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2023 Power Electronics and Energy Conversion Workshop

Development of High Power Medium-frequency Transformers for Solid State Transformer

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State of the Art Solutions

Magnetic Design of a 4.16 kV/1 MW Medium Voltage PV Plus Storage Solid State Transformer (PVS-SST)

A Novel MFT Insulation/Cooling Structure

Characterization of Partial Discharge in MFT

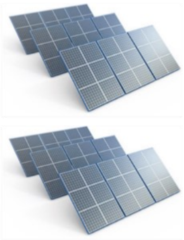
M4 Inverter

Multi-port

PV + Storage Solid State Transformer, PVS-SST

Medium-Voltage

1500V PV Panels



900V Energy Storage

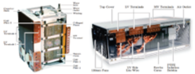
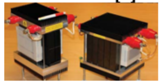
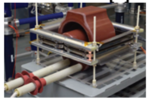
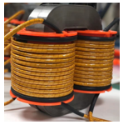
DOE DE-EE0008348 Award Amount: $3 million, PI: Dr. Alex Q. Huang

Medium Voltage
Distribution Grid

Multi-function

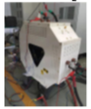
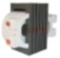
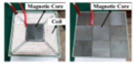
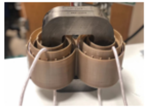
- MPPT
- Reactive Power Support
- Energy Storage
- Micro-grid
- Fast Frequency Response
- Other Grid Forming Functionalities
- • •

- ➢ **High Power**
  Power Rating: P >50 kW
- ➢ **Medium Frequency**
  Operating Frequency:
  100 kHz > f > 1 kHz
- ➢ **Core Materials:**
  - Amorphous
  - Ferrite
  - Nanocrystalline
  - Air
- ➢ **Cooling Methods:**
  - Liquid cooling
  - Heatsink cooling
  - Air cooling

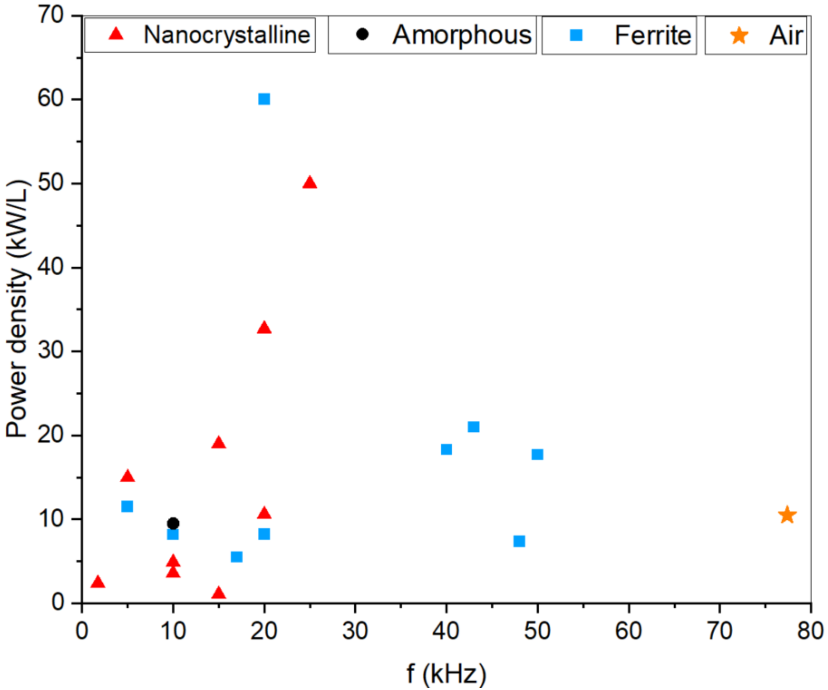
	Power Rating(kW)	Frequency (kHz)	Magnetic Core Material	Cooling Method	Insulation Voltage (kV)	Efficiency %	Power Density kW/L
ABB 2011[4] 	150	1.75	Nanocrystalline	Oil	15	96%	N/A
ETH 2013[5] 	166	20	Nanocrystalline	Water	N/A	99.5%	32.7
			Ferrite	Air		99.4%	8.21
CUT 2016[6] 	50	5	Nanocrystalline	Air cooled heatsink	6	99.66%	15
			Ferrite			99.58%	11.5
EPFL 2017[7] 	100	10	Nanocrystalline	Air cooled heatsink	>6	N/A	8.2
ABB 2017[8] 	240	10	Nanocrystalline	Air	PD (35kV)	N/A	3.6
ABB CERN 2017[9] 	100	15kHz - 22kHz	Nanocrystalline	Air Oil	PD (30kV)	N/A	1.1
UT Austin 2020 	200	15kHz	Nanocrystalline	Air	13 kV PDIV (5kV)	99.85%	>19.23

❑ Challenges

- ➢ **Efficiency:**
  system expectations
- ➢ **Power density:**
  volume/weight limitations
- ➢ **Thermal management:**
  materials limitations
- ➢ **Insulation design**
  Increasing electric insulation/reliability requirements

