Research and development of ester filled power transformers

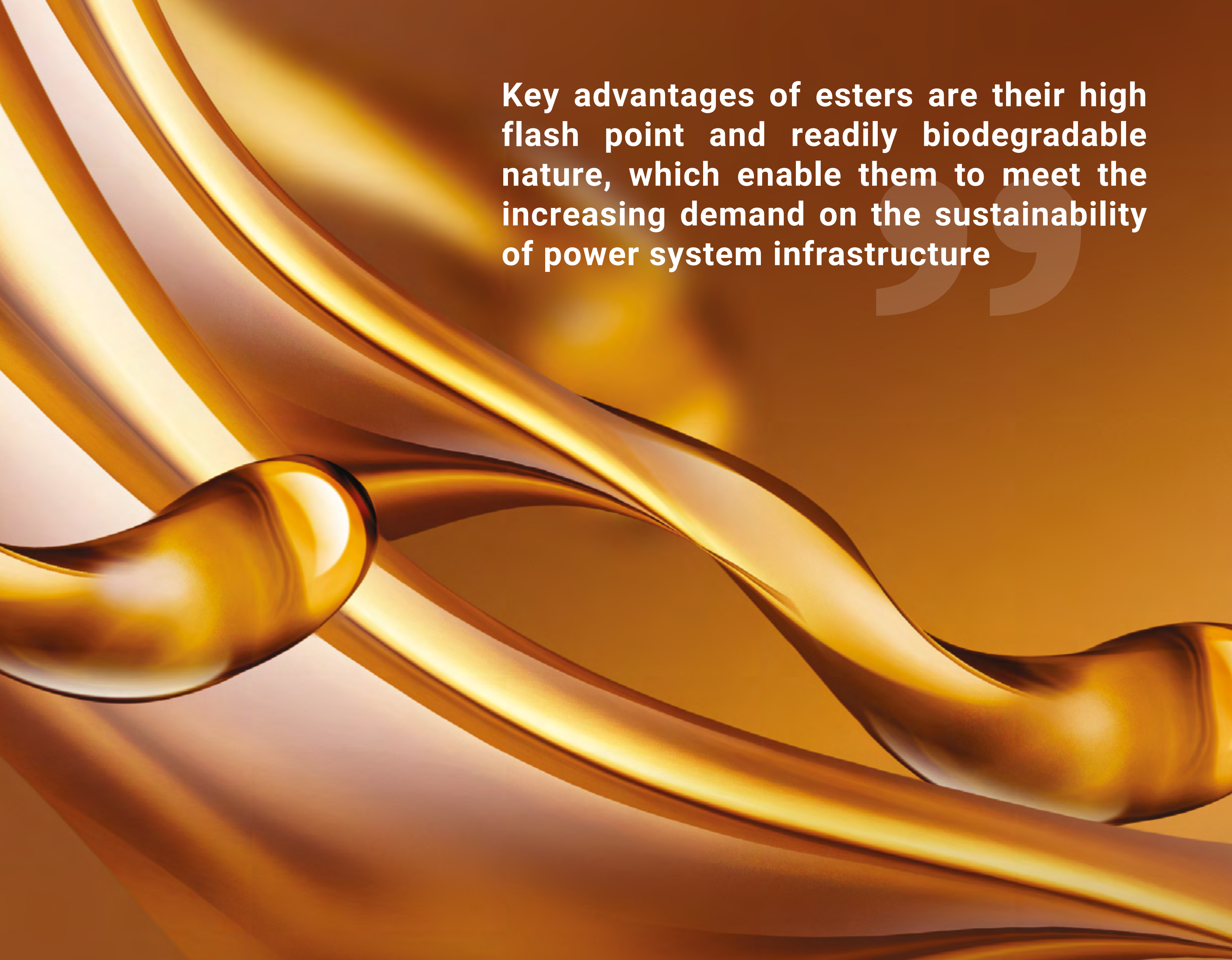
ABSTRACT

Ester-based insulating liquids are preferred for power transformers due to their fire safety features, minimal environmental impact, as well as the ability to prolong the lifetime of insulation paper compared to conventional mineral oil. The number of ester-filled high voltage power transformers has been increasing in recent years but remains low due to requirement of design modification and lack of experience with long-term operating performance. This article introduces some of the research contributions on the application of ester liquids in large power transformers made by the members of the University Transformer Research Alliance (UTRA) over the past two decades.

KEYWORDS

ageing, electrical characteristics, ester liquids, insulating characteristics, thermal characteristics

Z. D. WANG, S. Y. MATHARAGE, Q. LIU, S. TENBOHLEN, C. EKANAYAKE, T. K. SAHA, H. MA, Y. XU



Key advantages of esters are their high flash point and readily biodegradable nature, which enable them to meet the increasing demand on the sustainability of power system infrastructure

Introduction

Ester based insulating liquids are manufactured from natural resources such as vegetable oils or synthetically by reacting alcohols with acids. Key advantages of esters over conventional hydrocarbon-based mineral oils are their high flash point and readily biodegradable nature, which enable them to meet the increasing demand on the sustainability of power system infrastructure and make them ideal for the urban environment and other safety-critical applications. For more than forty years, ester liquids have been successfully used in distribution transformers. In 2014, over 600,000 distribution transformers worldwide were operating with ester liquids and about 25,000 power transformers, most of which were at low to medium voltage levels [1]. The number of ester-filled high voltage power transformers has been increasing in recent years but still remains low. Two of the key milestones in the development are the 420 kV/300 MVA natural ester filled power transformer in Germany, and the 400 kV/240 MVA synthetic ester filled power transformer in the United Kingdom [2]. The requirement of design modifications and lack of experience with long-term operating performance possibly affect the development. However, these challenges will be overcome with more experiences accumulated by manufacturers and end-users.

