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DIELECTRIC OILS & FLUIDS

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Corrosive Sulphur
& its Effect on Transformers

A Tale of
Two Esters

Characteristics of
Modern Transformer Oil

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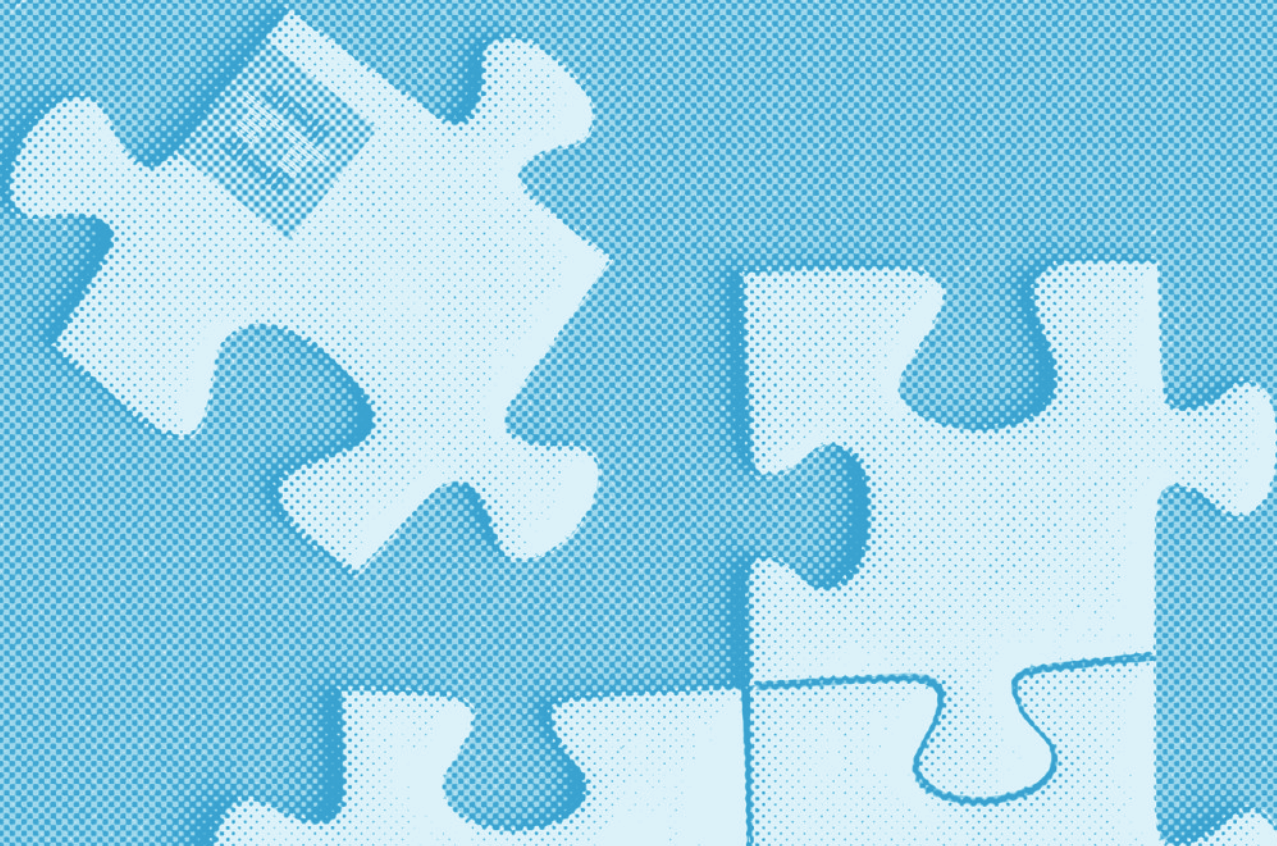
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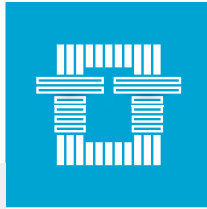
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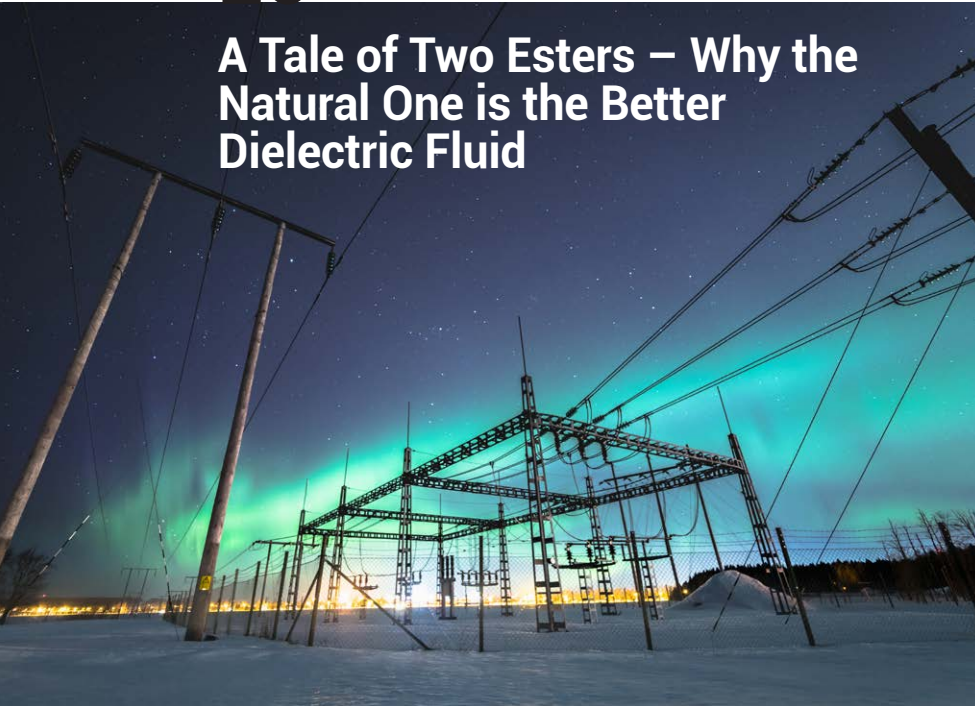


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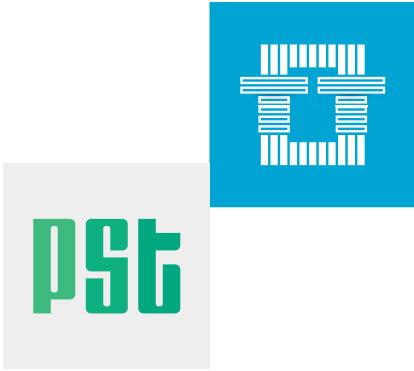
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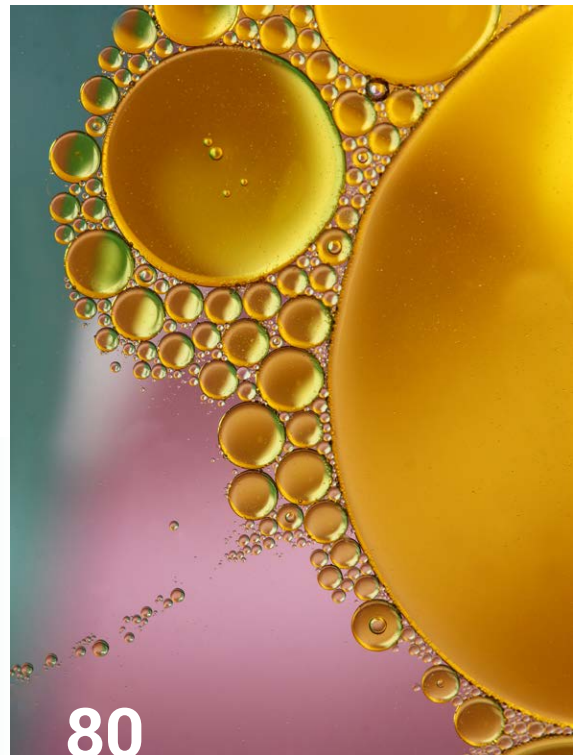
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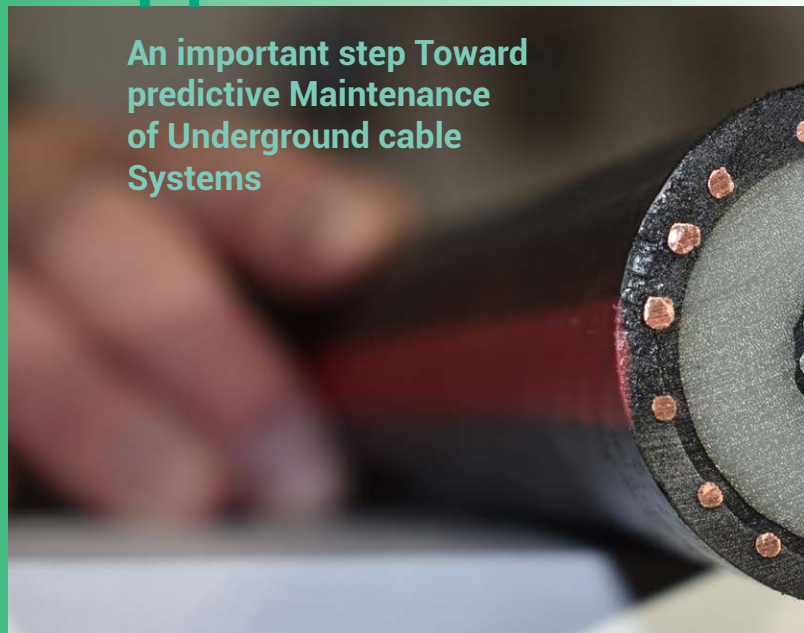


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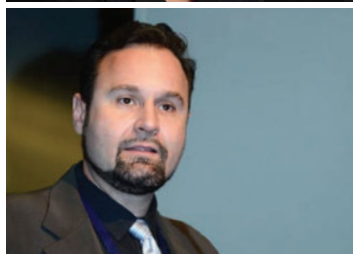
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ISSN 2642-2689 (Print)
ISSN 2642-2697 (Online)

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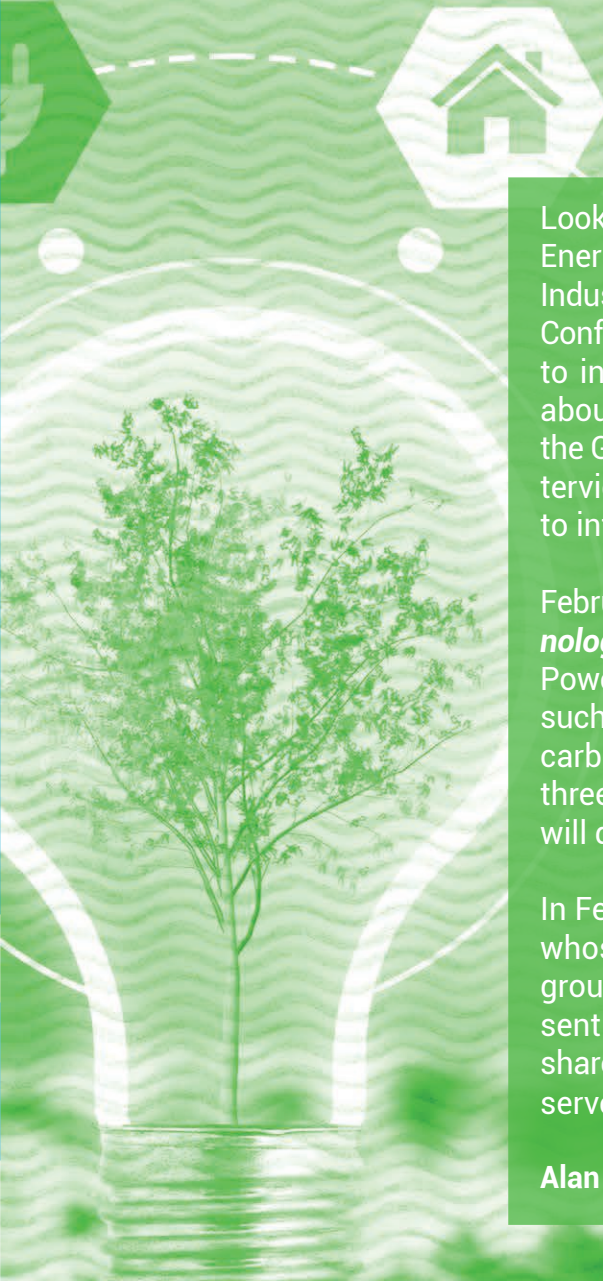
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COMING
IN FEBRUARY

Green Energy Special Edition



Looking ahead for February, I'm excited to focus on Green Energy and the transformation taking place in the Power Industry globally. Last year at the Renewable Energy, RE+ Conference and Expo in Anaheim, California. We were able to interview 29 SME's and thought leaders who spoke about the innovation and developments taking place in the Green Energy space. We will feature some of these interviews, along with articles from experts I was not able to interview in February.

February is also the launch of the new **Green Energy Technology** community, focused specifically on an area of the Power System that we think deserves its own community, such as wind, solar, geothermal, hydrogen, and more. Decarbonization, Digitalization and Decentralization: The three Ds of the Power Industry future are the forces that will drive us toward Green Energy.

In February's Special Edition we will present companies whose experts and thought leaders are taking pioneering, ground-breaking leaps forward in this field. We will present trusted and established "Thought Leaders" who will share innovative and revolutionary solutions that can best serve our industry.

Alan Ross, *Technical Director and Managing Editor, APC Media*

COMING IN FEBRUARY ISSUE

Dear Readers,

When we invited subject matter experts (SME's) to share their thoughts and ideas about the topic of insulating systems and fluids, little did I realize how much has changed in the space and how many qualified experts would jump at the chance to write or be interviewed. So much good content was available that we decided the annual issue would be delivered, once again, as a two-part issue, once in December as Part 1 and now this Part 2 in January.

As for technical articles, once again our Technical Advisory Board members have come through. Their unique ability to bring technical knowledge to life in such a compelling way is a delight to all of us at APC Technologies and for that we are tremendously grateful. Writing an 1800-word technical article with supporting graphs, charts or pictures is not an easy task. Publishing them is even harder given the adage, "Doctors bury their mistakes and publishers print them." Fortunately, we can adjust for our mistakes but due to the nature of digital publishing, the mistakes can live on forever.

I want to move past the two Oils & Fluids issues and onto something dramatically different for February 2023 with our theme being the Green Energy Revolution. I am as excited about this pivot as I have been for anything we previously pro-

vided for our Transformer Technology (TT) Community and for our commitment to Women in Power Systems (WPS). These past four years have been a labor of love for all of us at APC Technologies, a Division of APC Media.

As I've said before, when we made the decision to expand our focus into Power System Technology (PST), it came with some concern since Transformer Technology has become a great community of interest. Transformers are like engines in vehicles. Power systems are the vehicle, but they make up a whole system of transportation. We can report on sports cars with their unique engines and capabilities, and we can focus on 18-wheelers, or pick-up trucks, or SUV's. All are part of the system we call transportation, and all have engines and components that drive the system. (Pardon the pun please.)

As we expand our offering to the community, we will never abandon reporting on the heart of the power system, the transformer. We will add to it, great interviews and articles on the overall system that transformers support. Since there are so many changes taking place in power system technology, with the advent of Distributed Energy Resources (DER), Smart Grids, solid state technology and green energy to name just a few, our growth in this area is only natural.



**Doctors bury their mistakes
and publishers print them.**



Looking ahead for February, I am excited to focus on Green Energy and the transformation taking place in the power industry globally. As I mentioned last month, at the Renewable Energy, RE+ Conference and Expo in Anaheim, California, we were able to interview 29 SME's and thought leaders who spoke about the innovation and development taking place in the green energy space, so much so that I want to feature some of these interviews, and articles from those I was not able to interview.

While much of the issue content has been planned, there is still room for long form technical articles and short form perspectives. If you have an idea for a topic, please contact me directly at alan.ross@apc.media and give me a brief description of a topic you would like to present.

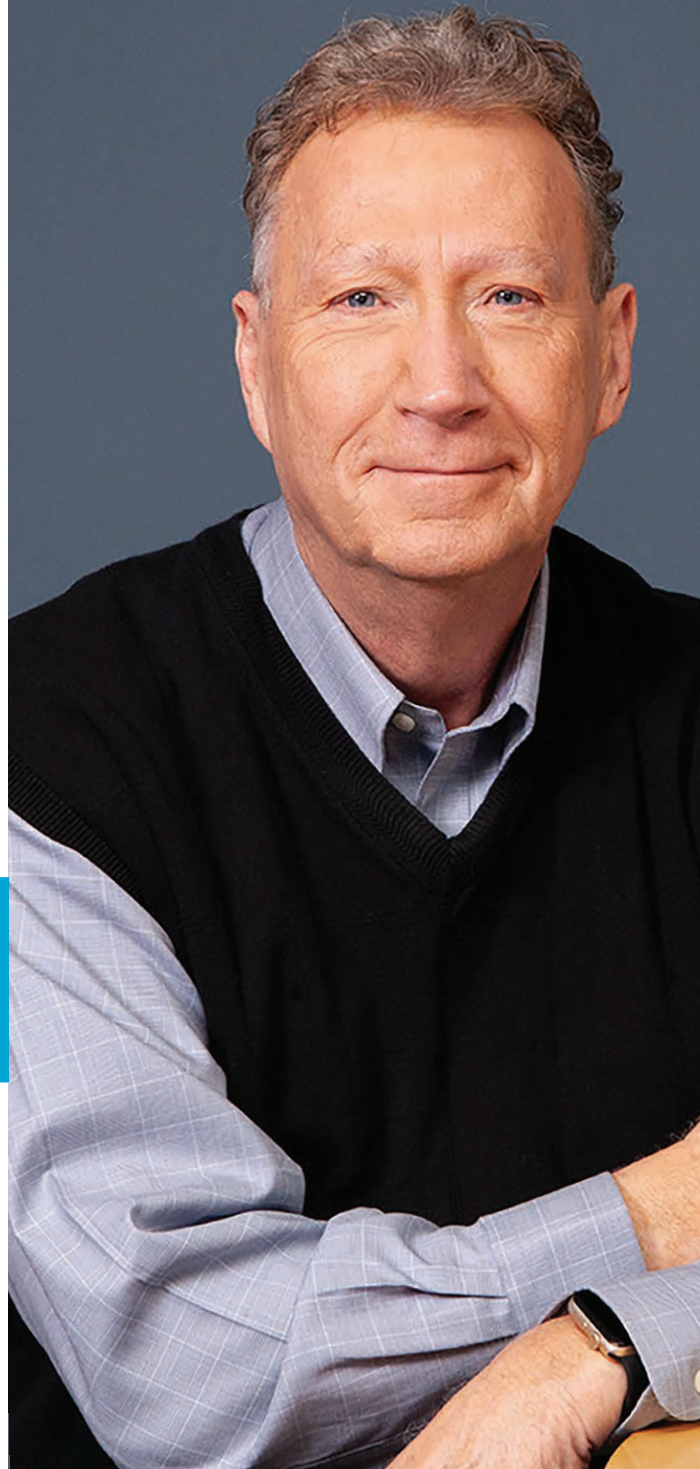
Be Blessed and Thank you,



Alan M Ross
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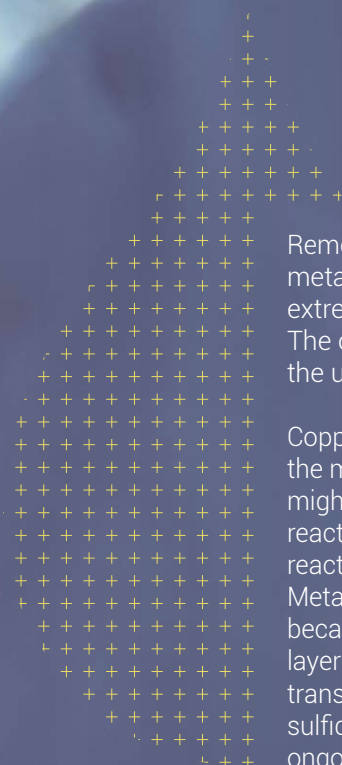
Alan M Ross



An in-depth look at Corrosive Sulphur and its effect on Transformers



Removing corrosive deposits from metal surfaces and paper is extremely difficult, if possible, at all. The only remedy would be to take the unit out of service.



Removing corrosive deposits from metal surfaces and paper is extremely difficult, if possible, at all. The only remedy would be to take the unit out of service.

Copper sulfide has been identified as the most corrosive compound that might be formed during chemical reactions in the transformer when reactive sulfur compounds are present. Metal sulfides can cause overheating because they may form a resistive layer on various surfaces in the transformer. On bushings, the copper sulfide on a conductor can indicate the ongoing corrosion process but might not be the cause of failure.

It should be noted that oils with a high sulfur content do not indicate a highly corrosive compound. The type of sulfur molecule needs to be identified to establish the severity of the reactive nature of the sulfur variant in the oil.

Units containing varnished or enamel-coated wires or thermally upgraded kraft paper are more resistant to the corrosive effect of reactive sulfur.

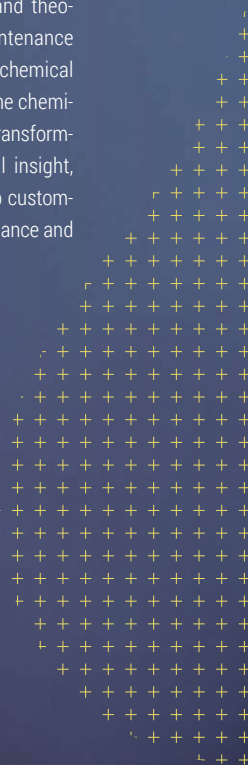
It was found that this corrosive reaction is time and *temperature-dependent*. Higher temperatures can lead to greater corrosion and larger amounts of metal sulfide formation. Sealed units are more susceptible to this problem; in free-breathing units, the oxygen and corrosive sulfur compounds compete for reaction sites on the copper and organometallic compounds. This slows down the formation of the conductive metal sulfides in free-breathing units but does not stop it.



Corné Dames is the Managing Director of Independent Transformer Consultants, always striving to keep on top of new developments and research. She has expertise as Laboratory Manager in the analysis of transformer oils and as diagnostician identifying problem areas in transformers, as well as profiling of transformers according to available results thus empowering the customer to take preventative steps in maintenance. Corné has vast practical and theoretical knowledge on reliability maintenance programs. Coming from a strong chemical background she has insight in all the chemical processes that are part of the transformer system. Coupled with technical insight, her knowledge and experience help customers optimize their reliability maintenance and electrical asset lifetime.

Introduction

Many transformer and equipment failures have been reported due to the effect of corrosive sulfur in oil-filled equipment. It is vitally important to look at condition monitoring and maintenance approaches in this type of scenario. The first question that comes to mind is, how is it possible for oil with corrosive sulfur compounds to have slipped through the quality control net of transformer oil diagnostics? Is it possible that the standardized tests cannot accurately identify oils with this corrosive compound? This has been the case before the IEC 60422 recommended ASTM 1275B and IEC 62353 as the applicable methods for determining corrosive sulfur. These methods will ensure greater accuracy in determining corrosive sulfur compounds in transformer oil.



We will discuss:

- Effect of corrosive sulfur
- The different forms of sulfur that might be present in transformer oils.
- The sources of sulfur in transformer oils
- Acceptable values for Corrosive Sulfur in new and reclaimed oils
- Test methods for Corrosive Sulfur detection
- The chemistry behind the formation of corrosive sulfur in transformer systems
- Electrical testing
- Condition monitoring of units with possible and definite contamination with corrosive sulfur
- Maintenance approaches for oils with corrosive sulfur.

