WEBINAR

Optimized Insulation System for Renewable Energy Generation Transformers

June 25th | 16:00 CEST | 10:00 EDT

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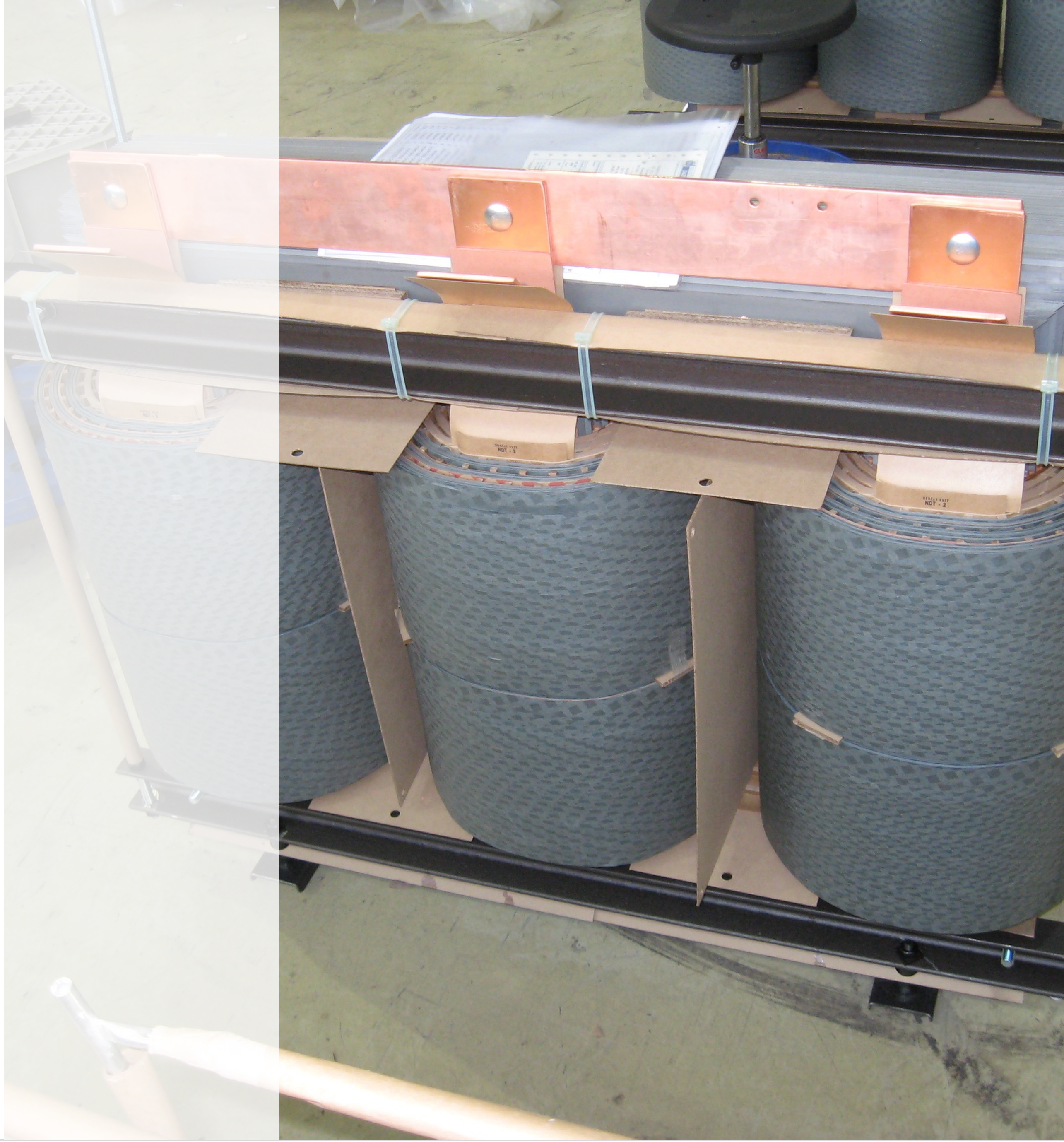

HOW TO ASK A QUESTION?

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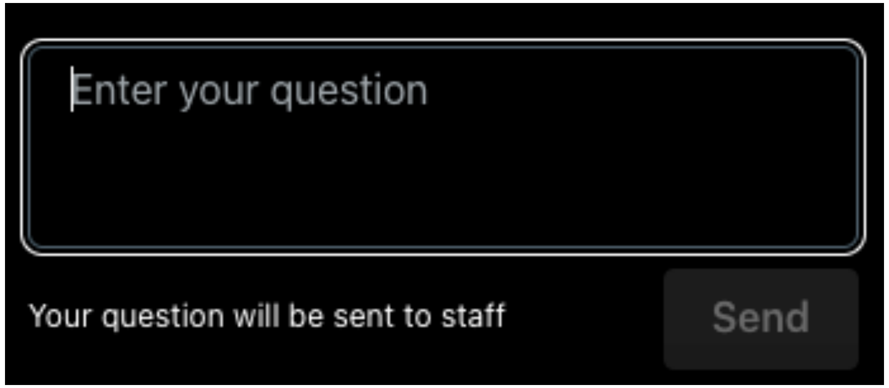

Type your question. This will only be seen by the event organizers.

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OPTIMIZED INSULATION SYSTEM FOR RENEWABLE ENERGY GENERATION TRANSFORMERS

KEVIN BIGGIE & ALEKSANDR LEVIN – 25 JUNE 2024

OPTIMIZED INSULATION FOR RENEWABLE ENERGY TRANSFORMERS

01 **Introduction / Industry Trends**

02 Challenges for Renewable Energy Transformers

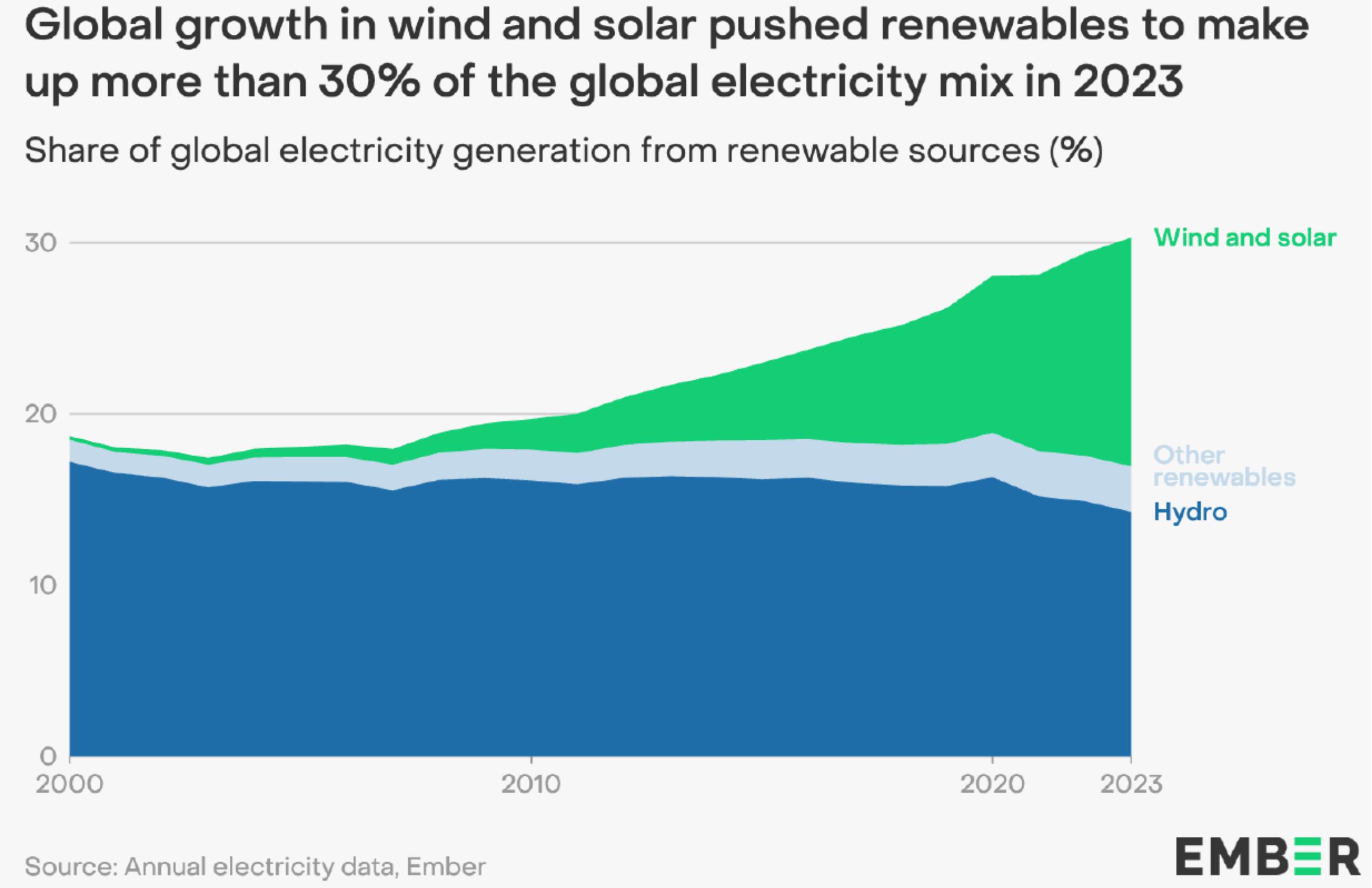
03 Solution: Weidmann Advanced DPE Insulation Paper