A tremendous amount of research activities has been conducted by manufacturers, utilities, research institutes, and

Column by the University Transformer Research Alliance (UTRA) www.university-transformer-research.com

When the liquids are contaminated with cellulose particles, ester liquids could perform better than mineral oil

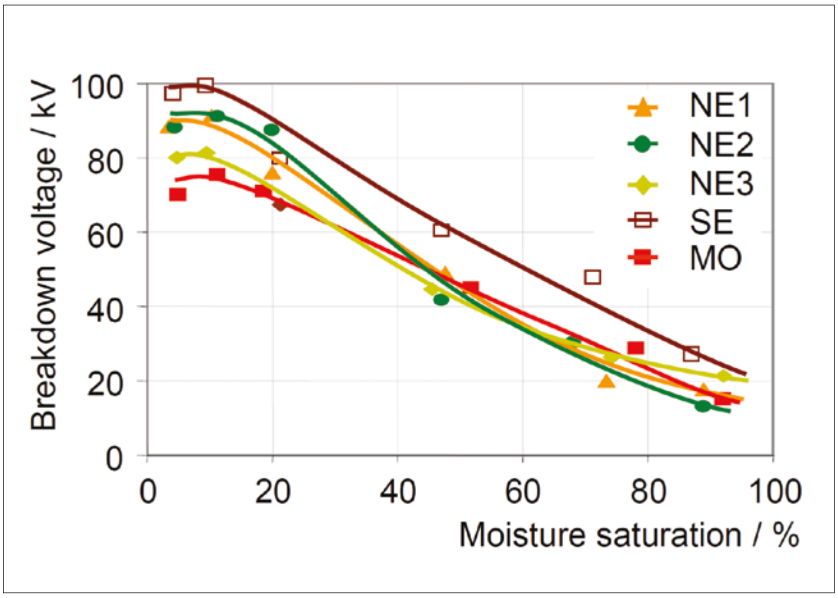


Figure 1. AC breakdown voltage of transformer liquids with moisture contamination in a quasi-uniform field (NE: natural ester, SE: synthetic ester, MO: mineral oil) [4]

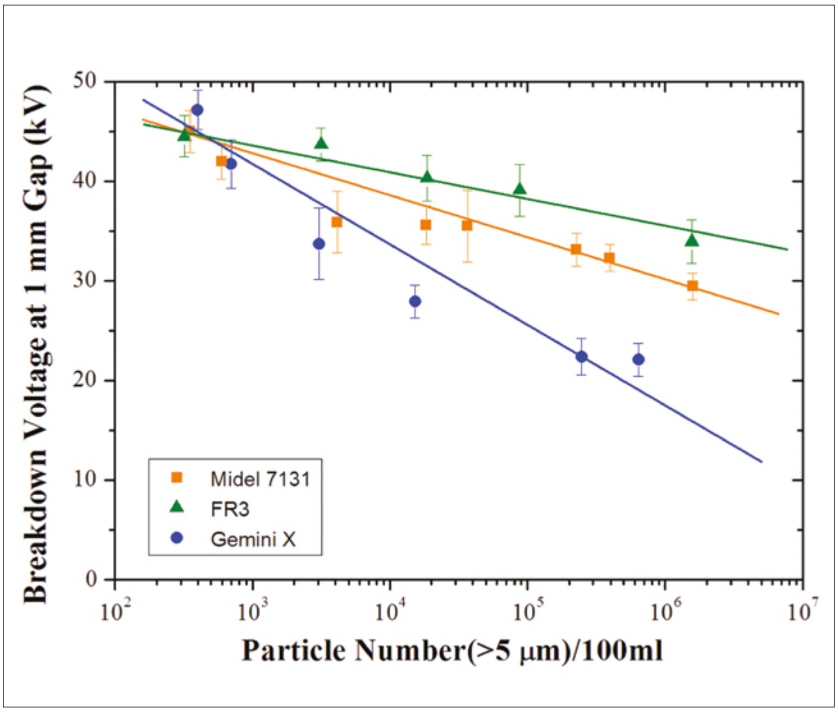


Figure 2. AC breakdown voltage of transformer liquids with cellulose contamination in a quasi-uniform field [16]

Studies have shown that partial discharge inception voltages of ester liquids are comparable to that of mineral oil

universities for the development of ester filled high voltage large power transformers. This article introduces some of the research contributions on the application of ester liquids in large power transformers made by the members of the University Transformer Research Alliance (UTRA) over the past two decades.

Electrical characteristics of ester liquids

Transformers operate under AC stress during most of their lifetime. However, they must also survive those odd switching or lightning impulse events. The majority of electric fields inside transformers has been controlled to be uniform or quasi-uniform. Divergent electric fields are avoided to the utmost in the design. However, there is a possibility for the existence of divergent fields due to manufacturing defects or contamination of insulation during the in-service operation. Hence, the electrical performances of dielectric liquids are studied under different waveforms (AC and impulse) and under different electric field distributions (uniform / quasi-uniform and divergent).

Under AC stress

It has been widely acknowledged that AC breakdown voltage under uniform / quasi-uniform fields indicates the liquid quality rather than reflects the liquid molecular composition. In this case, investigations have shown that AC breakdown voltages of dry and clean ester liquids under quasi-uniform fields are comparable with that of mineral oils [3].

The water content of the liquid could increase due to the ageing of cellulose insulation, migration of water between solid and liquid insulation, and external moisture ingression during the transformer operation. As shown in Fig. 1 [4], it is clear that high relative saturation of moisture in liquid reduces the AC breakdown voltage gradually, and a universal correlation between AC breakdown voltage and relative saturation level (rather than the absolute water content) seems to exist across different types of liquids. However, when the liquids are contaminated with cellulose particles, ester liquids could perform better than mineral oil. Fig 2 shows that the breakdown voltages of both ester liquids and mineral oil decrease with the increase of cellulose particle content [3, 16]. However, the breakdown voltage of mineral oil seems to be more sensitive to particle contamination than ester liquids. The possible reason is that the particle motion is restrained more in ester liquids under AC stress than in less viscous mineral oil [5].