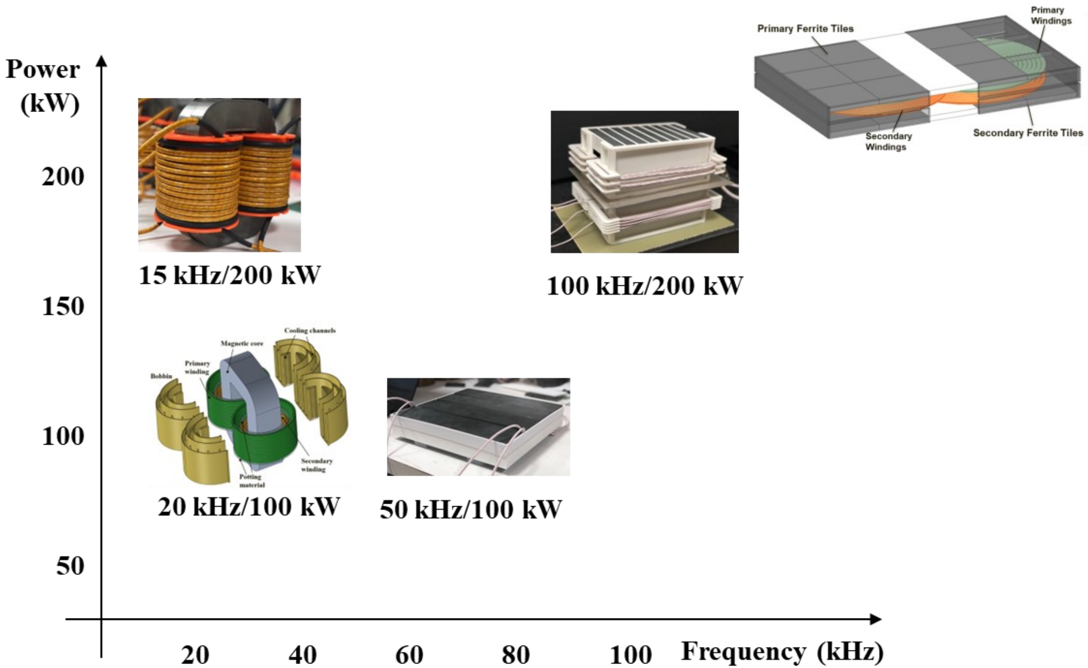
	Power Rating (kW)	Frequency (kHz)	Core Material	Cooling Method	Insulation Voltage (kV)	Efficiency %	Power Density (kW/L)	Hot Spot Temperature (°C)
UT Austin 2021[10] 	200	15	Nanocrystalline	Air	5.3 kV (**)	99.84	19.23	55
SEU 2021[11] 	250	10	Nanocrystalline	Air	18 kV (**)	99.76	4.9	62.6
ETH 2022 [12] 	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.



Map of MFTs (frequency and power density)

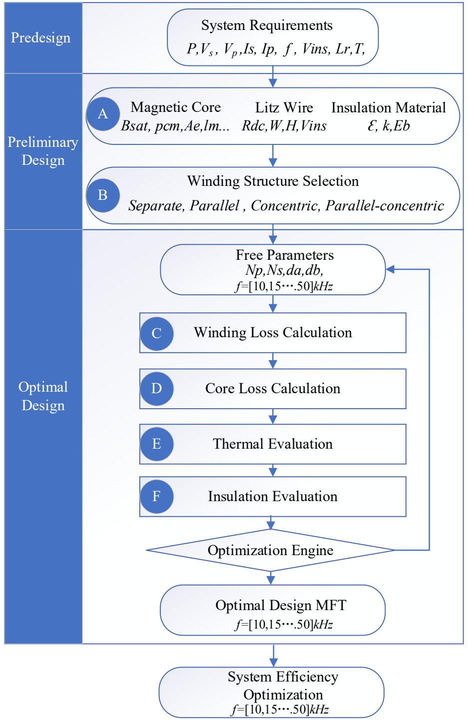
Magnetic Design of a 4.16 kV/1 MW Medium Voltage PV Plus Storage Solid State Transformer (PVS-SST)



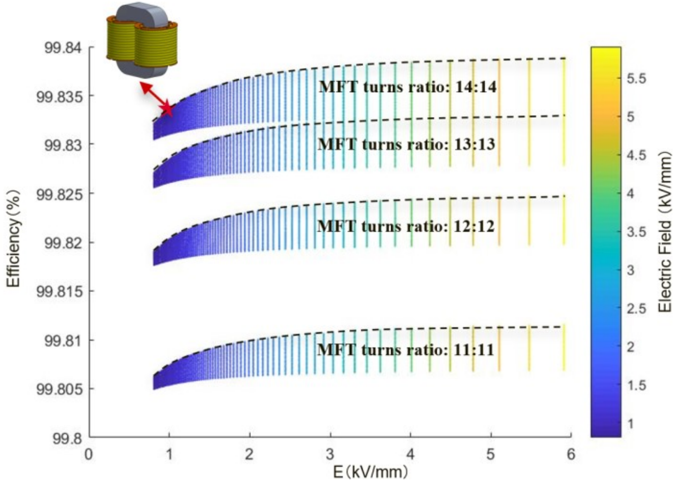
Optimization Methodology

- **Target:**
  - High efficiency
  - High power density
  - Superior insulation & thermal

- **Boundary conditions:**
  - Magnetic core dimension limitation
  - Electrical insulation requirements
  - Thermal limitation



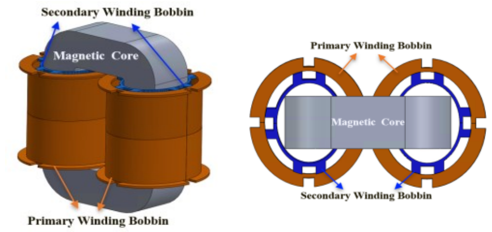
❖ **MFT design optimization flowchart**



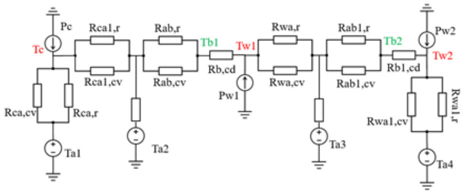
❖ **Efficiency versus maximum electric field of feasible MFTs according to the proposed design methodology**

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.

