INSULutions® DPE

Advanced, most cost-effective 100 percent cellulose insulating paper qualified for up to 140 °C Thermal Class in liquid-immersed transformers

ABSTRACT

Insulation materials (Transformerboard™, paper) and components of modern power and distribution transformers are made of 100 % cellulosic fibers. The cellulose materials are significantly more cost-effective compared to non-cellulose materials. WEIDMANN introduces its new advanced 100 % cellulose insulating paper INSULutions® DPE that is developed for the layer insulation of transformers and increases the value of cellulose insulation in several areas, including higher thermal rating in systems with mineral oil and ester liquids.

KEYWORDS

cellulose, insulation, thermal rating, dry-out, impregnation

Cellulose based insulation

Insulation materials (Transformerboard™, paper) and components of modern power and distribution transformers are made of 100 % cellulosic fibers. A system of these materials immersed in a mineral oil is an "industry proven" standard transformer insulation system recognized to be the most cost-effective and reliable option for these applications.

WEIDMANN has pioneered the development of specialized 100 % cellulose insulation materials, components and systems for transformers starting in 1920s and became the global leader in this technical market area. Even the commonly used term “Transformerboard™” was first introduced by WEIDMANN.

The selection of the cellulose for manufacturing of electrical insulation was a forward thinking decision, considering the renewable and sustainable character of this natural resource. This solution is ever more important and vital today with a global focus on the environmentally friendly industrial technologies. WEIDMANN continues to invest and innovate in the area of technology for 100 % cellulose insulation materials. Two recent examples of this development are ⁺INSULutions® DPE (DPE) – an insulating paper for transformer layer insulation, and Monoblock – a Transformerboard™ laminated using the structural elements of the cellulosic fibers (for more information on Monoblock please refer to [1]).

DPE is engineered using 100 % cellulose, overcomes the limits of traditional Kraft cellulose materials, and provides improvements of the most important insulation material properties: higher thermal stability (i.e. slower aging) in both mineral oil and ester liquids, faster drying, faster impregnation in all transformer insulating liquids and better dielectric performance. These improved properties allow engineers to design high efficiency transformers with a reduction of:

- transformer material and manufacturing cost
- transformer weight
- dry-out process time
- liquid impregnation time
- failure rate

WEIDMANN continues to invest and innovate in technology for 100 % cellulose insulation materials: paper, board, and laminated board

⁺INSULutions® DPE is a registered trademark of **WICOR** HOLDING AG.

The increased Thermal Class of DPE also allows for:

- longer life of the transformer
- increased kVA rating in the same footprint
- increased overload capability
- designing multiple-rating transformers

Nearly 100,000 transformers produced with DPE insulation are already in service today. The advantages and applications of DPE that are discussed in this paper have been validated during real life prototyping and commercial production of numerous transformers. These transformers include different voltage classes, kVA ratings, designs (single phase - three phase, wound core - stacked core, etc.), and different applications in various regions around the world.

Introducing INSULutions® DPE insulating paper

DPE paper was developed for application as layer insulation in transformers and can be used in high voltage windings, low voltage windings and in the high-to-low voltage insulation gap (Fig. 1). Distribution, industrial and small power transformers utilizing layer type windings can significantly benefit from the application of DPE insulating paper. Two versions of DPE are available for the layer insulation: standard and an increased Tensile Energy Absorption (TEA) version that is necessary for the successful use on the high speed strip insulation winding machines (Fig. 2).

DPE paper enhances the thermal stability, improves the dielectric characteristics, and facilitates faster drying and liquid impregnation rates while maintaining excellent mechanical properties for manufacturability