Corrosive sulfur effects

Corrosive sulfur leads to the formation of insoluble substances in oil, precipitate as sludge, or form copper sulfide deposits on copper conductors and paper insulating tapes. [1] During the inspection of transformers and shunt reactors windings, it was noted that the copper sulfide migrates within the paper layers of the insulating paper. In most cases, the copper sulfide concentration tends to be highest within the inner tape layers adjacent to the copper conductors; the tendency is to diffuse outwards.

A plausible explanation for this observation is that the higher concentration gradient of copper is at the surface of the copper conductor. It should also be noted that there is an increased temperature gradient

effect at the copper conductor surface or in its vicinity due to the high currents carried by the copper conductor. This will add to the increase of the reaction rate for the formation of copper sulfide due to the presence of corrosive sulfur and copper and high temperatures.

The different types of sulfur that might be present in transformer oils

The accepted scale of corrosiveness places elemental sulfur as the most corrosive element against copper, followed by hydrogen sulfide, mercaptans, sulfides, and disulfides. In compounds where the sulfur atom is part of an aromatic structure, the compound is considered non-reactive.

Sulfur is a common component found in crude oil as this substance is found in 0.5% of the earth's crust. Organic sulfur compounds are more reactive than inorganic types. Some sulfur compounds can aid in the oxidation stability of transformer oil. It might act as a metal passivator and deactivator by reducing the catalytic effect on oil oxidation. The manufacturer aims to remove or convert the reactive-corrosive sulfur compounds to more stable compounds like thiophenes and saturated disulfides during the refining process.

The steps implemented during the refining process to achieve the removal or conversion of reactive sulfur compounds are:

- a) Atmospheric distillation at various temperatures.
- b) Vacuum distillation

- c) Catalytic reaction
- d) Hydro-treating
- e) Hydro-generation

It should be noted that there might be some incomplete refining that would leave small amounts of mercaptans, or the hydrogenation process may produce elemental sulfur instead of hydrogen sulfide.

How does corrosive and reactive sulfur react in the transformer environment?

When corrosive and reactive sulfur comes into contact with copper and other metals, it can react. Copper is the most *vulnerable* metal to sulfur attack. The reaction of sulfur to combine with copper is problematic as it does not need high temperatures. It should be noted that different grades of copper contain different levels of oxygen. The design engineer needs to ensure the correct grade of copper is used for the application. The oxygen in the copper will then react with the reactive sulfur. Reactive sulfur will also react with other metals; the result will be the formation of copper sulfate (CuSO_4) or cuprous sulfite (CuSO_3), aluminum sulfate [$\text{Al}_2(\text{SO}_4)_3$] and other inorganic sulfates. [3]

From Non-corrosive to corrosive

Through investigation, it has been found that non-corrosive sulfur can become corrosive after being exposed to elevated temperatures on hot metal surfaces and then produce metal sulfides. It might be that the corrosion material can detach from the surface and become discharge nuclei or gas inception nuclei. This is only a concern with oils containing large concentrations of sulfur, not for oils with lower than recommended sulfur concentrations.

Sulfur sources in transformer systems

Sulfur can come from various components in the transformer system; oil is not the only source. Sulfur may also be present in gaskets, water-based glues, copper, and paper insulation contaminated during the paper manufacturing process. There is also the accidental introduction through incompatible hoses used during maintenance processes.

GROUP	CHEMICAL FORMULA	REACTIVITY
Elemental (Free) Sulfur	S	Very Reactive
Mercaptans (Thiols)	R-SH	Very Reactive
Sulfides (Thio-ethers)	R-S-R ₁	Reactive
Disulfides	R-S • S-R	Stable
Thiophenes	Five membered ring containing sulfur	Very Stable

R = paraffin with straight or branched chain hydrocarbon or cyclic hydrocarbon

Table 1: Sulfur and Sulfur compounds found in Crude oil [2]

During the manufacture of nitrile gaskets, sulfur is used as part of the curing process when the hardening of the material is done. All sulfur is supposed to be eliminated from the product by the end of the manufacturing process. When the manufacturing process is incomplete or some steps are skipped, it might be that not all the sulfur is removed. There does not appear to be any standard on what percentage of sulfur should remain in the final product. In some cases, the sulfur content of the end product is not monitored. Some third-party laboratories tests indicate a high concentration of reactive sulfur in some of these products.

Water-based glues used during the manufacturing process to secure the paper insulation may contain sulfur compounds. The amount of sulfur in electrical grade copper is 15ppm or less.



The sulfite process used during the pulping process for electrical kraft paper is acidic and uses sulfur dioxide, sulfuric acid, and calcium bisulfite. This is not the primary process used in the manufacture of kraft paper. The primary process used today for producing electrical grade kraft paper is sulfate also called alkaline pulping. Sodium hydroxide and sodium sulfide are used in the "cooking process."

The kraft process is slightly different in that the pulp is intentionally undercooked. This results in a darker substance with exceptional mechanical strength, using the same chemicals like sulfate and alkaline pulping. The pulp fibers in the kraft process do absorb some of the sulfur

compounds that cannot be removed via washing/rinsing processes. [3] Doble Materials Laboratory performed analysis to determine how much total sulfur compounds remains in the finished paper products. [2]

It was found that the sulfur content was quite significant in most of the samples.

Accidental contamination of oil with corrosive sulfur and reactive sulfur compounds can be because incompatible hoses have been used, or it might be that the hoses were contaminated by processing equipment used to process sulfur contaminated oil. It has been found that hoses made from natural rubber or gasoline hoses

contain high amounts of sulfur that can be easily transferred to the oil. Care should be taken in selecting hoses to perform any maintenance processes within the transformer as the wrong type of hose can have adverse long-term effects on the transformer unit.

Long term mitigation of copper sulfide

Once the industry became aware of the risks involved due to corrosive sulfur contamination, the question was asked: How can we mitigate the risk on our assets? It comes down to this; every transformer owner needs to evaluate their level of risk and adopt the appropriate strategy to manage it.

Techniques

Statistical evaluation of the survey indicates that metal passivators are most frequently applied, in 88% of the cases, including 5% of re-passivation. Oil change was carried out in 5% of the cases. Oil treatment processes (reclaiming) in removing corrosive sulfur compounds from the oil were performed in 4% of the cases, and the remaining 5% were other techniques or mixed actions. [4]

During the above survey, it was found that corrosive sulfur does not affect all countries worldwide.

Metal passivators

Triazole derivatives are used as metal passivators. This substance will chemically adhere to non-enameled, bare copper surfaces, forming a monomolecular layer (a coating on the surface, around 2 nm thick) that blocks copper involvement as a reactant in the copper sulfide formation and hinders copper catalytic activity as an oxidation catalyst. [5],[6],[7],[8].

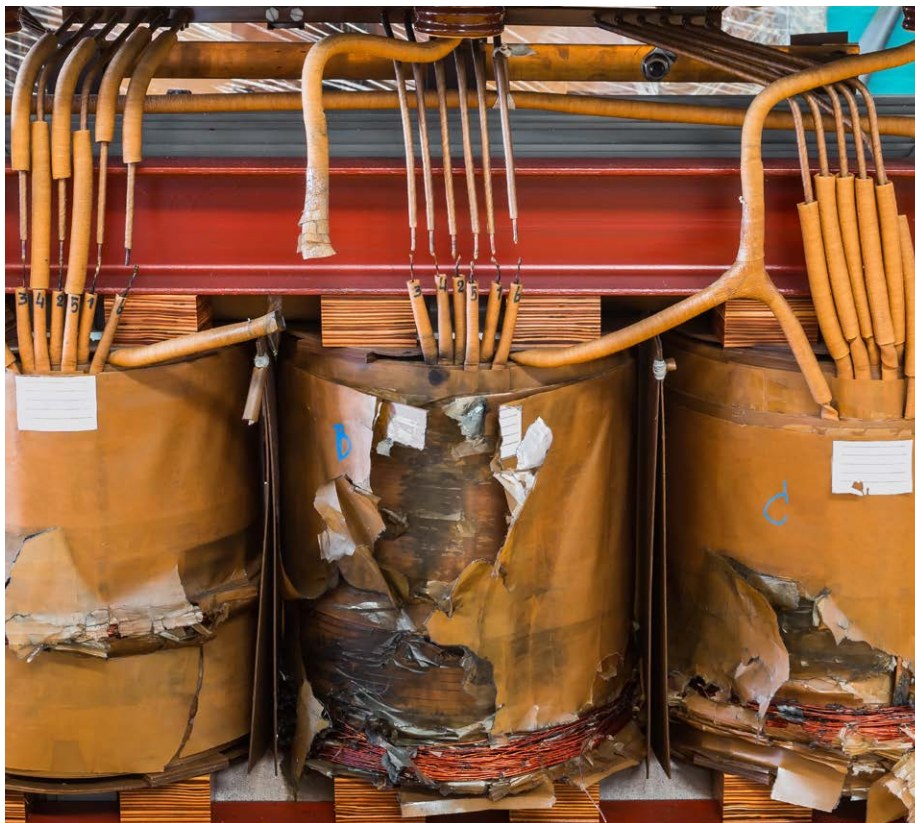
Metal passivators are polar compounds that tend to be absorbed in the paper and attach to other metal surfaces. The amount of metal passivator spent for coating other metal surfaces has not been quantified but is likely to be very small and below the standard deviation limits for the test method for metal passivator determination. Therefore, it is assumed that negligible amounts of added metal passivator spent for coating of other metal surfaces, whereas a higher amount is spent for absorption in cellulose materials, and this is likely to be more pronounced at elevated temperatures, which speed up transport of metal passivator into the paper [9],[10]

Metal passivators are sometimes called oil passivators, and this is incorrect. Naturally, the oil is the medium of transfer for the metal passivator to the metal surfaces and into the transformer's solid insulation. It should be referred to as "oil containing metal passivator."

The suggested concentration for the metal passivator is 100mg/kg, but amounts up to 200mg/kg in oil may be added to achieve a higher saturation level of the metal passivator layer on the copper surface. Concentrations of less than 50mg/kg of metal passivator are considered ineffective. [11]

Metal passivators and oil condition

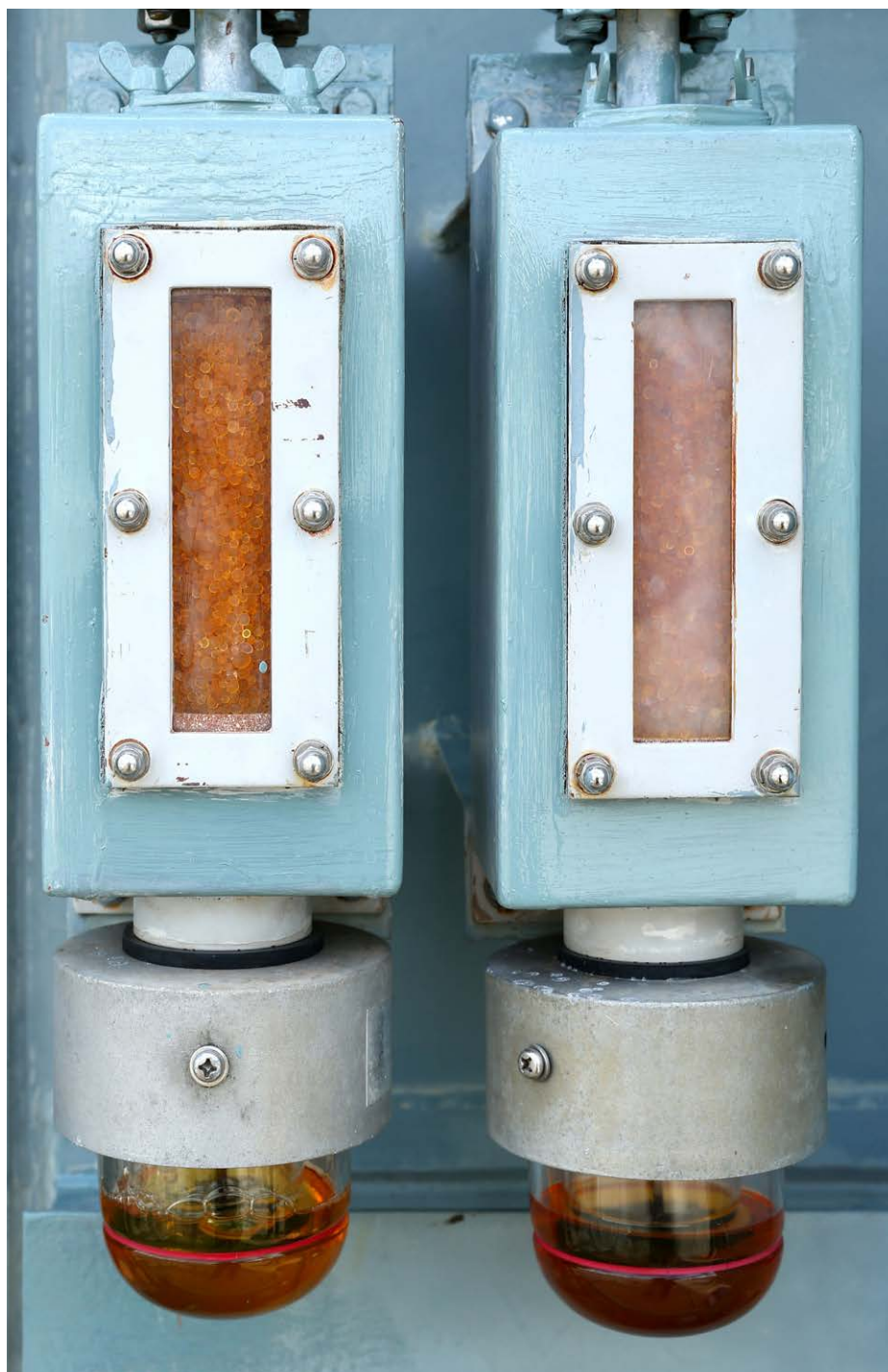
The long-term efficiency of metal passivators regarding temperature, oxygen, and oil aging products was investigated. Low base oil quality and higher amounts of acids in aged oils will decrease metal passivator stability.



PAPER	TOTAL SULFUR CONTENT*	TOTAL SULFATE CONTENT*
Kraft Paper - 1	700 ppm	205 ppm
Kraft Paper - 2	300 ppm	<7.5 ppm
TU-Kraft	700 ppm	158 ppm
Kraft Crepe Paper - 1	600 ppm	93 ppm
Kraft Crepe Paper - 2	500 ppm	30 ppm

* Total sulfur analysis was performed by ASTM Method D 129 and Total Sulfate analysis was performed by EPA Method 300.0

Table 2: Sulfur composition in various electrical papers [2]



Metal passivators were found to be highly efficient in new oils. The more oxidized the oils were, the the metal passivator efficiency decreased. This could be attributed to the degradation of metal passivator under the attack of peroxides and acids.

Conclusion

It is clear from all this that sulfur and sulfur-bearing compounds in transformer mineral oil can present a multi-faceted problem. Refining crude oil aims to remove as many

sulfur compounds through various processes, converting reactive compounds into stable ones.

There are many internal and external sources of sulfur within a transformer besides the oil.

Although the corrosive and reactive sulfur reactions can occur at ambient temperatures, it is theorized that higher temperatures may lead to the formation of corrosive or reactive forms of sulfur or reactive forms that allow reactions to occur between some sulfur compounds and metals.



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Transformer With Shell Diala S5 BD Successfully Tested By Siemens Energy For TenneT Project

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PERFORMANCE
NOW READILY
BIODEGRADABLE**



Shell supplied Shell Diala S5 BD, a state-of-the-art, readily biodegradable transformer oil, as part of a joint sustainability project of Siemens Energy, TenneT, and Shell. The collaboration decided to fill the power transformer for TenneT's transformer substation in Schwandorf, Germany with Shell Diala S5 BD. The unit is currently the biggest three-phase TenneT grid transformer in Germany with a rating of 650MVA / 400kV, and the power transformer is securing the high demand of energy in the southern part of Germany.

Shell Diala S5 BD is a state-of-the-art, readily biodegradable transformer oil made with Sulphur-free GTL Technology. The GTL innovation platform began in 2010, with the successful development and market introduction of Shell Diala S4 range. Based on the robust field experiences of Shell Diala S4 range and new market requests for more environmentally acceptable fluids, the further development of Shell Diala S5 BD was a logical step. Shell Diala S5 BD is a high-grade, inhibited transformer oil with a high degree of compositional consistency that meets and exceeds the ASTM D3487 (Type II) and IEC 60296 Ed5 (type A) specification in addition to OECD 301B. The oil is fully miscible and compatible with conventional mineral oils, which is beneficial for top-up, replacement, and standardization. Sulphur-free GTL Technology also eliminates the risk of corrosion caused by corrosive Sulphur and offers superb oxidation stability, resulting in extended transformer oil life. Shell Diala S5 BD also offers extreme cold temperature performance and is already generating demand from electrical projects that may experience arctic temperatures.



**Shell
Diala**

The transformer has successfully passed the factory acceptance test at the Siemens Energy factory in Nuremberg, Germany, and is ready for dispatch to its deployment site in the substation Schwandorf some 90 kms east of Nuremberg.

The end customer, TenneT, is a leading European grid operator and manages the high- and extra-high voltage grid in the Netherlands and large parts of Germany. As the first cross-border Transmission System Operator, TenneT designs, builds, maintains, and operates 24,500 km of high-voltage electricity grid.

After technical examination of the transformer oil's parameters, TenneT chose Shell Diala S5 BD. The performance of Shell Diala S5 BD is high-level with proven Shell Diala S4 range, combined with the big advantage of biodegradability. TenneT sees Shell Diala S5 BD transformer oil as an important step towards a more sustainable transformer.

"Shell believes that improving sustainability credentials does not mean sacrificing performance," said Ed van Schaik, Product Application Specialist for Shell Diala Transformer Oils. "Shell Diala S5 BD supports transformer operators in overcoming the biggest challenges currently facing the industry, by enabling their equipment to handle harsh cold climates and new environmental needs. By diminishing downtime and extending effective transformer life, Shell Diala S5 BD helps businesses lower Total Cost of Ownership of equipment."

"Without any compromises in terms of performance and durability, we jointly provide add value and strengthen our customer's market appearance," said Mate Sicenica, Sales Director of the Siemens Energy Transformer Factory Nuremberg. "On top, we take over responsibility towards our nature and society. A big thanks to Shell and TenneT for all their support and assistance during the whole project execution."

SHELL DIALA S5 BD TRANSFORMER OIL EXCELLENT COLD TEMPERATURE PERFORMANCE



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Tale of Two Esters

Why the Natural One is the Better Dielectric Fluid

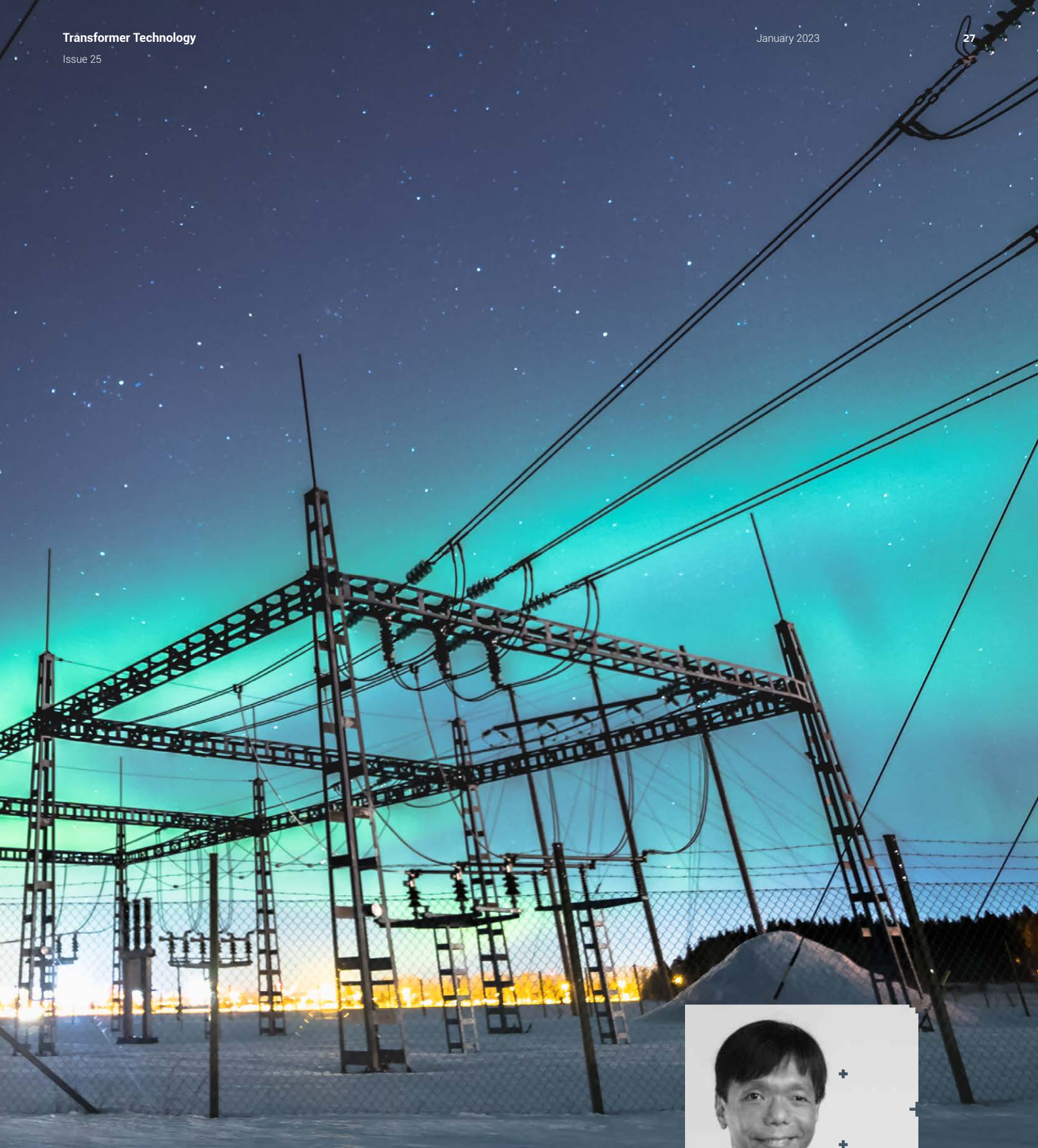
by **Kin Yu Lam**

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In the quest to replace banned PCB compounds as an alternative liquid insulation for the fire safety of transformers and similar electrical equipment, ester-based dielectric fluids are often

the preferred choice because of their environmental benefits and good compatibility with conventional mineral oil. Despite its commercial introduction more than a decade later than syn-

thetic ester fluid, natural ester, which is largely derived from vegetable seed oil, is by far the market leader now among alternative dielectric fluids, it being used in some 3 million transformers globally [1].

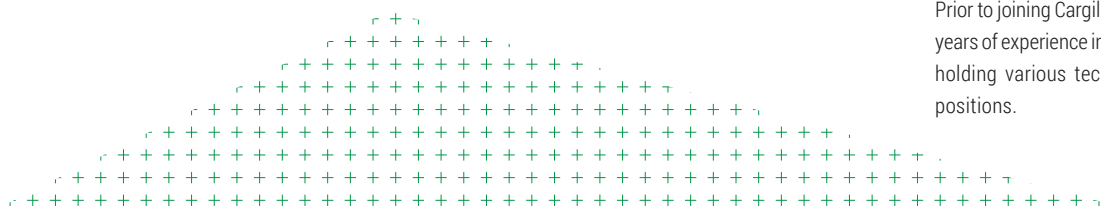


This article reviews and discusses what makes natural ester the insulating

liquid of choice over synthetic ester under most conditions.