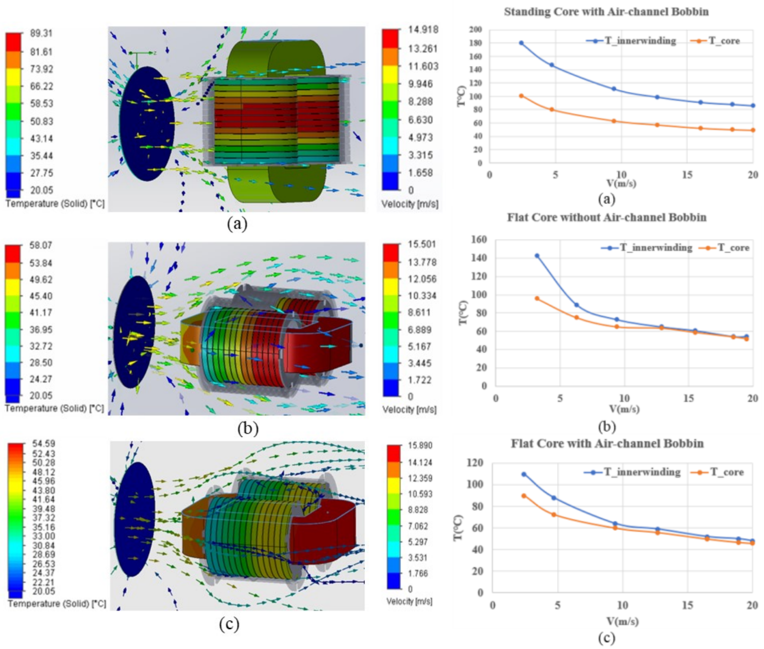
❑ Cooling Design



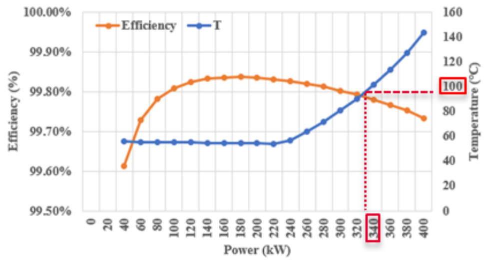
❖ 3D printed two layers bobbin design



❖ Steady state thermal network

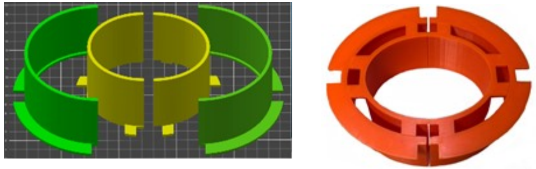


❖ Fluid thermal simulation of cooling structures @200kW



❖ MFT efficiency & temperature

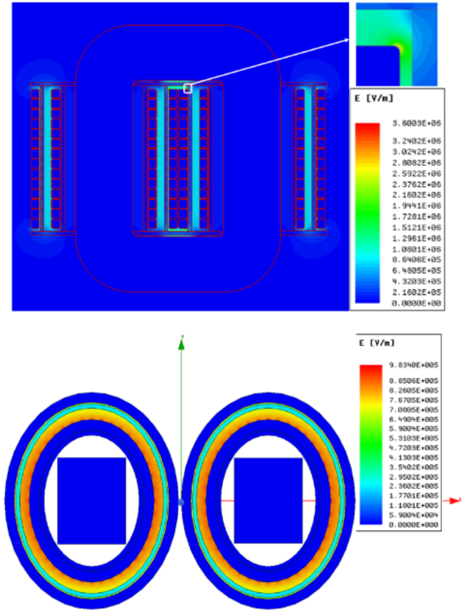
❑ Insulation Design



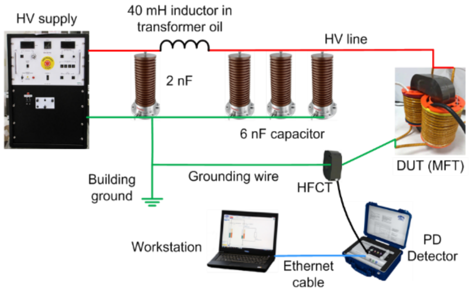
❖ 3D printed bobbin

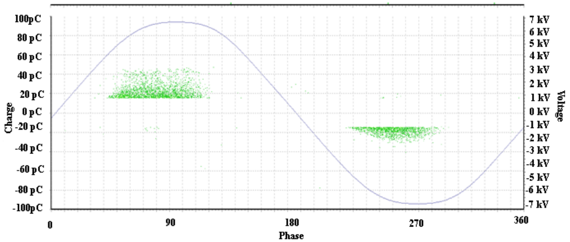
	Thickness (mm)	Material	Dielectric Strength@25 °C	Dielectric Constant	Thermal conductivity
Bobbin	3	Acrylonitrile Butadiene Styrene (ABS)	16.7 kV/mm	2.87	0.17 W/mK
Insulation tape	0.05	polyimide	102 kV/mm	3.5	0.12 W/mK

❖ Insulation structure and materials



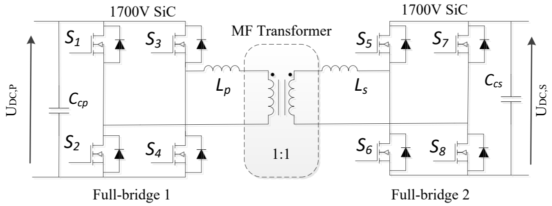
❖ Maxwell electrostatic simulation under applied voltage of 7.5 kV