04 DPE = Higher Thermal Class Paper, Explained

05 Transformer Design Concepts by Applying Higher Thermal Class DPE Insulation Paper

06 Summary

RENEWABLE ENERGY GENERATION GROWTH
HAS BECOME A MAJOR ENERGY SOURCE



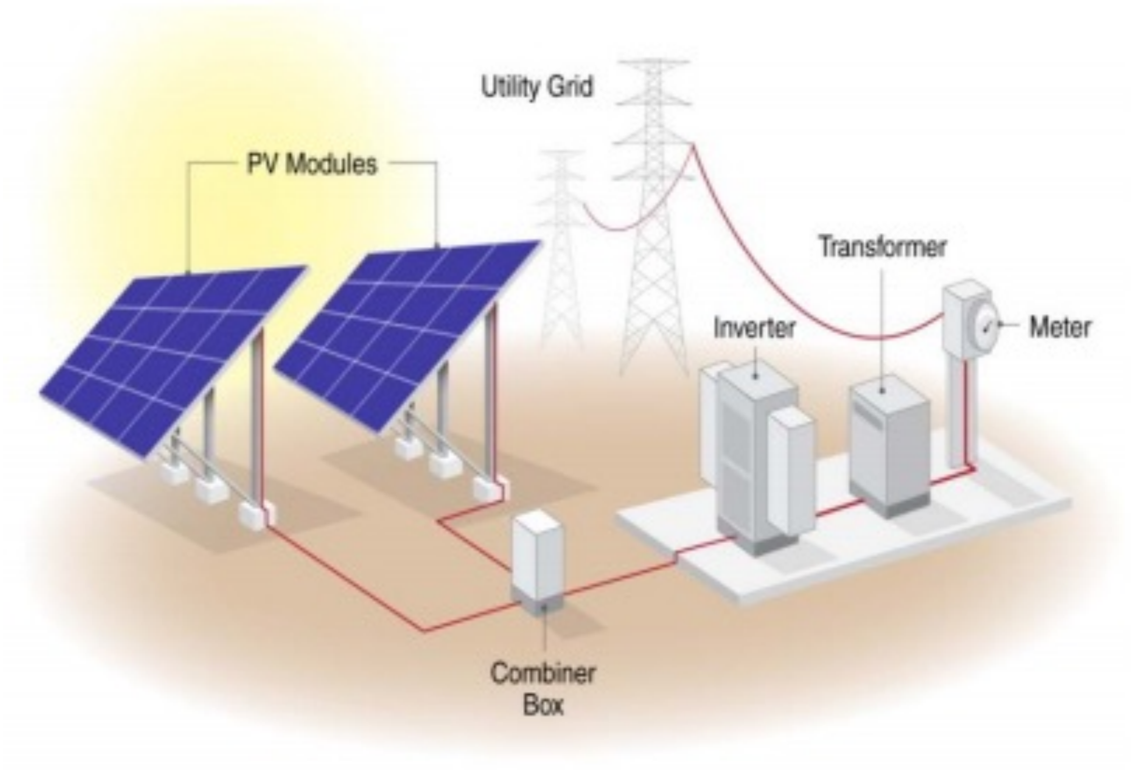
The 3.5 GW Midon solar plant

Image: CGDG

RENEWABLE ENERGY GENERATION TRANSFORMERS

CHARACTERISTICS & TRENDS

- Large industrial scale generation installations can have hundreds of transformers per site
- Transformers for renewable energy generation have become larger and larger (2500 kVA and above)
- Voltages are also increasing (36 kV and above rated voltage, up to 250 kV BIL)
- Commonly these transformers are designed with layer-type windings up to 6300 kVA and even higher

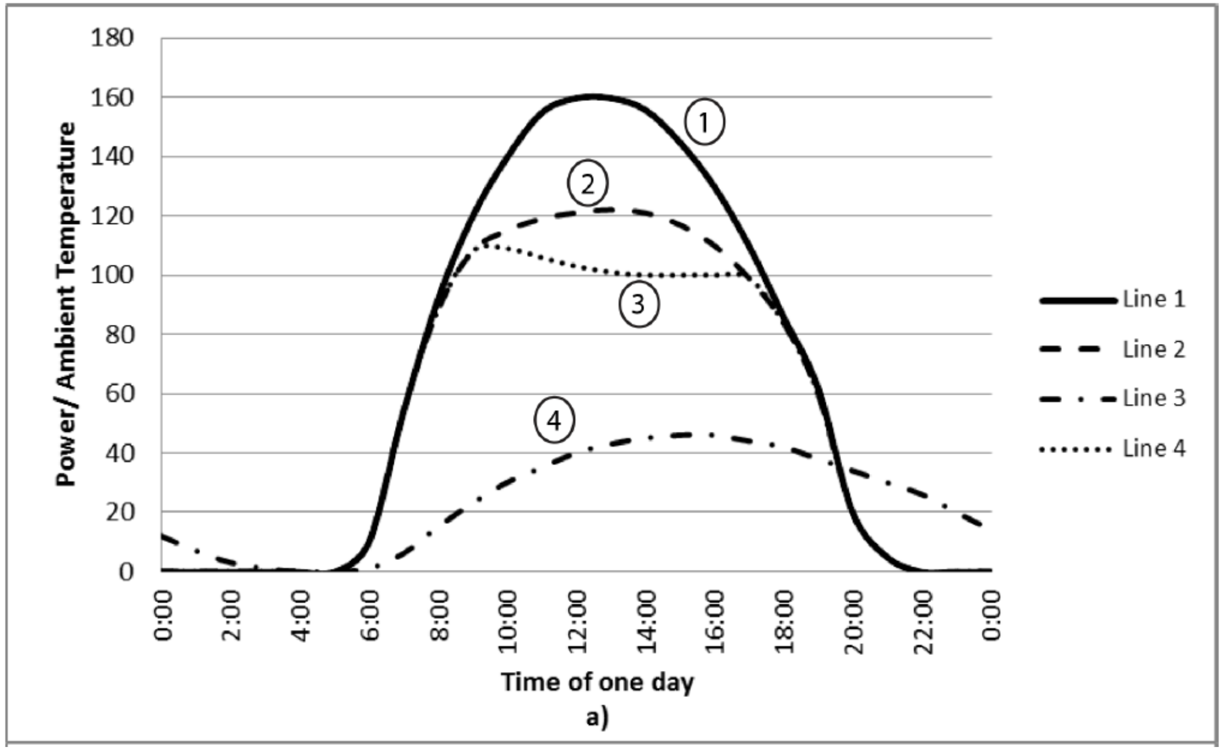


OPTIMIZED INSULATION FOR RENEWABLE ENERGY TRANSFORMERS

RENEWABLE ENERGY GENERATION TRANSFORMERS

OEM & END-USER CHALLENGES

- Intermittent / variable character of renewable power sources
- Un-utilized excessive transformer capacity (leading to excessive capital investments and increased site footprint)
- Unfavorable power generation / power loss ratio (no-load losses continue with zero or reduced power generation)
- Sites can be at locations with high ambient temperatures (shorter life span, reduced reliability)



IEEE C57.159™: Load profile of a solar power generation inverter connected transformer; (3) = Transformer active load (% of nominal nameplate power)