Kin Yu Lam is currently the Regional Application Engineering Leader with Cargill Bioindustrial based in Singapore. Kin Yu holds a Bachelor and a doctorate degree in chemistry from Newcastle University in the United Kingdom. Prior to joining Cargill, Kin Yu has over twenty years of experience in the lubricants business holding various technical and managerial positions.



Fire Safety Assurance for New and Retro-filled Transformers

As ester-based dielectric fluids were originally developed to replace PCB compounds, it is not surprising that the prevention of pool fire in the event of transformer failure is still widely regarded as the key objective for selecting such fluids over mineral oil. In a recent study conducted by an IEEE task force [2], however, the fire point of one of the commercial synthetic ester fluids was found to be at the borderline 300°C limit for the K-class less flammable liquid and it even dropped below the limit after 424 hours of thermal ageing at 180°C. This raises concerns about its compliance to relevant fire safety regulations.

With a typical fire point above 350°C, meeting the limit for the K-class liquid is never an issue for both unused and in-service natural ester fluids. The high fire point of natural ester also means it is effectively the only option for on-site retro-filling of transformers previously running on mineral oil, since it can tolerate up to 7% (by weight) of mineral oil contamination without showing a significant drop of its fire point (Figure 1) [3]. For retro-filling with synthetic ester, even for those consistently meeting the K-class liquid standard, the fire point would drop below the required limit at much lower residual mineral oil levels, thereby necessitating a complete oil change under factory environment.

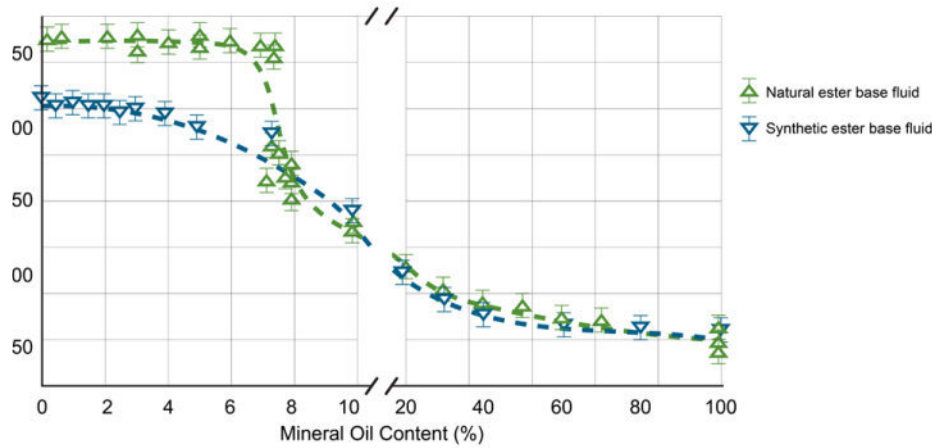


Figure 1. Fire points of natural and synthetic ester fluids at different residual mineral oil contents

WHILE FIRE SAFETY AND ENVIRONMENTAL BENEFITS ARE KEY ISSUES IN THE SELECTION OF DIELECTRIC FLUIDS, PERHAPS THE MOST IMPORTANT FACTOR THAT SETS NATURAL ESTER APART FROM SYNTHETIC ESTER IS THE FORMER'S PROVEN ABILITY TO RETARD THE AGEING OF CELLULOSE PAPER INSULATION.

Environmental Benefits Beyond Biodegradability

Apart from providing greater assurance of fire safety in new and retro-filled transformers, natural ester is also preferable over synthetic ester from an environmental perspective. While both esters are readily biodegradable and non-toxic to the environment, only natural ester is derived from plant crops widely available globally and inherently sustainable. That means apart from being more cost effective, the carbon footprint of natural ester is also much lower than synthetic ester. According to the Building for Economic and Environmental Sustainability (BEES) tool developed by the US National



Institute of Standards and Technology (NIST), the lifecycle greenhouse gas emission from FR3® Fluid, the most used natural ester fluid derived from soybean oil, is only about 20kg per 1,000 liters, or just 1.8% that of mineral oil, making it effectively a carbon neutral fluid [4].

In contrast, as the raw materials of synthetic ester are mostly derived from petroleum sources, its carbon and environmental footprint is expected to be similar to mineral oil. With the drive toward sustainability and in particular, zero carbon, becoming increasingly a business mandate, natural ester is obviously the preferred choice of fluid for most end users.

Equipment Lifespan and Reliability

While fire safety and environmental benefits are key issues in the selection of dielectric fluids, perhaps the most important factor that sets natural ester apart from synthetic ester is the former's proven ability to retard the ageing of cellulose paper insulation.

As shown in the IEEE C57.100-1999 sealed tube accelerated ageing tests, the useful lifespan of cellulose paper can be extended by up to 12 times in natural ester as compared to mineral oil [5-6] because of its unique double

moisture removal actions through absorption and hydrolysis [7]. This ability to continuously dry the paper insulation in transformers is one of the most important properties of natural ester as a dielectric fluid, as apart from operating temperature, high moisture level is another main cause of cellulose paper degradation.

Continuous removal of moisture not only extends the life expectancy of paper insulation, but it can also help to significantly reduce the risk of dielectric breakdowns as well, as moisture is the main culprit in the reduction of dielectric

BESIDES THE PROLONGED INSULATION LIFE THAT COMES WITH IMPROVED RELIABILITY AS DESCRIBED ABOVE, ITS UNIQUE ABILITY IN RETARDING THE DEGRADATION OF CELLULOSE PAPER ALSO MAKES NATURAL ESTER THE FLUID OF CHOICE FOR INCREASING THE LOADING CAPACITY OF TRANSFORMERS.

strength in paper insulation [8] and in the formation of bubbles on the paper surface [9]. Natural ester's outstanding moisture handling properties therefore play an important part in enhancing the reliability of transformers and in reducing the maintenance needed for drying both paper and liquid insulations regularly.

Although synthetic ester is capable of absorbing even more moisture than natural ester due to its higher moisture saturation point, its ability to prolong the lifespan of cellulose paper has never been demonstrated to the same extent, most likely due to the lack of favorable hydrolytic properties in eliminating moisture chemically.

With the more sterically hindered molecular structure, synthetic ester is generally less susceptible to hydrolysis. This means it is less able to consume the potentially high level of moisture held in the liquid. Even when hydrolysis eventually takes place in synthetic ester, as evidenced in a recent study on the ageing behavior of insulating liquids under high humidity and air exposure [10], the shorter chain fatty acids formed as a result are much more aggressive to the insulation paper. Conversely, in natural ester, the long chain fatty acids formed from hydrolysis are generally non-aggressive and actually help to stabilize the cellulose structure in the paper insulation against degradation [11].



Photo: Cargill

Loading Flexibility and Network Optimization

Based on results obtained from accelerated ageing tests on cellulose insulating papers as described earlier, both the IEC and IEEE standards for high temperature insulation systems [12-13] make provisions for the thermal class of standard and thermally upgraded Kraft papers to be increased by 15°C and 20°C, respectively, with natural ester fluid. As a result, the hot spot temperature limit for natural ester-filled transformers can also be raised proportionately, leading to the possibility of increasing the rated load capacity.

With the feasibility of increasing the nameplate capacity by up to 50% at 95K AWR [14] without the use of costly aramid material, the more compact natural ester-filled transformers can be deployed for applications where space constraint may be an issue, for example, in skid units at solar farms and in towers or nacelles of wind turbines [15].

Increasingly the extra loading capacity provided by natural ester-filled transformers is also becoming the key enabler for driving network optimization while achieving energy and material sustainability using the so-called sustainable peak loading approach [16]. With the availability of historical loading profile data obtained from smart meters, conventional mineral oil transformers with low average load factor can be identified and replaced by more compacted units running on natural ester fluid. While the extra loading capacity from the smaller natural ester-filled sustainable peak loading transformers can be utilized to cope with the peak loading demand without affecting insulation life, the lower no-load loss of the smaller units can help to improve utilization and overall energy efficiency for the power grid, as well as significantly reduce the use of non-renewable materials in building the transformers [17].

For synthetic ester-filled transformers, it is not possible to increase the loading capacity in the same way due to its inability to

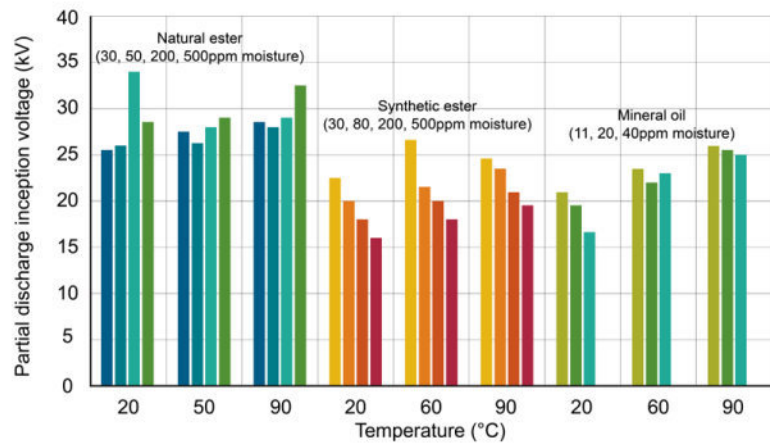


Figure 2. Partial discharge inception voltage of natural ester, synthetic ester and mineral oil as measured according to IEC TR 61294:1993 at different temperatures and moisture levels

achieve higher thermal class with conventional cellulose papers. To build synthetic ester transformers with increased rated load at higher AWR, solid insulation of higher default thermal class [18], such as the much more expensive Aramid paper, would have to be used, making it much less economically viable.

Dielectric Properties and Impact of Harmonics

As for dielectric properties, both natural and synthetic esters tend to have lower streamer inception voltage than mineral oil under extremely inhomogeneous fields due to their more polar molecular structure. Although this means lower breakdown voltage from ester fluids in impulse tests using highly divergent electrode systems, in practice, it would not be a major issue in the design of internal leads connecting the windings to the bushings and tap changers in power transformers, as it has been shown that there would be no significant difference in the breakdown voltage limits for test electrodes down to 3 mm [19].

On the other hand, the partial discharge inception voltage (PDIV) of natural ester as determined in accordance with IEC TR 61294:1993 is significantly higher than synthetic ester and mineral oil (Figure 2) [20]. The high level of unsaturated fatty acids in natural ester, which tend to slow down the propagation of discharge within its molecule, is thought to be the main reason for this phenomenon.

Apart from providing greater safety margin for transformers designed to be partial discharge free with mineral oil, the higher PDIV of natural ester also makes it the preferred choice of fluid for transformers connected to renewable energy resources. With its higher PDIV and thermal stability as compared to mineral oil, the use of natural ester fluid has been found to be effective in reducing hydrogen gas generation and sludge formation in transformers exposed to harmonics rich output from solar inverters (results to be published). In addition, a simulation study has also proven that the use of natural ester in place of synthetic ester could help reduce X-wax formation in transformers of high field strength, including those

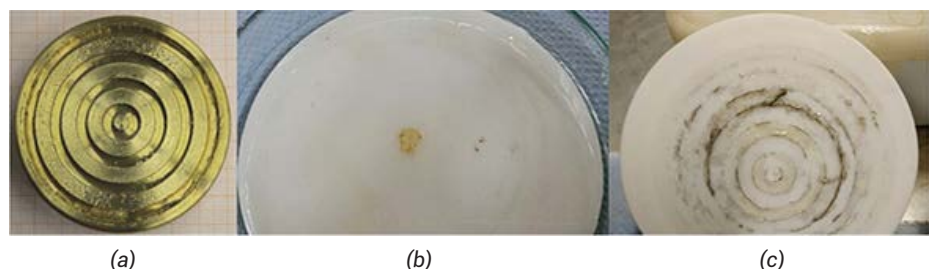


Figure 3. Partial discharge simulating test for X-wax formation. (a) brass electrodes used to represent the winding wires in transformer; (b) trace of ageing product formed after the test with natural ester liquid; (c) X-wax formed after the test with synthetic ester liquid

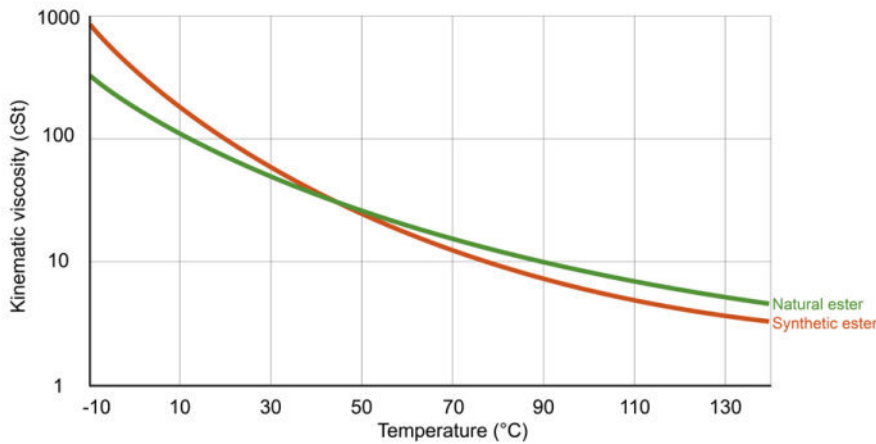


Figure 4. Kinematic viscosity of natural ester and synthetic ester

used in wind turbines, again due to its ability to suppress partial discharge activity (Figure 3) [21].

Low Temperature Properties

Despite the higher pour point as compared to mineral oil and synthetic ester, in most cases the general recommendations for energization under cold conditions as described in clause 4.4.4 of IEEE C57.93-2019 [22] are considered sufficient for low temperature startup of natural ester-filled transformers. Unlike mineral oil, the existence of free water is not a main concern at low temperatures for both natural and synthetic esters.

From the perspective of cold starting, the main benefit of synthetic ester is its low tendency to form crystals at low temperatures, which is particularly advantageous for power transformers equipped with devices like Buchholz relay that come with fluid conservators. However, at temperatures above pour point, the viscosity of synthetic ester is significantly higher than that of natural ester (Figure 4), which may reduce the fluid flow inside the cooling ducts of the windings, leading to poorer heat transfer and cooling efficiency.

The Real Issue of Oxidation Stability

Although some users may still consider oxidation stability to be a concern for natural ester, much of this misinformation has been corrected by extensive studies and field experiences [23].

While natural ester is by nature more susceptible to oxidation than synthetic ester and mineral oil because it is mostly made of unsaturated fatty acids, with advanced refining and formulating technologies it is capable of operating in free breathing transformers for many years without exceeding the critical control limits for in-service insulating liquids. Even in the unfavorable situation where impregnated parts are left exposed to air without submerging in the fluid, it would still take more than two weeks under hot and humid

Fluid type	Natural ester	Synthetic ester	Limits for in-service liquid/paper [25-26]
<i>High humidity accelerated ageing test under open air (80°C; 80-100% humidity; 4 weeks)</i>			
% Increase in viscosity @40°C	13%	0%	<15%
Breakdown voltage (avg/max) (kV)	20.3/26.5	13.4/14.4	>30
Moisture content (ppm)	1,368	1,696	<400
Total acid number (mgKOH/g)	0.06	0.05	<0.5
Dissipation factor @90oC/50Hz	0.012	0.016	<0.5
<i>High temperature accelerated ageing test under open air (130°C; ambient humidity; 5 weeks)</i>			
% Increase in viscosity @40°C	20%	0%	<15%
Breakdown voltage (avg/max) (kV)	61.1/68.9	57.0/64.4	>30
Moisture content (ppm)	376	94.2	<400
Total acid number (mgKOH/g)	0.25	0.03	<0.5
Dissipation factor @90oC/50Hz	0.056	0.032	<0.5
Retained tensile strength of paper insulation (%)	61.4%	34.0%	>50%

Table 1. Test results on natural ester and synthetic ester dielectric fluids after accelerated ageing tests under open air condition [10]

APART FROM PROVIDING GREATER SAFETY MARGIN FOR TRANSFORMERS DESIGNED TO BE PARTIAL DISCHARGE FREE WITH MINERAL OIL, THE HIGHER PDIV OF NATURAL ESTER ALSO MAKES IT THE PREFERRED CHOICE OF FLUID FOR TRANSFORMERS CONNECTED TO RENEWABLE ENERGY RESOURCES.

conditions for a well formulated natural ester fluid to show any sign of thin film oxidation, thereby making it feasible to carry out most routine maintenance and repair work on transformers without much concern and inconvenience [24]. In a recent study aimed at evaluating the ageing characteristics of different types of dielectric fluids under open air conditions, most of the critical parameters of natural ester associated with fluid oxidation were found to be within the limits for in-service liquids (Table 1) [10]. And even though the breakdown voltage recorded from all the samples subjected to high humidity dropped below the limit for in-service liquids due to the high level of moisture present, those from



Ester fluid type	Number of records		H ₂	CH ₄	C ₂ H ₆	C ₂ H ₄	C ₂ H ₂	CO
			Soybean natural ester	4,378	90th percentile	112	20	232
	95% confidence level	(105-118)	(19-22)		(219-247)	(17-20)	(1-1)	(150-179)
Synthetic ester	157	90th percentile	64	104	124	150	13	1344
		95% confidence level	(52-82)	(49-135)	(105-362)	(79-215)	(0-33)	(937-1526)

Table 2. DGA thresholds of soybean natural ester and synthetic ester as per the IEEE DGA Guide for ester fluids [27]

WHILE THE EFFORT SPENT ON ENHANCING OXIDATION STABILITY AND LOW TEMPERATURE CHARACTERISTICS HAS ENABLED SYNTHETIC ESTER TO BE USED IN SOME NICHE APPLICATIONS, BY AND LARGE IT HAS ALSO COMPROMISED SOME OF THE MOST IMPORTANT PROPERTIES THAT COME WITH NATURAL ESTER, INCLUDING RAW MATERIAL AVAILABILITY, COST EFFECTIVENESS AND SUSTAINABILITY.



The overall results, therefore, bring home the point that free breathing conditions are not suitable for all liquid-filled transformers, as the reduction in dielectric strength and increase in paper insulation degradation rate are areas of bigger concern than the oxidation of natural ester. In comparison to synthetic ester, natural ester would enable transformers to better cope with temporary free breathing conditions in the event of a breach in the sealing system before the necessary maintenance work can be carried out.

Condition Monitoring Capability with Dissolve Gas Analysis

As the most widely used alternative dielectric liquid, a large amount of dissolved gas analysis (DGA) data has been collected for natural ester fluid derived from soybean oil. As shown in Table 2, the 90th percentile thresholds of the combustible gases for soybean oil based natural ester are statistically much more reliable than synthetic ester, as indicated by the much smaller variance (95% confidence level) [27]. DGA results can therefore be analyzed and interpreted with much higher confidence level for this type of natural ester fluid.

When Natural is Better than Synthetic

While the effort spent on enhancing oxidation stability and low temperature characteristics has enabled synthetic ester to be used in some niche applications, by and large it has also compromised some of the most important properties that come with natural ester, including raw material availability, cost effectiveness and sustainability. With regard to the key aspects of dielectric fluid as summarized in Table 3, one would have to conclude that in the tale of the two esters, the natural one is indeed the better choice over the synthetic one in most applications.

natural ester were significantly higher than synthetic esters.

More importantly, the retained tensile strength of the insulation paper samples immersed in synthetic ester also dropped below one of the end-of-life criteria of 50% after the ageing test at high temperature (Table 1).

This clearly demonstrates that the presence of air and moisture would pose an even bigger threat to the paper insulation. With natural ester the paper insulation is in fact much better preserved under such conditions due to its unique paper drying properties as described earlier [5-7].

	Natural ester	Synthetic ester
Base fluid type	Vegetable oil	Pentaerythritol ester
Fire point	>350°C	~305-315°C
Biodegradability/toxicity	Best in class	Readily/non-toxic
Biobased/carbon footprint	Yes/very low	No/similar to mineral oil
Increase of cellulose paper lifespan	Up to ×12	Marginal
Increase in thermal class of cellulose paper	15-20°C	No
General dielectric properties	Equivalent to mineral oil	Equivalent to mineral oil
Partial discharge inception voltage	Higher than mineral oil	Lower than mineral oil
Crystallization at -25°C	Yes	No
Viscosity at -10°C	~330cSt	~730cSt
Fluid oxidation stability	Adequate	Good
DGA Diagnostic capability	Robust	Limited

Table 3. Comparison of key properties of natural and synthetic esters

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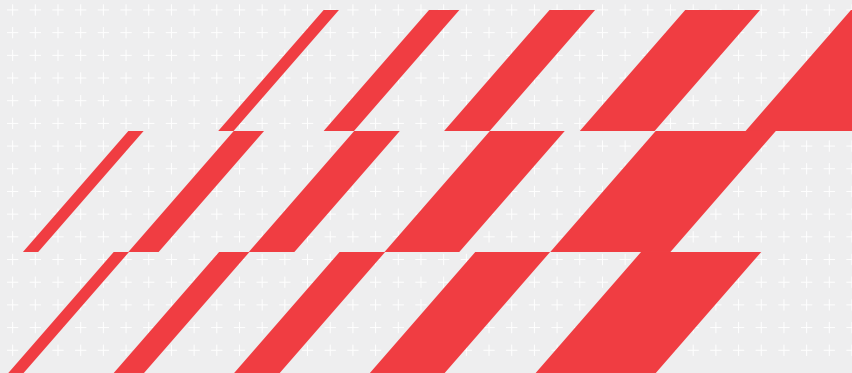
Inspire the Next

Raleigh North Carolina cityscape at night



Hitachi Energy establishes Engineering Design Center in Raleigh, North Carolina for its North American transformer manufacturing operations

Hitachi Energy's Transformers business is establishing a North American Engineering Design Center at the company's regional headquarters in Raleigh, North Carolina. Located on the Centennial Campus of NC State University, the Raleigh offices will now have a dedicated wing to host its critical transformer design engineering team. This new Center of Excellence brings together the business unit's talented engineers into a central hub to support in-demand engineering activities and will also serve as a focal point for the group's technical recruiting efforts.



Power transformer designed, engineered, and manufactured by Hitachi Energy



Why Raleigh?

Selecting Raleigh was an easy decision. Raleigh has seen significant growth over the last few years with numerous companies specializing in technology and innovation flocking to the area. The transformer business within Hitachi Energy intends to tap into that energy to draw in the best talent to expand its existing community of world-class engineers.

The area is also appealing for the nationally recognized universities and research institutions located throughout Raleigh and surrounding communities, which also make it attractive for families and students seeking access to a variety of continuing education opportunities.

“ Establishing this Engineering Design Center in an attractive location like Raleigh, allows us to expand on our strong factory-based design centers and take advantage of a strong, diverse pool of engineering talent developed by the presence of so many well-known educational institutions. Raleigh is a very livable community, which we believe will be attractive to qualified candidates from around the country and the world, who are interested in participating in the clean energy transition with one of the leading transformer manufacturers in the world. ”

Steve McKinney

Head of Transformers Business, North America

Like most manufacturing companies, Hitachi Energy's operations focus on continuous improvement and other lean techniques to establish efficient and streamlined workflows.

“ If one factory does something a certain way, and another factory does it differently, we have missed the opportunity to simplify our design processes for consistent and repeatable quality; for our employees and ultimately customer satisfaction. ”

Susmitha Desu

Head of Engineering, Transformer Business, North America

The benefits of bringing teams together have been documented in numerous studies. Many point out better problem solving, increased potential for innovation, more engaged employees, and overall improved morale.

Hitachi Energy's Transformer business in North America continues its goal of becoming the area's Employer of Choice. Offering the flexibility of a modern work/life balance and the excitement of one of the nation's most admired locations, the company aspires to build a team of engaged engineers that truly make a difference.