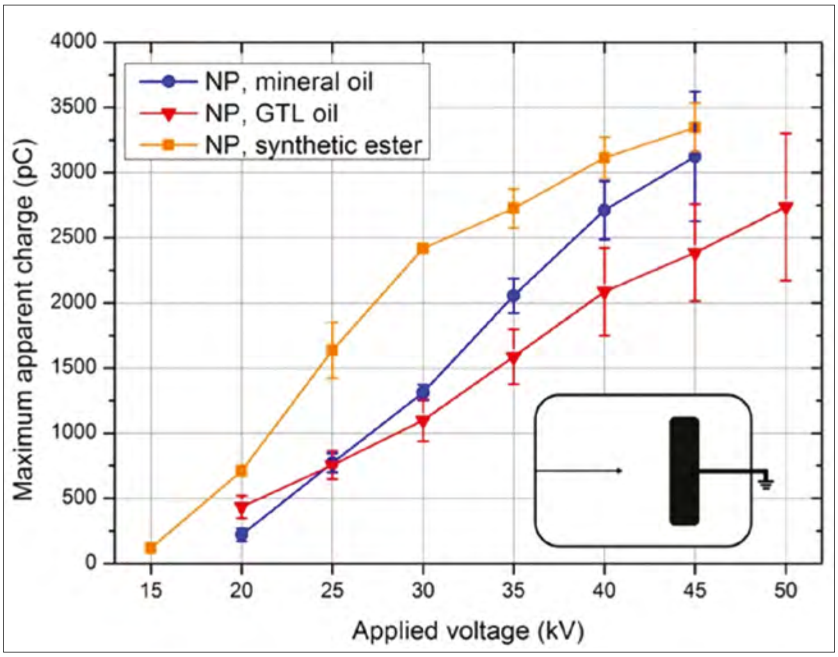
Partial discharge (PD) measurements have been used in factory testing and online condition monitoring of power transformers. In laboratories, it is often studied under strongly divergent electric fields, which facilitates the PD inception but avoids the breakdown. Studies have shown that partial discharge inception voltages of ester liquids are comparable to that of mineral oil [6, 7]. However, at voltages above inception, as seen in Fig. 3, ester liquids have shown higher PD amplitudes and much higher PD repetition rates compared to the mineral oil [8]. In addition, PDs under negative half cycles are more visible in ester liquids than in mineral oil. The intensive PD activities in ester liquids are likely related to space charge accumulation caused by the electronegativity of oxygen atoms in ester molecules. Further research has shown that increase in temperature would help the space charge dissipation and hence reduce the PD repetition rate in ester liquids [9].

Pressboard barriers are used in transformers to guide insulating liquid and to improve dielectric strength by dividing large oil gaps into smaller ones. Most of the electrical stress on the pressboard is perpendicular to the surface. However, due to geometric constraints, certain pressboards will experience tangential electric fields along the surface. If these tangential fields are not well controlled, discharges could initiate and propagate along the pressboard surfaces, which are often referred to as creepage and surface tracking phenomena. Studies have shown the pressboard surface tends to promote the development of discharges, and this discharge promotion effect is much more evident in ester liquids than in mineral oil, especially when the samples are stressed at higher voltages [10, 11]. In addition to the conventional carbonised tree marks, white marks were observed along the ester liquid impregnated pressboard surface at lower voltage levels compared to mineral oil-impregnated pressboard [11]. This is likely due to the higher discharge intensity and higher viscosity of ester liquids. Attention should be paid to the weaker resistance of ester-impregnated pressboards to surface tracking when applying ester liquids in large power transformers.

Studies conducted under uniform / quasi-uniform electric fields have shown that lightning impulse breakdown voltages of ester liquids and mineral oil are comparable with differences typically less than 15 %

Under impulse stress

Lightning impulse breakdown characteristics are another critical set of parameters of an insulation system, and the test



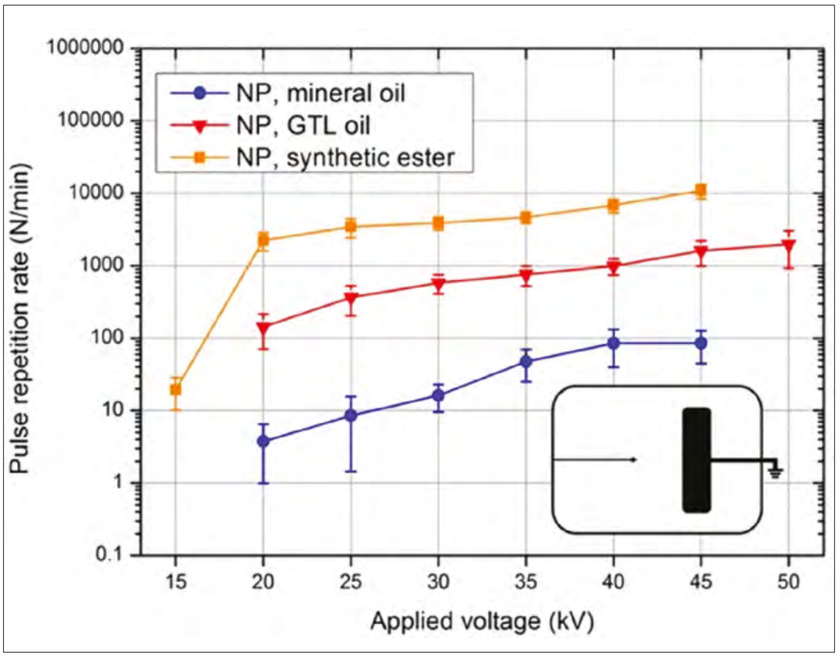


Figure 3: PD magnitudes and repetition rate of transformer liquids under a needle-to-plane configuration [8]