RENEWABLE ENERGY GENERATION TRANSFORMERS

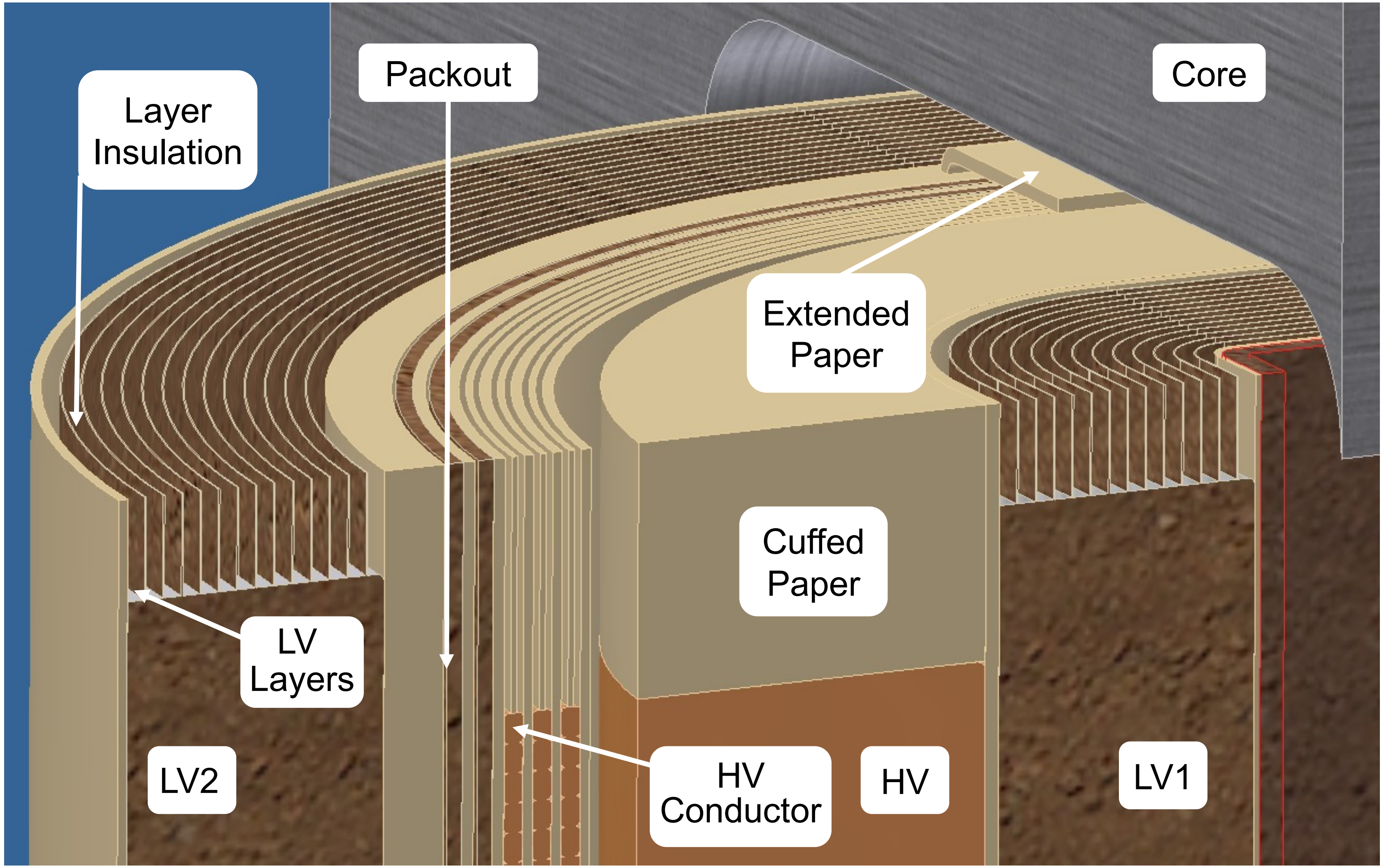
TRANSFORMER DESIGN CHALLENGES

- Issues related to inverter-connected renewable energy generation systems lead to increased thermal, electrical and mechanical stresses on transformers

- Challenges with large layer-type transformers using large quantities of insulation paper:
  - Long time for paper drying and liquid impregnation leads to reduced OEM productivity
  - Quality problems / failures in OEM HV factory test from insufficient drying and impregnation
  - Larger size = higher cost

LAYER-TYPE TRANSFORMER WINDINGS

KEY SOLID INSULATION MATERIAL = PAPER



RENEWABLE ENERGY GENERATION TRANSFORMERS

OPTIMIZED INSULATION SYSTEM

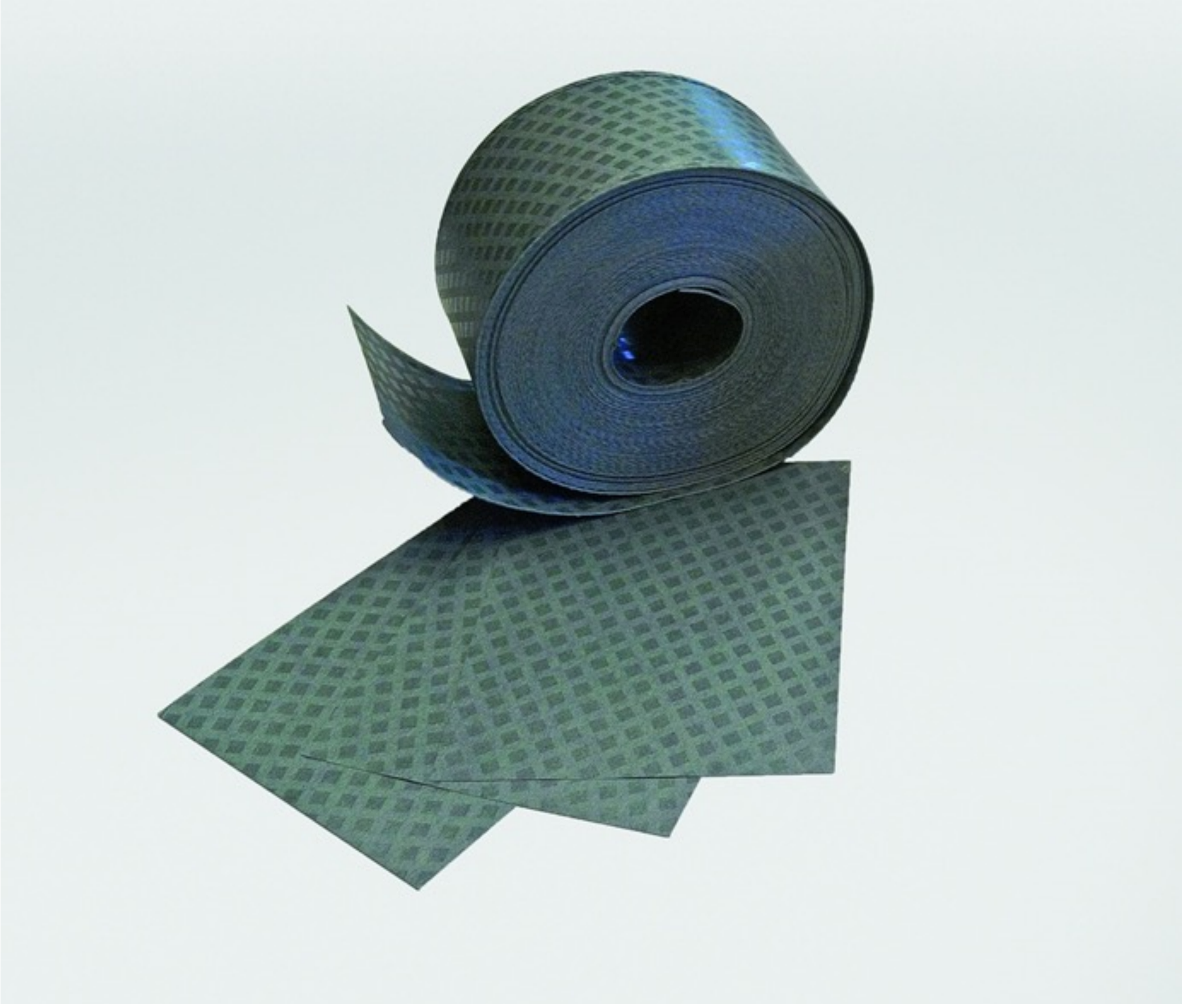
- Transformer solid insulation largely defines the major transformer characteristics:
  - Size, weight, footprint and cost
  - Losses and efficiency
  - Long-term reliability and resilience

- As layer insulation paper is they key material, a special "Engineered Paper" with enhanced properties can provide new opportunities for optimization and improved performance
  - Withstand higher temperatures
  - Faster & higher quality processing at the OEM factory
  - Improved dielectric performance
  - Reduced size and weight
  - Cost effective paper = reduced cost transformer