HITACHI

Inspire the Next



Characteristics of Modern Transformer Oil



by Chris Kenney	President
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Chris Kenney spent the majority of his time in the refining industry in the sales and marketing of specialty hydrocarbon fluids, more specifically in transformer oil sales. Chris has worked in sales and sales management with Ergon Refining, Cross Oil, Petro Canada and most recently, Calumet Specialty Products. In all these assignments, he was at the forefront in business development roles dedicated to developing net new transformer oil market share. Chris is an expert in the technical aspects of both naphthenic and paraffinic transformer oils and has established worldwide contacts in the power transformer industry and US utility industry. Chris holds a Bachelor of Arts from St. Joseph's University, and currently resides in Acworth, GA with his wife Karen. Chris is available for either full, or part-time consultation arrangements regarding the sale and marketing of transformer oils.

This article will focus on the characteristics of modern hydrocarbon transformer oil as it relates to current refining technologies being used to guarantee the highest quality finished products available and adherence to all ASTM 3487 standards. In a recent article in Transformer Technology, I presented the fact that refining methodologies used to refine current production hydrocarbon-based transformer fluids have improved greatly over the past number of years. All the major refiners of finished transformer oil stock have completed various degrees of refinery upgrades in terms of hydrotreating severity. The units in place today all meet the minimum standards of heat and pressure that can be used to reform their crude slates to varying degrees of finished quality.

Some have significantly upgraded their vessels to produce very high-quality materials which far significantly exceed the minimum standards.

Although we hear much in the news and political sphere about the evils of the hydrocarbons which make our current life so enjoyable, the fact remains, many industries are inextricably linked to the use and dependence on hydrocarbons in various form for many years to come. It is true, new technologies and products have arisen to maybe one day replace conventional oil-based transformer fluid, but for the meantime and at least the foreseeable future, most large OEM substation and large power transformer manufacturers will continue to hydrocarbon-based products to fill their units.

In the standard grouping of **ASTM 3487** tests used to prove the quality of current insulating oil acceptance, there are certain tests which speak directly to the improvement in oil refining technology. **ASTM D2440** is one of them. **ASTM D2440** is a standard test which measures an oil's resistance to oxidation either in normal operating conditions or under more severe conditions, such as heat, vibration, shock loading, surge voltages or general high electrical stress. The chemical reactions to conditions inside the transformer can result in sludge build up and elevated acidity. Like most chemical reactions, heat is a major accelerator. Much of the severe decay of transformer oil can be and is prevented by regular testing of the oil inside the unit. Like a good doctor who orders regular blood work.



Much of the deterioration of the oil can be prevented by dealing with the factors causing the breakdown in the first place. The reason modern day naphthenic based transformer oils are able to perform their resistance to oxidation so well in the field is due to the plant modernization factors mentioned above. Naphthenic hydrocarbon compounds are classified as closed-chain or ring compounds. They are a non-aromatic ring structure of carbon atoms.



Contained within all petroleum compounds before being severely hydrotreated are also non-hydrocarbons or often referred to as hetero compounds. These hetero compounds may be classified as sulfur, oxygen or nitrogen atoms. There are also naphthenic acids present in the distillate prior to treating as well as trace metals, esters, alcohols, ketones, and peroxide compounds. It should be noted that all these compounds have one thing in common—an oxygen atom. If allowed to proceed, all these compounds will act upon each other and the original oil. The resulting product will be sludge. A finished hydrocarbon-based transformer oil must be relatively free of all these hetero compounds. Today's naphthenic transformer oils are highly refined to perform the heat transfer and arc quenching demands made upon them. They are very resistant to oxidation and resulting issues that come from oil breakdown.

Over the past few years, type 1 transformer oils have virtually disappeared from user's RFQ specification requirements. There was a day when these "so called" type 1 oils were the primary oils used among the direct to utility market. The major oil companies, who no longer for the most

part, offer transformer oils, all had type 1 offerings. The only difference in the type 1 and type 2 is due to % content in oxidation additive in each product. I assume buyers moved to type 2 oils because price differentials pretty much disappeared, and they received more oxidation protection for essentially the same price.

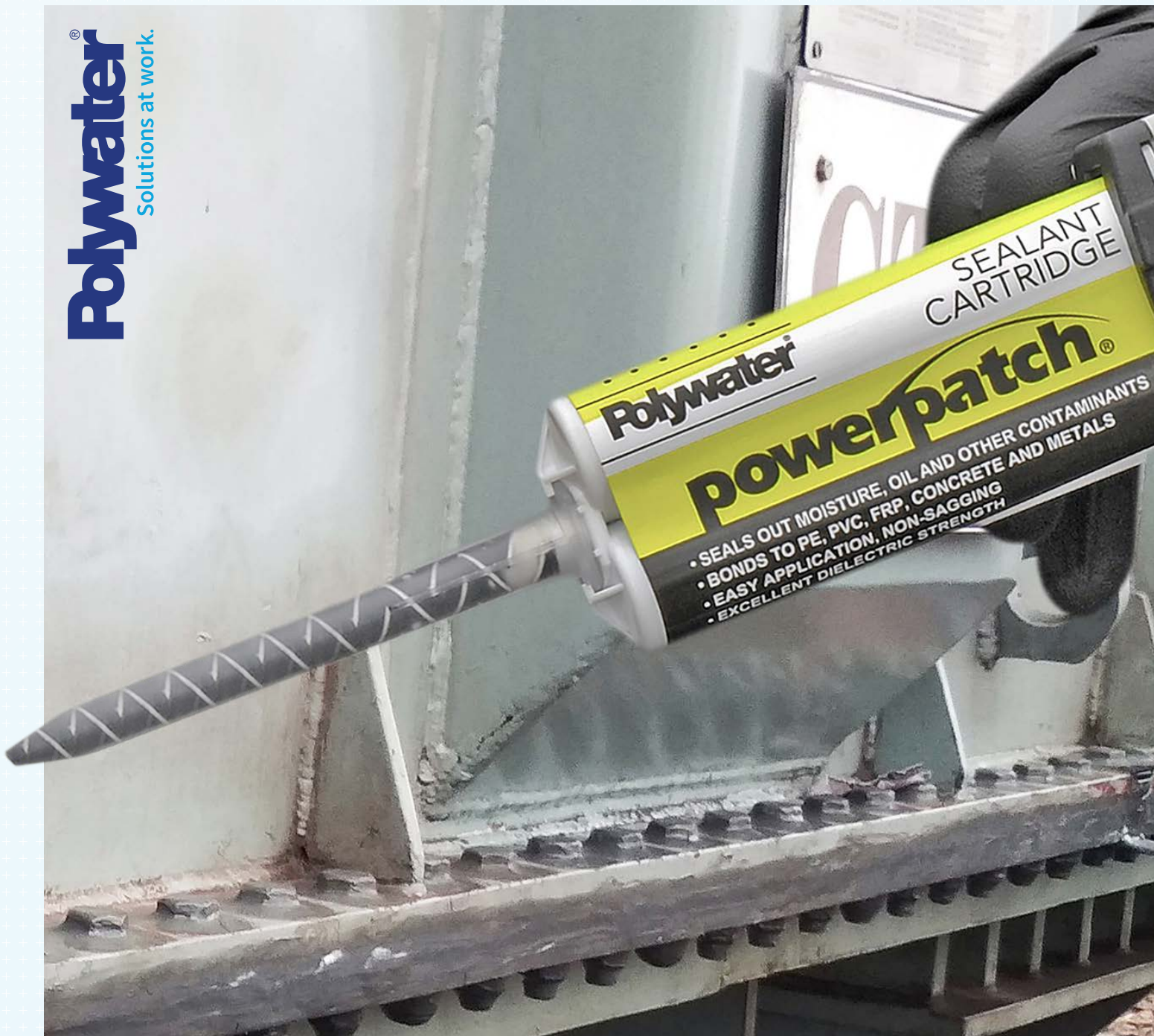
ASTM D2440 is not normally considered an acceptance specification at the time the oil is received by the buyer. The normal acceptance tests are normally **ASTM D1816** which is a dielectric strength test as well as moisture content. In rare instances, power factor is taken at delivery site. Crude selection also plays a role in degree of difficulty for the refiner to overcome when running his crude slate at the refinery. Naphthenic crudes are generally not especially acidic or sour. Some of the best naphthenic crudes are actually quite clean relative to other crudes refineries are asked to deal with.

For the foreseeable future, the transformer industry can look forward to a dependable, stable supply of high-quality hydrocarbon based transformer fluids coming out of a more than a few upgraded naphthenic base oil producers here in North America.



Gasket Repair made Quick and Easy

Polywater
Solutions at work.



Transformers and switchgear in substations and switchyards need to operate efficiently for the grid to supply the power needed by industry, commercial establishments and households. Important to access and affordability of electrical power is the reliable operation of the many power transformers in the power grid. The leakage of dielectric oil from transformers impacts the continuity and quality of the electrical service supplied by power transformers during their operation. Quick and cost-effective infield repair of oil leaks using the innovative sealant technology from Polywater, PowerPatch® is often used to minimize such performance degradation.

Compared to traditional repair processes, the use of Polywater® PowerPatch has proven to be a faster and more cost-effective oil leak remediation method in many cases.

Oil leaks are generated in a variety of ways, through pinholes, welding defects, worn gaskets and radiator cooling fin corrosion or rust. The loss of dielectric fluids from a power transformer can have many deleterious effects. High temperatures due to oil loss, affect the quality and dependability of the supply of power. High heat also contributes to accelerated decomposition of the solid

insulation which leads to accelerated aging of the transformer. Leaks also provide a gateway for atmospheric gases, such as oxygen and nitrogen, into the transformer. They degrade oil quality and further accelerate de-polymerization.



Oil leaks also create open pathways for moisture to enter the transformer. Moisture contributes to the natural aging processes within the transformer to reduce its useful life. The effective sealing of these pathways with PowerPatch helps to reduce the effects of moisture critical to improved grid performance and power quality.

Correcting problems caused by oil leaks can be complicated, costly, and time-consuming. Often, conventional leak remediation processes require long shutdowns of power to the transformer while repairs are being made. The use of in-field leak sealing processes that minimize

the time to repair/replace can lower the opportunity costs of lost service.

To better understand the time and financial impact of different corrective actions in the repair of transformer leaks, we will compare traditional gasket replacement to gasket leak repair using Polywater's PowerPatch leak repair system. We assess the time and cost needed for each process to stop an oil leak in the bell tank gasket. It will be assumed that the transformer is in proper functioning condition, but the nitrile gasket has failed. The Table 1 (next page) compares these two processes to stop a main gasket oil leak: Conventional Gasket Replacement and the use of the PowerPatch Leak Repair System. First a description of the transformer leak and resources required for replacement. In this particular instance we will use the example of a 22 MVA – 60 / 13.8 kV – 192 5/920 4. A transformer that weighs 37,100 kg in total, of which 18,600 kg fall to active parts, 8,900 kg to the oil, and 4,000 kg to the tank. In this example, the transformer in question has developed a defect: An oil leak from the main gasket between the tank and the tank cover.



CLOSE-UP OF POWERPATCH GASKET SEAL

Gasket Replacement (The traditional method)

Work required: Replacement of gasket between the main tank and tank cover. See Table 1 (next page).

Traditionally, gasket replacement procedures require a lot of equipment: A 30-ton telescopic crane, a holding tank with a minimum capacity of 3,000 l (2,600 kg), an oil treatment system with a minimum oil treatment capacity of 5,000 l/h, a power unit of 80 to 100 kW (in the event there is no energy source), a tool kit, measuring instruments, safety equipment, service materials, (gloves,

insulated blankets, grounding cables), and auxiliary equipment (chain blocks, hoists). On top of this long list of material requirements, the other most crucial resource is human labor in the form of 3 to 4 electro-mechanical technicians and 1 crane operator.

Table 1

Work Steps	Gasket Replacement	Gasket Repair
Shut-Down Energy & Verify	X	X
Raise Tank Top with Crane	X	--
Remove Original Gasket Material	X	--
Prepare and clean gasket perimeter	--	X
Lower Active Part back into tank	X	--
Place & Adjust Bolts	X	--
Apply quick cure putty over leaking areas	--	X
Abrade area around active leaks	--	X
Apply PowerPatch on perimeter & bolts	--	X
Transfer Oil to Oil Treatment Tank	X	--
Treat oil over two cycles-RH of 5 ppm	X	--
Monitor oil treatment over 24 hours	X	--
Final Oil Test Sample	X	--
Remove Earthing Cables	X	--
Reenergize Transformer	X	X

In short, oil tank gasket leaks are time-consuming and costly to rectify with conventional methods. Heavy equipment is required to lift the top and active part of the transformer to gain access to the gasket. Opening the tank exposes the transformer oil to moisture and atmospheric gases, which require oil treatment to reduce their deleterious effects.

Gasket Repair with PowerPatch

Work to seal the gasket: See Table 1.

With Polywater's method, the only equipment required to make immediate repairs to the gasket is a PowerPatch Kit and a team of 5 - 6 electro-mechanical technicians.

PowerPatch Features

The PowerPatch Leak Repair System offers a safe and effective alternative to conventional gasket replacement.



The PowerPatch system is used to seal the perimeter of the tank cover to stop active oil leakage. There is no need to lift the top of the tank, which limits exposure of the oil to the harmful effects of moisture and gases. The costs and time required for oil treatment are eliminated when PowerPatch is used.

Among the many features of PowerPatch, is its high-pressure resistance of 13.7 bar (199 psi) when adhered to steel. High pressure resistance pressure allows its use on large oil-filled power transformers and in sealing leaks in SF₆ insulated switchgear. Another valuable feature of



FULL GASKET, BOLT AND NUT SEALING

PowerPatch is its high dielectric breakdown voltage to minimize the potential for partial discharge in the transformer.

The multi-use PowerPatch cartridges (EPCT) are designed for repairs as small as pinholes in cooling radiator fins and valves and as large as oil tank main gasket repair. The application of the permanent resin described above can be applied with either 50-ml or 250-ml PowerPatch cartridges. The 50-ml cartridge is ideal for smaller repairs, while the 250-ml cartridge can be used for medium or larger repairs such as those found around flanges and bushings. The cartridges are multiuse to minimize resin waste, to reduce repair costs.

The two-part resin cartridges ensure accurate mixing of Parts A and B for maximum adhesion and consistent working times.



PREPARED SURFACE BEFORE APPLICATION

Other PowerPatch packages are available for other types of transformer repairs. The EP package consists of two small containers of resin Parts A and B. They are mixed manually, after which the combined resin can be applied with a wooden spatula to irregularly shaped areas needing repair. Both EPCT and EP packages include a quick-setting putty stick for the repair of active oil leaks, as described in the leak repair process above. PowerPatch Slow-Cure (EPSC) comes with 290-ml of Parts A and B and is used for large-area repairs. Its use is recommended for large, high-voltage transformers where the slower cure time of EPSC ensures sufficient working time for applying resin to the repair area.



FINISHED SEAL

Summary

The proper functioning of oil and SF₆ insulated equipment, essential components of electrical grids around the world, is critical. The quick and cost-effective repair of power transformer leaks ensures reliable and high-quality electrical services to homes, businesses, and industries. Using versatile and innovative sealant technology from Polywater for on-site repair of oil leaks has been shown to lower both the cost and time required. The costs of lifting- cranes, oil treatment systems, and other equipment needed for on-site gasket replacement were over \$10,000 higher than using the PowerPatch Leak Repair System. The use of Polywater PowerPatch leak repair products reduces transformer shutdown time from 24 hours to 8 to 10 hours and results in much lower costs.



For more information on Polywater PowerPatch, scan the QR code or contact us at global@polywater.com

Nurul Noor



The Siemens Energy logo is positioned in the top right corner. It consists of the word "SIEMENS" in a bold, teal, sans-serif font, with the word "ENERGY" below it in a purple, sans-serif font. The letters in "ENERGY" are spaced out, giving it a modern, digital feel.A simple, teal-colored icon of two curved lines, resembling a pair of quotation marks, is centered above the main text block.

We are also working towards strategic partnership and alliances within the energy industry ecosystem in which we will all collaborate and help each other.

Special Projects Manager
at Siemens Energy Malaysia

Interview with **Nurul Noor**

Dorotea Filipan: Hello. My name is Dorotea Filipan. I am the Project Manager of Women in Power Systems, an APC Media global organization that advocates for women in all different positions in the energy industry. My guest today is the wonderful Nurul Noor. She is a Special Projects Manager of Siemens Energy Malaysia. Nurul, welcome, thank you for being here.

Nurul Noor: Thank you for having me, Dorotea.

DF Now, you are a Special Project Leader for Cybersecurity in Siemens Energy Malaysia, is that correct?

NN I actually work together with a counterpart in Singapore. We work hand in hand, very much looking into strategic alliances and partnerships. We work very closely with researchers and universities, and we look forward to working closely with stakeholders in the energy industry. We are also working towards a sort of energy ecosystem in which we will all collaborate and help each other. Regardless of what business somebody is in. If they are in the energy industry, we would want to work toward a partnership.

The power industry is so important that I am often inspired to be part of the creative energy innovations.

DF That sounds ground-breaking! Something that we as WPS strongly advocate for is this interaction and collaboration. We believe that networking is the way to a better future. Now, would you tell us a little bit about your journey? What inspired you to dive into a career in the energy industry?

NN The power industry is actually one of the largest in the world and it is a sector that's vital to the life of a lot of people across the globe. Our economy and culture are only possible thanks to a steady stream of energy. This means, that in this industry you are automatically a part of something big. Therefore, I was truly inspired to be a part of it with the hope that I could be involved with energy innovation. Currently, I'm involved with several special projects for the company, which we've called the *Online Energy Shop and Strategy Alliance and Partnership*. Our current focus is on cybersecurity as the pandemic has taken the world to a totally different level of digital presence. This represents a major potential threat that needs urgent attention worldwide. So here again, part of

my team's effort is to build a solid ecosystem of collaborations and together to tackle this and other problems in this field. That is what inspires me every day.

DF Wow, that really is a vital cause you and your team have taken on. Not to mention a big one. What were some of the greatest challenges that you have had to face and overcome, specifically for this cybersecurity project and in your career in the energy industry as a whole?

NN My greatest challenge was actually curbing my own drive. I was doing a team project and taking over too much responsibility on the management side. I was a little too enthusiastic and started trying to handle as many items for the group as possible, believing that the more I did for the group, the better it would be. But as a result, I stretched myself too thin. So I started sacrificing a lot of my personal time and ended up being sleep-deprived. In the end, I realized that I could not do everything by myself and that having a competent team to divide the tasks of a large project is the best thing you can have and I'm very thankful for my team. We work very closely with everyone across the globe, especially with the US team. They have a totally different perspective in terms of cybersecurity and are very generous in exchanging information with us.

DF This is excellent and it brings us back to the importance of networking and global collaboration to create a better energy future for everyone. I would like to go back to what you said about stretching yourself too thin because you felt that you have to do more and more for your team. It's something we've all had to happen to us at



least once. So it is very important to be conscious of it and try to nurture a healthy work/life balance.

NN Exactly, this balance between home and work and work and pleasure is something that we try to promote as well because we are aware of the problem since we're all guilty of it in some way or another.

DF That is so important, isn't it? To have that sort of support from your professional environment.

NN Very much so. I started off this career journey with my manager, who has been very motivating and supportive. She encouraged me to complete my Microsoft Certified Azure AI Engineer Associate certificate. It was difficult but she was there for me every step of the way and I cherish that support to this day. And even more recently, because of all my participation, the VP has been very kind to write me a personal letter of recommendation to apply for the Cambridge Rising Women Leaders Program Scholarship 2022. So that's the kind of amazing support that I get from my company and the reason why this topic of support and acknowledgment is very close to my heart. I would encourage women in our industry to keep doing their best, keep vibing, good energy, and sooner or later the universe will place all the right people around you who will see it and who will help you to fly high.

DF That is fantastic. Congratulations on this letter of recommendation and on this acknowledgment, because that is what being valued and supported looks like: Your superior acknowledging your effort and your quality and rewarding it.

I would encourage women in our industry to keep doing their best and keep vibing good energy. The universe will then place all the right people around to help you fly high!

NN Thank you. Yes, exactly, it makes all the difference.

DF But this Cambridge program is not the only way in which you have been expanding your abilities if I remember correctly. You also quite recently returned to school and started your PhD in sociology.

NN Yes, this is a very personal thing for me. I've always had this question about people understanding people. So that is why I decided to study humans through sociology. My recent research was based on understanding millennial women.

DF That sounds very interesting. And do you feel that you will be able to apply this knowledge to the position and the business that you're currently in?

Strategy, alliances, and partnerships are not just straightforward, they also involve a lot of understanding and people skills and reading people's body language. My knowledge in Sociology will definitely help me strategize better when I meet people in a business capacity.

NN Oh, definitely. I'm currently handling strategic partnerships and alliances and am deeply involved in relationship-building. We have been meeting a lot of universities recently, talking about numerous kinds of relationships and collaborations. We agreed that our experts would visit each other and exchange knowledge and skills. The universities have got grad students working on new inventions, so they want the industry to be part of it. Strategy, alliances, and partnerships are not just straightforward, they also involve a lot of understanding and people skills and reading people's body language. My knowledge in Sociology will definitely help me strategize better when I meet people in a business capacity.

I'll give you one simple example. We have many engineers on the team and when they communicate, they used to speak in technical jargon and our Managers couldn't understand them. But when they were asked to simplify and explain, it was difficult for them. That's where the communication breaks and it will create unnecessary frustrations. But that is something that can actually be worked on successfully.

DF Yes, that is a very frequent issue in our industry. Technical people talking to salespeople and vice versa and each side has its own language so to say.



Photo: Siemens Energy

And then when those two worlds collide, communication issues happen. It is excellent to hear that companies and individuals are becoming aware of it and are looking for solutions. I would like to go back to the letter of recommendation from your VP, commending you for your work. Would you consider that to be the proudest moment in your career or would you like to add another one?

Even as a mother, I am still learning a lot from my children. My daughter taught me to 'Kill them with kindness!'

NN Oh, yes, that was very heart-warming for me and definitely one of my proudest moments. But the proudest moment in my career would be when I was put in charge of a new team and was able to present my interpersonal skills and deliver the best that I can. I was able to prioritize large workloads and share learning across diverse teams. I was immediately able to communicate all the problems, present potential solutions, improve interpersonal communication and improve problem-solving, all with a clear head in a fast-paced environment. We handle a lot of requests, we have to analyze a lot of details when it comes to coming up with a proposal for big companies, for big clients. But at the same time, I was appointed as the main committee for the launch of a ground-breaking ceremony of a cybersecurity hub in Asia Pacific for Siemens Energy. This was the first step for me into cyber security. And that same VP saw me being passionate about it. That's where he started to pull me into the next project, which is the strategy, alliance, and partnership focusing on cybersecurity. So this is my most recent achievement that I am very proud of.

DF And once again, a big congratulations from every one of us at WPS because again, one of the things that we do is to celebrate each other's achievements and hold each other up high. Now, I would like to switch gears a little and go back to some of your earlier points. You are clearly very passionate about your work but how do you stop it from dominating your life? How do you balance it out?

The company often send memos and videos on wellbeing issues to constantly remind us to keep the balance in life.

NN Our top managers here are very good at reminding you to keep the balance. If you send an email outside of office hours, eventually somebody will reach out, and remind you in a very considerate way that you shouldn't be working outside of your hours and that you should use this time for yourself. We also receive a lot of well-being memos from our HQ. They come up with fantastic videos to remind you that the job is not everything and that life has got so much more to it. On top of that, I make sure that my weekend is dedicated purely to my family and myself. On a Friday night we head to the movies and catch whatever is running at the cinema and we come back so happy. Over the weekend, I purely dedicate myself to my kids' karate and swimming, helping them with school projects which again can be challenging but fulfilling at the same time.