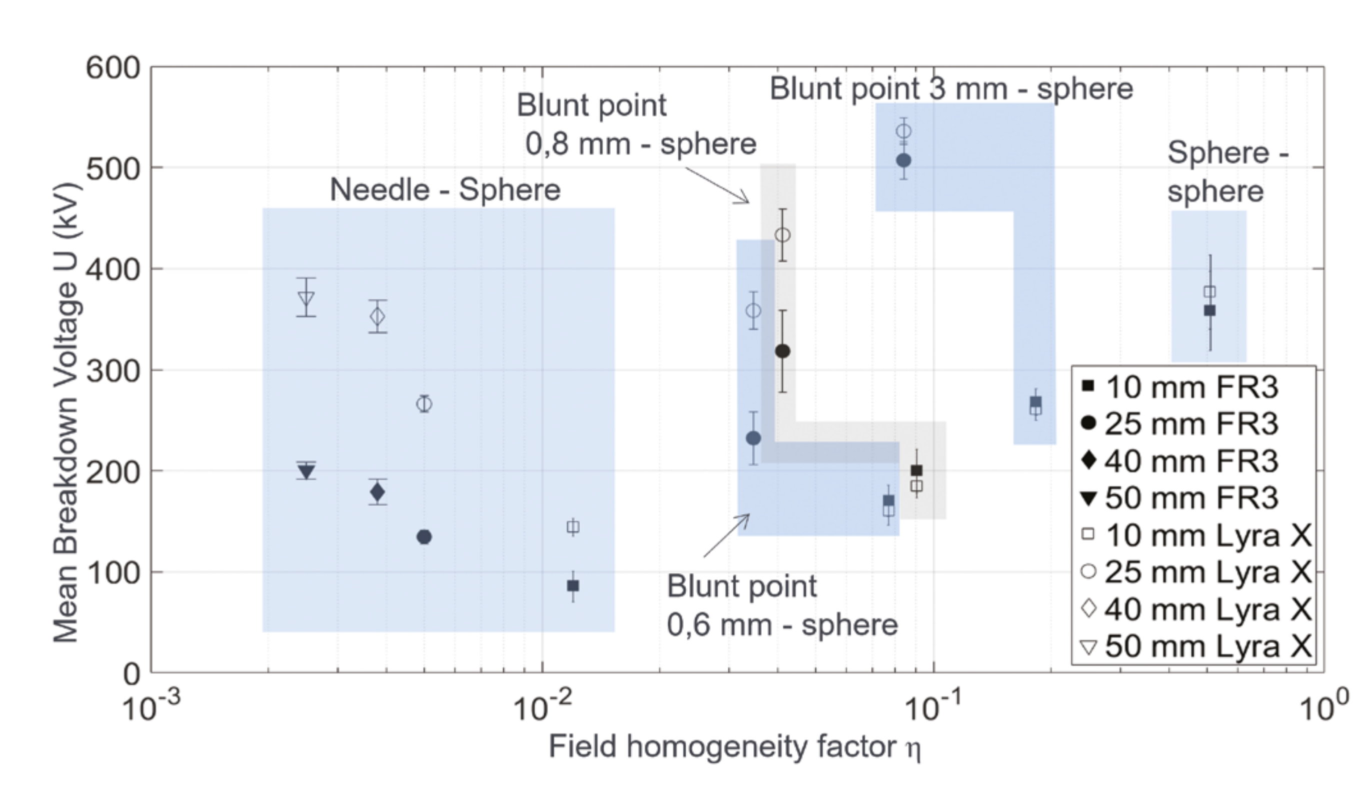


Figure 4: Dependency of mean lightning impulse breakdown voltage on field homogeneity for natural ester (FR3) and mineral oil (Lyra X) under different field homogeneity factors [15] (Field homogeneity factor = average electric field / maximum electric field)

is commonly used during factory acceptance tests. In contrast to AC breakdown strength, lightning impulse voltage is typically considered to be more related to the liquid's intrinsic molecular properties. Studies conducted under uniform / quasi-uniform electric fields have shown that lightning impulse breakdown voltages of ester liquids and mineral oil are comparable with differences typically less than 15 % [12-14].

The difference in lightning impulse breakdown voltage between ester liquids and mineral oil increases with the increase in gap distance or the decrease in electric field homogeneity. As shown in Fig. 4 [15], ester liquids and mineral oil have comparable breakdown voltages under quasi-uniform electric fields; however, more evident differences are observed when the field homogeneity factor (field utilisation factor) becomes smaller.

This is explained by the fundamental studies on streamer initiation and propagation in ester liquids under lightning impulse voltages. Comparison of both streamers stopping length and propagation velocity under the same condition (Fig. 5 and Fig. 6) has shown that streamers in ester liquids propagate further and faster than those in mineral oil at the same voltage level; ester liquids have a much lower acceleration voltage than mineral oil [16]. The acceleration voltage is defined as the voltage level above which streamer velocity increases quickly. It is of importance to indicate the liquid's ability to prevent fast events that are relevant to lightning impulse breakdown at large gaps [17]. The presence of a parallel pressboard reduces the positive acceleration voltage in mineral oil but not

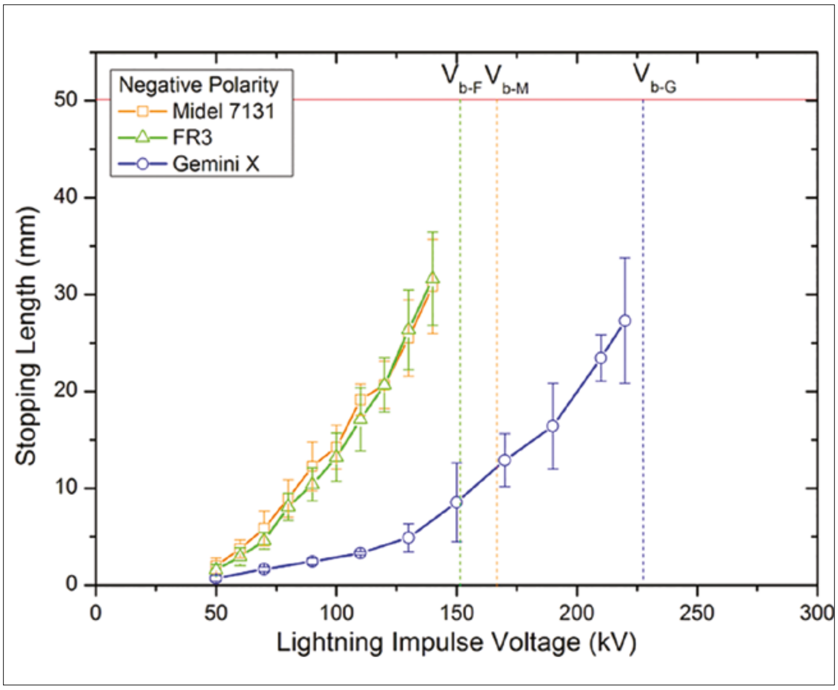


Figure 5. Streamer length comparison under negative lightning impulse at 50 mm needle-plane gap [16]

The thermal properties of esters differ from mineral oil, particularly for the notable difference in viscosity

