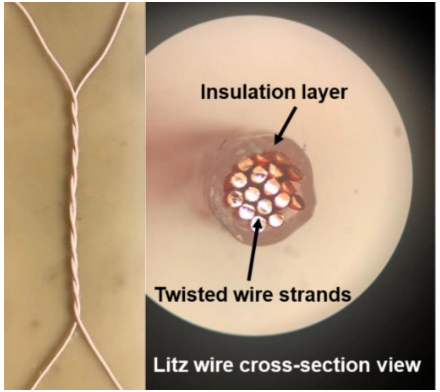
❖ **PD pattern diagram**
under 20 kHz peak-to-peak 7 kV PWM waveform

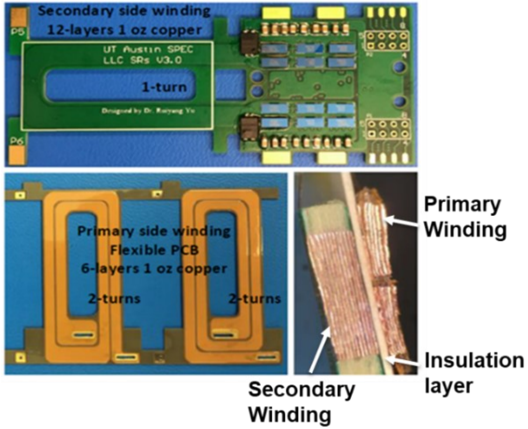


❖ **Simplified model for PD occurrence**

E_q is the field caused by the space charge deposited by a discharge;
E_0 is the geometric field ; E is the resulting field in the cavity.

High Frequency PWM PD Test

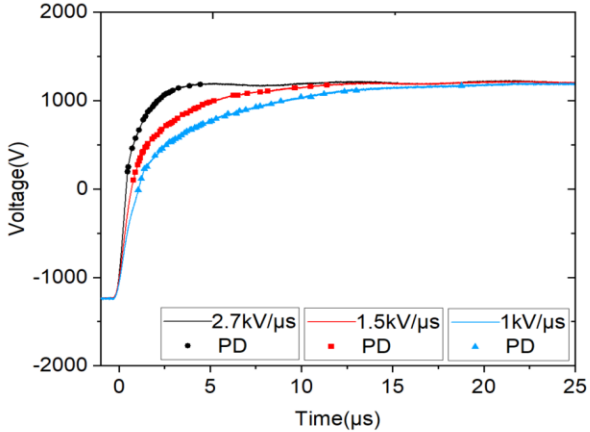


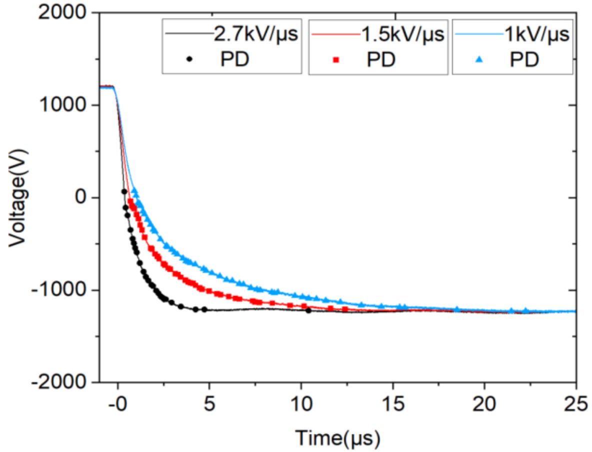


❖ Twisted Litz wire test sample and cross–section view.

❖ Direct parallel PCB windings and cross–section view.