DF That sounds absolutely wonderful. I would like to continue with this perspective of you as a mother. You have one daughter and two sons, correct?

NN Yes, correct.

DF So from the perspective of a business-woman in energy, but also the perspective of a mother of a girl who is someday going to enter the business world and potentially the energy industry, do you feel that your daughter is going to have the same opportunities and the same ease or difficulty entering the business world as your sons?

RF Oh, I love this question! Coming from Asia, we probably are slightly backward compared to other countries, in the world. Equity is something that is probably not widely accepted yet. In fact, even my daughter

had to face this already. There are times that I am very impressed with my daughter's patience when she faced difficulty and remained calm and gave back kindness. I don't think I would have had that strength at her age. I love it that even though I am their mother, I am still learning from my children. There's a saying that you *kill people with kindness*. That's something I learned from my daughter.

DF It's always so inspiring when we can learn something from a younger generation. Especially when they teach us how to be better. It really makes you feel like they are that next, better version of us that we will leave behind. And there is always something that you are able to learn from another person, no matter how much younger or older you are.

And it is exactly wonderful young people like your daughter who are going to be the driving force for the future. You said she already





faces adversity and you yourself have seen how important support is when you enter the industry. Are you perhaps active in that field privately? Are you perhaps a member of some organization or program that offers that kind of support and encouragement?

NN Very much so. In fact, I've been recently approached by the top manager who is currently leading the women club in the company. We spoke about collaborating with the Girl Guide Association schools and universities on CSR knowledge sharing and how energy can be part of the activities within the community.

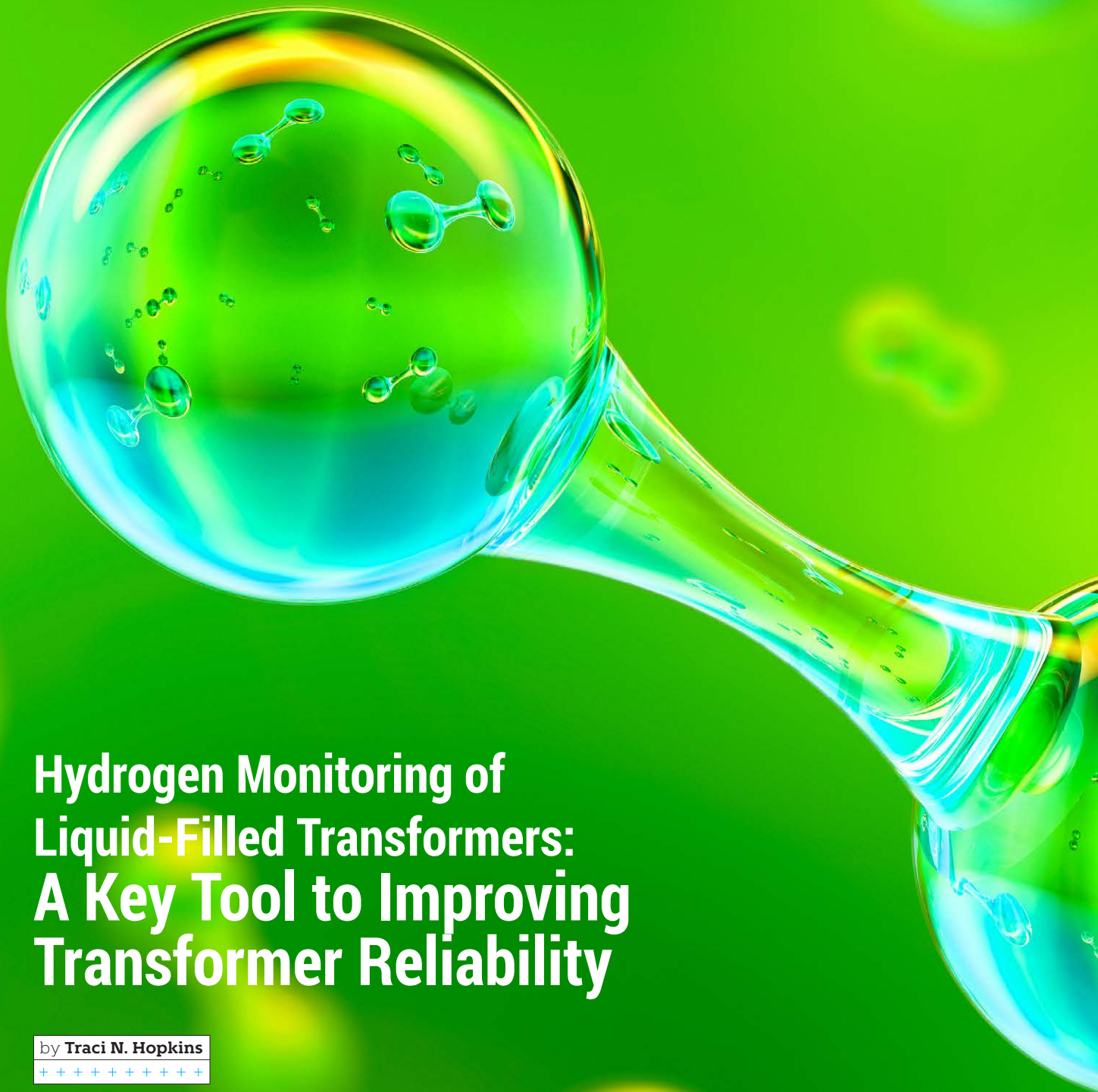
My daughter is deeply involved with the Girl Guides and I frequently share videos about their activities on my LinkedIn profile. We created a parent group that supports the program and after my daughter was awarded two Disney Princess awards, (the only one from the state), the next year we helped 18 other girls to be awarded as well. I shared the ceremony in one of my videos. The manager saw it and approached me about wanting to collaborate with the Girl Guides. Helping young girls get recognition, and acknowledgment in Asia is a very important personal goal for me.

We also organized a lunch and coffee session recently with the women of Siemens Energy Malaysia. Because the company is so big, we didn't even know each other in many cases, or because of Covid had never met face-to-face. This gave us a chance to get to know each other and share a lot of things. We talked about work and simply connected with a lot of mutual respect on that day. And now when we email each other, the communication is just so much warmer and clearer.

DF Everything that you have said has been so inspiring for us women who are already in the energy industry, but you also have given me so much enthusiasm and so much hope for what positive things await the next generation. And I very much look forward to continuing working with you in the future to help achieve that networking and those goals and help leave behind a better power industry than we found it. Thank you so much for being here today, Nurul. I have enjoyed this interview very much and I hope that it is only the first of many.

NN Thank you so much for having me. I hope we will work together again in the future.

DF This has been a Women in power systems interview with Nurul Noor from Siemens Energy Malaysia. Thank you very much and goodbye.



Hydrogen Monitoring of Liquid-Filled Transformers: A Key Tool to Improving Transformer Reliability

by **Traci N. Hopkins**
+++++

Transformers are the heart of any power system. Starting at generation through transmission and down to distribution, transformers play a key role in the delivery of power to end users. From homes to offices and everywhere in between, individuals expect high quality, reliable power to be available on demand twenty-four hours per day, seven days a week, 365 days per year.

When that power supply is interrupted or becomes unreliable, it is only then that they realize the scope of their dependency on this everyday resource.

Due to this ever-increasing demand, and the innate criticality of these assets to the system, it is imperative that we monitor the health of these valuable and expensive assets at

every available point throughout their lifecycle. This includes utilizing continuous monitoring systems to help transformer owners and custodians understand early and often the health and status of the transformer's solid and liquid insulating systems. One key early detection tool that is often overlooked or misunderstood is hydrogen monitoring.



Traci Hopkins works with energy companies in Latin America for H2scan, a leading hydrogen sensor manufacturer. She is an advisory board member for Women in Power Systems and was named an IEEE Senior Member in 2022 and is a Certified Reliability Leader. Before joining H2scan, she served as senior training and education advisor at SDMyers.

Increased Power Demand Taking its Toll on Transformers

The demand for reliable and sustainable power continues to grow, and as demand increases, so do the stresses placed on the assets that are currently in-service. Unfortunately, these increased stresses aid in accelerating the aging of the insulating systems, thus reducing the reliable life of these critical assets.

A transformer's liquid insulating system typically contains mineral oil. Transformer mineral oil is made up of a hydrocarbon chain that can degrade when exposed to heat and oxygen. When an abnormal event occurs inside the transformer, with enough energy, the hydrocarbon chain breaks down and produces hydrocarbon gases. These gases are generated beginning at 150°C, well above recommended "safe" operating temperatures. When transformer mineral oil breaks down, the first key gas to be produced is hydrogen (H₂).

Hydrogen begins to form around 150°C, and it is an indicator that an abnormal condition has appeared, and further investigation is needed to determine the next course of action. Figure 1, borrowed from *Transformer Maintenance – Facilities Instructions, Standards, and Techniques, United States Department of the Interior Bureau of Reclamation, Washington DC, USA*, is a visual explanation of the gases produced and the temperatures necessary for these gases to be generated.

Hydrogen gas is clearly present at all fault temperatures. As the temperature of the fault increases, so does the rate of production of hydrogen gas. Because it is the first gas to appear and the only gas to be continuously present during thermal and electrical faults, hydrogen can be thought of as an early warning or "check engine light," alerting transformer operators to a potentially significant issue inside the transformer. The issue could be the result of overheating, mechanical problems like loose connections, or potential failure. The presence of hydrogen alerts operators that something is actively generating gas inside the transformer that should be investigated and addressed.

When transformer mineral oil breaks down; the first key gas to be produced is hydrogen (H₂)

As the temperature of the fault increases, so does the rate of production of hydrogen gas.

Hydrogen Detection

In most instances, determining current transformer health involves taking an annual oil sample. This practice provides a variety of valuable information on the health and status of the transformer. For example, the condition of the paper can be determined by understanding the Degree of Polymerization (DP) values from Furan testing. It can also determine if a thermal or electrical event has occurred from the profile of gases found in the sample, help you understand the current condition of the oil and much more. However, the manual oil sampling process is not without its own challenges.

Manual Oil Sampling

Obtaining a good representative sample of transformer oil is an artful process that requires a great deal of accuracy, concentration, and repeatability. More often than not, this process can be riddled with errors from improper sampling technique to poor shipping and mishandling of the sample; both by the technician in the field and in the technician in the laboratory. Furthermore, manual oil samples only provide a snapshot of gas levels at a specific point in time and do not allow the reliability or operations manager to account for anything that may occur between manual sampling schedules.

Figure 2, borrowed from *The Transformer Maintenance Guide 3rd edition*, S.D. Myers, Tallmadge, Ohio, USA clearly illustrates the solubility of gases in transformer oil.

In this illustration, it is clear that hydrogen does not like to remain in the oil and will typically escape from the transformer unless the tank is extremely airtight. This can be an issue for capturing the complete gas profile of a transformer that is only sampled once per year. If an oil sample shows Methane, Ethane, Ethylene or Acetylene with no hydrogen, it means that the hydrogen has either escaped from the transformer or from the sample. It is imperative to understand that hydrogen is generated whenever the listed gases are generated.

Continuous Hydrogen Monitoring

When an online monitoring system is introduced to a transformer, many users think that manual sampling is no longer required. This is not true. Continuous monitoring allows transformer custodians to better understand the health of that asset on a consistent real-time basis rather than on an annual schedule. Online monitors provide more pieces to the asset health puzzle by filling in the gaps between manual samples.

The information between manual samples allows reliability professionals to make better, more informed condition-based decisions with real time data. Real-time monitors alert users to issues inside the transformer at the moment when the gas is generated. This provides users with a much better understanding of how and why

the gas was generated, whether it was a through-fault, a temporary overload, a cooling failure, or even for no apparent reason. While multi-gas solutions provide the most useful data for analysis, they are complex machines that require maintenance and are often difficult and expensive to maintain. Single gas hydrogen monitoring systems are cost effective and allow reliability managers to deploy devices across many transformers. Today, low-cost solid-state hydrogen sensors require no maintenance and allow transformer owners and managers to better understand the health of their assets between annual sampling and better manage the life of these assets, decreasing the likelihood of a catastrophic failure.

Selecting a Hydrogen Monitor

Hydrogen monitoring is not a new idea; in fact, hydrogen monitors

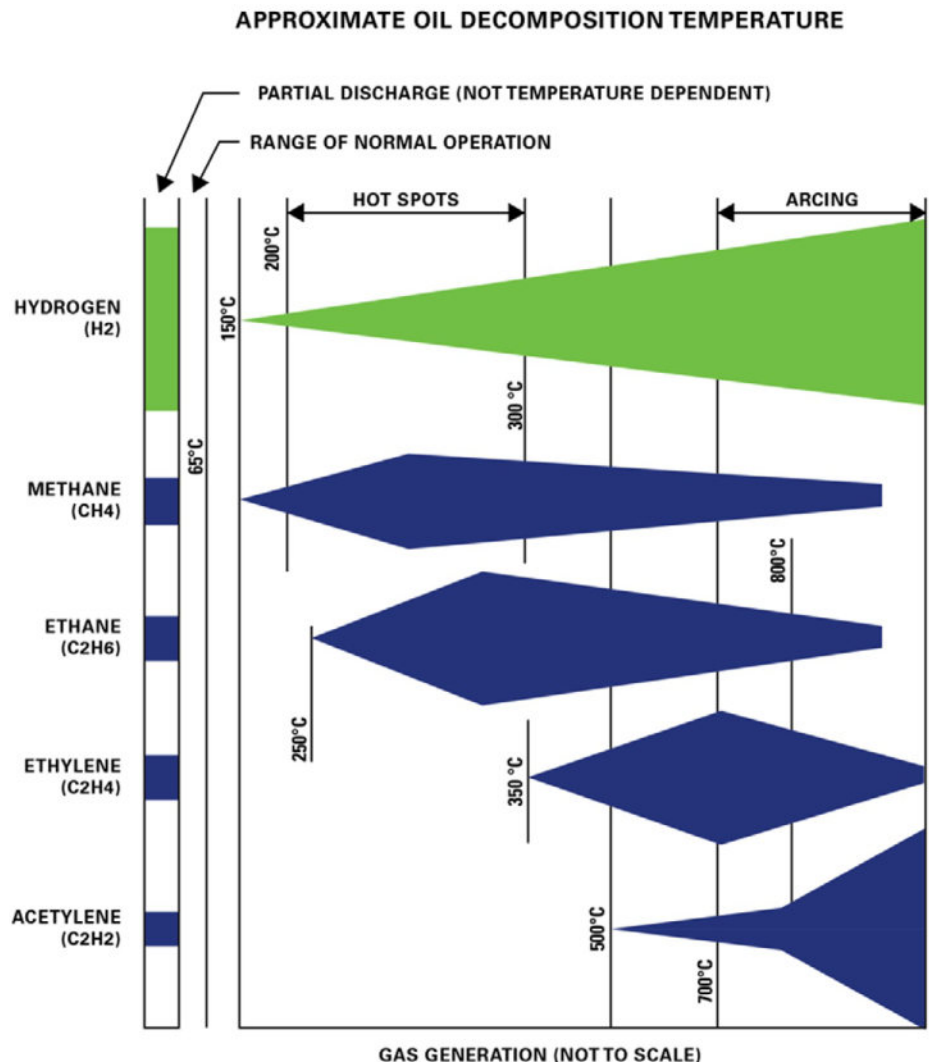


Figure 1. USBR.GOV

have been in use for 40 years, and are still the most popular type of online gas monitoring used. Today, transformer reliability professionals have an overwhelming variety of DGA monitoring systems to choose from ranging in both cost and functionality. During the selection process, it is important to consider sensor life, overall lifetime cost, and data access.

Sensor life is critical. From a reliability perspective, users want a device that will provide accurate information for as long as possible without the need for calibration or replacement. On average a hydrogen sensor will last one to five years. This is because the sensing element is either consumed or reaches end of life due to chemical changes when exposed to hydrogen or other environmental factors like destructive gases or heat.

However, certain solid-state sensors are not consumed in the presence of hydrogen; instead, hydrogen is able to move in and out of the certain solid-state sensors lattice without consuming or changing the chemical makeup of the sensor. This freedom of the hydrogen to move in and out of lattice causes a change in the resistance of the sensor. This change is measured in nano-ohms (10^{-9} ohms). Because solid-state sensor is a natural magnet for hydrogen, and the solid-state sensor does not require carrier or reference gas, nor is an extraction required to provide a measurement of hydrogen in oil or in the transformer head space. In fact, the limiting factor for a certain solid-state sensor is not the sensor at all. The life is determined by the electronics that manage the administration of the sensor. Therefore, robust electronics are typically provided which allow for a 10-to-15-year life of the sensor.

Overall lifetime cost of the sensor is another critical consideration. When selecting sensors for transformer monitoring applications transformer custodians should understand additional costs that may occur after installation. These costs may include repeat calibration of the sensor to maintain accurate readings, replacement of moving or rotating parts such as pumps,



Solubility of Gases in Transformer Oil

Hydrogen¹	H ₂	7.0% by volume
Nitrogen	N ₂	8.6% by volume
Carbon Monoxide¹	CO	9.0% by volume
Oxygen	O ₂	16.0% by volume
Methane¹	CH ₄	30.0% by volume
Carbon Dioxide	CO ₂	120.0% by volume
Ethane¹	C ₂ H ₆	280.0% by volume
Ethylene¹	C ₂ H ₄	280.0% by volume
Acetylene¹	C ₂ H ₂	400.0% by volume
Static equilibrium at 101.325 kPa and 25°C		

Figure 2 SDMYERS.COM

¹ Denotes combustible gas

and replacement of the hydrogen sensing element. For traditional DGA monitors, this can be multiple times over the life of the transformer asset. In the case of certain solid-state sensors, we return to the life of the electronics behind the sensor which are typically rated for a 10–15-year lifespan.

Finally, data access is important. What good is a monitoring system to your reliability program if you cannot access the data? There are many applications that require alarm relay contacts, others might require an analog output (typically 4–20mA) or a communications protocol like Modbus RTU or DNP. It is important to understand the requirements for

your organization so that data can be retrieved and analyzed for proper condition-based monitoring.

Conclusion

Reliability of assets is the expectation that an object will perform as designed without interruption. Hydrogen monitoring of our transformers from initial install to end of life with high quality, long lasting, cost effective, maintenance free sensors, ensures that end users enjoy condition-based monitoring programs instead of time-based programs. This allows the reliability professional to make educated informed decisions that will extend the life of these valuable assets.

Innovation in Insulation Systems

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Nomex®

In the last three decades, there have been important evolutions in the use of advanced insulation systems for liquid-filled transformers. Before that, more than 60 years ago, some new synthetic fibers were discovered, leading to the development of meta-aramid papers. With the commercialization of silicon fluids, it impacted the development of electrical insulation systems for liquid-filled transformers in the late 70's and early 80's.

However, in recent years the use of natural esters coupled with solid insulating materials of higher performance (like aramid Nomex® insulation) has been emerging as another insulation system for more flexible and resilient transformers [1]. The development of ester fluids, synthetic or natural, has answered the need to have transformers that would use biodegradable and sustainable liquids. Spreading initially in traction transformers and small distribution transformers, these fluids have also emerged in applications like solar and wind turbine transformers, and more recently larger power transformers for transmission and distribution networks, as well as industrial uses.

They are also becoming a more and more popular solution in urban substations due to the safety of these liquids in case of fire, as compared to traditional mineral oils.

An important aspect of the use of combined solid and liquid materials is to have a good understanding of the properties of their combination. In that sense, the characterization through the analysis of insulation system thermal performance is critical. This is needed to support the development of adequate design rules for transformers using that specific combination of materials. The IEC 60076-14 and the IEEE Std. C57.154™ are probably the most descriptive standards that exist today in the world providing detailed information on the use of combinations of those materials. However, to serve this, as indicated earlier, a characterization of the thermal behavior is critical, and the IEEE Std. C57.100™ provides details of procedures for the thorough evaluation of insulation system thermal properties.

While those standards have been developed in the last two decades, the innovative approach taken recently has led to the certification of an insulation system for liquid-filled transformers by a third-party entity, for the first time ever. This is aimed to ensure the highest quality of the generated test data, as well as an indicator that will be used by transformer manufacturers or transformers users.

The system certified can then be compared and benchmarked to existing insulation systems like cellulose and mineral oil that are being used for decades.

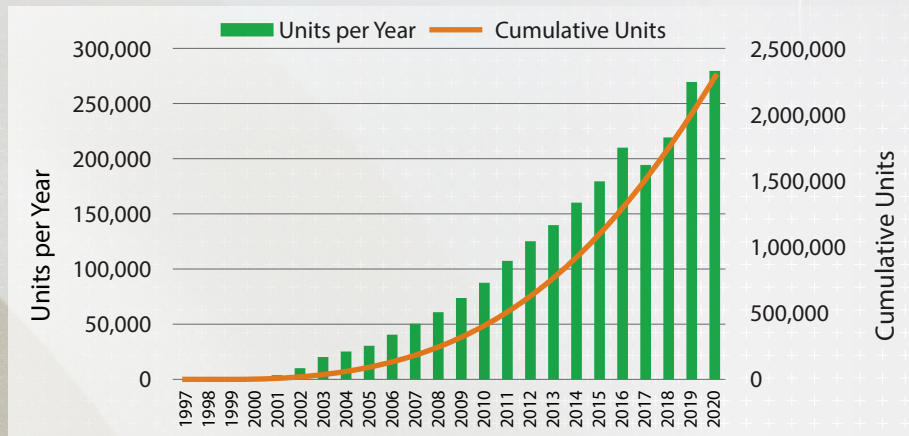


Figure 1: Estimated number of transformers filled with natural ester globally

1. The interest in natural esters fluids

Mineral oil has been considered the most preferred liquid insulation over the past 140 years for power transformers. With its strong credentials as an efficient dielectric and cooling medium coupled with low cost, it sounded unlikely that any alternative liquid could significantly replace the mineral oil, at least in a short time. As the environmental impact and, more recently, sustainability has been a growing concern, including for electrical equipment, the need to look for alternatives to materials that could impact the environment during a spillage or even worse during a failure that could result in fire, has led to the consideration of materials that would improve the safety as well as the sustainability.

That scenario has favored the acceptance of fire-safe, eco-friendly, and sustainable materials like vegetable esters. The use of natural esters coupled with solid insulating materials of higher performance provides a solution for overcoming such complex requirements that transformers must meet.

We can see that the use of natural esters has grown exponentially (see Figure 1), even if initially it was limited to small distribution and industrial transformers only. While

most ester applications were combined with conventional cellulose papers and pressboards, the association with thermally upgraded cellulosic papers has also been considered. It was then a natural step to look at enhanced cellulose papers with aramid ingredients, a new generation of thermally stable papers invented and commercialized less than a decade ago [2]. The transformers would benefit not only from improved fire safety performance and reduced environmental footprint. Additionally, it would have improved overloadability and better resistance to high ambient temperature which becomes more significant for insulation systems, particularly in the case of more frequent heat waves that appear now during each summer. It would be however foolish to consider that winter is better for transformers and their insulating materials as ambient temperature may help to cool the transformer and limit the aging of the insulating materials. Cold waves also lead to increased consumption of energy and the important dependency on heat generated from electricity. This has led to dramatic situations of blackouts during the winter season, as well.

As overheating can happen in transformer windings resulting from higher power demand due to several conditions, looking at the lifetime of the insulation system is important in order to anticipate the lifetime of the transformer.