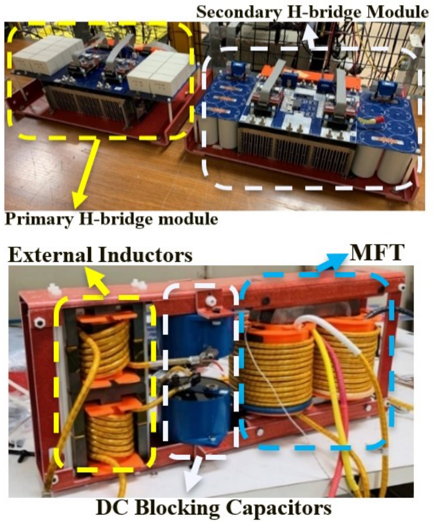




❖ Partial discharge test

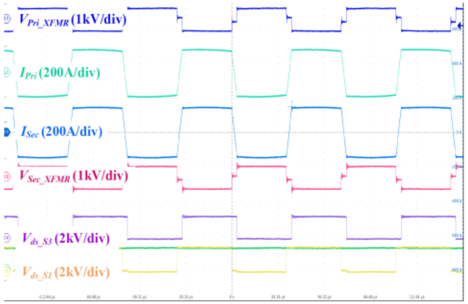
❑ Experimental Verifications



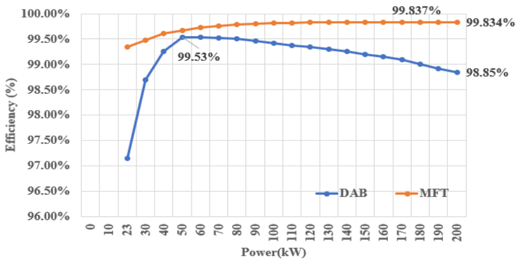


❖ **200 kW DAB converter**

❖ **Thermal camera image of the MFT steady state at 15 kHz and 200kW output power**

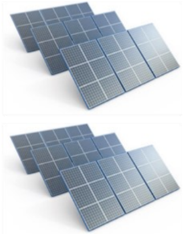


❖ **Experimental waveforms of MFT @ 15 kHz and output power 200kW (5μs/div)**



❖ **Measured DAB converter efficiency and MFT efficiency**

1500V PV Panels



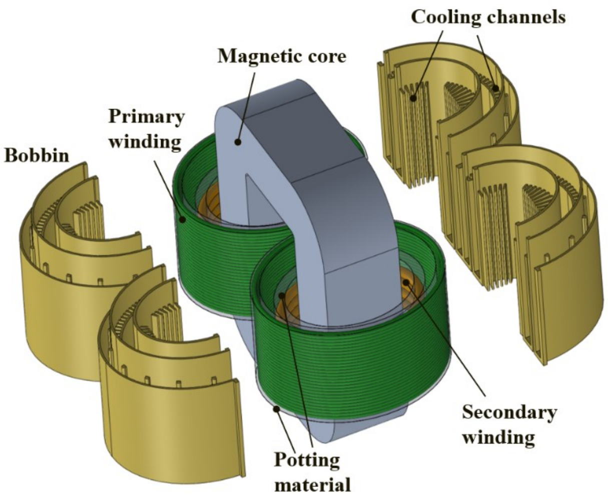
900V Energy Storage

Medium
Voltage
Distribution Grid

4.16 kV/1 MW PV Plus Storage Solid State Transformer

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

A Novel MFT Insulation/Cooling Structure

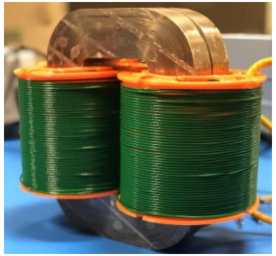


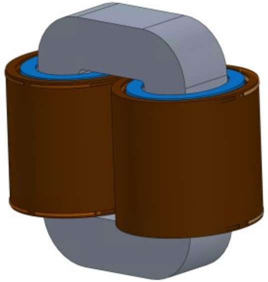
➢ **Novel MFT insulation/cooling structure:**

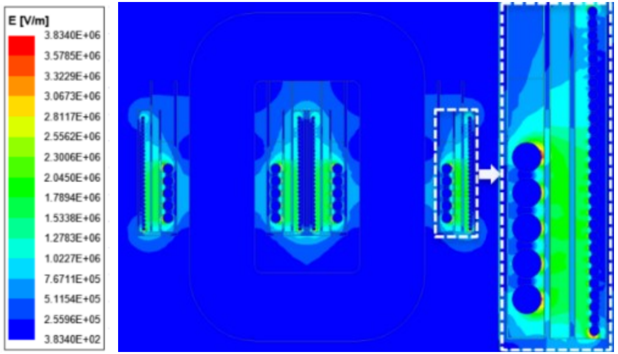
- **Potted windings**
- **Two layers 3D printed** bobbin with **heatsink fins**

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.