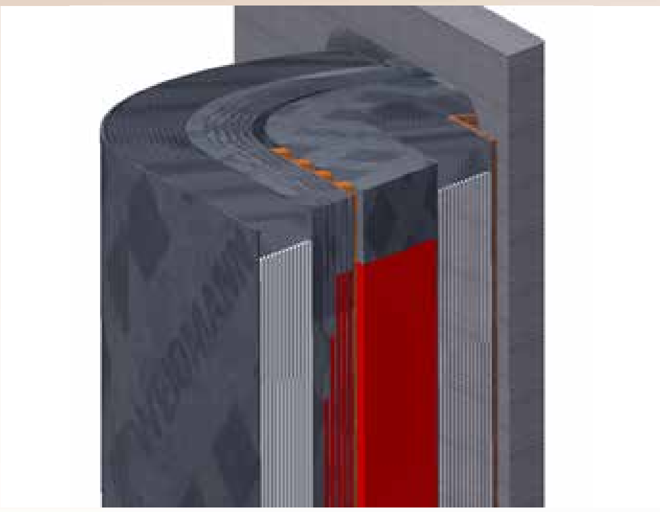

Figure 1. Sketch of layer type transformer winding

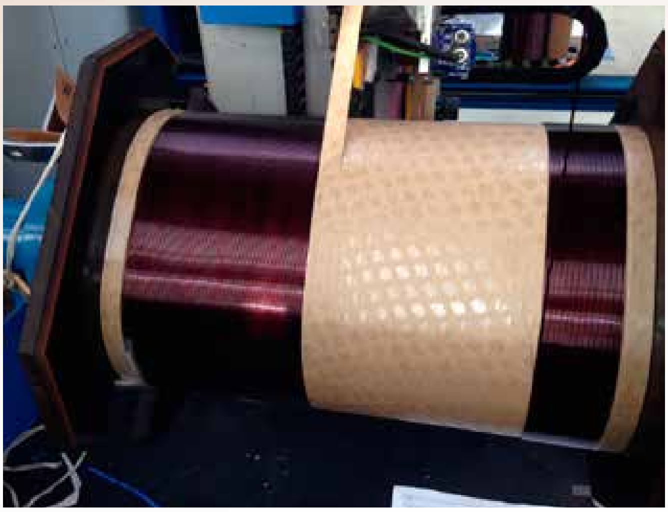

Figure 2. High speed strip insulation winding machine

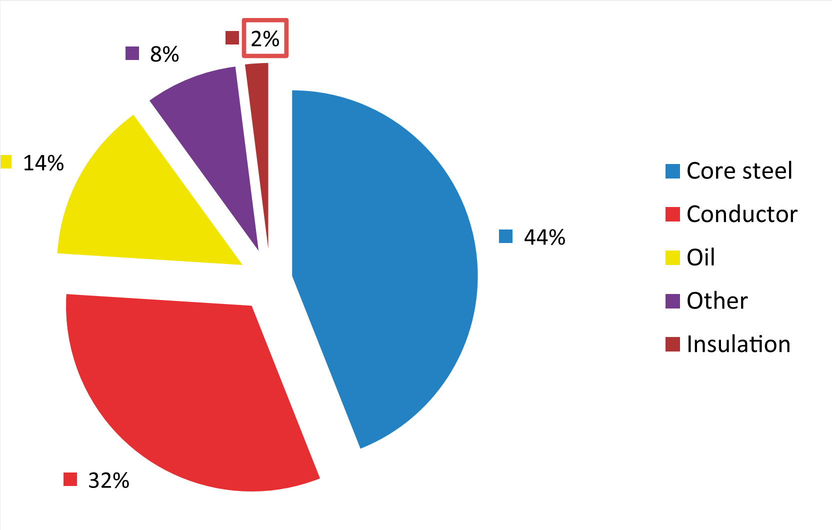

Figure 3. Example of transformer materials cost structure: insulation has a high leveraged value

Nearly 100,000 transformers produced with DPE insulation are already in service today

Cellulose insulating papers make up just 1 % to 2 % of the total transformer materials cost (Fig. 3). This gives the insulation papers a very high leveraged value when compared to the cost of other active transformer materials such as winding conductor and electrical steel. The paper performance has a significant impact on cost, weight, size and efficiency of the transformer. In addition, the characteristics of insulating paper also affect the cost and duration of key manufacturing processes including transformer dry-out and liquid impregnation.

The insulating paper aging rate defines the normal transformer life and other key transformer characteristics. More specifically:

- paper thermal rating defines the temperature limits of the transformer design
- paper dielectric properties define the size of the windings and the distances between the transformer parts
- paper mechanical properties are key for the successful production process and long term reliability in the field (short circuit strength)
- paper drying rate defines the cost and duration of the factory dry-out process, as well as a quality of the final product
- paper impregnation rate defines the duration of the liquid impregnation process and also significantly affects the quality

DPE paper has advanced properties delivering significant opportunities including transformer cost reduction as well as other improvements (Table 1).

DPE – 100 % cellulose paper, the most cost-effective insulation option

DPE is a 100 % cellulose paper which is produced using WEIDMANN proprietary technology and WEIDMANN proprietary manufacturing processes. DPE "engineered paper" was developed to enhance the paper thermal stability, improve the dielectric characteristics, and facilitate faster drying and liquid impregnation rates while maintaining excellent mechanical properties for manufacturability.