OPTIMIZED INSULATION FOR RENEWABLE ENERGY TRANSFORMERS

WEIDMANN DPE PAPER

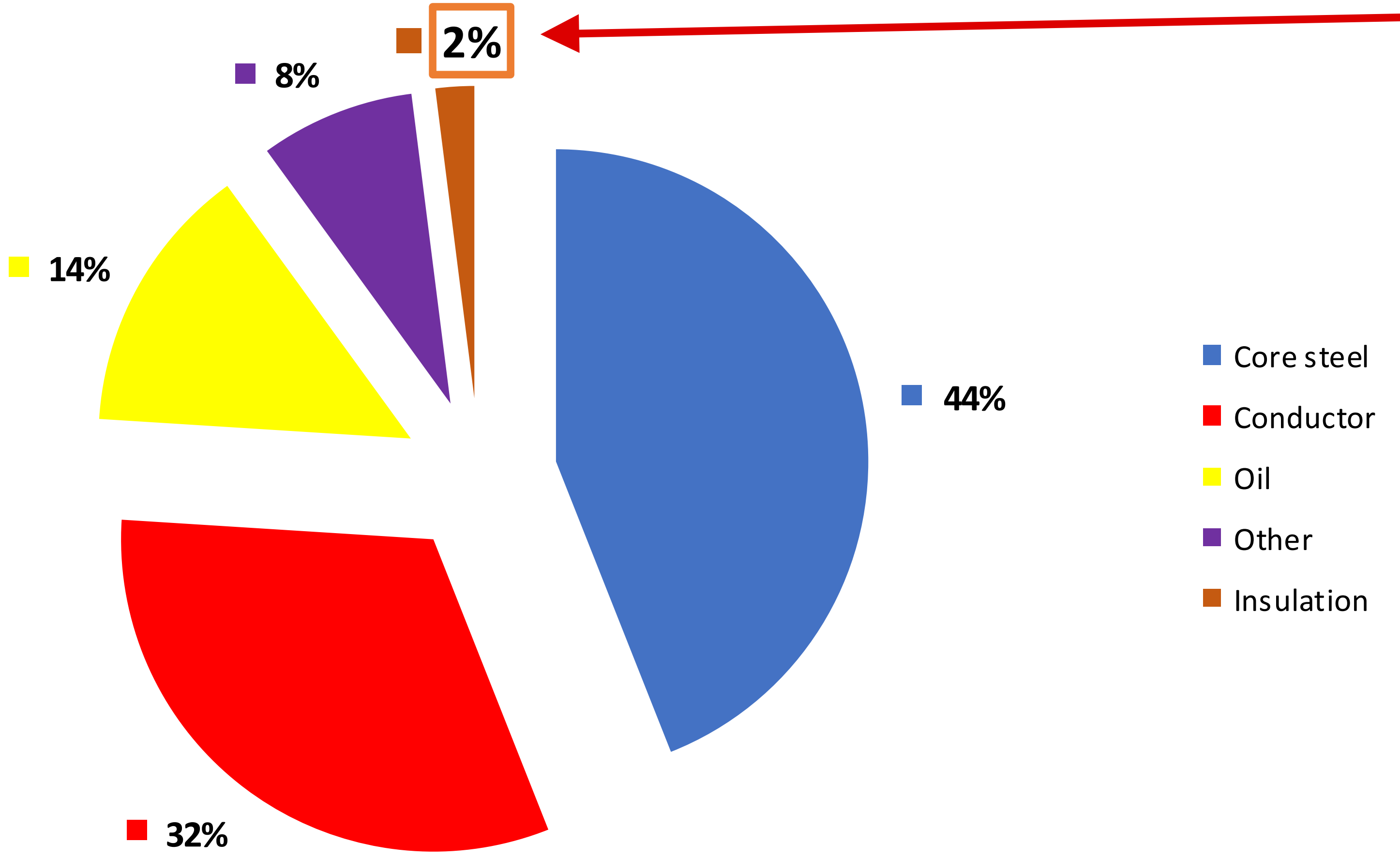
DIAMOND PATTERN ENHANCED (DPE)



- Special grade of layer insulation paper for liquid-immersed layer-type transformers
- INSULutions™ DPE is engineered using 100% cellulose to minimize cost, yet it overcomes the limits of traditional Kraft cellulose papers, providing:
  - Higher thermal endurance (in both mineral oil & ester liquid) – slower aging
  - Better (faster) drying – quality & productivity improvement
  - Better (faster) impregnation with dielectric liquids – quality & productivity improvement
  - Better dielectric performance – potentially improved dielectric insulation design

INSULATION PAPER IN LAYER-TYPE TRANSFORMERS

SMALL PORTION OF TOTAL TRANSFORMER COST – EXAMPLE BREAKDOWN



- Relative price difference by using DPE paper vs. standard TUK paper has little effect on overall transformer cost (< 1%)

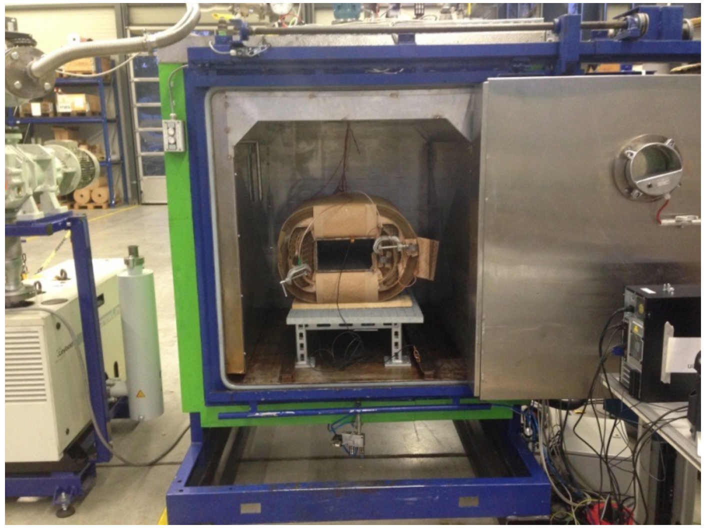
WEIDMANN DPE PAPER

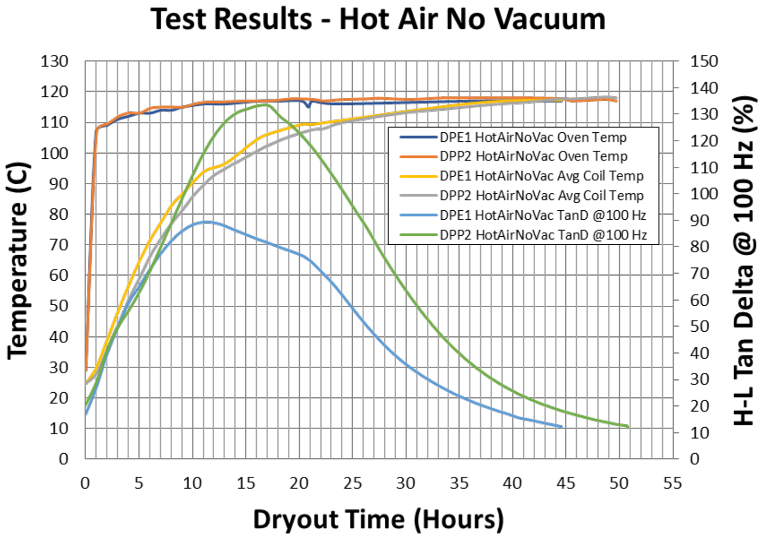
BETTER (FASTER) DRYING

- **DPE dries up to 30% faster than other cellulose papers**

- Faster drying rate has been confirmed using 4 different methods:
  - Laboratory dry-out rate test – heated scale
  - Laboratory paper sorption-desorption isotherms test – sorption analyzer
  - Dry-out rate study on full-size coils in a large drying chamber performed by Hedrich GmbH
  - Studies of factory dry-out processes of assembled transformers at four different transformer OEMs

- <u>Benefits of faster drying:</u>
  - Improved transformer quality – reduced failure rate in factory test & in the field
  - Less initial moisture in the transformer – longer and more reliable long-term operation in the field
  - Reduced factory transformer dry-out time = savings on the cost of transformer processing and increased production throughput (optimized manufacturing)





WEIDMANN DPE PAPER

BETTER (FASTER) IMPREGNATION WITH DIELECTRIC LIQUIDS

- **DPE impregnates up to 30% faster both in mineral oil & ester liquids**

- Faster impregnation rate has been confirmed by:
  - The results of a special impregnation study where the rate of migration of two liquids through 0.254 mm / 10 mil paper samples, oriented in the machine direction (MD) and hanging in shallow dishes of the liquids at 80 °C under vacuum, was measured for both mineral oil and an ester liquid

- Benefits of faster liquid impregnation:
  - Improved transformer quality and reduced failure rate in the factory HV test and in the field
  - Improved impregnation in transformers with ester liquids, which have a higher viscosity
  - Reduced factory transformer impregnation time = savings on the cost of transformer processing and increased production throughput (optimized manufacturing)

- **DPE higher thermal rating and faster impregnation rate make it the paper of choice for layer-type transformers with ester liquids**

WEIDMANN DPE PAPER

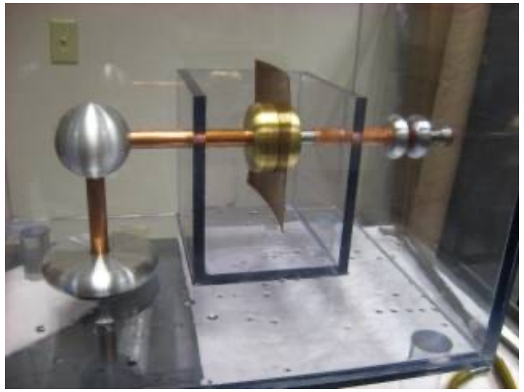
BETTER DIELECTRIC PERFORMANCE PAPER

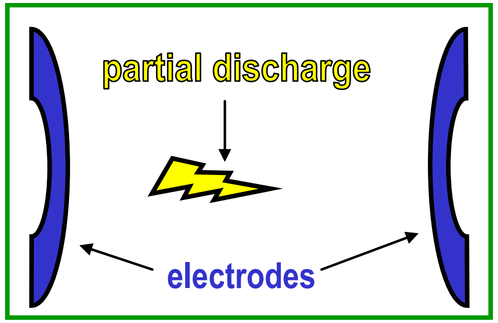
- **Designed to have the best dielectric performance for cellulose-based layer insulation paper**