2. Test method for thermal evaluation of insulation system

The test method is described in the IEEE Std. C57.100™-2011 [3], the "IEEE Standard Test Procedure for Thermal Evaluation of Insulation Systems for Liquid Immersed Power and Distribution Transformers". These procedures help evaluate the thermal capability of an insulation system by carrying out relative thermal aging where a candidate insulation system is aged and compared to an industry-proven system (IPS) to determine the relative performance of the two systems. While lengthy and complex, this evaluation allows for the development of a life expectancy curve for the candidate system.

The two materials considered for a thermal evaluation described below were the thermally upgraded cellulose paper enhanced with aramid DuPont™ Nomex® 910 immersed in the high-oleic sunflower natural ester A&A Parodi Paryol Electra 7426. For this testing, the sealed tube test methodology was selected from Annex B of the standard: "Materials testing – standard test procedure for sealed tube aging of liquid-immersed transformer insulation".

As test is carried out, critical parameters like material ratio, presence of water must be carefully monitored as they will have an impact on the end-of-life of the insulation system. The method to prepare the insulation materials through impregnation process before placing in sealed tubes is also a critical element of the preparation of this test. Also, the combination with other materials used in transformers like copper, magnetic steel, pressboard, paper and insulating fluid (see Figure 2). The tubes are then sealed with a nitrogen blanket and equipped with a pressure relief valve.

3. Evaluation of insulation system

The first step in the test procedure is to age the industry proven system at three specific temperatures to determine the end-of-life criteria as a target for the aging test of the new candidate material. The industry proven system is a combination of Thermally Upgraded Kraft (TUK) paper with mineral oil. A minimum of three cells must be tested at the three specified temperatures for a time determined by the life equation for TUK paper, as defined in IEEE Std. C57.12.00™. This reference life curve is based on the expected life of 180 000 hours (20.5 years), when the TUK paper is continuously exposed to the temperature of 110°C (the temperature index of the reference insulation system).

For evaluation of a candidate insulation system, the list of materials loaded to the aging cells is the same as in the reference system, except the new fluid and the new insulating paper: in our case the fluid tested is the natural ester Paryol Electra 7426 while the paper is the Nomex® 910.

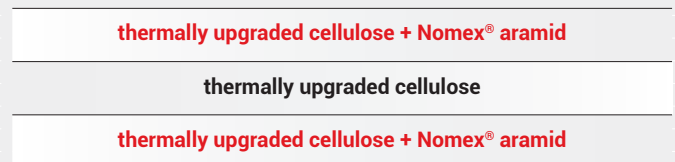


Figure 3. Simplified structure (cross-section) of aramid enhanced thermally upgraded cellulose paper Nomex® 910

As indicated previously, the choice of a natural ester for this study is important as the trend for new insulation system with environmentally friendly fluids is clear nowadays. Similarly, the need of an innovative solid insulating materials led to the choice of the Nomex® 910 paper, a paper designed for liquid immersed transformers. This paper is made of thermally upgraded cellulose



Figure 2: Materials loaded into the aging cell – example

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combined with aramid ingredients (Figure 3). This engineered paper can be used to allow for higher operating temperature of transformer windings. When used at conventional operating temperatures, the solution can provide extended insulation and transformer life.

For the best quality of test results, this evaluation of the insulation system required long preparation and proper selection of additional aging temperatures that helped improving the curve fit of the Arrhenius' equation.

The program ended up with more than forty (40) sealed tubes being aged in laboratory ovens. Insulation system was aged for five to seven different durations at each aging temperature, while a regular test would only require three durations. Upon completion of testing and generation of data on the achieved end-of-life of the system, the test information was validated by an independent third-party body, the Underwriters Laboratories, Inc.

4. Temperature index achievement

At pre-selected temperatures, the individual aging cells were aged to reach the paper end-of-life point. This end-of-life point, typically set at 50% of the remaining tensile strength in the past, was set to 29.6% to match the value reached for the industry proven system. Once this condition was obtained at each pre-selected temperature, the life curve (Arrhenius' curve) was plotted with end-of-life time vs. temperature. This curve was then projected to 180 000 hours to arrive at the relative temperature index of the evaluated candidate insulation system (Figure 4).

The Arrhenius curve for the tested insulation system has been model by the following equation:

$$LIFE = e^{\left[\frac{17087}{T+273} - 30.778 \right]}$$

where:

LIFE is the life in hours and T is the aging temperature in °C.

As a result of the assessment verified by the third-party laboratory, the temperature index of the system has been defined as 125.5°C at 180 000 h.

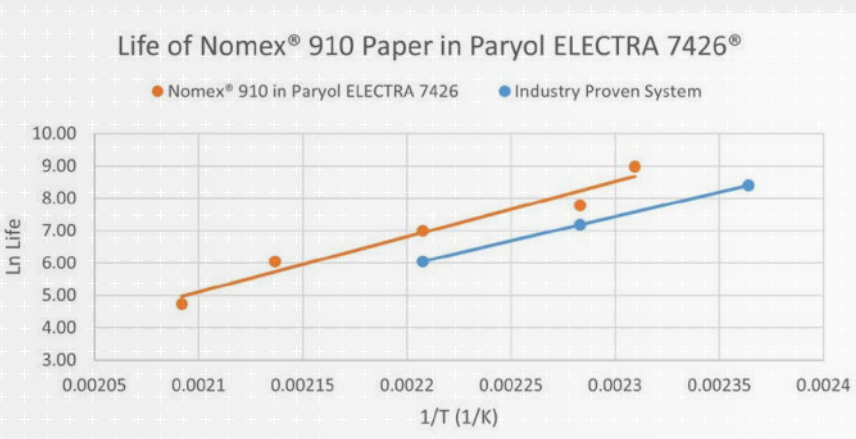


Figure 4: Thermal performance life curve of Nomex® 910 paper in Paryol Electra 7426 compared with industry proven reference system

The resulting thermal class is then 130. Today this system is the only and first ever insulation system for liquid filled transformers that has been certified. While this UL certification concept did emerge in the 1960's and 1970's for insulation systems for dry type equipment like motors, generators or dry type transformers, it is only now that it is extended to fluid filled transformers (Figure 5).

5. Continued aging test program

As this is a first step, we know that for better understanding of performance of various insulation systems it will be critical to conduct further studies. The number of advanced insulation materials that exist today will also open for more combinations that will need to be evaluated thanks to this presented methodology. We hope that this new step leading to the certification of insulation systems will allow a better understanding of the materials and their combinations. This should also lead to a better adjustment of the future design of transformers as they integrate these advanced insulation systems, providing more flexibility to users and transformer manufacturers to meet more and more critical operating requirements.

Electrical Insulation System Components
 DuPont Specialty Products USA, LLC
 Nomex Business Center, 5401 Jefferson Davis Hwy, North Chesterfield VA 23234
 System Component: Nomex® 910
 System Designation: Nomex® + Ester 130
 System Class: 130(B)
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 Voltage/Variés:

Construction Details (Table I)

The use of this insulation system is limited to the combination of materials specified below. Where more than one item is designated under insulation function, they may be used together, unless otherwise indicated; or they may be used as alternates to one another. Functions designated "optional" are not necessarily required for every design. Insulation thicknesses and/or layers below indicated are minimum.

Description: Liquid Immersed distribution transformer EIS
 Note: Intended for use in liquid immersed distribution transformers evaluated to IEEE Std C57.154

Bare Conductor - copper wrapped or interleaved with Nomex 910

Designation	min(mm)	comments
AAA, Fingert, Parodi, S o A Paryol Electra 7426		Dielectric Fluid - Natural Ester
DuPont Specialty Products USA, LLC Nomex® 910	5 (0.13)	Cellulosic/aramid paper any sheet insulation or tape described in this table with no minimum thickness requirement may be used as a minor sheet material

Designation	comments
Various Manufacturers Pressboard	pre-compressed or calendered cellulosic material
Weidmann Electrical Technology AG HWal T4	Cellulosic Pressboard Cellulosic Pressboard any material described in this table with no thickness requirement may be used as a spacer or a wedge

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Figure 5: Description of insulation system "Nomex® + Ester 130" in UL IQ database

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**POWER SYSTEMS
TECHNOLOGY**

SPECIAL SUPPLEMENT



CEO of Camlin
Americas

Interview with **Keith Redfearn**

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Consumers expect when they switch the light on, the lights come on, today the grid requirements are significantly more complex than they were when it was first designed.

Keith Redfearn



Alan Ross: I'm Alan Ross with APC Media. I'm the Managing Editor, and I am delighted to have Keith Redfearn as my guest today who is the CEO of Camlin Americas. There's a Grid Edge conference that we're going to be doing at IEEE next year. I'm the chairman of the Smart Grid Reliability Alliance and I can promise you everything that I'm going to ask you. Including the problems with the grid, as well as the challenges.

So welcome. Thank you for joining me.

Keith Redfearn: Thank you, Alan.

AR There's a lot going on in the grid right now, and I know as you look at a vision for Camlin Americas, you have to be looking at this grid that you're going to be able to implement that vision through. It's kind of the road that you have to build your house on. Now I wasn't going to ask you about generation, but remind me to come back to that when we start talking about distributed energy resources, wind and solar. Because they in themselves are a solution, but to one problem

decarbonisation, they are also a problem creating an inverter-based system. So, we're going to talk about that. However, from your perspective, looking at things from a reliability resiliency standpoint, what are the challenges that you see of the grid?

KR I think first and foremost, Alan, consumers expect us to have a fully resilient grid. They expect when they switch the light on, the lights come on, today the grid requirements are significantly more complex than they were when it was first designed. I think the accelerated deployment of distributed energy resources has, to the point you made earlier, an upside. It absolutely helps us on the journey to decarbonise, however in the pursuit of a zero-carbon future we cannot afford to negatively impact grid performance.

So, technology wise, if we look back to the mid 2000's when the industry first started talking about a smarter grid, it was in its infancy. There were a lot of good ideas, but the technology wasn't there to facilitate the deployment at scale of the smarter grid, we are now in a position where technology is no longer a limitation, it has become a facilitator of what's required to support grid modernisation. As we continue to deploy more distributed energy resources on transmission and distribution networks, we must

YOU CAN NOT EFFECTIVELY SUPPORT TRANSIENT GENERATION WITHOUT A GOOD BALANCE OF STORAGE.



understand what is required to effectively operate the grid to ensure it remains reliable and resilient.

This is one of the major challenges that we in the industry must overcome by working in close partnership with utilities, regulators and the wider eco-system.

AR I'm a reliability guy, and reliability is that an asset or a system works as it was designed for as long as it was designed, without failure or disruption. That's reliability. That's one issue that we've got. The grid has been fairly reliable from that perspective. We've had glitches here and there, which is to be expected. The other one is you mentioned it resiliency. One of the resiliencies is getting it back up when it goes



down, usually due to natural disaster event such as fire, hurricanes, tornadoes. And resiliency is making sure you bring stability back to the grid as quickly as possible so it again becomes reliable. That's a problem. That particular thing you said, technology is our friend. Now how can technology help in those instances when you talk about natural disasters?

KR So clearly you still have to have the generation capacity to bring the system back up again. Whether that's traditional fossil fuel, nuclear, or an abundance of distributed energy resources, each need to be resynchronized and connected to the grid. Now that's not a simple task following a black start, effectively the whole grid has sat down.

Traditionally you'd have to bring that up very slowly, one section at a time, and make sure you maintained grid stability. If we had a connected system of distributed energy resources set up as microgrids, you could most likely accelerate the restoration process. You wouldn't be relying on the full infrastructure of a transmission grid to be restored, small pockets of generation in community microgrids could be restored immediately and then reconnected back to the grid over time. So, there's a great example of where technology can facilitate a faster power restoration without necessarily being delayed by a traditional black start procedure.

AR Let's go to technology for a bit. When you think about the technological advances, a lot of that has happened in the area of protection systems. Protection systems, and relay networks are so much better than they were in the past. We're moving away from mechanical to electromechanical to solid state. We talk a little bit about the technology as it relates to protection systems and anything else that is there today that wasn't there in the past. I have another question for you, which is how it relates to this thing that you just talked about, *microgrids*. I think that's what we're going to have to do a lot more of in the future.

KR Traditional network protection systems have performed well for many years. They were developed and designed for a top-down power flow network, from generation through transmission to distribution. Now, as we deploy newer more flexible forms of generation those long-established power flows no longer apply. Typical protection schemes and associated devices have predetermined settings based on a predominantly static grid configuration, for traditional mechanical relays this is relatively straightforward. Modern electronic relays allow for multiple settings to be programmed and selected remotely to ensure

they remain effective, irrespective of generation mix & associated dynamic power flow.

These new digital devices give significantly more flexibility and control over adverse power flows associated with the proliferation of DER generation ensuring the safe and reliable delivery of power, even when a network is isolated as part of a microgrid configuration. This is a simple but effective example of how technology allows more flexibility on the grid.

AR Do you think microgrids are primarily, from a generation perspective, going to be DER wind and solar? Which are what powers a microgrid. So, you really don't have transmission as much as you go from generation to distribution. Is that what it's going to look like?

KR I think so, and I think you missed out on an element which is storage. You can not effectively support transient generation without a good balance of storage. That storage may be in the form of a battery, flywheel, pumped storage or one of the many new forms of storage currently in development, they play an important role in overcoming the transient nature of wind and solar.

It's that energy mix that is going to allow microgrids to really take off. We could say we have turned the clock back more than a hundred years in returning to a collection of loosely coupled microgrids generating and consuming power locally then leveraging the wider grid infrastructure as backup.

Personally, I don't think we will ever be able to cost effectively scale "normally" disconnected microgrids as default operation. However, there are certainly instances where islanding a section of network during a grid outage, both planned and unplanned, would allow a community to operate in a microgrid environment without an extended loss of service. For instance, across the US West coast where utilities have challenges with continuous supply through fire season.

AR That's a great word picture for me because we shut it all down when we should be thinking about building it so you don't have to shut down. I want to go back to this topic of technology and reliability and resilience and how the various technologies that help in one area can hurt in another. Particularly "DER".

Now there's a new reg or an order coming out in 2222, and it is specifically aimed at this whole new generation world of DER. What does that say, and what does it mean?

MORE AND MORE MOVING FORWARD, THE COMPLEXITY INVOLVED IN OPERATING THE GRID IS GOING TO REQUIRE MORE AUTOMATED INTELLIGENCE, GRID CONTROL WILL BE SEMI-AUTONOMOUS.



KR FERC's aim is to reduce the barrier of entry into the wholesale market for smaller DER participants. By establishing a minimum aggregation of 100KW, FERC have significantly reduced the size of generation required to participate in a wholesale transaction. Now, from my perspective that is fantastic. That allows many more participants to deploy & distribute DER generation and accelerate the journey towards our collective decarbonisation targets. However, it also adds significant complexity to the grid as in that scenario there's an expectation that grid capacity is infinite, irrespective of where or at what time of day DER is connected, the grid will consume all available generation and distribute appropriately.

For those in the industry there is a fundamental understanding that the grid has finite capacity coupled with physical network constraints that must be continuously managed, there's a cost to generate, there's a cost to distribute. Continuously optimising grid operation to reduce constraints and curtailment is key to maximising grid efficiency, this can no longer be effectively managed manually.

Moving forward grid optimisation can only be achieved through automation and deployment of new technology, only by calculating real time and predicted power flows, identifying and minimising grid constraints, can we

optimize grid configuration to maximize the effectiveness of DER. This is a very difficult equation to solve, it must be solved in real time to ensure the grid always operates within acceptable limits.

AR You have mentioned something I read and it was about a greater operating control. What do you mean by a greater operating control?

KR More and more moving forward, the complexity involved in operating the grid is going to require more automated intelligence, grid control will be semi-autonomous. What I mean by that is the advanced control system is going to determine the optimal configuration of the network in real time, based on greater understanding of grid operating conditions, increased knowledge of the grid assets and hence improved insight into the capability and capacity of those assets. Grid control operators will remain present to handle the exception cases, I expect this mode of operation to become the norm within the next five years.

AR Technology is making decisions that we used to use human brain power to make and technology. So, you're going to grade the entire grid in terms of AI and machine learning. Where are we with that? Is it still nascent technology or have you seen it working?



KR If you're referring to actual grid control of the transmission and distribution network, then we will continue to rely heavily on the traditional advanced control systems operating semi autonomously. However, a couple of examples of where I have seen machine learning effectively be applied today is for smart meter connections, that is leveraging the huge volumes of smart meter data and network topology to greatly improve the accuracy customer connections. Also, we at Camlin are looking at leveraging machine learning to improve our insight into real time asset performance. By leveraging our vast library of historical asset data and our many years of field experience coupled with our industry renowned SME's we have been able to demonstrate a far deeper understanding of how assets both perform and fail under a diverse range of operating conditions. Its clear that assets operating in a "grid the future" will face very different challenges and that deep real time insight into assets will be required to ensure continued and reliable service.

Typically, machine learning has been able to develop insights based on complex patterns, to be truly effective this should be contextualised with support from subject matter experts. Now, is there a place for that in grid control? Absolutely.

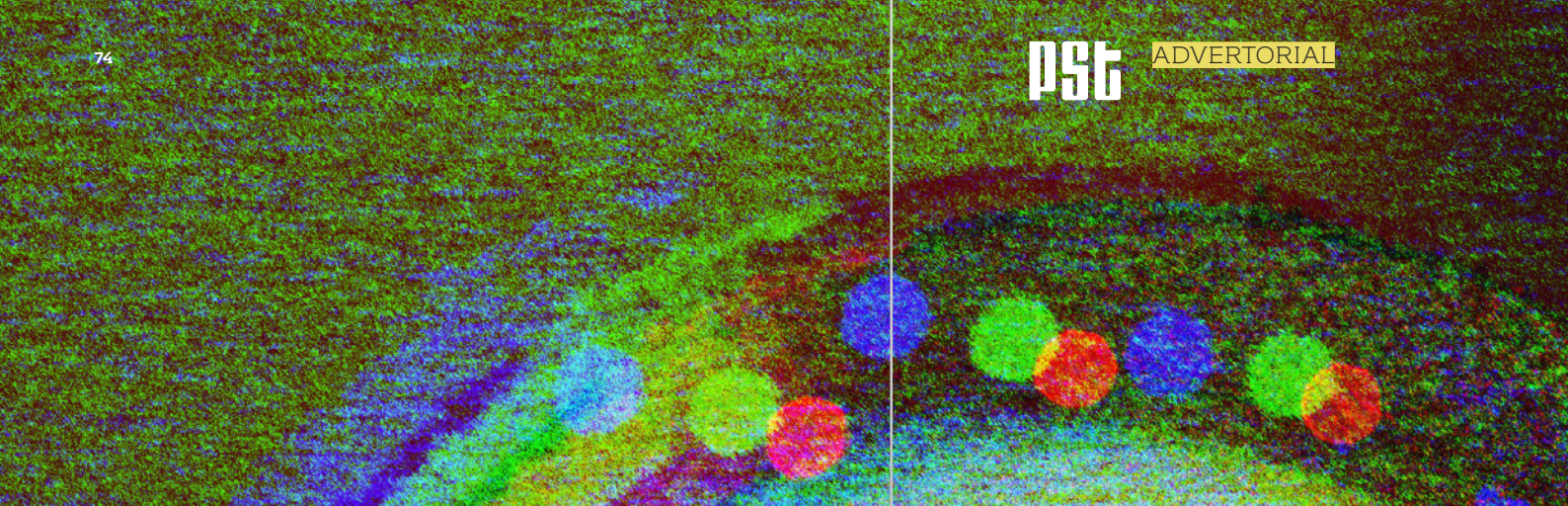
As the grid gets more complex being able to accurately predict what is likely to occur on the

network over the next 24 hours and beyond is becoming increasingly more important. Determining the optimal grid configuration and what contingency do we have should it deviate from a predicted state is where I believe machine learning has a big part to play. However, as of today we are far from deployment.

AR This is fascinating, again Thank you Keith. That was a wonderful.

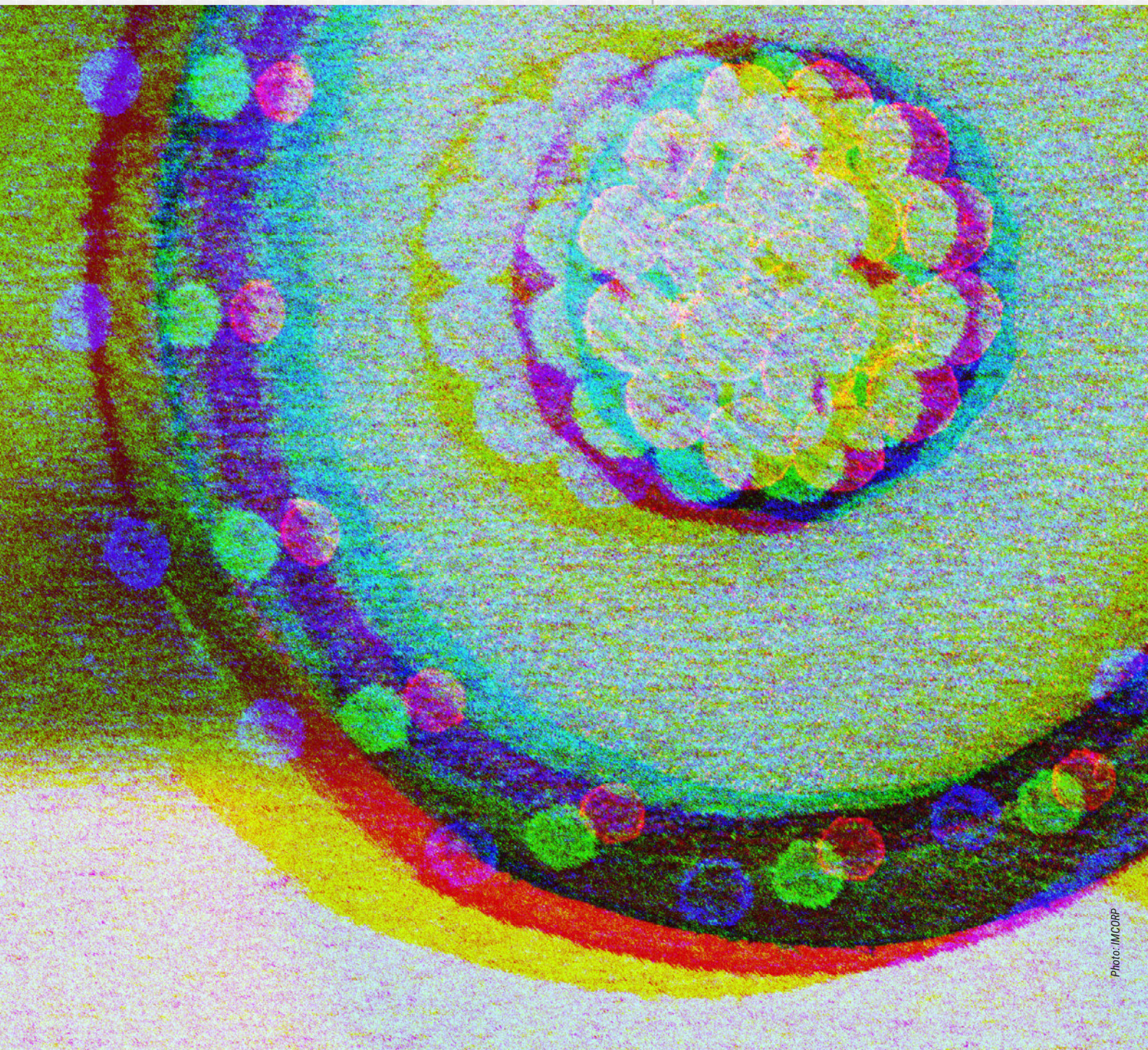
KR Thank you very much, Alan. I appreciate it.