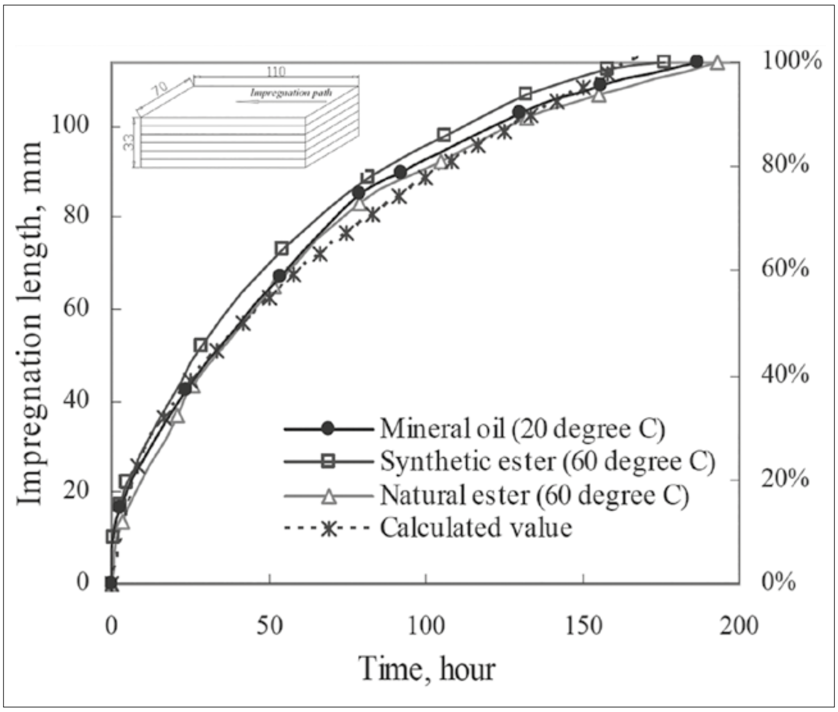


Figure 7. Impregnation of a pressboard block [22]

for the ester liquids, probably because the acceleration voltage of the open ester liquid gap is already a low value [18].

Once initiated, streamer propagation is generally faster in ester liquids than in mineral oil, so the avoidance of streamer / discharge inception is likely to be even more important for the design and construction of ester filled power transformers in order to avoid breakdown, particularly under factory test stresses. In addition, considering that the difference of breakdown voltage between ester liquids and mineral oil increases at larger gap distances, it might be wise to use additional pressboard barriers to prevent large divergent field gaps in ester filled power transformers [13, 16].

Thermal design consideration

In addition to being an insulation medium, liquid in transformers also acts as a cooling medium. The thermal properties of esters differ from mineral oil, particularly for the notable difference in viscosity. Both computational fluid dynamic (CFD) modelling and experimental studies have been conducted using a simplified winding model under oil-directed (OD) and oil-natural (ON) cooling modes [19, 20]. Under OD cooling mode, at the same inlet flow rate, ester liquids could have a more uniform flow and temperature distribution compared to mineral oil due to the higher viscosity of ester liquids. This could be a benefit to prevent the occurrence of liquid reverse flow at a higher inlet flow rate. However, it has to be noted that at the same inlet flow rate, ester liquids will inevitably cause higher pressure loss compared to mineral oil and hence it would require more powerful pumps [19, 20]. Under ON cooling mode [21], in particular, for a retrofilling perspective, the total liquid flow rate in the winding is dictated by the thermosiphon force and the pressure drop in the whole cooling loop. Under the same transformer geometry, ester liquids have a lower total liquid flow rate than mineral oil mainly due to the higher viscosity of ester liquids, which would likely lead to higher hotspot temperature in ester liquid filled transformers.

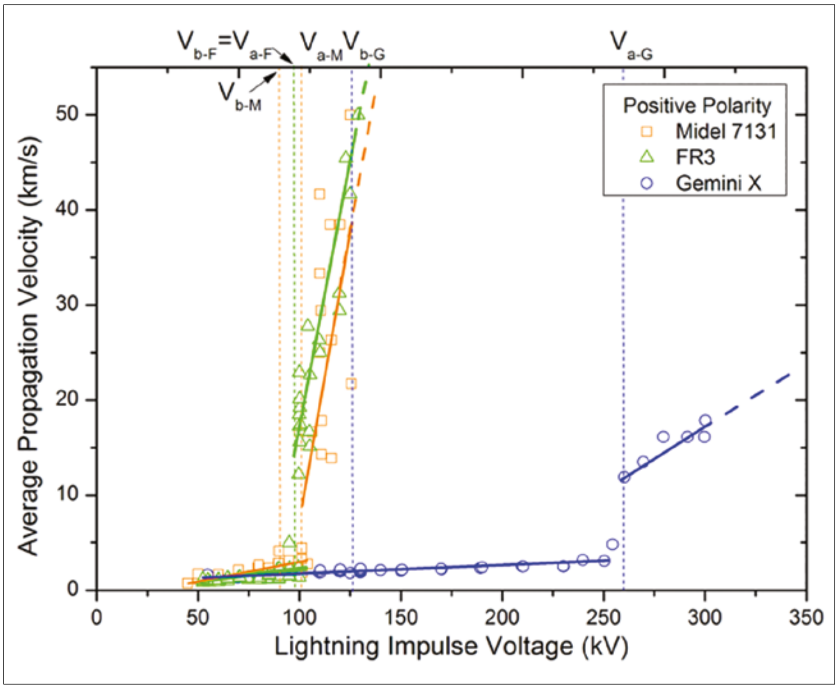


Figure 6. Streamer velocity comparison under positive lightning impulse at 50 mm needle-plane gap [16]

The temperature of 60 °C was found as the balance point, at which both the viscosity and the capillary action of ester oils are similar to that of mineral oil at 20 °C

Ageing of ester liquids can occur through a combination of oxidation, hydrolysis and pyrolysis, depending on the environmental conditions