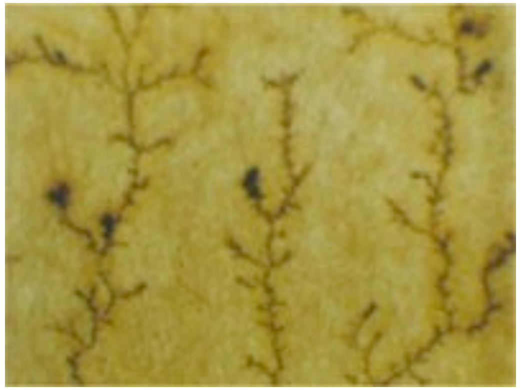
- Compared with and selected among 17 paper grades during specially designed layer insulation electrical tests involving 60 Hz AC voltage, impulse voltage, and partial discharge (PD) measurements

- Consequently, a complete transformer insulation design methodology was developed based upon DPE dielectric criteria and performance

- Benefits of advanced dielectric properties:
  - Insulation design safety factor can be increased, leading to a reduction in factory HV test failure rates
  - Dielectric (insulation) design can be optimized, with a reduction of insulation clearances, and subsequent reduction of size, weight and cost of the coil, core and entire transformer







OPTIMIZED INSULATION FOR RENEWABLE ENERGY TRANSFORMERS

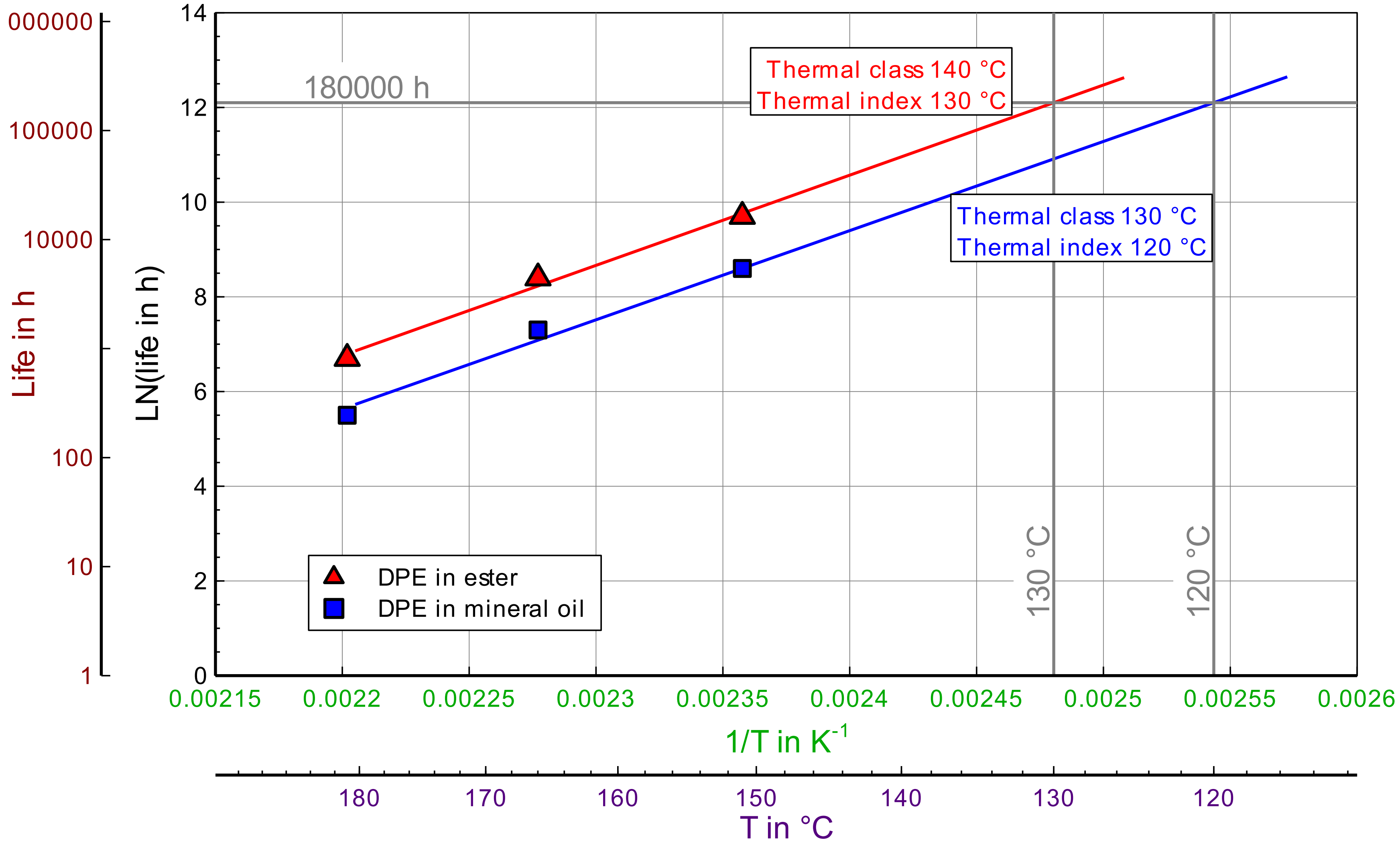
DPE = HIGHER THERMAL CLASS PAPER

SLOWER AGING, LONGER LIFE

- INSULutions™ DPE is qualified for the following Thermal Classes:
  - **130 ºC in mineral oil** (10 °C higher than Thermally Upgraded Kraft paper)
  - **140 ºC in ester liquid**
- Weidmann completed extensive series of aging tests per IEEE C57.100™-2011 “Standard Test Procedure for Thermal Evaluation of Insulating Systems for Liquid-Immersed Distribution & Power Transformers”
  - The standard describes an approach for determining the end-of-life criteria of transformer insulating systems, and a procedure to define the insulation system life equation and Thermal Index, which then relates to the Thermal Class of the insulation system
  - Aging tests took more than 2 years to complete

DPE = HIGHER THERMAL CLASS PAPER

AGING TESTS LIFE CURVES IN MINERAL OIL & ESTER LIQUIDS



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DPE = HIGHER THERMAL CLASS PAPER

TRANSFORMER DESIGN TEMPERATURE LIMITS

Limits Based on Standard IEC Terminology

INSULATION SYSTEM	INSULATING MATERIAL AND LIQUID	TRANSFORMER AVERAGE WINDING TEMPERATURE RISE (AWR), K	TRANSFORMER WINDING HOT-SPOT TEMPERATURE RISE, K	SYSTEM THERMAL CLASS, ºC
INDUSTRY PROVEN *SYSTEM*	Kraft in mineral oil	65 / 70	78	105
	TU Kraft in mineral oil	75	90	120
DPE SYSTEM	DPE in mineral oil	85	100	130
	DPE in ester liquid	95	110	140

Limits Based on Standard IEEE Terminology

INSULATION SYSTEM	INSULATING MATERIAL AND LIQUID	TRANSFORMER AVERAGE WINDING TEMPERATURE RISE (AWR), K	TRANSFORMER WINDING HOT-SPOT TEMPERATURE RISE, K	SYSTEM THERMAL CLASS, ºC
INDUSTRY PROVEN SYSTEM	Kraft in mineral oil	55	65	105
	TU Kraft in mineral oil	65	80	120
DPE SYSTEM	DPE in mineral oil	75	90	130
	DPE in ester liquid	85	100	140

OPTIMIZED INSULATION FOR RENEWABLE ENERGY TRANSFORMERS

BENEFITS & APPLICATION OPTIONS

USING HIGHER THERMAL CLASS DPE INSULATION PAPER

- Let's explore the application options to utilize the benefit of higher thermal class DPE paper in layer-type transformer insulation systems

- New international standards support the application of higher temperature insulation systems in transformers:
  - IEEE C57.154-2022™ – "Standard for Distribution, Power, and Regulating Transformers Using Higher Temperature Insulation Systems"
  - IEEE 1276-2020™ – "Guide for the Application of High-Temperature Insulation Materials in Liquid-Immersed Distribution, Power and Regulating Transformers"
  - IEC 60076-14, Power Transformers – Part 14: "Liquid-immersed power transformers using high-temperature insulation materials"

BENEFITS & APPLICATION OPTIONS
HIGH TEMPERATURE RATED DESIGNS

- Application of Weidmann's enhanced insulating paper DPE in layer-type transformers allows:
  - With mineral oil – increase up to 75 °C Average Winding Rise (AWR) temperature
  - With ester liquids – increase up to 85 °C AWR temperature
- Insulation system thermal class options using DPE paper (IEEE terminology):