WEIDMANN has a unique position in the industry with multiple paper machines strategically located in the USA and Europe that are specifically designed to manufacture only electrical grade papers. This provides the necessary redundancy to ensure un-interrupted supply of the papers. WEIDMANN's new state-of-the-art paper machine in Urbana, Ohio USA (Fig. 4) produces papers with excellent sheet formation and mechanical strength (Fig. 5).

The major advantages of the 100 % cellulose insulation include:

- renewable and environmentally sustainable natural product
- reliability has been industry proven
- most cost-effective option

The price point of DPE comes at a fraction of the cost of some of the non-cellulose materials that have been recently introduced to the industry. The small premium over traditional papers makes DPE an excellent option for broad scale applications (Fig. 6)

WEIDMANN has a unique position in the industry with multiple paper machines strategically located in the USA and Europe, which are specifically designed to manufacture only electrical grade papers

Table 1. Advantages of DPE application compared to the standard paper

Transformer Materials Cost	↓	9 %*
Transformer Weight	↓	5%*
Dry-out Time	↓	30%*
Liquid Impregnation Time	↓	25%*
Failure Rate	↓	30%*

(*data reported by transformer OEMs)

Figure 4. WEIDMANN new paper machine in Urbana, OH USA

Figure 5. WEIDMANN and competitor paper formation (paper 0.76 mm / 3 mil; 0.75 g/cm3)

DPE - increased thermal rating

The thermal rating of insulating paper in insulating liquid defines the limit of the thermal design of the transformer. The application of the higher temperature materials opens several new opportunities for transformer designers and transformer end users. Some of these advantages include: longer transformer life, reduced initial and Total Ownership Cost, reduced transformer weight, increase of the kVA output in the same footprint and increased overload capability.

DPE paper has been thoroughly tested including over two years of carefully designed and executed aging experiments. These tests have been completed and confirmed that DPE paper ages slower and has a higher Thermal Class than the standard Kraft (K) and thermally upgraded Kraft (TUK) papers in both mineral oil and ester liquid. Table 2 and Table 3 present the results of the thermal aging analysis. Table 2 is based on the IEC standard requirements and Table 3 is based on IEEE standard requirements.

The price point of DPE comes at a fraction of the cost of some of the non-cellulose materials that have recently been introduced to the industry

DPE paper has been thoroughly tested including over two years of carefully designed and executed aging experiments

Figure 6. Relative price of 100 % cellulose (Thermally Upgraded Kraft, DPE) and blended material papers

Table 2. Thermal rating of DPE paper (based on IEC standard requirements)

Insulation System	Insulating Material and Liquid	Transformer Average Winding Temperature Rise (AWR), K	Transformer Hot-Spot Temperature Rise, K	System Thermal Class, °C
Industry Proven System	Kraft in mineral oil	65 / 70	78	105
	TUK in mineral oil	75	90	120
DPE System	DPE in mineral oil	85	100	130
	DPE in ester liquid*	95	110	140

*Testing of DPE in Envirotemp™FR3™ (Registered Trademarks of Cargill®) is ongoing and temperatures shown are based on the currently available WEIDMANN test data.

Table 3. Thermal rating of DPE paper (based on IEEE standard requirements)

Insulation System	Insulating Material and Liquid	Transformer Average Winding Temperature Rise (AWR), °C	Transformer Hottest Spot Temperature (Temperature Index), °C	System Thermal Class, °C
Industry Proven System	Kraft in mineral oil	55	95	105
	TUK in mineral oil	65	110	120
DPE System	DPE in mineral oil	75	120	130
	DPE in ester liquid*	85	130	140

*See note to Table 2 above.

A series of sealed tube aging tests were conducted in accordance with the requirements of IEEE C57.100™-2011 "Standard Test Procedure for Thermal Evaluation of Insulating Systems for Liquid-Immersed Distribution and Power Transformers" (similar IEC test is IEC 62332-2 "Standard on Electrical Insulation Systems (EIS) - Thermal Evaluation of Combined Liquid and Solid Components - Part 2: Simplified Test").

The standards provide a methodology to assign the Temperature Index of the new insulation system based on the data derived from the testing of the "industry proven system" and new system. TUK in mineral oil was tested as the "industry proven system" and DPE in mineral oil and natural ester liquid were tested as the new systems. The TUK material for the aging tests was carefully selected to correctly represent the "industry proven system".