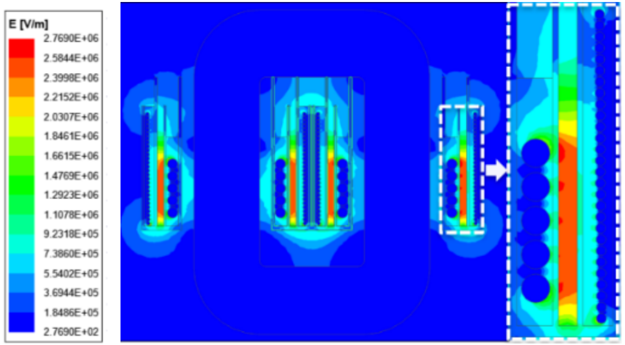
Windings Potted Design







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



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

Insulation Considerations

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

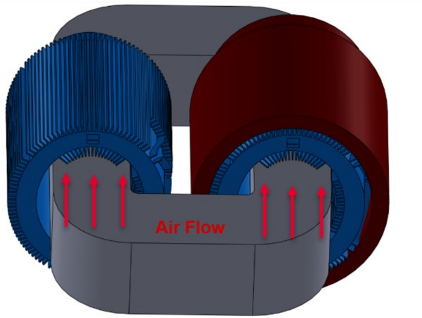
Polyether ether ketone (**PEEK**) filament is one of the best materials on the market. Exceptional mechanical, thermal, and electric properties make this an ideal material for this application.

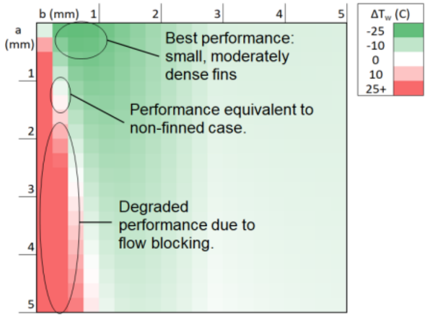
Potting Material Candidates

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

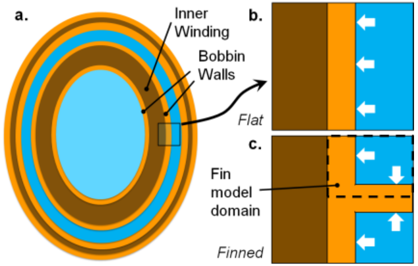
SilGel® 612 was selected due to the lowest viscosity, longest pot life which helps to remove air bobbles during the vacuum fabrication process.

❑ Cooling Considerations



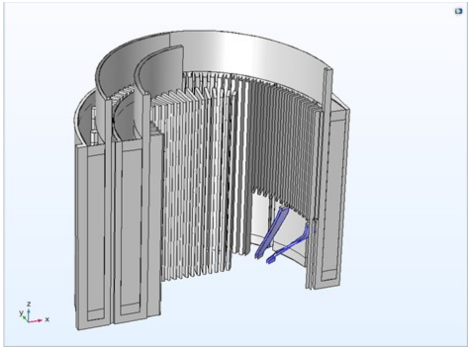


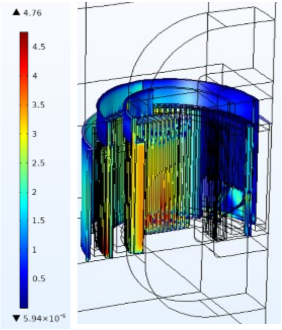
❖ **Temperature reduction**

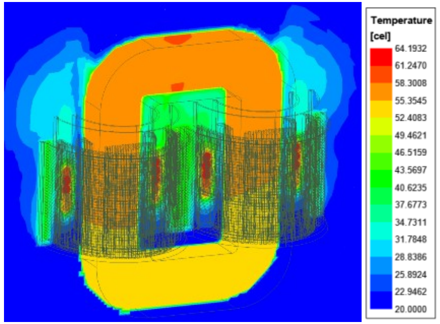


❖ **Fin thickness and pitch**

❑ Cooling Considerations



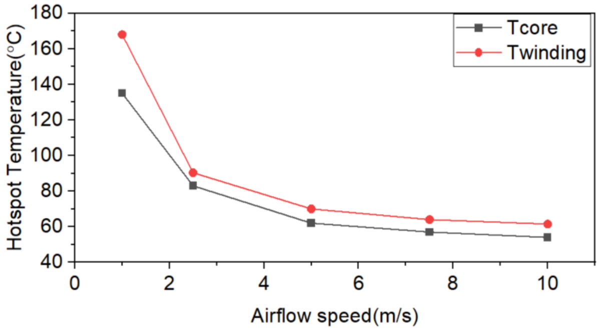




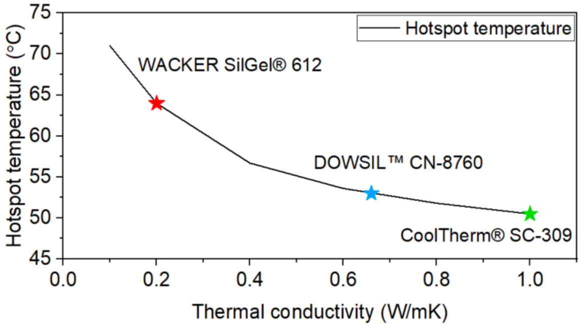
❖ **Airflow speed passing through the bobbin air channels**