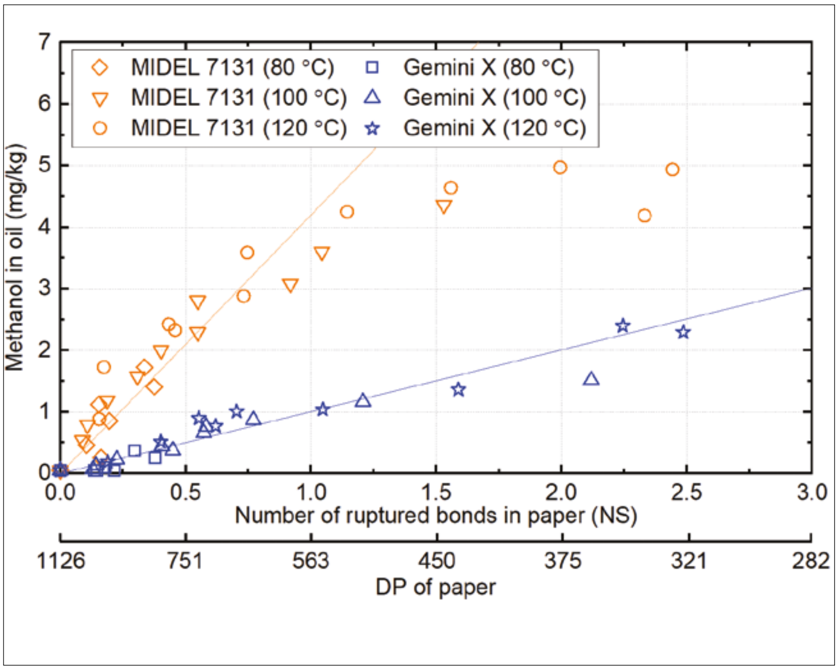


Figure 8. Methanol content in liquid against the ageing state of paper insulation [25]

Impregnation of solid insulation

Impregnation of solid insulation, including paper and pressboard, is of importance for preventing premature dielectric failures in transformers. The impregnation of the pressboard is a nonlinear process, and the impregnation speed will decrease with the impregnation depth. In terms of liquid properties, the factors which affect the impregnation process are the viscosity and surface tension of the oil. As shown in Fig. 7, a higher temperature can effectively reduce the viscosities of ester liquids but adversely reduce the surface tensions of the liquids. The temperature of 60 °C was found as the balance point, at which both the viscosity and the capillary action of ester oils are similar to that of mineral oil at 20 °C [22].

Ageing, condition monitoring and diagnostics

Ester liquids possess different chemical compositions and physical properties compared to conventional mineral oil. Thus, it is essential to understand the impact of these differences on the ageing behaviour of esters and ester-based insulation systems and develop methods to assess the degree of degradation.

Ester liquids combined with new solid insulation such as aramid enhanced cellulose may allow transformers to operate over 20 °C higher than conventional transformers with mineral oil and thermally upgraded paper

Ageing of ester liquids can occur through a combination of oxidation, hydrolysis and pyrolysis, depending on the environmental conditions [23]. Due to a large number of polyunsaturated fatty acids, the oxidation stability of the natural ester is lower compared to mineral oil. Therefore, antioxidants are commonly used in natural esters to mitigate the effect of oxidation. There are many different test methods for the oxidation stability of natural esters. In addition to titration methods stipulated in IEC 61125 standard, it has shown that pressure differential scanning calorimetry can successfully measure the deterioration of oxidation stability of the natural ester [23].

With the increase of water content in a transformer, ester liquids are likely to undergo a hydrolysis process producing long-chain high molecular weight carboxylic acids (HMA). Studies have shown that high amounts of HMA in an insulation system has negligible influence on paper ageing compared to water soluble low molecular weight acids (LMA) [24]. However, it is necessary to further investigate the effect of the high acidity of ester liquids on copper and steel materials, particularly to look at whether there are corrosion effects at high temperatures.

Ageing of paper insulation

Much research has been conducted to understand the ageing behaviour of ester-paper composite insulation systems and the possibility of applying existing condition monitoring tools for ester-based insulation systems [25-28]. Laboratory ageing studies have shown that esters could slow down the ageing of paper insulation. It was proposed that reduction of water in the insulation due to hydrolysis of esters and esterification of active hydroxyl groups in cellulose could contribute to the slower paper ageing rate in ester liquids compared to mineral oil. Paper ageing indicators such as 2-FAL and methanol were observed during the ageing experiments [25, 26]. However, there have been issues raised about their stability in certain ester liquids and partitioning within the insulation system, which require further investigations to validate the ability to use such chemical indicators for ester-based insulation systems. Furthermore, studies have shown ester liquids combined with new solid insulation such as aramid enhanced cellulose may allow transformers to operate over 20 °C higher than conventional transformers with mineral oil and thermally upgraded paper [27, 28].

High conductivity of esters significantly influence the dielectric response behaviour of pressboard insulation with low moisture content, but it is not significant when the moisture content of pressboard insulation is above 3 %

Dielectric response measurements

Dielectric response measurements are used as a non-invasive method to estimate the water content in transformer insulation. Therefore, testing its applicability towards ester filled transformers is vital. Based on the current research outcomes, one can conclude that the dielectric response behaviour of ester impregnated pressboard insulation qualitatively resembles to that of mineral oil impregnated pressboard, which contains two distinct relaxation processes, including Quasi-DC (q-dc) conduction features at low frequencies and loss peak behaviour at mid-frequency range [29].

The high conductivity of ester liquids significantly influences the dielectric response behaviour of pressboard insulation with low moisture content. However, this effect is not significant when the moisture content of pressboard insulation is above 3 %. Research has proven that existing dielectric response measurements based on moisture diagnostic tools, which are defined for mineral oil-paper systems, could overestimate the moisture content in paper insulation in ester–paper insulation systems. According to current findings, the dielectric response of ester impregnated pressboard insulation has different temperature dependence behaviour compared to that of mineral oil impregnated pressboard [30, 31]. This is caused by the hygroscopic nature of ester liquids. These factors should be considered when the existing dielectric response measurements based moisture analysis software is extended to ester–paper insulation systems.

Summary

Ester liquids have advantages over conventional mineral oil regarding fire safety, environmental impact, and prolonging the lifetime of insulation paper. Having started with distribution transformers and through research and development activities, the use of ester liquids has now moved up to higher voltage levels. Currently, esters are successfully applied for power transformers at 400 kV voltage level. Some of the key research from members of UTRA that helped developing ester liquid-filled high voltage power transformers are stated in this article. The topics covered include electrical and thermal characteristics, solid insulation impregnation, ageing performance and condition monitoring.