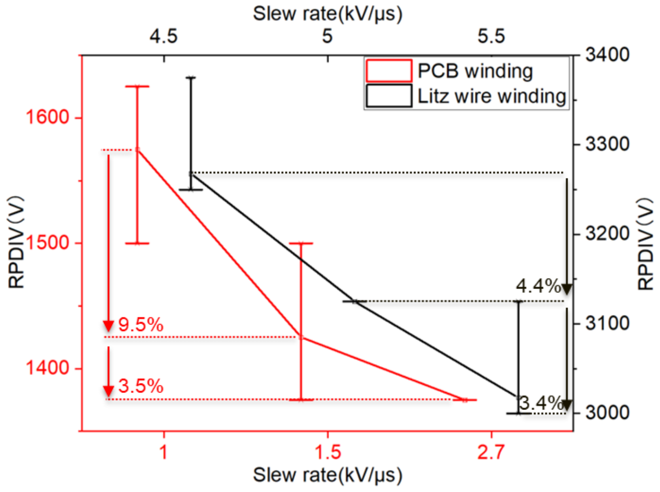
High Frequency PWM PD Test

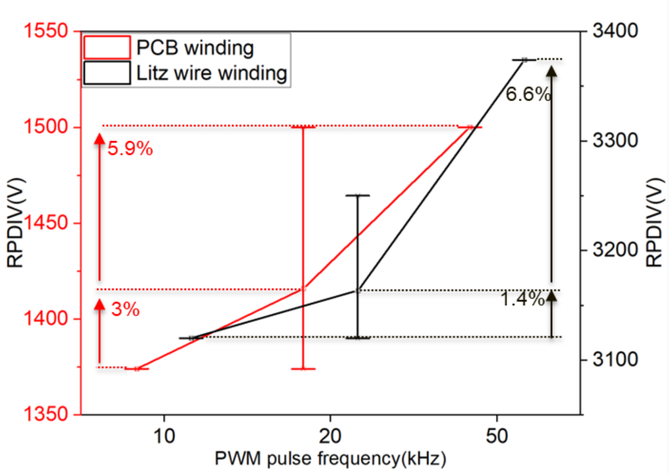




❖ **(PCB winding sample, f=10 kHz, v=±1.25 kV）**

High Frequency PWM PD Test

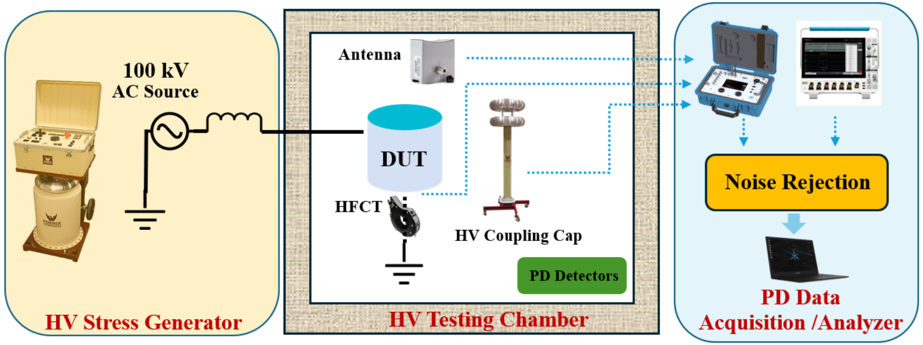




❖ **RPDIV under different slew rates**
PCB/Litz wire winding sample, f=10 kHz

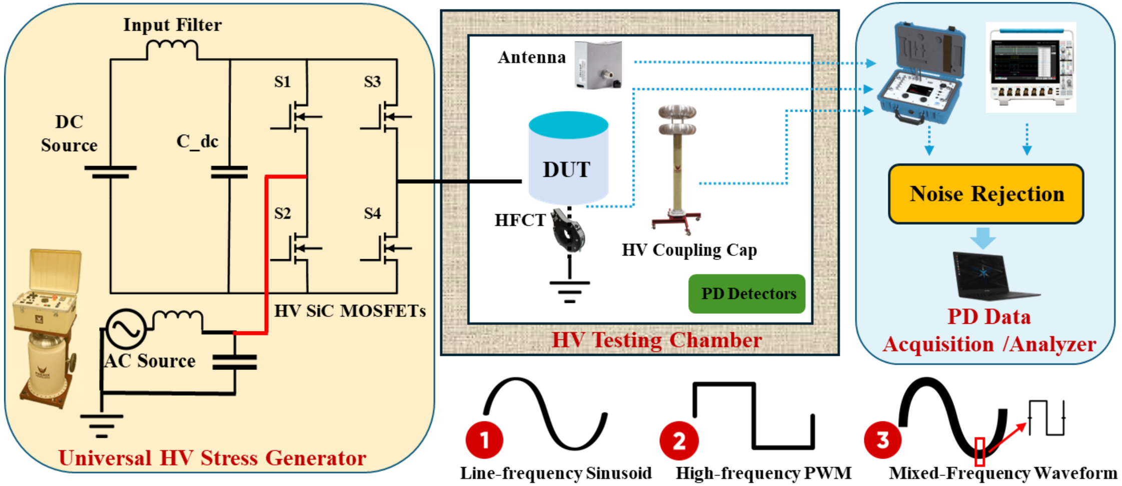
❖ **RPDIV under different frequency**
Litz wire winding sample, dv/dt=5 kV/us,
PCB winding, dv/dt=2.7 kV/us.