WEIDMANN performed six different aging experiments including three full-term and three short-term studies. To ensure the accuracy and repeatability of the results, duplicate papers were produced by two different WEIDMANN paper facilities and tested in two separate WEIDMANN R&D Centers.

Based on the test results, the DPE paper life curve has been obtained (Fig. 7) and the Temperature Index and Thermal Class were assigned (Table 2 and 3). WEIDMANN DPE has Thermal Class of 130 °C in mineral oil (25 °C higher than Kraft paper and 10 °C higher than thermally upgraded Kraft paper) and 140 °C in natural ester liquid. Recently published IEC [2] and IEEE [3] Standards provide general background information supporting the application of high temperature insulation systems in liquid-immersed transformers.

DPE – faster drying rate

The engineered composition and unique manufacturing process for DPE paper resulted in lower initial moisture content and accelerated rate of the moisture removal during the transformer dry-out process when compared to the currently used standard Kraft papers.

Faster drying properties of DPE papers were proven and quantified using four different methods to study moisture dynamics in DPE and transformers that utilized this paper as the layer insulation:

- laboratory dry-out rate test on the samples of the paper using gravimetric analysis
- laboratory paper sorption-desorption isotherms measurement using sorption analyzer by proUmid GmbH & Co. KG
- dry-out rate study on the full size coils in the large drying chamber performed by Hedrich GmbH
- studies of the factory dry-out process of the assembled transformers in four different transformer OEMs

All studies consistently demonstrated that transformers utilizing DPE paper are dried-out between 20 % and 30 % faster when compared to standard Kraft papers. Fig. 8 represents a study of an actual factory drying process for a 50 kVA transformer, where dryness of the transformer insulation was measured during the entire drying cycle utilizing an actual OEM drying oven. Insulation Dissipation Factor (DF) was used as a measurement parameter of dryness (it's expressed in per unit (p.u.) values on the graph, where unity being the initial DF before drying process). In this specific example, the transformer with DPE paper reaches acceptable level of moisture content 22 % faster than the transformer with standard Kraft paper.

The faster drying rate of DPE provides a very good opportunity for factory dry-out

DPE has Thermal Class of 130 °C in mineral oil (25 °C higher than Kraft paper and 10 °C higher than thermally upgraded Kraft paper) and 140 °C in natural ester liquid

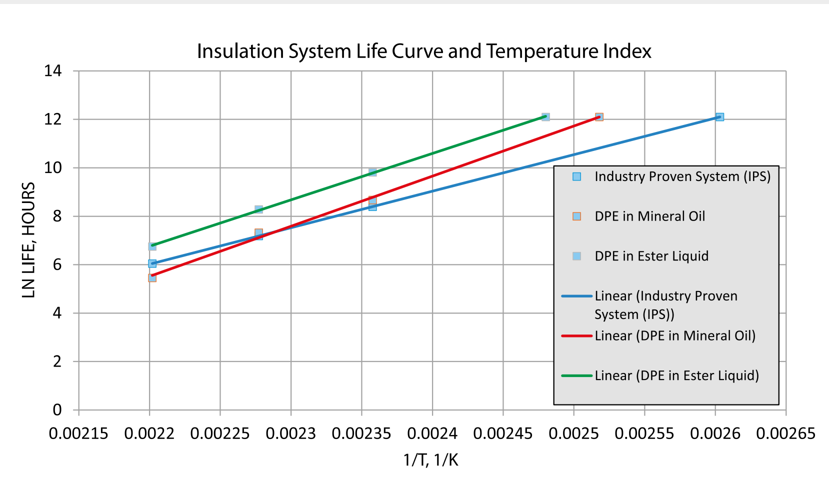

Figure 7. DPE paper life curves and Temperature Indexes in mineral oil and ester liquid

All studies consistently demonstrated that transformers utilizing DPE paper are dried-out between 20 % and 30 % faster when compared to standard Kraft papers

time reduction, resulting in a drying process cost savings and increased production throughput. In addition, the better quality of drying had a significant impact on reduction in failure rates during final test.

DPE – faster liquid impregnation rate

Transformer impregnation with the insulating liquid has a significant impact on manufacturing cycle time. The rate of the impregnation of the insulating material is a function of the material's rate of liquid absorption, liquid temperature and process pressure (impregnation under vacuum or at ambient atmospheric pressure), etc.