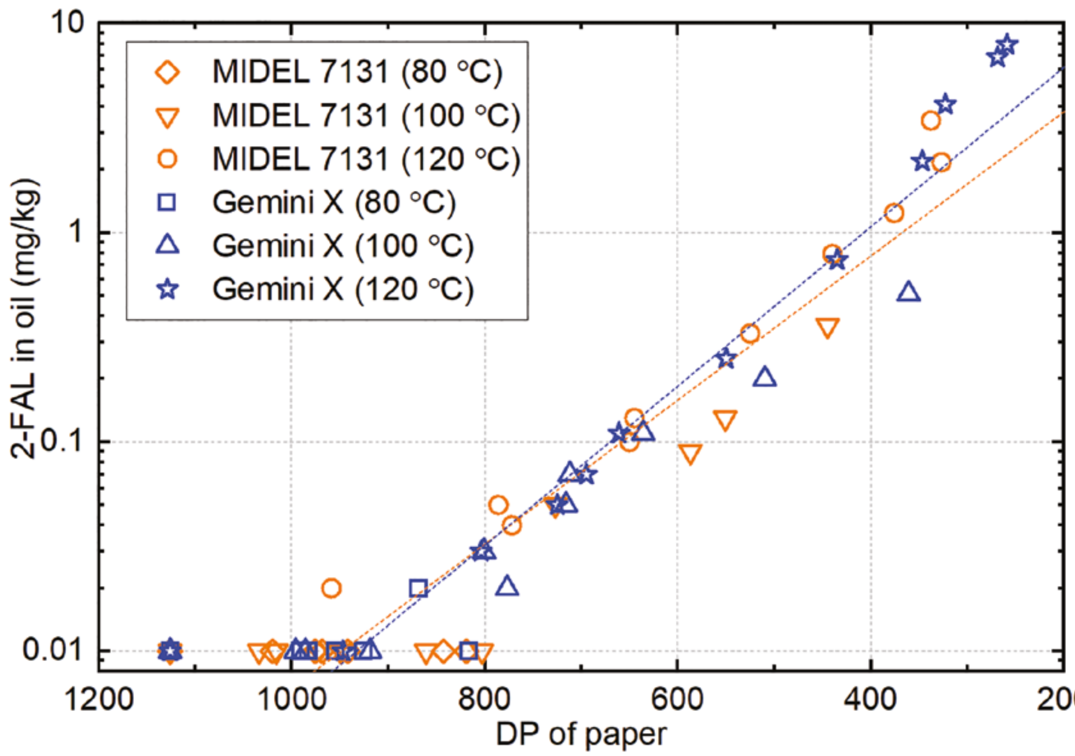


Figure 9. 2-FAL content in liquid against the ageing state of paper insulation [25]

Bibliography

[1] K. Rapp, J. Luksich, A. Sbravati, *Application of Natural Ester Insulating Liquids in Power Transformers*, MyTransfo Conference, Turin, Italy, 18–19 November 2014

[2] *Alternative Transformer Fluids Energy Management - Transformers*, ed: Siemens (https://assets.siemens-energy.com/siemens/assets/api/uuid:ed332bfb-500f-4325-b641-2b726174f6f5/ipdf-alternative-fluids.pdf).

[3] X. Wang, Z. D. Wang, *Study of dielectric behaviour of ester transformer liquids under ac voltage*, IEEE Transactions on Dielectrics and Electrical Insulation, vol. 19, no. 6, pp. 1916–1925, 2012

[4] S. Tenbohlen et al., *Application of vegetable oil-based insulating fluids to hermetically sealed power transformers*, CIGRE Session 2008, Paris, France, paper No. A2-102, 24–29 August 2008

[5] X. Wang, Z. D. Wang, J. Noakhes, *Motion of conductive particles and the effect on AC breakdown strengths of esters*, in IEEE International Conference on Dielectric Liquids (ICDL), Trondheim, Norway, 26–30 June 2011

[6] Z. D. Wang et al., *Discussion on possible additions to IEC 60897 and IEC 61294 for insulating liquid tests*, IET Electric Power Applications, vol. 5, no. 6, pp. 486–493, 2011

[7] Z. Liu, et al., *Partial discharge inception voltages of transformer liquids under various electric field conditions*, 19th International Symposium on High Voltage Engineering (ISH), Pilsen, Czech Republic, paper 426, 23–28 August 2015

[8] Q. Liu, et al., *Electrical and thermal behaviours of synthetic transformer liquids*, in CIGRE Session 2016, Paris, France, paper No. D1-201, 2016

[9] Y. M. Huang, Q. Liu, Z. D. Wang, Ef*fects of temperature on partial discharges and streamers in an ester liquid under AC stress,* IEEE Transactions on Dielectrics and Electrical Insulation, vol. 26, no. 5, pp. 1512–1519, 2019

[10] X. Yi, Z. D. Wang, *Surface tracking on pressboard in natural and synthetic transformer liquids under AC stress*, IEEE Transactions on Dielectrics and Electrical Insulation, vol. 20, no. 5, pp. 1625–1634, 2013

[11] X. Yi, Z. D. Wang, Creepage *discharge on pressboards in synthetic and natural ester transformer liquids under ac stress*, IET Electric Power Applications, vol. 7, no. 3, pp. 191–198, 2013

[12] W. Lu, Q. Liu, *Effect of cellulose particles on impulse breakdown in ester transformer liquids in uniform electric fields*, IEEE Transactions on Dielectrics and Electrical Insulation, vol. 22, no. 5, pp. 2554–2564, 2015

[13] Q. Liu, Z. D. Wang, *Breakdown and withstand strengths of ester transformer liquids in a quasi-uniform field under impulse voltages*, IEEE Transactions on Dielectrics and Electrical Insulation, vol. 20, no. 2, pp. 571–579, 2013

[14] S. Haegele et al., *Lightning Impulse Withstand of Natural Ester Liquid*, Energies, vol. 11, no. 8, p. 1964, 2018

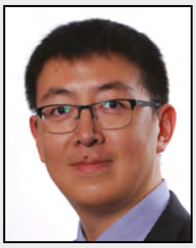
[15] S. Haegele et al., *Comparative study on inhomogeneous field breakdown in natural ester liquid and mineral oil*, in IEEE Conference on Electrical Insulation and Dielectric Phenomena (CEIDP), pp. 375–379, 16–19 Oct 2016

[16] Z. D. Wang et al, *Ester insulating liquids for power transformers*, in CIGRE A2 209 colloquium, Paris, 2012

Authors

Zhongdong Wang (FIEEE, FIET, Ph.D.–1999, M.Sc.–1993, B.Eng.–1991) is a Professor of Power Systems and Pro-Vice Chancellor and Executive Dean of the College of Engineering, Mathematics and Physical Sciences at the University of Exeter, United Kingdom. Her research interests include smart grids and low carbon electrical energy networks, in particular condition monitoring techniques, thermal, electrical transient and magnetic modelling techniques for power system networks, dielectric insulation ageing mechanisms, alternative environmentally friendly liquid insulating materials, and transformer asset management.