DEEP LEARNING CHARACTERIZATION OF PD DEFECTS

AN IMPORTANT STEP TOWARD PREDICTIVE MAINTENANCE OF UNDERGROUND CABLE SYSTEMS



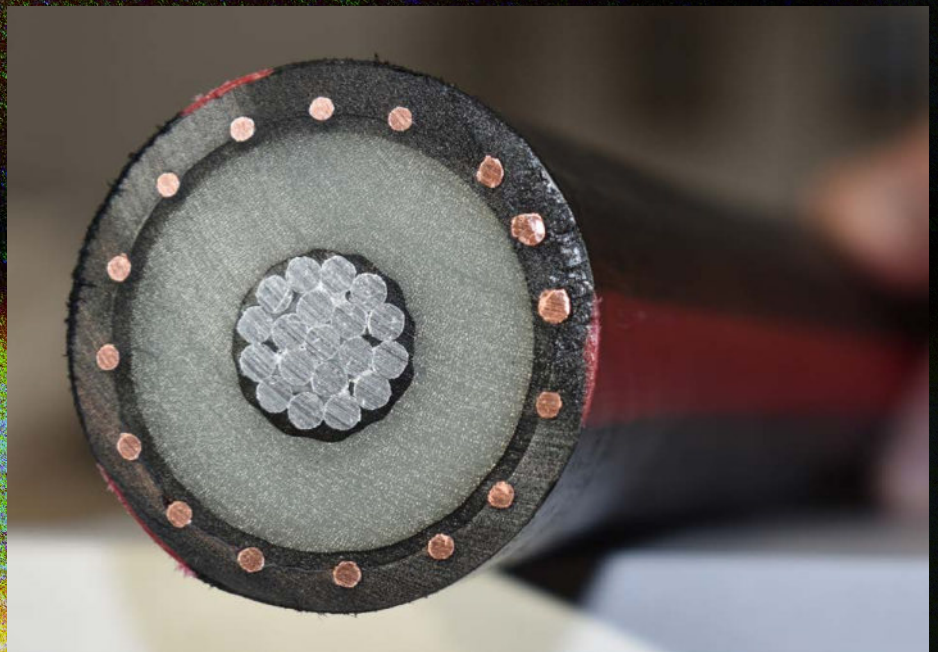
The challenges of evaluating and maintaining underground cable systems are considerable and increasing rapidly. In the second of three articles, IMCORP explains the deep learning models it is developing for automating the detection and characterization of partial discharge defects and determining the remaining useful life of cables.



The idea behind machine learning is that, given enough determinations about the known past, a computer can be taught to generate the same determinations in the present and, eventually, to predict the future.

Meteorologists, for example, create databases of information on the conditions such as atmospheric pressure and wind speed that led up to previous weather events, like hurricanes. Then they program a computer, using complex mathematical models they develop and refine until the machine can describe the storms as they actually happened based on the same information. Having learned to "predict" past storms, the computer can now use information about present conditions to predict future ones.

The key to machine learning is the size of the database used to "train" the computer. The more information you have, the greater the accuracy with which the machine can learn to make predictions. The database IMCORP is using to train its computer to diagnose the condition of underground cable is massive: it comprises the labels assigned by human analysts to characterize tens of millions of instances of partial discharge (PD) defects in the approximately 300 million feet of shielded underground cable systems tested by IMCORP over 20+ years.



The Training Data

The essential problem is that there is no visual inspection of underground to teach the computer to distinguish PD signals from ambient noise, locate the PD along the cables, and characterize the defects to determine which might pose the greatest risk of cable failure, the first step was to create training datasets containing this information.

As electromagnetic waves travel in a cable system, PD signals manifest themselves as patterns with specific properties in voltage time series, as the example in figure 1 shows. Data on these digitized signals are included in the condition profiles of more than 258,000 cable phases in IMCORP's database.

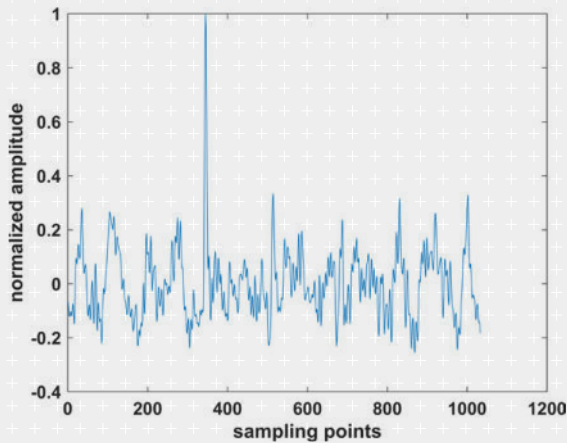


Figure 1.
Voltage time series of a PD signal.

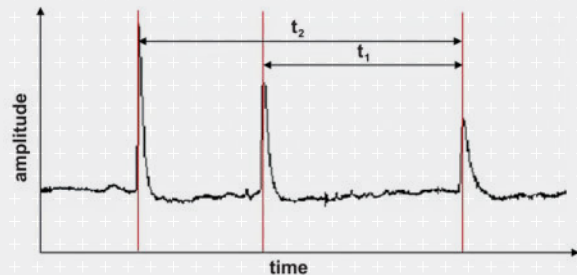


Figure 2.
PD time series with time markers.

These data were gathered using instruments that capture PD signals with bandwidths higher than those at which conventional instruments usually operate. This allowed IMCORP to arrange the digitized signals as time series in its training datasets. The origin points of PD defects were determined by measuring the time intervals, represented by t_1 and t_2 in figure 2, between voltage changes in the series.

The next step was to characterize the signals—that is, to identify the PD signals and assign labels to them, including location, PD type, and other features. Two different approaches to training the model would be explored: shallow and deep learning.

In shallow learning, the computer can only use specific and predefined inputs. Before information can be fed into the model, human experts need to define meaningful input numbers representing features of the data; this process is called “feature extraction.” In our investigation, the experts were signal analysts, who provided the labels for both the time series signals and their features. One training dataset comprised 4,076,749 instances of digitized signals characterized by 23 features each. Based on these features, the series were bundled into two groups in the dataset—those that did and did not represent PD.

One training dataset comprised 4,076,749 instances of digitized signals characterized by 23 features each.

In deep learning, feature extraction is unnecessary. Information can be fed to the computer in native numerical forms, such as digitized waveforms, and it will find the meaningful features on its own and progress to the training stage from there. The second dataset we used for training comprised 965,310 labeled signals in a digitized format. Of these, 264,810 indicated PD, while 700,500 represented ambient noise. The signals were captured from underground cables of different lengths and grouped by length, as shown in figure 3.

With the signals distributed along the cables according to their lengths, it was now possible to indicate the locations of origin for the true instances of PD. Those originating from the beginning of a cable were listed as “NE,” from the end of the cable as “FE,” and from between them as “MID.” Figure 4 shows the distribution of the true PD locations in the second training dataset.

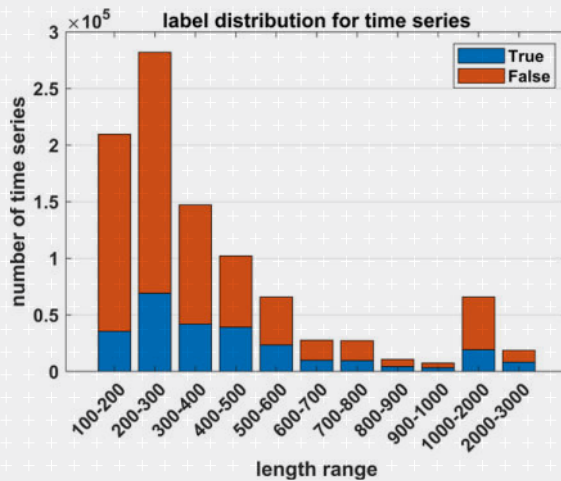


Figure 3. Number of labeled instances versus length range [ft.].

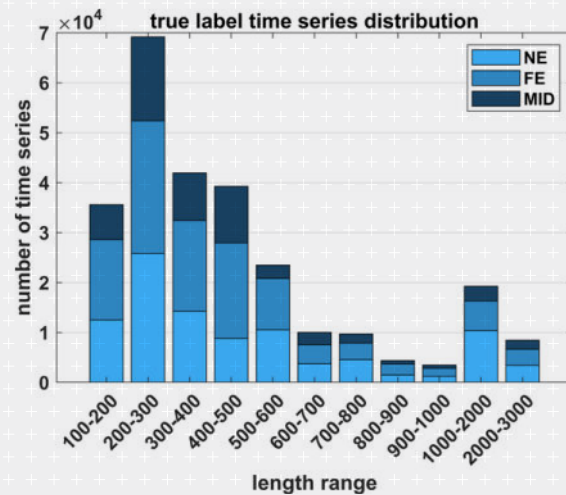


Figure 4. True label distribution by length range [ft.].

Model Training and Results

In the human brain, neurons work together in networks to allow us to function. Through machine learning, computer scientists seek to enable computers to function—or at least think—like humans by building neural networks artificially through the use of algorithms. The two methods they use—shallow and deep learning—differ in the number of “layers” the neural networks contain. In both approaches, programmers experiment with different algorithms until the computer can replicate the performance of a human carrying out a given task—in this case, identifying PD signals and their locations and labeling their features in the same way as human analysts, given the same signal measurements from the field.

In the human brain, neurons work together in networks to allow us to function.

Shallow learning methods are sometimes preferred over deep learning if fewer data are available or computational requirements are an issue. The algorithms are sometimes better in terms of understanding how the results are being produced, which is simpler. Deep learning methodologies, on the other hand, while not as simply explained, can use data on a larger scale.

IMCORP performed experiments with both shallow and deep learning models to determine which better equipped the computer to carry out the tasks at hand. The purpose of the first set of experiments was to enable the computer to differentiate PD signals from ambient noise signals at different locations of origin along underground cables. The objective for the models was to meet three expectations:

- The computer should be able to separate PD from noise signals with 90-95 percent accuracy, as compared to the human analysts' assessments contained in the training data
- False-negative classifications (that is, PD signals identified as noise) should be as few as possible
- False positives (noise identified as PD signals) could be tolerated between 0 and 10 percent of the time.

The computer significantly underperformed these criteria using shallow learning models. It was able to distinguish between PD signals and noise with only 91 percent accuracy. A second, “hybrid,” approach used deep learning but was based on extracted features, not signal waveforms. Its accuracy rate was 95 percent. A third approach did even better: using deep learning with signal waveforms as inputs, it achieved 96.3 percent accuracy for the first 200 feet of cable, as figure 5 shows.

Through machine learning, computer scientists seek to enable computers to function—or at least think—like humans by building neural networks artificially through the use of algorithms.

The second set of experiments sought to teach the computer to diagnose the types of PD defects (that is, to characterize them as a human signal analyst would) that were identified at different locations of origin along the cables.

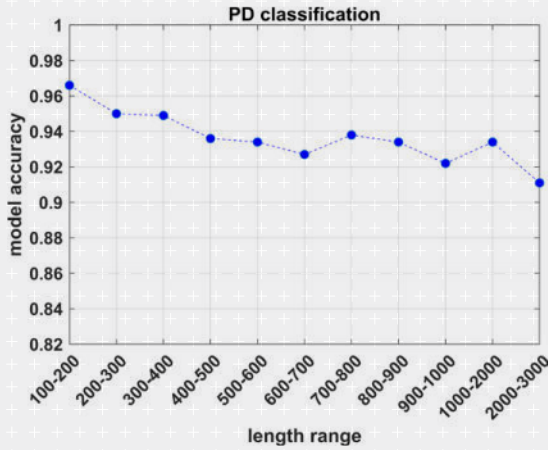


Figure 5. PD versus non-PD classification accuracy of the deep learning model.

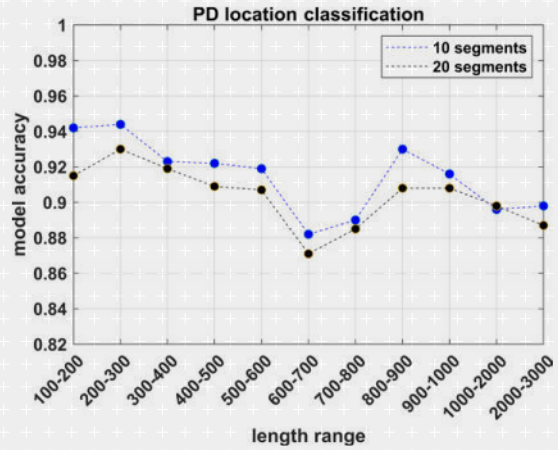


Figure 6. PD location classification accuracy by length range [ft.].

In a third experiment, the computer transformed the PD signals from defect locations into images (called phase-resolved partial discharge, or PRPD, images) that could be graphed and classified into five categories of defects. The highest risk of imminent cable system failure is posed by defects of the electrical tree type, shown in figure 7. Being able to determine whether a PD is caused by an electrical tree allows utilities to assess the risk to which a particular cable system asset is subject.

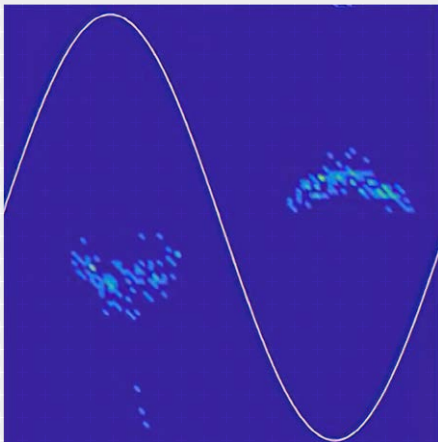


Figure 7. PRPD of electrical tree-type defect. The x-axis represents one period of the 50/60 Hz sinusoidal excitation voltage and the y-axis the PD magnitudes in pico-Coulomb. Blue, green, yellow, and orange represent different densities of PD events in increasing order.

class accuracy on test set: 96.7%

true class	1	27	3		4	1	77.1%	22.9%
	2	1	21				95.5%	4.5%
	3	1		8			88.9%	11.1%
	4	1			250		99.6%	0.4%
	5					20	100.0%	
		90.0%	87.5%	100.0%	98.4%	95.2%		
		10.0%	12.5%		1.6%	4.8%		
		1	2	3	4	5		
		predicted class						

Figure 8. PRPD image classification accuracy for five defect classes, numbered in the figure as (1) electrical tree, (2) corona PD on high-voltage potential, (3) corona PD from ground-up to high-voltage potential, (4) no recognizable PRPD, and (5) surface tracking.

As figure 8 shows, the computer achieved an accuracy rate of 96.7 percent on the classification of 3,007 images into the five defect types.

In sum, deep learning outperformed shallow learning methodologies both in distinguishing PD signals from noise and determining what types of defects were occurring at specific points along the cables, especially electrical tree-type defects, which pose the highest risk of imminent cable system failure. To date, IMCORP has achieved 97 percent accuracy with deep learning models. The other 3 percent may be attributable to human mislabeling of signal characteristics and to natural signal attenuation as the cable length ranges increase. We continue to work to improve the accuracy at which the computer can match the performance of human signal analysts in characterizing PD defects at specific locations along underground cables.

The new approach IMCORP is developing enables deep learning models to use the feature labels generated by analysts to autogenerate the best features on which to base predictions.

Practical Implications

Proactive and predictive maintenance for underground cables calls for much greater technical capacity than is currently possible. The expert knowledge required by human analysts for traditional interpretation of PD signals is difficult to establish or teach. Training a reliable signal analyst can take months. Existing technology also allows for different investigations and measurements of given signal time series, controlled by the analyst—a time-consuming manual process with results that contain a subjective element.

The new approach IMCORP is developing enables deep learning models to use the feature labels generated by analysts to autogenerate the best features on which to base predictions.

Automated PD location and classification provide a time savings over human analysis by 52 percent, on average, and of up to 500 percent in the analysis and interpretation of complex datasets—time that can be put to better use by the human experts responsible for the condition and efficient operation of underground cable systems. Furthermore, the automated process can serve as a quality assurance tool that makes diagnostic procedures more consistent, allowing key performance metrics to be reliably tracked.

Finally, the automated assignment of risk factors to assets in underground cable systems enables repairs to be prioritized. The methods presented here will allow cable network owners and operators to base their strategic and proactive investments on the actual health conditions of their systems rather than on the very limited portions of the systems they are able to test.

At IMCORP, further studies on classifying images of PRPD are underway. The deep learning signal waveform characterization of PD defects is an important step toward developing a predictive maintenance system for underground asset management.



The final article in the series will discuss predicting the remaining useful life of underground cable.



Steffen Ziegler holds a Master of Science degree in Electrical Engineering from the Karlsruhe Institute of Technology - Germany. Since 1999 Mr. Ziegler is working for IMCORP and is currently the Director for Signal Analysis and Artificial Intelligence. Past positions include Manager for Research and Development. He has specialized in the field of digital signal processing applications and machine learning and deep learning applications for Underground Power Cable Systems.



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Lisa Ferraro Parmelee is a freelance editor and writer who specializes in making technical and academic subjects accessible to general readers. The fields in which she works include engineering, international development, public policy research, business, and history, among others.



Dielectric Fluids – Evolving Technologies

Introduction

Dielectric fluid or oil is a critical component in an oil-filled transformer – be it power, distribution, or any special transformers, reactors, or switchgear. As the name implies, the main job of dielectric fluid is to provide liquid insulation. The major functions and characteristics of oil are the following:

- Provide good liquid insulation to all conducting parts in a transformer
- Impregnate paper insulation by filling the voids effectively to remove air bubbles
- Function as a coolant
- Good chemical stability during the lifetime of a transformer
- Inert to materials used in a transformer
- Act as the information carrier on the health of a transformer
- Should comply with HSE requirements (HSE stands for health, safety, and environment)

Savita Oil Technologies Limited (SOTL) has a large portfolio of transformer oils covering the first two categories of oils

Therefore, it is extremely important to select the right oil for the right end application. The following major oil types are currently established technically and commercially:

1. Mineral Oils, the major workhorse of the industry (Both paraffinic and Naphthenic)
2. Environmentally friendly, biodegradable, and fire-safe Ester oils for specialty applications (Both Natural ester & Synthetic ester) for all applications especially for renewable energy projects like floating solar & Wind Power etc.
3. Silicone Oils with limited scope for applications
4. New, emerging specialized oils (e.g., Bio-based oils and Gas-to-Liquid oils)

Mineral oil-based transformer oils in Savita Oil Technologies Ltd (SOTL)

Technology developments in Savita kept pace with the progress made globally in the field of transformer Oils. Here's how technological evolutions have taken place in the field of transformer oils.

Historically, Naphthenic oils were popular in Europe and the USA due to the ready availability of Naphthenic crude-based base oils and it continues to be so even today. However, in South Asia and Southeast Asia, Paraffinic Oils are being used predominantly due to technical reasons relevant to the warm climate in these regions. The warm climate meant that low-temperature properties such as pour point and viscosity at subzero temperatures are largely irrelevant for this region. The technical reason coupled with more readily available paraffinic crude-based base oils gave impetus for the oil technology companies such as Savita Oil Technologies (SOTL) to carry out extensive research to develop paraffinic-based transformer oils in addition to Naphthenic transformer oils.

In the initial decades of the mid-1960s and 1970s, paraffinic transformer oils, though suitable for Asian conditions, were considered inferior in Europe and the USA where low-temperature properties are essential. However, continuous research and technology developments over the decades in oil refineries globally enabled SOTL to develop high-quality Paraffinic oils that are on par with naphthenic oils in all respects with only minor, insignificant differences in properties and function. SOTL's paraffinic oils meet all the international standards such as IEC (Highgrade, inhibited, uninhibited) or IEEE, ASTM, and several national standards. Here's table 1 highlighting important properties of present-day paraffinic oils and Naphthenic oils produced by SOTL.



As one can see from the table, there is very little to choose between a paraffinic and a Naphthenic oil. Most of the properties are comparable. Differences, when they arise, are not significant to make a difference in the performance of a transformer.

Having said that, Savita offers both types of oils and leaves the final choice to the end user.

Significantly, Transol GEPX (Paraffinic) is time-tested for even EHV applications, e.g. 400 kV class. Savita's Naphthenic grade transformer Oil, Transol, is, of course, used widely for all applications involving 765 kV class and also for demanding applications of HVDC transformers.

Transol products are further supported by technical services backed by Savita's oil condition monitoring expertise. Needless to say, dielectric fluids require expert advice on usage and condition monitoring, both of which are provided by Savita.

In summary, Savita's portfolio of products based on mineral oils (TRANSOL brand products) fluids satisfy the three D's of performance criteria for transformer applications:

- Durability
- Dependability and
- Delivery of performance at an optimum cost

Feature	Naphthenic Oil, Transol HGX	Paraffinic, Transol GEPX
Pour Point	-40°C; Comparable	-40°C; Comparable
Viscosity index	Lower (80)	Higher (104)
Refining Satbility: Sulfur Content:	<10ppm	<10ppm
Interfacial tension	45	48
Aromatic content	Higher, 4 to 8%	<4%
Flash Point	135°C min	140°C min
Oxidation stability	-	Responds better to inhibitors
Negative Impulse strength in Non-uniform field	140kV @10mm gap	147kV @10mm gap
Solubility of sludge formed in Oil	Naphthenic oils dessolve sludge better	<4%

Table 1

Ester Technology Developments at SOTL

The ester fluids technology of Savita is yet another landmark development that has taken place in the past decade in Savita. Savita's Natural ester product, Biotransol, is backed by a process patent. Esters offer unique advantages over mineral oils in certain areas of application. A comparison of the properties of ester oils with mineral oils is shown in table 2.

It is clear from the table that the ester oils score over mineral oils concerning fire class and biodegradability. These two properties ensure superior fire safety (being a K-class fluid) and environmental friendliness respectively for ester oils over mineral oils.

Besides the above advantages, the higher water saturation of ester oils compared to mineral oils (see the above table for comparison) means more tolerance of ester oils to moisture in a transformer. This translates to slower aging of paper insulation in ester oils compared to mineral oils as explained below.

In a landmark paper, presented by the Savita research team at the prestigious international conference in Rome in 2019 (International Conference on Dielectric Liquids), spectroscopic evidence (XPS & FTIR) was presented to show how a Natural Ester Oil, Biotransol, interacts with cellulose polymer (paper insulation) to slow down aging and enhance paper life. A simplistic representation of how it is achieved by a Natural ester is depicted in figure 1.

The paper describes how a natural ester oil (e.g., bioTRANSOL) chemically modifies paper insulation to produce a hydrophobic paper. In effect, the paper surface would repel water which can otherwise cause paper degradation. The hydrophobic protection of the paper surface is provided by Natural ester oil and this accounts for the slow aging of the paper insulation. This phenomenon was not found to be occurring with mineral oil under the same conditions as our study.

The slow aging of paper insulation in ester oils has resulted in IEC standards allowing higher temperature rises for ester-filled transformers compared to mineral oil-filled transformers.

Using this standard, an end-user can leverage the higher temperature allowance to either operate an ester-filled transformer at higher loading than a mineral oil-filled transformer or operate at a similar loading and get better asset life due to its slow aging effect. Table 3 gives the temperature rises allowed by the IEC standard IEC 60076 -14(2013).