DPE paper has a significantly faster rate of impregnation compared to the standard Kraft paper in both mineral oil and higher viscosity ester liquids. Fig. 9 summarizes the results of the impregnation study where the rate of migration of oil in the paper machine direction (MD) was measured for two papers under vacuum for mineral oil and Envirotemp™FR3™ natural ester liquid.

DPE's faster impregnation rate reduces production processing time and supports savings associated with reduced cycle times. Improved impregnation is especially important and beneficial for applications in ester liquids where their higher viscosities require longer time to impregnate and sometimes result in material not being impregnated and a transformer that is prone to a higher factory test failure rate. DPE paper higher thermal rating and faster rate of impregnation make it an ideal choice for the application in transformers with ester liquids.

Improved liquid impregnation is especially important and beneficial for applications in ester liquids where their higher viscosities require longer time to impregnate

DPE – superior dielectric characteristics

A selection of a paper that allows for the optimization of the transformer dielectric design was one of the major objectives of the DPE development process. In order to compare different papers, a special test setup was designed to simulate the electrical stresses of the layer insulation of distribution transformers and to conduct the series of tests using AC voltage, partial discharge (PD) measurements and impulse voltage. Seventeen different grades of cellulose papers were studied: different fiber composition, density (0.8 – 1.1 g/cm3), elongation (2 % – 50 %), thickness of individual paper layers from 0.038 mm to 0.38 mm (1.5 mil –15 mil), combinations of the multiple layers to the total sample thickness from 0.038 mm – 3.8 mm (1.5 mil – 150 mil), thermally upgraded and non-thermally upgraded papers, epoxy dot coated papers and non-coated. A total of 1350 different paper samples were tested in this test series.

DPE paper demonstrated the best overall dielectric performance in this extensive study. Consequently, a complete transformer insulation design methodology was developed based on the DPE dielectric criteria. Application of this methodology to a broad range of transformers confirmed the possibility of an optimized transformer design with a significant material and cost savings (Table 1). WEIDMANN supports its customers in the application of DPE in the insulation design of their transformers.

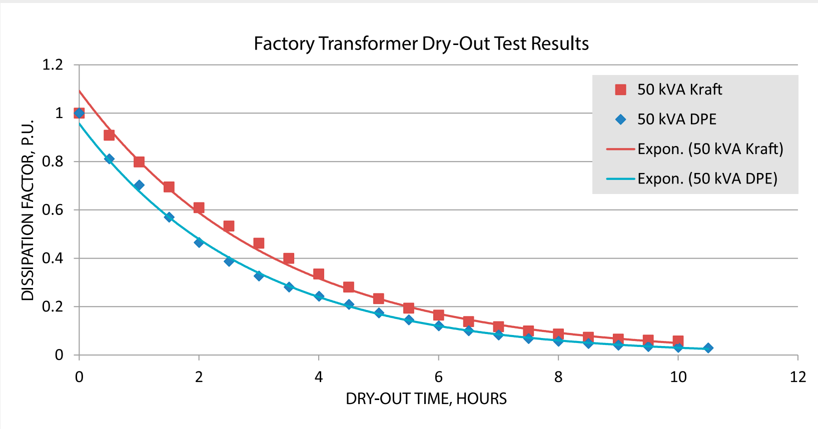

Figure 8. Results of dry-out study of transformers with DPE and standard Kraft papers

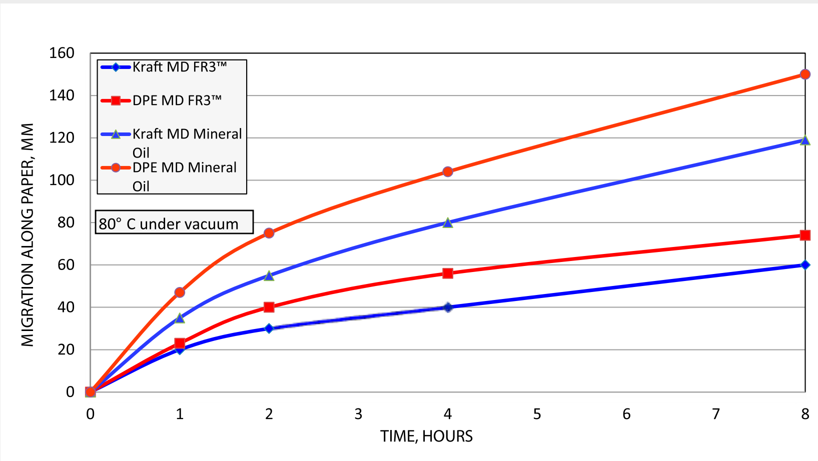

Figure 9. Results of study of liquid impregnation rate of DPE and standard Kraft paper (0.254 mm / 10 mil paper in machine direction MD)

A complete transformer insulation design methodology was developed based on the DPE dielectric criteria

DPE – excellent mechanical properties

Robust mechanical performance is a prerequisite for the application as transformer layer insulation, where the material is subjected to multi-directional mechanical forces during production of the windings and long term operation in the field.