❖ **MFT temperature distribution**

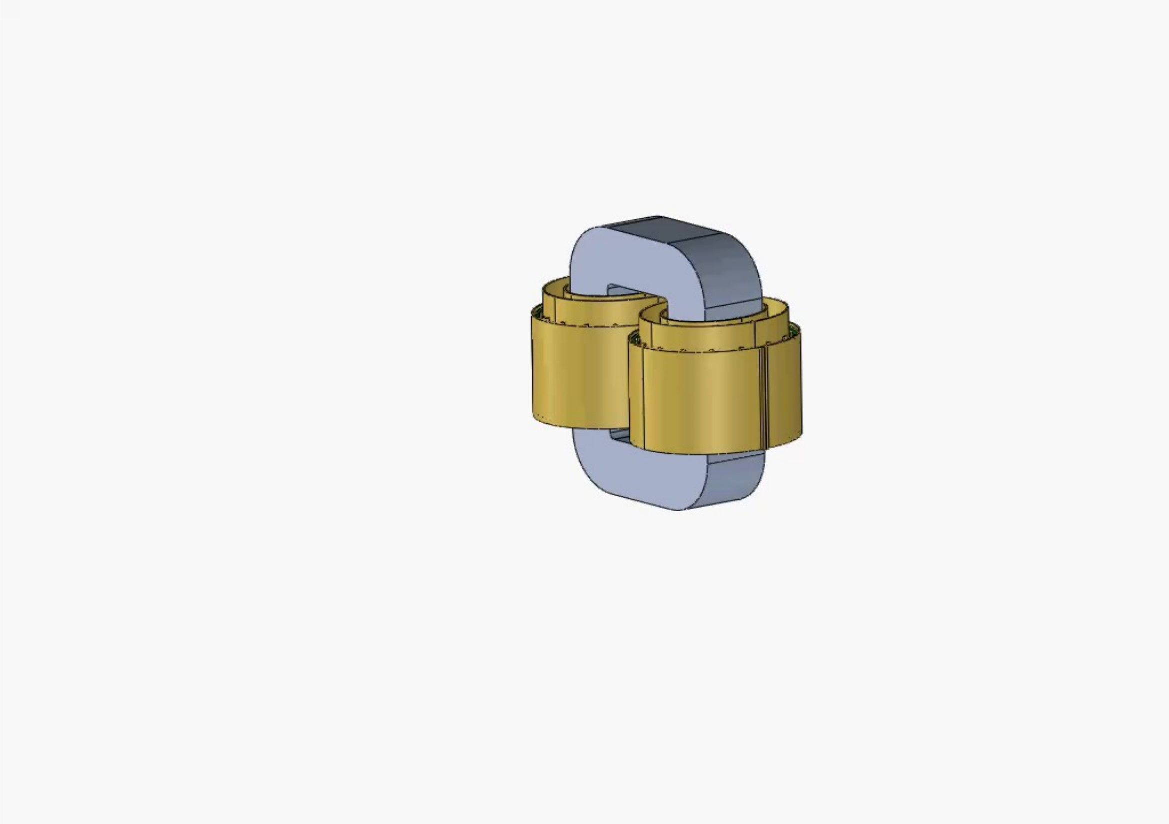
❑ Cooling Considerations

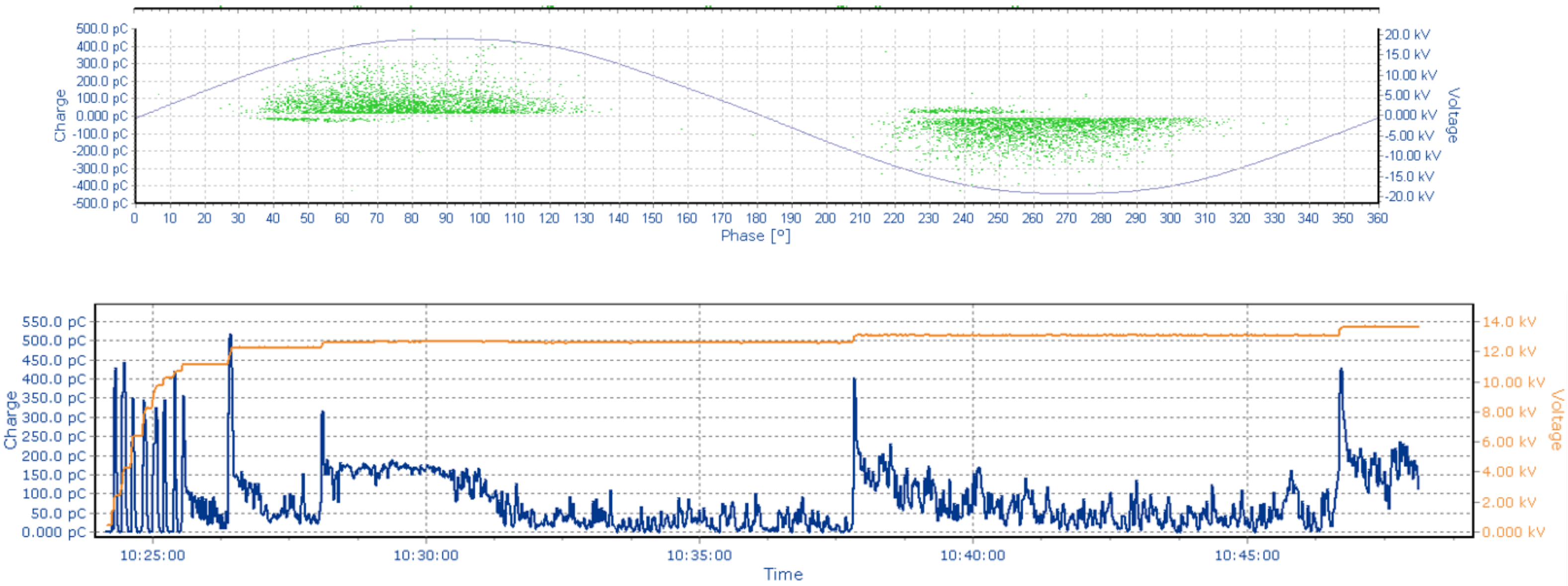


❖ **Effect of inlet airflow speed on core / windings hotspot temperature**

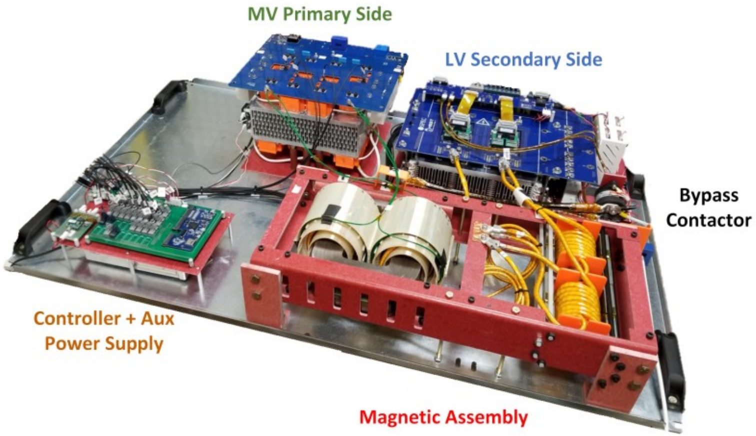


❖ **Effect of encapsulant thermal conductivity on hotspot temperature**



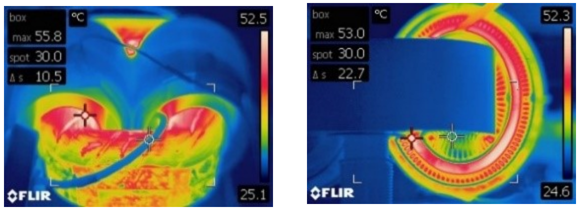


❖**Partial discharge insulation test (20 kV peak)**

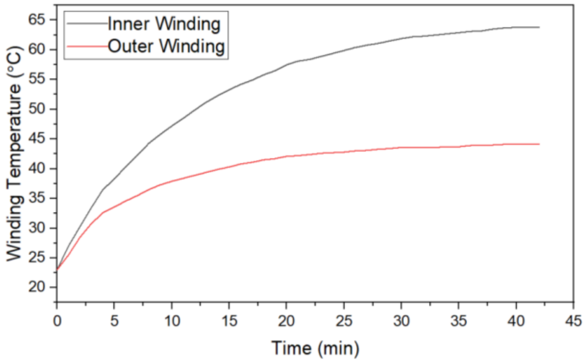


DOE DE-OE0000905 Award Amount: $2.2 million, PI: Dr. Alex Q. Huang