100 kV PD test platform



100 kV 60Hz Partial Discharge Test Platform

Universal PD test platform



100 kV Multi-function Partial Discharge Test Platform

- Multiple HV Waveforms
- Test Voltage : 0 V – **100** kV
- Low background noise: < 3 pC
- Overcurrent Protection

Welcome to talk!

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Related Publications

1. **Z. Guo** et al., "*A Novel High Insulation 100 kW Medium Frequency Transformer,*" in IEEE Transactions on Power Electronics, 2022, doi: 10.1109/TPEL.2022.3205646.
2. **Z. Guo**, A. Q. Huang, R. E. Hebner, G. C. Montanari and X. Feng, "*Characterization of Partial Discharges in High-Frequency Transformer Under PWM Pulses*," in IEEE Transactions on Power Electronics, vol. 37, no. 9, pp. 11199-11208, Sept. 2022, doi: 10.1109/TPEL.2022.3169747.
3. **Z. Guo**, R. Yu, W. Xu, X. Feng and A. Q. Huang, "*Design and Optimization of a 200-kW Medium-Frequency Transformer for Medium-Voltage SiC PV Inverters*," in IEEE Transactions on Power Electronics, vol. 36, no. 9, pp. 10548-10560, Sept. 2021, doi: 10.1109/TPEL.2021.3059879.
4. **Z. Guo**, W. Xu, A. Vetrivelan and A. Q. Huang, "Magnetic Design of a 4.16 kV/1 MW Medium Voltage PV Plus Storage Solid State Transformer (PVS-SST)," 2023 IEEE Applied Power Electronics Conference and Exposition (APEC), Orlando, FL, USA, 2023, pp. 1-5, doi: 10.1109/APEC43580.2023.10131543.
5. **Z. Guo**, C. Chen, Z. Chen and A. Q. Huang, "A High Power High Isolation Medium Frequency Transformer With A Planar Matrix Structure," 2023 IEEE Energy Conversion Congress and Exposition (ECCE), Nashville, TN, USA, 2023, pp. 5827-5830, doi: 10.1109/ECCE53617.2023.10362495.
6. **Z. Guo**, C. Chen, R. Yu and A. Q. Huang, "A High Power 200kW Medium Frequency Transformer With Improved Thermal Management," 2023 IEEE Energy Conversion Congress and Exposition (ECCE), Nashville, TN, USA, 2023, pp. 5587-5591, doi: 10.1109/ECCE53617.2023.10362391.
7. **Z. Guo**, A. Q. Huang and, X. Feng, "*Comparison of Partial Discharge (PD) Characterizations under 60 Hz Sinusoidal Waveform and High-frequency PWM Waveform*," 2022 IEEE Energy Conversion Congress and Exposition (ECCE).
8. **Z. Guo**, T. Chen, R. Yu and A. Q. Huang, "*GaN-based ±5kV/100kHz PWM Generator for Advanced Partial Discharge Characterization*," 2021 IEEE Energy Conversion Congress and Exposition (ECCE), 2021, pp. 5894-5898, doi: 10.1109/ECCE47101.2021.9595274.