Unique manufacturing processes preserve the inherent mechanical performance of the cellulosic fibers that results in the excellent mechanical properties of DPE. For example, the tensile strength of DPE is significantly higher than some non-cellulose materials recently proposed for the application in the high temperature transformers (Fig. 10). DPE paper received very favorable comments from the OEM's winding machine operators on the paper performance during the winding process. A special version of DPE paper with increased Tensile Energy Absorption (TEA) for the high speed strip insulation winding machines (Fig. 2) is also available.

DPE – easily distinguishable, blue color paper

DPE paper has a blue color (Fig. 11) and is easily distinguishable from other insulating papers. A thorough DPE oil compatibility test, in accordance to ASTM D 3455 standard [4], has been performed several times in both mineral oil and ester liquid. DPE paper passed the standard acceptance criteria (interfacial tension, neutralization number, dielectric strength, dissipation factor), all with good margins. This confirms that DPE is acceptable for application in both mineral oil and ester liquid. One transformer OEM has also performed the oil compatibility test on the transformer with DPE one year after the transformer production and reported a complete compliance with the requirements.

Opportunities and examples of application

The set of advanced characteristics of DPE paper has been proven to provide an array of opportunities for transformer cost savings, efficiency increase, life extension, overload capability increase, quality improvement and failure rate reduction. DPE paper can be successfully and economically used for both standard thermal rated and higher thermal rated transformers in both mineral oil and ester liquids. DPE is very cost effective with just a small premium over standard Kraft Paper (Fig. 6).

Increased thermal rating and advanced dielectric properties of DPE give transformer OEMs several options on how to take advantage of these characteristics: the transformer can be designed as a high temperature transformer with the standard insulation design criteria or as a standard temperature transformer with the DPE insulation design criteria. Another option is to combine both the advantages of the higher temperature and superior DPE insulation design. In many cases, a simple substitution of the standard Kraft paper to DPE paper can result in significant savings.

Here are some possible options of DPE applications in both mineral oil and ester liquids, depending on the requirements of the transformer OEM and End User:

- smaller, lighter and reduced cost transformers (one of the specific purposes can be to offset the size, weight and cost increase associated with the higher efficiency transformers compliant with the new efficiency regulations, for example, US Department of Energy new 2016 distribution transformers efficiency rules; European EcoDesign regulation, especially the next 2021 level; Chinese standardized S11-S13 levels for the higher efficiency transformers, etc.)

- increase kVA rating of the transformer in the same footprint (an attractive solution to cope with an increased energy demand in the space-limited urban environment)

- extend the expected life of a transformer - the increased thermal rating of DPE paper results in slower aging of the insulation; the utility assets amortization can be spread over the longer life of the equipment

- utilize the higher overload capability of the transformer with DPE. It is generally recognized that every 10 °C

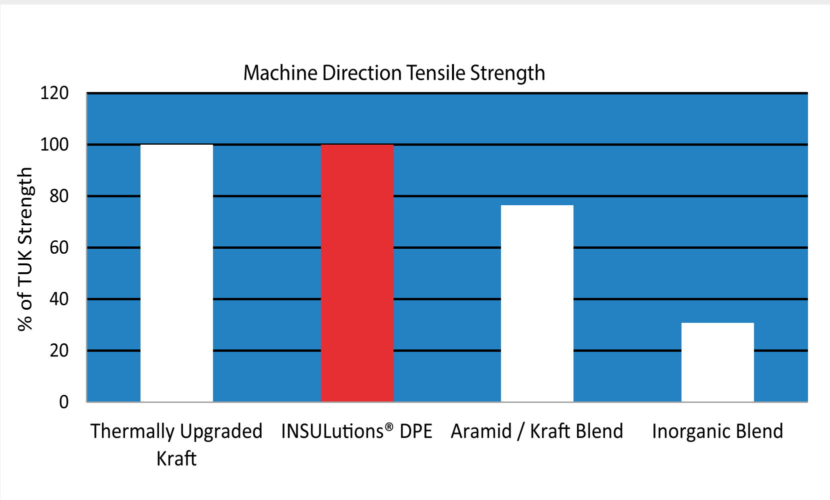

Figure 10. Tensile strength comparison of TUK, DPE and blended material papers

The tensile strength of DPE is significantly higher than some non-cellulose materials recently proposed for the application in the high temperature transformers