Temperature	65 °C systems (TUK paper or DPE paper and mineral oil)	75 °C systems (DPE paper and mineral oil)	85 °C systems (DPE paper and ester liquid)
Ambient	30	30	30
AWR Above Ambient	65	75	85
Hot Spot Above AWR	15	15	15
Hot Spot Limit	110	120	130
System Thermal Class	120 (E)	130 (B)	140

BENEFITS & APPLICATION OPTIONS

LONGER LIFE IN OPERATION

- In normal operation
  - Transformer life – defined by aging rate of the insulation paper
  - Aging rate of the insulation paper – defined by insulation system temperature in operation
- By substituting “normal” thermally upgraded kraft (TUK) paper with “enhanced” DPE paper
  - Obtain additional 10 °C temperature “safety margin”
  - Provides more than two times longer insulation life
  - Increases transformer resilience against increased ambient and/or operational temperatures
- Insulation paper life can be described using the so-called activation energy theory developed by Swedish scientist Svante Arrhenius
- The Arrhenius “life equation” for the system with TUK & mineral oil can be found in IEEE Std. C57.12.00™

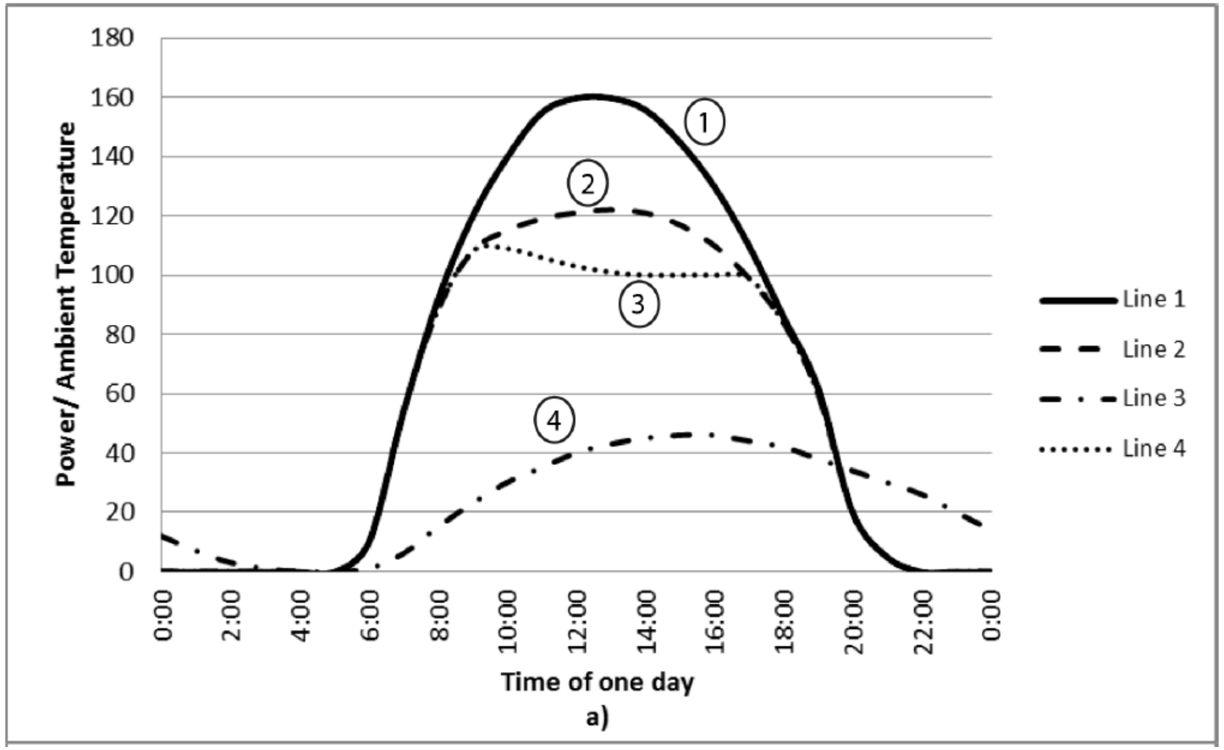
$$\text{LIFE} = e^{\left[\frac{15000}{T+273}\right]-27.064}$$

System Temperature (Winding Hot Spot), °C	Transformer Life, hours
110	180000
100	514000

BENEFITS & APPLICATION OPTIONS

HIGHER OVERLOAD CAPABILITY

- By substituting “normal” thermally upgraded kraft (TUK) paper with “enhanced” DPE paper…
- Option 1: Same size (rated capacity) transformer with about 20% higher overload capability (no to minimal design changes)
- Option 2: Smaller (rated capacity) transformer with equivalent overload capability, but smaller in size, weight, cost, and no-load losses (higher efficiency)



Example: 100 kVA solar power generation inverter connected transformer (3), with “Initial Load” = 30% of nameplate power, and “Peak Load” duration = 8 hours

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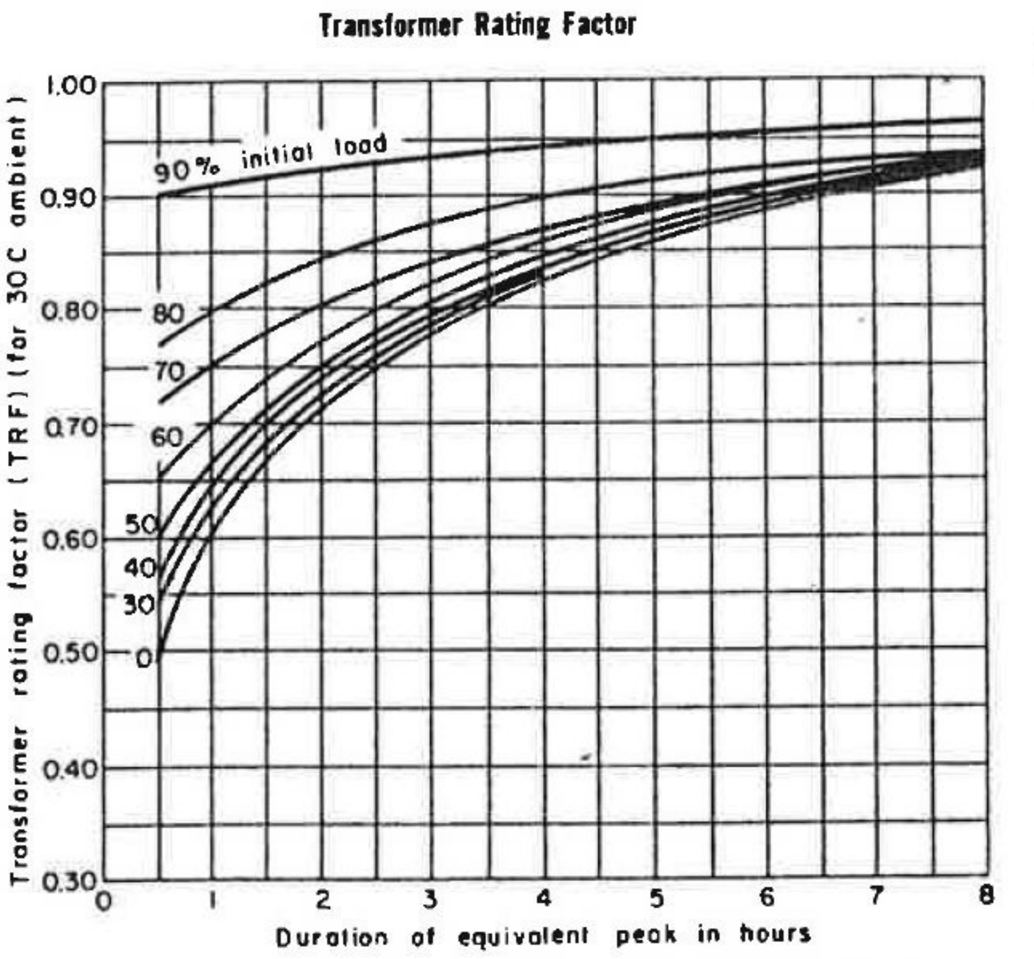
BENEFITS & APPLICATION OPTIONS