Shanika Matharage (Ph.D.–2017, B.Sc.–2011) is a Lecturer in the College of Engineering, Mathematics and Physical Sciences at the University of Exeter, United Kingdom. His research interest focuses on electrical power network assets in the areas of their condition monitoring, ageing mechanisms, novel insulation materials and asset management.



Qiang Liu (SMIEEE, Ph.D.–2011, M.Sc.–2008, B.Sc.–2005) is a Reader of the Department of Electrical and Electronic Engineering at The University of Manchester, United Kingdom. His research interests focus on dielectric liquids and liquid impregnated insulation systems and their applications in high voltage equipment. The research topics include pre-breakdown and breakdown mechanisms, ageing assessment, thermal modelling, asset management, alternative insulation materials and high voltage testing.

Stefan Tenbohlen (Dr. Ing.–1997, diploma–1992) is a Professor and Head of the Institute of Power Transmission and High Voltage Technology at the University of Stuttgart, Germany. His main research fields are high voltage technique, power transmission and electromagnetic compatibility (EMC).

[17] Q. Liu, Z. D. Wang, *Streamer characteristic and breakdown in synthetic and natural ester transformer liquids under standard lightning impulse voltage*, IEEE Transactions on Dielectrics and Electrical Insulation, vol. 18, no. 1, pp. 285–294, 2011

[18] Q. Liu, Z. D. Wang, *Streamer characteristic and breakdown in synthetic and natural ester transformer liquids with pressboard interface under lightning impulse voltage*, IEEE Transactions on Dielectrics and Electrical Insulation, vol. 18, no. 6, pp. 1908–1917, 2011

[19] M. Daghrah et al., *Experimental Study of the Influence of Different Liquids on the Transformer Cooling Performance*, IEEE Transactions on Power Delivery, vol. 34, no. 2, pp. 588–595, 2019

[20] X. Zhang et al., *Numerical investigation of influences of liquid types on flow distribution and temperature distribution in disc type ON cooled transformers*, in IEEE 19th International Conference on Dielectric Liquids (ICDL), Manchester, UK, 25–29 June 2017

[21] X. Zhang, *Investigation of the total flow rates in oil natural transformer retrofilling scenarios*, in IEEE 20th International Conference on Dielectric Liquids (ICDL), 23–27 June 2019

[22] J. Dai, Z. D. Wang, *A Comparison of the Impregnation of Cellulose Insulation by Ester and Mineral oil*, IEEE Transactions on Dielectrics and Electrical Insulation, vol. 15, no. 2, pp. 374–381, 2008

[23] Y. Xu et al., *Oxidation stability assessment of a vegetable transformer oil under thermal aging*, IEEE Transactions on Dielectrics and Electrical Insulation, vol. 21, no. 2, pp. 683–692, 2014

[24] N. Azis, Q. Liu, Z. D. Wang, *Ageing assessment of transformer paper insulation through post mortem analysis*, IEEE Transactions on Dielectrics and Electrical Insulation, vol. 21, no. 2, pp. 845–853, 2014

[25] S. Y. Matharage et al., *Aging assessment of synthetic ester impregnated thermally non-upgraded kraft paper through chemical markers in oil*, IEEE Transactions on Dielectrics and Electrical Insulation, vol. 25, no. 2, pp. 507–515, 2018

[26] K. Bandara et al., *Performance of natural ester as a transformer oil in moisture-rich environments*, Energies, vol. 9, no. 4, p. 258, 2016

[27] X. Zhang et al., *overload distribution transformer with natural ester and aramid-enhanced cellulose*, IEEE Transactions on Power Delivery, vol. 36, no. 3, pp. 1829–1836, 2021

[28] X. Zhang et al., *Dual-temperature evaluation of a high-temperature insulation system for liquid-immersed transformer*, Energies, vol. 11, no. 8, p. 1957, 2018

[29] K. Bandara, C. Ekanayake, T. K. Saha, *Analysis of frequency domain dielectric response of pressboard insulation impregnated with different insulating liquids*, IEEE Transactions on Dielectrics and Electrical Insulation, vol. 23, no. 4, pp. 2042–2050, 2016

[30] K. Bandara, C. Ekanayake, T. K. Saha, *Modelling the dielectric response measurements of transformer oil*, IEEE Transactions on Dielectrics and Electrical Insulation, vol. 22, no. 2, pp. 1283–1291, 2015

[31] K. Bandara et al., *Investigation of moisture influence on dielectric response of ester oil impregnated pressboard*, in IEEE Power & Energy Society General Meeting, 26–30 July 2015

Authors

Chandima Ekanayake (SMIEEE, Ph.D.–2006, Tech. Lic–2003, B.Sc.–1999) is a Senior Lecturer in the School of Information Technology and Electrical Engineering at the University of Queensland, Australia. His research focuses on instrumentation for condition monitoring & protection of power system assets and developing ageing models based on laboratory and field measurements to quantify the ageing of assets due to multi-factor ageing.

Tapan Kumar Saha (FIEEE, Ph.D.–1994, M. Tech–1985, B.Sc.–1982) is a Professor of Electrical Engineering in the School of Information Technology and Electrical Engineering at the University of Queensland, Australia. His research interests include condition monitoring of electrical plants, power systems and power quality.

Hui Ma (SMIEEE, Ph.D.–2008, M.Eng. (research)–1998, M.Eng.–1994, B.Eng.–1991) is a Senior Lecturer in the School of Information Technology and Electrical Engineering at the University of Queensland, Australia. His current research is on Power System Asset Management, focusing on sensing and signal processing to improve the visibility of electricity network asset condition and machine learning with uncertain reasoning for applications in electricity networks with high penetration of renewables.

Yang Xu (Ph.D., M.Sc., B.Sc.) is a Professor and Director of Electrical Insulation Research Center at Xi'an Jiaotong University, China. His expertise is in the evaluation of electrical insulating systems, environmentally friendly insulating fluid, and new applications of optical sensors.