Advanced characteristics of DPE provide opportunities for transformer cost savings, efficiency increase, life extension, overload capability increase, quality improvement and failure rate reduction

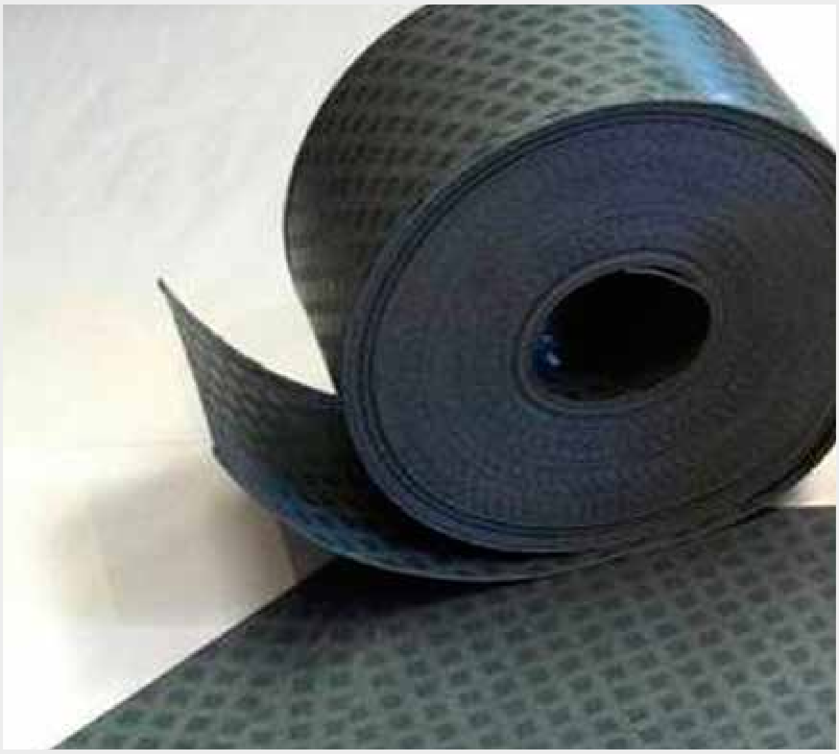

Figure 11. DPE – blue color

increase in transformer winding temperature results in a 12 % transformer kVA output increase. This can be a win-win savings solution for the OEM and utility including a very economical solution to design transformers for wind and solar power generation using the real load diagram for sizing of these units

- multiple-rating transformer can be designed with mineral oil or ester liquids based on the higher thermal rating of the DPE paper, for example 55 °C / 65 °C, 65 °C / 75 °C, etc. This concept can be used for installation of smaller kVA transformers with variable load or for increasing the transformer kVA rating in the same footprint; the concept can also provide an opportunity for transformer loss optimization and efficiency increase

- increased reliability in demanding applications such as industrial, network, underground and submersible transformers, transformers for the alternative energy generation systems, liquid-immersed transformers for indoor installation as well as traction, mobile transformers and step-up voltage regulators

- faster liquid impregnation and higher temperature rating of DPE paper make it an obvious choice for application in transformers with ester liquids (material savings, failure rate reduction, high temperature transformers design, etc.)

In many cases, a simple substitution of the standard Kraft paper to DPE paper can result in significant savings

- improve economics, efficiency and quality of the moisture dry-out and liquid impregnation manufacturing processes

- reduce overall failure rate in the factory test and in the field.

Series and prototype transformers for different applications are produced with DPE insulation by transformer manufacturers in various regions around the world (for example, Fig. 12 and 13).

Conclusion

The development of WEIDMANN DPE paper fulfills the market need in the advancement of 100 % cellulose insulating materials for transformers. The cost effective material (a fraction of the cost of non-cellulose materials) is proposed for improving both standard thermal rating and higher thermal rating transformers in both mineral oil and ester liquids.