❖ **Assembled DABSST with the developed MFT prototype**

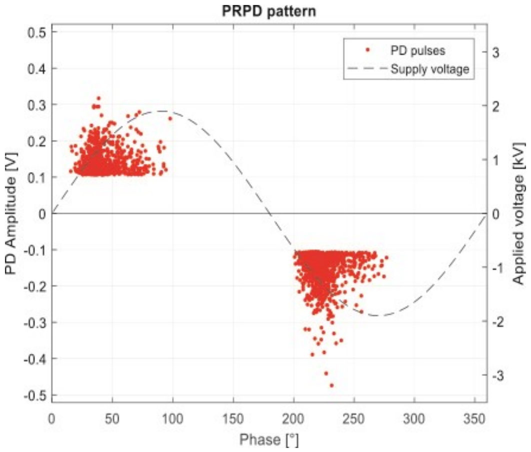


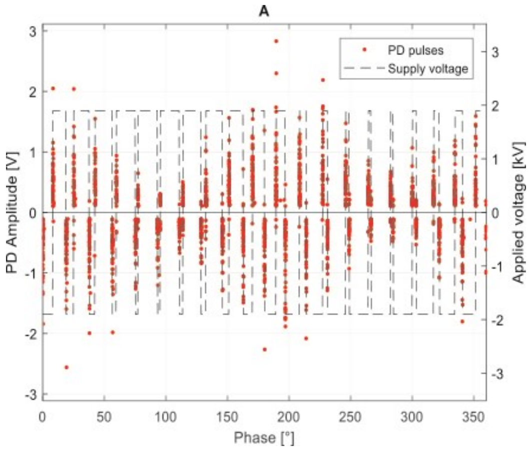
❖ **Thermal camera image of the MFT steady state temperature**



❖ **Recorded temperature rise curve of the windings with thermocouples**

Characterization of Partial Discharge in MFT



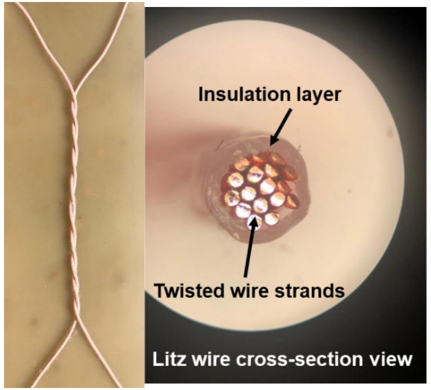


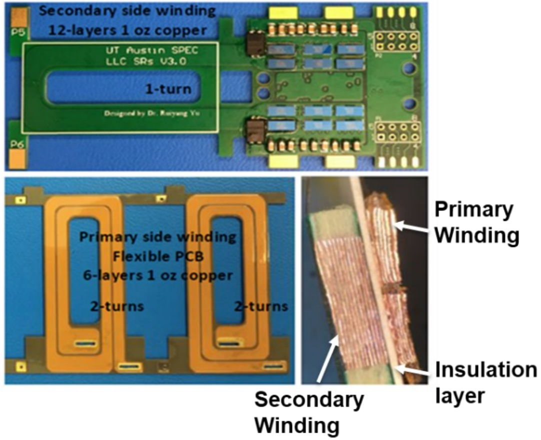
- ❑ **Working waveform Partial discharge(PD) test?**
- ❖ **Different voltage**
- ❖ **Different dv/dt**
- ❖ **Different frequencies**

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.