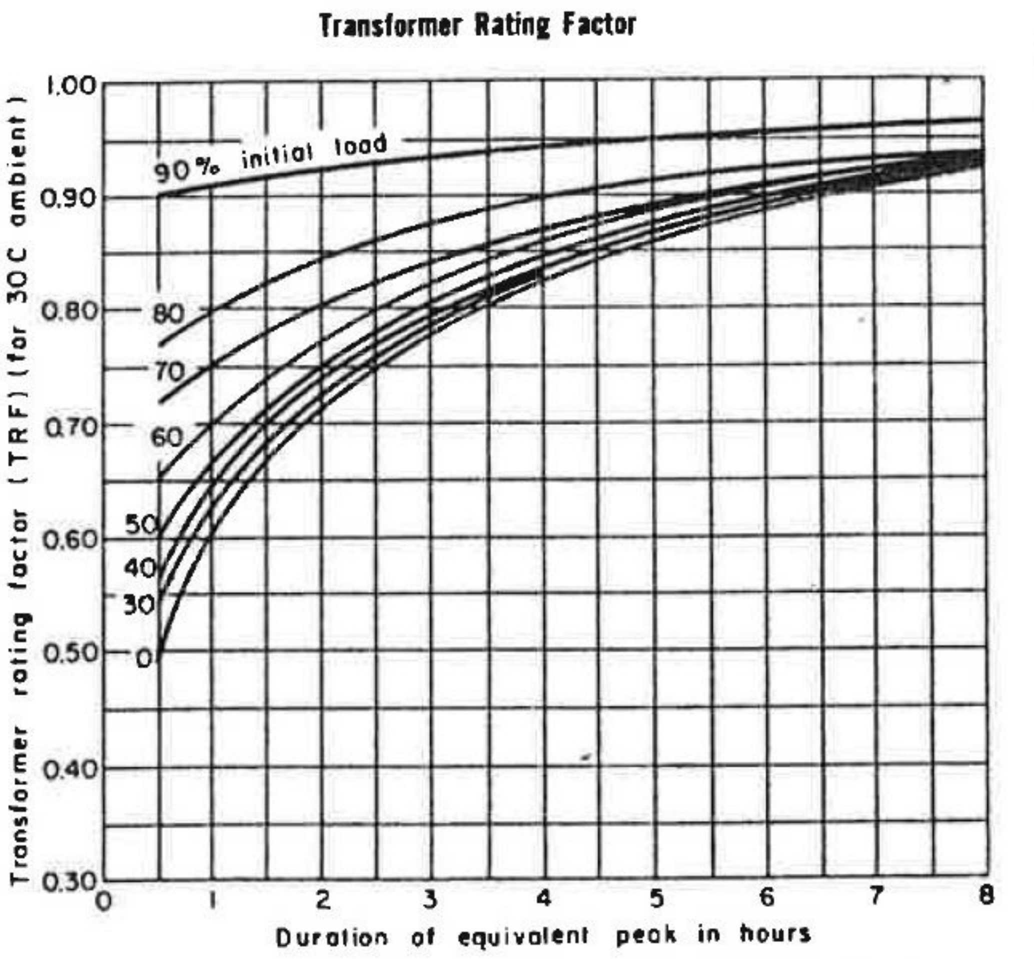
HIGHER OVERLOAD CAPABILITY – OPTION 1 – SAME SIZE TRANSFORMER



- Example 100 kVA transformer with "normal" thermally upgraded kraft (TUK) paper and mineral oil (65 °C AWR insulation system):
  - 30% equivalent "Initial Load" with 8 h equivalent "Peak Load"
  - TRF = 0.93
  - Allowable "Peak Load" = 100/0.93 = 107.5 kVA
- Example same size 100 kVA transformer, but substituting TUK with "enhanced" DPE paper and mineral oil (75 °C AWR insulation system):
  - 20 % higher overload capability
  - Allowable "Peak Load" = 130 kVA

BENEFITS & APPLICATION OPTIONS

HIGHER OVERLOAD CAPABILITY – OPTION 2 – SMALLER TRANSFORMER



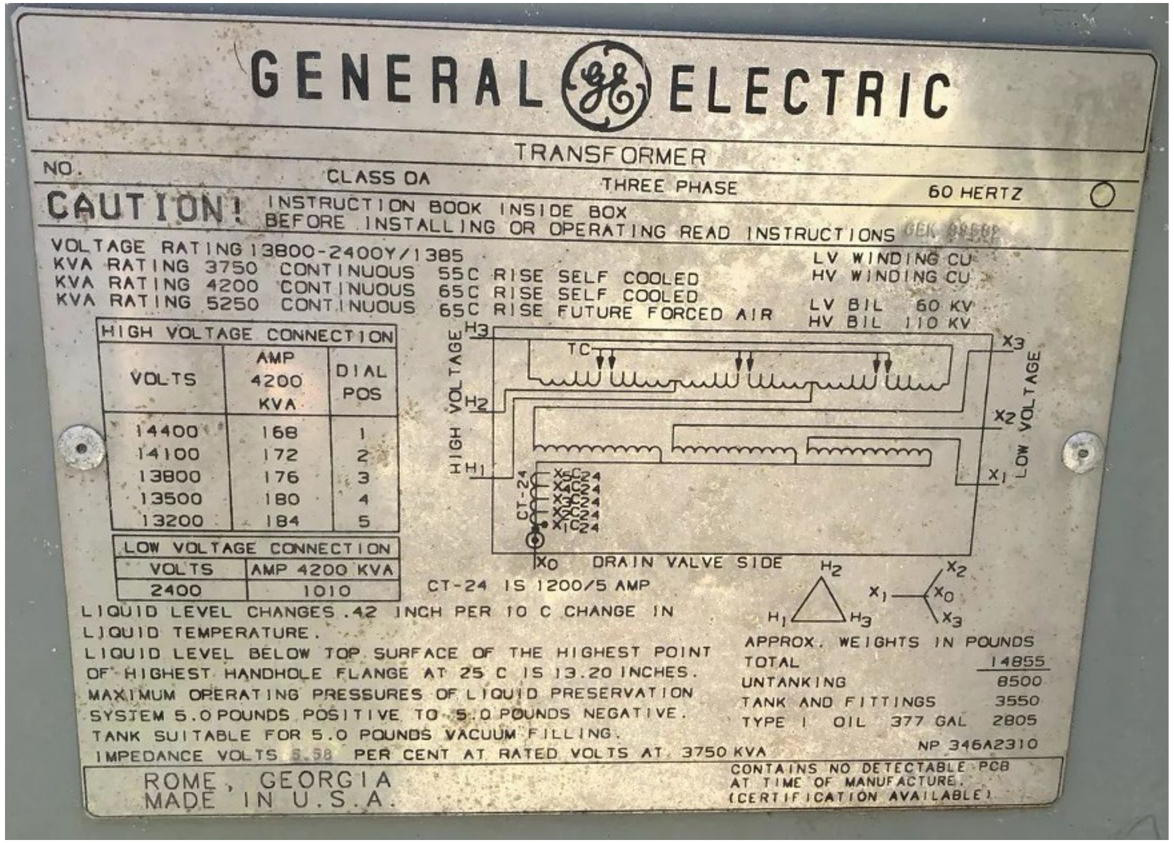
- Instead of a 100 kVA transformer…
- Example smaller (size, weight, cost) 90 kVA rated capacity transformer can be designed with "enhanced" DPE paper and mineral oil (75 °C AWR insulation system)
  - Allowable "Peak Load" = 116 kVA
  - For same 8-hour peak without any additional insulation deterioration

BENEFITS & APPLICATION OPTIONS

DUAL TEMPERATURE NAMEPLATE DESIGNS

- Historical analogy:
  - Late 1950's – Thermally Upgraded Kraft (TUK) paper developed
  - 1962 NEMA (USA) – officially recognized TUK in standard TR-1-1962, established 65 °C AWR (TUK + mineral oil)
  - In the beginning, industry introduced dual temperature nameplate transformers 55 °C / 65 °C AWR
  - Today, 65 °C AWR is the norm in North America and being recognized in IEC standards and around the globe

- **"Enhanced" DPE paper allows new dual temperature nameplate transformers:**
  - In mineral oil – 65 °C / 75 °C AWR
  - In ester liquids – 65 °C / 85 °C AWR or 75 °C / 85 °C AWR



BENEFITS & APPLICATION OPTIONS

DUAL TEMPERATURE NAMEPLATE DESIGNS – BENEFITS

- Improvement on higher overload capability concept
  - Higher overload capability transformers = overload is limited in time
  - Dual temperature nameplate transformers = allows either nameplate rating continuously
- Promising design concept for renewable energy applications
  - Great for variable loads when transformers operate below nameplate rating for significant periods
  - Allows optimized designs (size, weight, efficiency, sustainability) without compromising performance & reliability
- Same concept is known in Europe as "Sustainable Peak Load Transformer"
  - Discussion is ongoing as part of the EU GREEN DEAL initiative led by European Copper Institute

BENEFITS & APPLICATION OPTIONS
SUSTAINABLE PEAK LOAD TRANSFORMERS

- EU Green Deal impact assessment
  - Share of electricity in energy use will rise from 23 % in 2015, to ~30 % in 2030, and ~50 % in 2050
  - Electricity distribution networks' peak load capacities will have to be reinforced substantially (heat pumps & EVs)

- Sustainable peak load transformers provide a solution
  - Can be applied in all cases where the difference between peak and average demand is proportionately high
  - Typical case for distribution networks and renewable energy generation transformers

- They can technically be loaded continuously at peak load kVA
  - Will not affect transformer reliability or lifetime
  - Use of peak load capacity will only be limited in time to keep annual load losses below the desired value