The unique combination of higher thermal rating, faster drying and faster liquid impregnation rate, advanced dielectric performance and excellent mechanical properties have been proven to provide a spectrum of opportunities for transformer cost savings. DPE delivers the OEM and End User cost effective solutions, longer transformer life, higher overload capability, quality improvement and lower failure rates.

Bibliography

[1] T. Wolfinger, Lamination of Transformerboard using the structural elements of cellulosic fibers; Transformer Magazine Vol. 2, Issue 4, 2015

[2] IEC 60076-14: 2013 Power Transformers – Part 14: Liquid-immersed power transformers using high-temperature materials

[3] IEEE Std C57.154™- 2012 IEEE Standard for the Design, Testing, and Application of Liquid-Immersed Distribution, Power, and Regulating Transformers Using High-Temperature Insulation Systems and Operating at Elevated Temperatures

[4] ASTM 3455-11Standard Test Methods for Compatibility of Construction Material with Electrical Insulating Oil of Petroleum Origin

Figure 12. 1000 kVA / 24 kV prototype transformer, Končar D&ST, Croatia

Figure 13. 75 kVA / 95 kV BIL transformers, MAGNETRON S.A.S, Colombia

Acknowledgement

Authors express their gratitude to the colleagues at WEIDMANN who contributed to the DPE research and development, thorough testing, manufacturing process refinement and technical support of our customers.

Contact
EUROPE/AFRICA
WEIDMANN
ELECTRICAL TECHNOLOGY AG
Neue Jonastrasse 60
8640 Rapperswil,
Switzerland
T: +41 (0) 55 221 4103
sales.wetag@wicor.com

Contact AMERICAS
WEIDMANN
ELECTRICAL TECHNOLOGY INC.
One Gordon Mills Way
St. Johnsbury, VT 05819
USA
T: +1 802 748 8106
service.weti@wicor.com

Contact ASIA/PACIFIC
WEIDMANN ELECTRICAL
INSULATING SYSTEMS
(SHANGHAI) CO., LTD.
3F Block A, Building 8
No. 188, Xinjun Ring Road, Minhang District
Shanghai 201114 China
T: +86 21 6237 6388
customer.service@weidmann.com.hk

Authors

Michael A. Franchek attended Ohio State University and received his B.S.E.E. in Electric Power Systems Engineering in 1977 and M.S.E.E. in 1978. He was University's Candidate for America's Outstanding Electrical Engineering Senior and named General Motors National Scholar 1976 and 1977. He was a Teaching Associate Professor at Ohio State University for two years. After graduating from Ohio State, he joined Westinghouse Electric Corporation as a Senior Design Engineer in Muncie, In, USA. In 1984 he accepted a position with EHV-WEIDMANN Industries Inc. as Vice President of Technical Services in St. Johnsbury, VT. He later became the Vice President of Technical Marketing for WEIDMANN Systems International Inc. in Lyndonville, VT. In 1997 he was assigned the position of Vice President of Technology for WEIDMANN Technical Services, and the General Manager of WEIDMANN-ACTI Inc. His current position is Vice President of Technology and Innovation. He has written several technical papers which include: Computer Model Simulating Impulse Distribution in HV Transformer Windings" – IEEE; "Test Your Transformerboard IQ" – Electric Equipment News; "Transformerboard Lead Exits" – Electrical Manufacturing; "Conductor Insulation Test in Oil, Aramid vs. Kraft" – IEEE; "Uprating Transformers for Performance and Reliability" – Doble Conference. He is an IEEE Transformer Committee member and Chairman of the Dielectric Test Sub-Committee and Chairman of the Working Group for The Application of High Temperature Insulation.

Aleksandr Levin received the M.S.E.E. degree from Ural Federal University, Russia in 1978. He also completed a post-graduate Electrical Engineering Studies in Russia's Electrotechnical Institute, Moscow in 1988. For 20 years he worked for the transformer department of JSC Uralelectro. Mr. Levin held positions of transformer designer and, later, chief of the transformer design department. In 1998 he joined WEIDMANN and was responsible for the technical development and support of CIS market. In 2001 he became a Technical Service Engineer with WEIDMANN USA, where he continues to work as a Senior Engineer. Mr. Levin participated in and led numerous transformer design and optimization projects (both power and distribution, both liquid-immersed and dry-type), as well as R&D projects on insulating materials development and implementation. Mr. Levin is an active member of IEEE Transformer Committee, where he is currently a secretary of the IEEE WG C57.159 Guide on Transformers for Photo-Voltaic Energy Generation and a member of several Task Forces, Working Groups and Sub-committees.