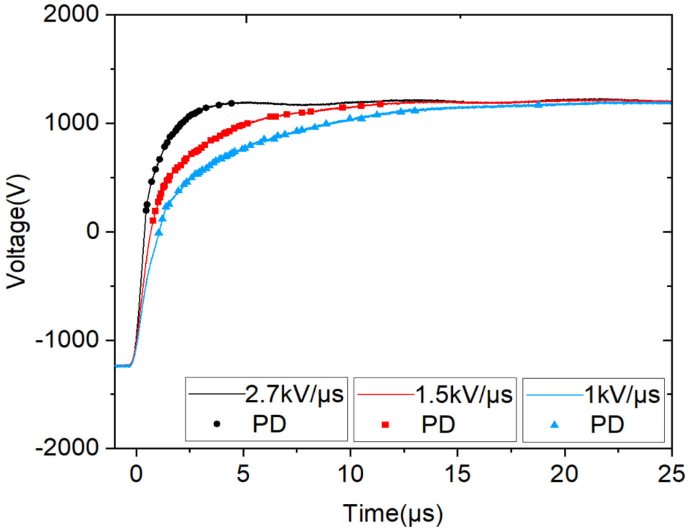


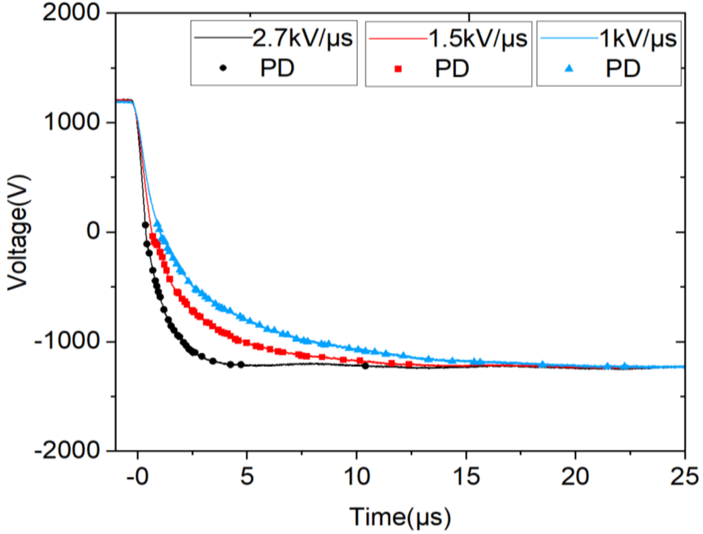


❖ **Twisted Litz wire test sample and cross–section view.**

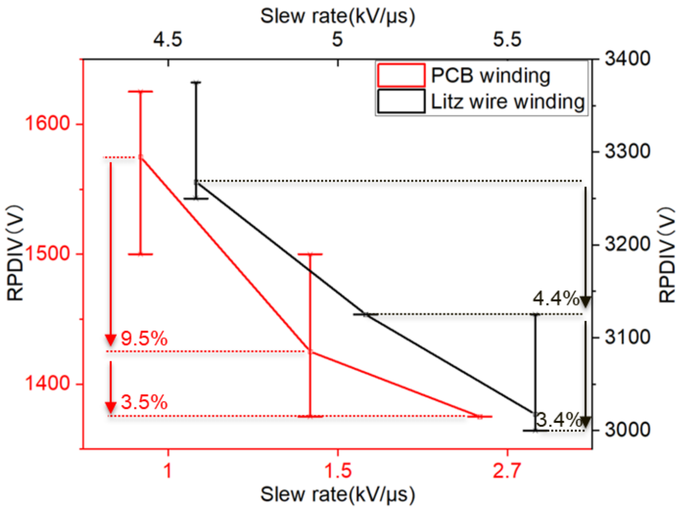
❖ **Direct parallel PCB windings and cross–section view.**

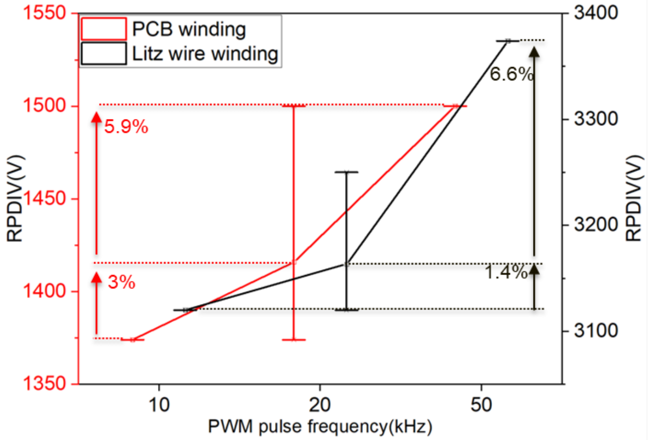
Z. Guo, A. Q. Huang, R. E. Hebner, G. C. Montanari and X. Feng, "Characterization of Partial Discharges in High-Frequency Transformer Under PWM Pulses," in IEEE Transactions on Power Electronics, vol. 37, no. 9, pp. 11199-11208, Sept. 2022.





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





❖ **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.


THANK
YO