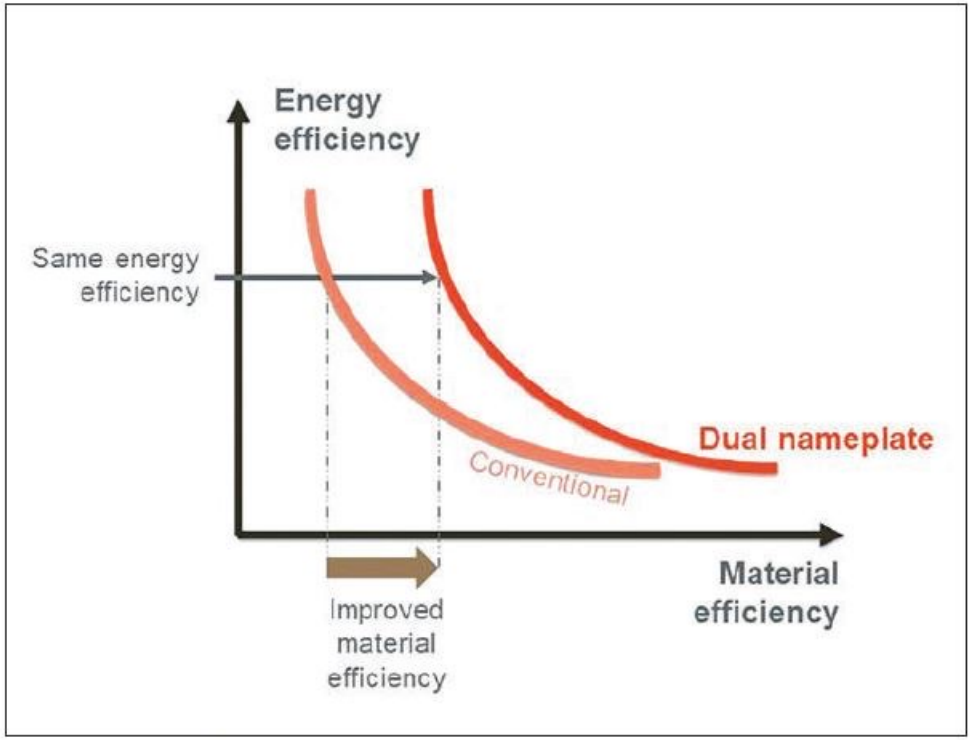


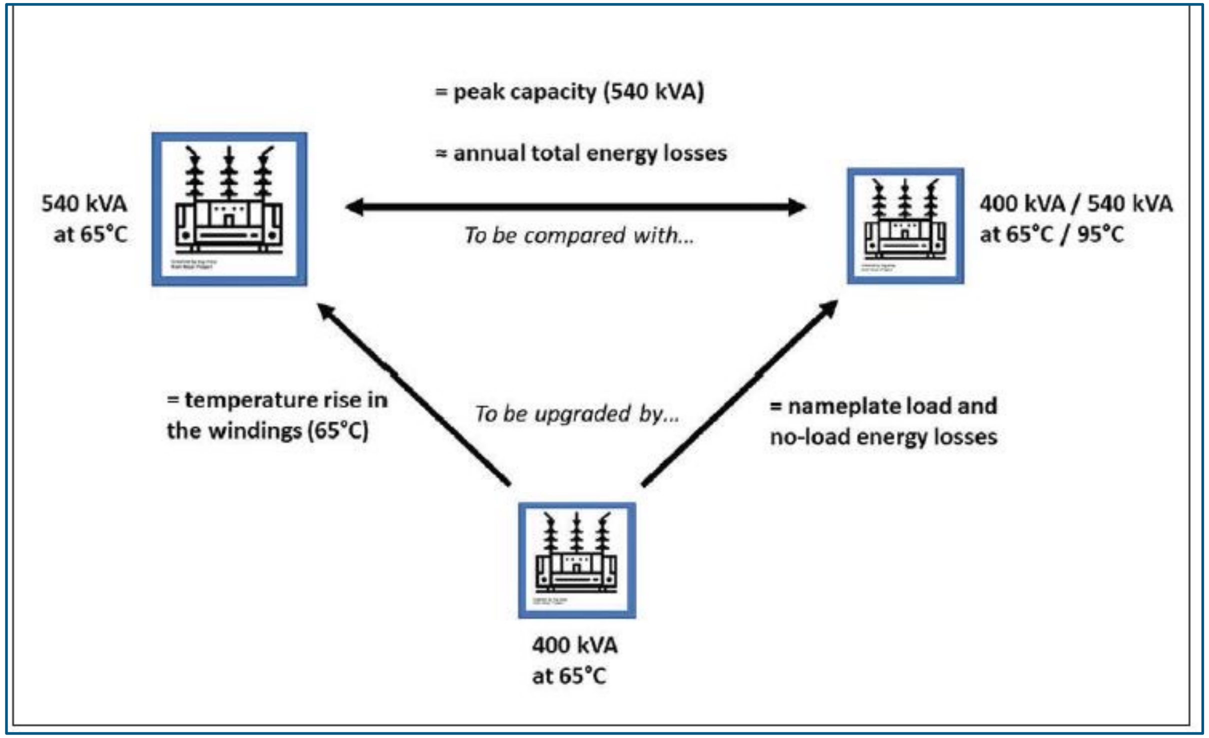
Figure 1. Energy efficiency versus material efficiency: a conventional transformer compared with a sustainable peak load transformer ("Dual nameplate")

From "Sustainable peak load transformers", A. Baggini, et al., Transformers Magazine, vol. 9, issue 3, 2022

BENEFITS & APPLICATION OPTIONS

SUSTAINABLE PEAK LOAD TRANSFORMERS – DESIGN EXAMPLE STUDY

- Example: 400 kVA / 540 kVA sustainable peak load transformer
  - Designed according to prevailing minimum energy performance standards for a 400 kVA unit
  - Load losses will exceed the nameplate value during the short periods of peak load up to 540 kVA
  - However, no-load losses are fixed at a lower value than that of a conventional 540 kVA unit
  - Increase in annual load losses will be compensated by the decrease in annual no-load losses



From European Copper Institute – Copper Alliance, Publication Cu0277

OPTIMIZED INSULATION FOR RENEWABLE ENERGY TRANSFORMERS

SUMMARY

USE OF DPE IN RENEWABLE ENERGY GENERATION TRANSFORMERS

- Renewable energy generation transformers
  - Variable loads, inverter connection harmonics, high ambient temps, etc. lead to increased thermal, electrical and mechanical stresses on transformers
  - Large capacity, high voltage, layer-type transformers with lots of paper have challenges with quality and cost
- DPE Solution – Combination of faster dry-out rate, faster impregnation and enhanced dielectric performance
  - Contributes to improved quality and reliability of renewable generation transformers
  - Reduces FAT (Factory Acceptance Test) failure rate
  - Increases transformer reliability and resilience in operation
- DPE Solution – Higher thermal class and enhanced dielectric performance, allows:
  - Optimized insulation system design
  - High temperature rated designs
  - Longer life in operation
  - Higher overload capability
  - Dual temperature nameplate designs
  - Sustainable peak load transformers

Q&A

REFERENCE

1. IEEE C57.154™-2022 IEEE Standard for Liquid-Immersed Transformers Designed to Operate at Temperatures Above Conventional Limits Using High-Temperature Insulation Systems
2. IEEE 1276™-2020 IEEE Guide for the Application of High-Temperature Insulation Materials in Liquid-Immersed Distribution, Power, and Regulating Transformers
3. IEC 60076-14:2013 Guide for the design and application of liquid-immersed power transformers using high-temperature insulation materials
4. IEEE C57.159™-2016 IEEE Guide on Transformers for Application in Distributed Photovoltaic (DPV) Power Generation Systems
5. M. Franchek, A. Levin "INSULutions® DPE - Advanced, most cost-effective 100 percent cellulose insulating paper qualified for up to 140 °C Thermal Class in liquid-immersed transformers", Transformers Magazine, Volume 3, Issue 2, 2016
6. B. Greaves, T. Prevost, J. Contreras, J. Rodriguez, C. Gaytan "Thermal aging performance of enhanced cellulose insulation in natural ester liquid", 2024 EIC Electrical Insulation Conference (EIC), Minneapolis, MN, US, June 2-6, 2024
7. A. Levin, K. Biggie, L. Dreier, B. Greaves, T. Prevost, D. Tschudi "Experimental study of sealed tube accelerated aging test parameters and determination of the thermal class of transformer board" IEEE Transactions on Dielectrics and Electrical Insulation, Vol. 29, No. 5, October 2022
8. A. Baggini, A. Cracco, B. De Wachter, P. Hopkinson, M. Karmarkar, F. Nuno, A. Sbravati "Sustainable peak load transformers – a material and cost-effective solution for distribution grid upgrades", Transformers Magazine, Volume 9, Issue 3, 2022