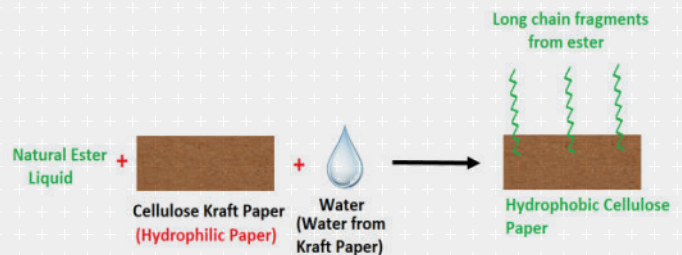


Figure 1

Chemical Modification of Paper Surface

Property	Mineral Oil	Synthetic ester	Silicones	Natural ester
Water Saturation @23°C, ppm	55	2600	220	1100
Fire Point,°C	160-180	>300	>350	>350
Fire classification	O	K	K	K
Biodegradation	No	Readily bioderadable	No	Readily bioderadable
Oxidation Stability	Good	Good	Excellent	Susceptible to oxidation

Table 2

Fire classification of insulatine liquids is as per 61100 standard

Insulation system	Solid Insulation Thermal class	Top Liquid Temperature (K)	Average Winding Temperature (K)	Hot Spot Temperature rise (K)
Kraft paper/Mineral Oil	105	60	65/70	78
Kraft Paper/Ester Oil	120	90	75	90
TUK/Ester oil	140	90	95	110

Table 3

The temperature rise limits are based on normal cooling medium temperatures according to IEC 60076 - 1

Extensive Research Programme on Dielectric and Heat transfer properties of Biotransol HF and Transol Synth 100 to provide design guidelines

Both the ester fluids (Natural ester, Biotransol, and synthetic ester, Transol Syn 100) have been studied extensively under a joint research program conducted between Savita Oil and a reputed OEM (Ms. CG Power and Industrial Solutions). The results of the study produced 5 post-graduate research dissertations and 7 publications at IEEE conferences. These studies showed:

1. Savita's Biotransol HF and Transol Synth 100 are technically on par with the best available grades of Natural ester and Synthetic ester oils
2. In large Oil gaps, the dielectric properties of any ester oil are slightly inferior to mineral oils
3. Heat transfer efficiencies of the ester oils are also inferior to mineral oils mainly due to the higher viscosity of ester oils vis-à-vis mineral oils
4. The publications finally provide guidelines for transformer design for ester-filled transformers taking into account the above differences.

Field Experience & Condition Monitoring

Ultimately, what gives confidence to customers about new technologies like ester fluids is the field experience and condition monitoring. Figure 2 is a representative graph showing condition monitoring data of Biotransol Natural ester-filled transformers carried out over more than 3 years (and continuing) for a prestigious Utility for their 72.5kV class power transformers.

As can be seen from the above plots, the dielectric and chemical properties of the Natural ester oil (Biotransol) have virtually remained unaffected over the 3 years of our study.

Savita's Transol Synth 100 is being used successfully for distribution transformers, achieving the desired objectives of biodegradability, and fire safety combined with very good oxidation stability.

Retrofilling aged mineral oil-filled transformers with ester Oils – A New Trend in Technology

Retrofilling refers to changing aged oil from an old transformer with a new oil when the oil has degraded to a point where it cannot be reclaimed. Ester liquids are increasingly being used for retrofill applications.

Objectives of retrofilling with an ester liquid

Retrofilling with esters has the following general objectives:

1. Enhancing fire safety of the transformer and up-gradation of the fire classification from class O to class K. Additional expected benefit is the biodegradability of the new oil.
2. Enhancing the life of the paper and hence of the transformer asset
3. The third objective could be to enable the user to operate the transformer at 10% higher than the originally rated load without affecting the life of the transformer asset.

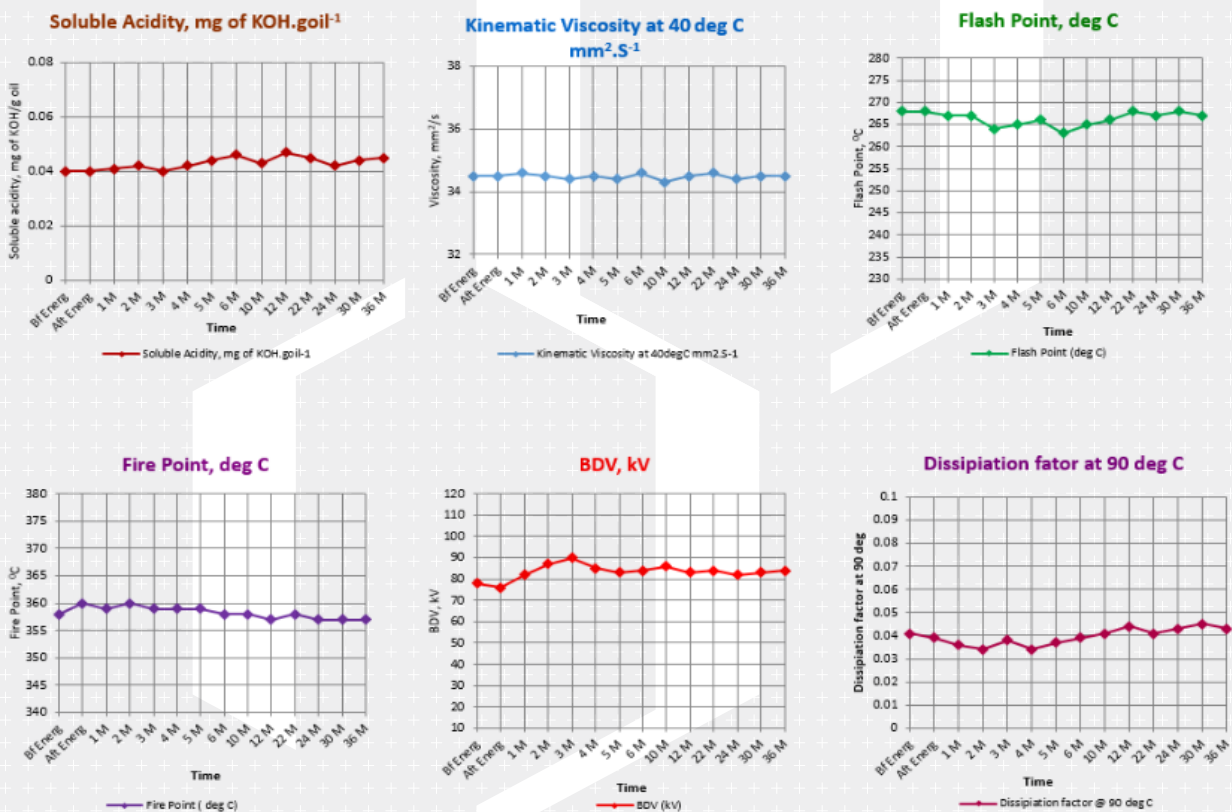


Figure 2

General Process followed for retrofill in brief

Firstly, the old oil needs to be removed from the transformer as much as possible. It is virtually impossible to drain out the old oil completely. However, the residual oil sticking to the paper insulation will have to be flushed out using a small portion of the ester liquid. The flushing operation should be carried out once or twice. The objective is to make sure that the contamination of the ester liquid with the old mineral oil is no more than 7 to 10%. It is important to stick to this limit since any higher level of contamination of the ester liquid with the mineral oil will result in a fall of fire point below 300°C and hence will not qualify to be called a K-class liquid.

If the mineral oil-filled transformer is of free-breathing design, the retrofilled transformer with the natural ester will have to be sealed by adding a conservator and a rubber bag. This precaution is, however, not necessary if the alternative liquid is a synthetic ester. This is due to the higher oxidation stability of a synthetic ester liquid compared to a natural ester liquid. However, it is important to check the compatibility of ester liquids with the gaskets already fitted in mineral oil-filled transformer.

Savita's Natural ester Biotransol has been popular in India for retrofill projects, having completed several retrofills successfully. All these projects are being monitored closely by the technical team of Savita to ensure that the objectives of retrofill are fulfilled.

Conclusions

The selection of a transformer fluid type depends upon the objectives dictated by the end user. However, once the right type of fluid is selected, the choice of a vendor is extremely important. Savita is a preferred vendor because of the following reasons:

- Decades of experience in the field of manufacturing, research, marketing, and technical services which are backed by a strong R&D and Quality assurance team
- Savita has been in the transformer oil business for the past close to 60 years and has contributed significantly to the evolution of technologies
- Savita's technical team participated in national and international standard committees (e.g. IEC & Cigre committees), presented papers at international conferences, collaborated with OEMs, Utilities and premier academic institutes and generally has a big presence in this important product line. The R&D head of Savita has recently published a book on the topic TRANSFORMER OIL APPLICATION ASPECTS, which is published by a reputed publisher in Europe.

SOTL is committed to follow UNSDGs (United Nations Sustainable Development Goals) in all their product and process activities for a better world.

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High Reliability Instrument Transformers with Oil-Paper Dielectric

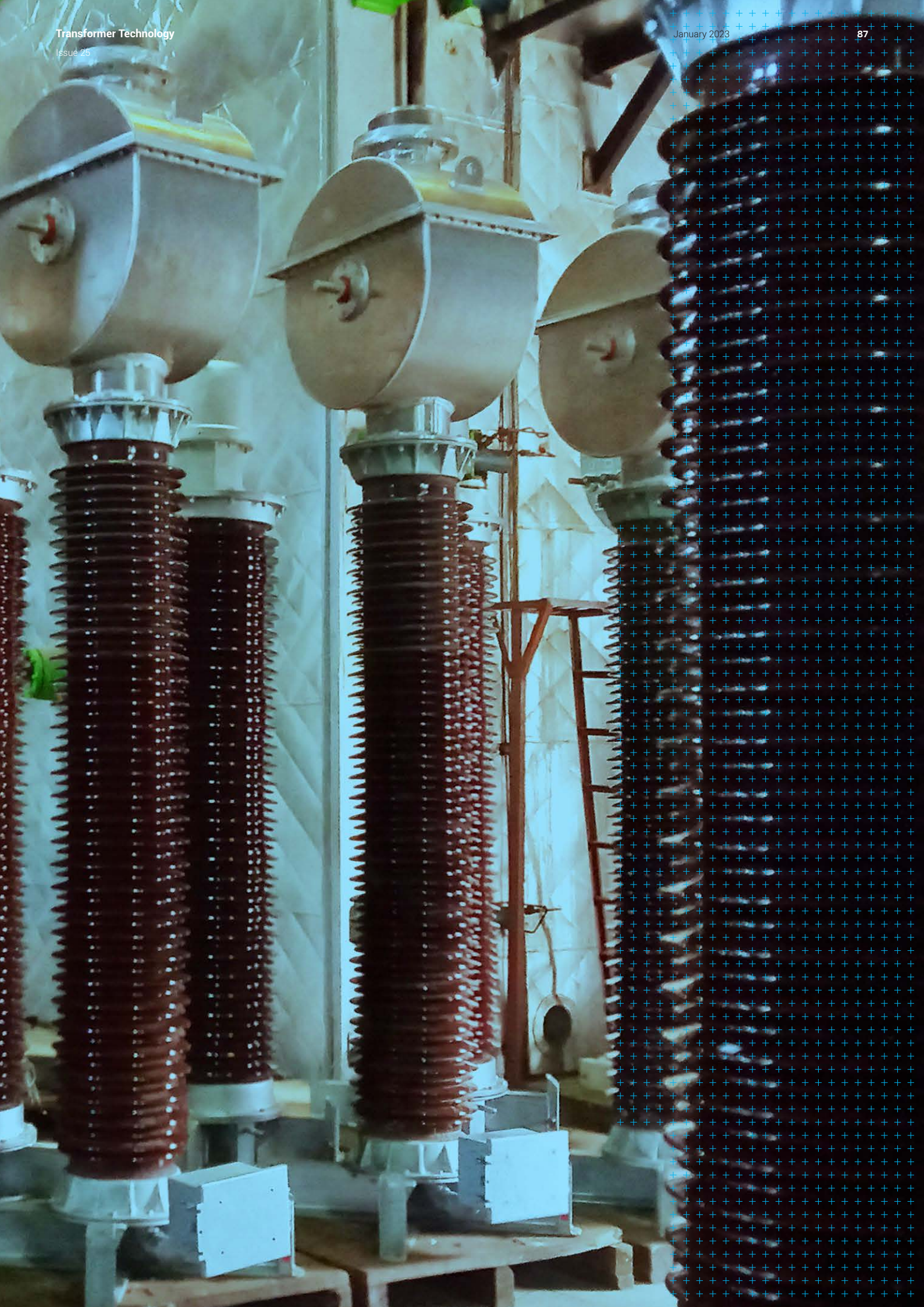
by **Dave Keshavdas**

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Instrument transformers with oil-paper insulation is a proven technology that has provided service since more than seven decades. As the technology has matured, it is even more important today to understand this technology to bring cost effective and reliable transformers to the market.



Dave Keshavdas received the M. Eng degree in Electronics from University of York, UK in 2001 and M.S in Electrical Engineering from Purdue University, USA in 2003. He is an expert in high voltage instrument transformers with over 18 years' experience and works as the Technical Director at ITC, manufacturer of instrument transformers since 1979.



Oil-Paper Dielectric

Any insulation either partially or completely loses its insulating behavior when the electric stress exceeds the electric strength of the insulating material. Such a loss can be temporary or permanent, which corresponds to self-healing and non-self-healing insulation. Due to the statistical nature of insulation breakdown, a different value of breakdown voltage occurs for every event of electric stress.

In practice, however, what does not lead to breakdown is easier to determine. This “withstand stress” must be capable of being determined strictly from the dimensions and the nature of the insulating materials. In an oil-paper insulation, it is of the form $E_0 d^{-b}$ kV/mm for a dielectric of thickness d (mm), where E_0 and b are constants determined empirically. See Figure 1. For very small thicknesses, the electric strength is not large because of the presence of weak spots, voids, holes, etc. in the individual sheets of papers. With the increase in the number of sheets (6-10), mutual overlapping of these weak spots reduces the probability of their occurrence in the same place.

Electrical Design

Designing the insulation for the LI voltage is a common pitfall in high voltage design. It is incorrectly believed that the short duration transients such as the impulse voltage creates the maximum damage to the insulation.



Although the peak dielectric stress during the LI voltage is high, the breakdown strength of oil-paper insulation, as well of oil-gaps is significantly higher with impulse than during AC voltage test.

Generally, about 2.5 times higher strength can be assumed for LI voltages compared to 1 min AC test voltage. Due to its higher energy content, a long duration AC voltage does more damage to the insulation than an extremely short duration impulse voltage. Moreover, a long duration AC voltage applied at a lower level can also do more damage than 1 min AC test voltage. It is generally accepted that the lifetime of the oil-paper insulation follows an exponential relationship with respect to the breakdown strength as follows:

$\log t + n \log E_b = \text{constant}$
 n is about 30-40 and depends on the type of material.



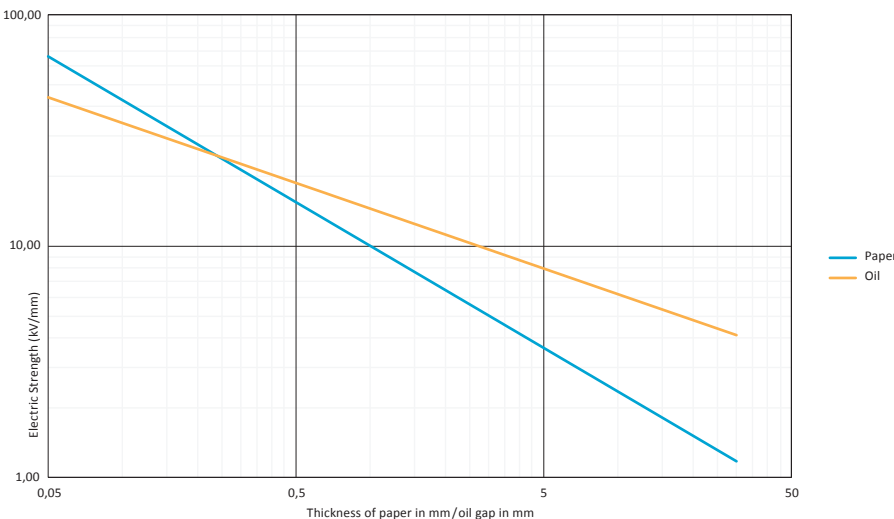
For $t = 1$ min and $E_b = 15$ kV/mm as the limiting stress for the dimensioning voltage, this limits the electric stress at no more than 8.6 kV/mm at operating rms voltage for a design life of 30 years. In practice, the electric stress is designed not to exceed 3.5 kV/mm at operating rms voltage.

Electro-thermal Design

Due to the Arrhenius effect, thermal breakdown is a more serious problem than higher electric stress. The Montsinger effect suggests that only 8 K rise in temperature halves the life of the paper insulation between the temperature of 80°C and 140°C.

The dielectric losses in an instrument transformer become important as the system voltage increases, as the losses are proportional to the square of the system voltage. The losses increase the temperature of the dielectric, with the risk of overheating, eventually leading to thermal breakdown. Given the relative

Figure 1: Electric Strength of oil and paper





permittivity of the dielectric and tan delta measurement, it is possible to calculate the critical voltage leading to thermal breakdown at any given operating temperature. As the ambient temperature rises there is a theoretical limit to which an instrument transformer can be operated safely under conditions of high voltage and high ambient temperature.

The tan delta value can be reduced through the process of drying. Extensive drying, however, can cause premature ageing and damage to the paper insulation due to depolymerization. A low DP value, measured indirectly through furan analysis of the oil, reduces the life of insulation. A well dried paper insulation is considered as having a residual moisture content of 0.3% - 0.5%.

To reduce the damages from thermal effects, the use of high strength thermally upgraded kraft and crepe papers allows a higher operating

temperature by about 10 K without any reduction in the life. Paper winding by machine or application by hand should be carried out with adequate tensioning such that there is no reduction in the mechanical strength on heating. This can be quality controlled using, for example, hardness tests before and after drying.

Design and Manufacturing for Reliability

The electric field in an instrument transformer is mostly non-uniform. An important characteristic of the non-uniform field is unequal distribution of the field between the electrodes. When the electrodes have identical profiles, the field is maximum on the surface of the electrodes and minimum in the middle. For dissimilar electrodes, the highest electric intensity occurs on the

As the ambient temperature rises there is a theoretical limit to which an instrument transformer can be operated safely under conditions of high voltage and high ambient temperature

electrode with the smaller curvature and the minimum on the opposite electrode.

Insulation for Voltage Transformer

The primary winding of an inductive voltage transformer should be

done with an adequate number of turns to allow a low flux operation at the working voltage. A magnetic field flux density of up to 0.8 T is recommended at 1.2 times the working voltage. To overcome the stresses during the lightning impulse each winding layer acts as a capacitance foil while the inductance of the coil has a negligible effect. The winding layer capacitances can be made approximately uniform by reducing the winding lengths at the higher voltage layers. An appropriately dimensioned high voltage electrode in a voltage transformer will reduce the stress significantly. Similarly, the electrode earthed in service will confine the voltage distribution in the space between the electrodes and eliminate spurious discharges from the earthed core sharp edges. To reduce the surface discharges from the high voltage electrode, it is necessary to wrap it with semi-conductive or insulation paper. In free oil gaps between any areas of high potential difference, impurities in the oil reduces the dielectric strength of oil substantially and increases the probability of a complete breakdown. To avoid this, free oil gaps can be prevented by inserting papers perpendicular (barriers) to the field.

Insulation for Current Transformer

A carefully shaped core housing in live tank CT will make the insulation

profile such that the boundary surfaces follow the equipotential surfaces, and the tangential stresses are minimized. With increasing service voltage, it is necessary to increase the inner diameter of the housing proportionately.

Field analysis should be carried out to determine the stresses in

the diagonal direction for the core housing. A design without any intermediate shields is possible up to the system voltage of 550 kV which is also convenient to manufacture.

Capacitive Grading for Bushing Tube

The bushing tube is capacitively graded with single sided insulation shields or screens inserted at certain positions to give a uniform axial or radial distribution. To reduce the effects of field enhancement, the free oil gaps in the insulation must be minimized.

The use of semi-conductive screens can be utilized to reduce the field enhancement at the foil edges.

Degassed, vacuum filtered mineral oil, with residual moisture at less than 5 ppm, at a temperature of 60-75°C is filled in the transformer. The oil penetrates the voids in the paper through capillary action. Once the vacuum is released and air is let in, the voids in the paper creates a partial vacuum which lead to absorption of the oil. The air exerts a positive pressure and contributes together with capillary action in filling the voids with oil.

The most important factor that influences the ingress of oil is the capillary structure, the geometry of the capillaries and their accessibility. The gaps in the paper layers influence the ingress of oil especially for very tightly wound kraft paper layers, where the flow of oil can only be in a direction

The viscosity of the oil and surface tension at the oil-gas interface also affect the capillary rise and the flow rate in paper. The volume of the oil that enters inside the capillary is inversely proportional to the viscosity. The viscosity of the oil decreases when the temperature increases, therefore the rate of impregnation is faster at higher temperature. At 40°C, complete oil impregnation in paper requires about 7 days, whereas at 70°C, it can be achieved within 48 hours.

Corrosion Proof Body

To ensure longevity of the instrument transformer, the tank body should be absolutely corrosion proof throughout its lifetime. The tank if made of mild steel material should be hot dip galvanized to ISO 1461. In case the end-user requires high aesthetics, a duplex system can be adopted. Alternatively, the body can be of powder coated stainless steel AISI 304/316 or powder coated marine grade aluminum alloy 5083. All hardware should be made of stainless steel to AISI 304/316.

Hermetic Sealing

The various terminals of the instrument transformers as well the tank surfaces should be machined and sealed with high quality hydrogenated nitrile or viton rubber seals suitable for up to 160°C or higher. The transformer should be

The use of semi-conductive screens can be utilized to reduce the field enhancement at the foil edges. It should be ensured that no conductive foils or electrodes are bare or exposed in oil.

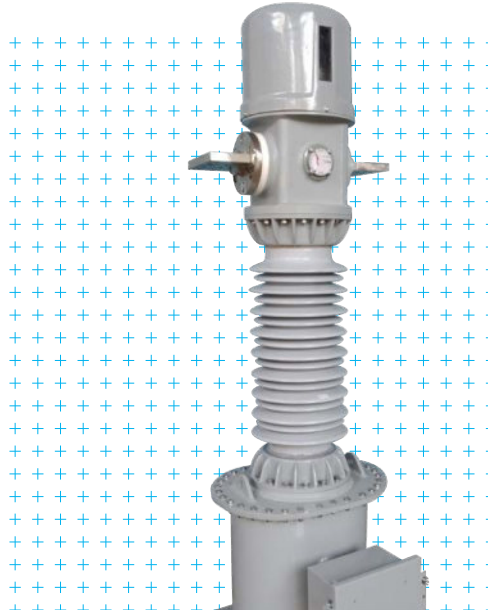
It should be ensured that no conductive foils or electrodes are bare or exposed in oil. Due to the nature of capacitive bushing, it is of course not possible to keep both the axial and radial stresses constant.

The boundary discharges on the paper are more likely due to surface level impurities and moisture. Therefore a design with uniform axial distribution and minimal axial stress is superior. The axial field strength limit is 1 kV/mm at the dimensioning voltage. The radial field strength can be allowed to vary but has to be kept well within the breakdown limit of 15 kV/mm at the dimensioning voltage.

Oil Impregnation

After drying of the paper insulation, instrument transformers are filled with oil under vacuum of less than 0.5 mbar. The air remaining in the gaps of the paper is evacuated during this vacuum phase.

parallel to the layers. The residual air in paper strongly affects its permeability as it slows down the speed of oil impregnation. When the oil penetrates a capillary, the residual air inside becomes compressed by the capillary forces and hence the internal pressure builds up. For this reason, to reach a faster ingress of oil it is very important to have less air inside. The efficiency of removal of trapped air is dependent on the vacuum level.



leak tested at a positive pressure of 1.5 bar without and with oil at the manufacturing stages before and after oil filling, respectively.

High Safety Features

Stainless Steel Bellow

Mineral oil expands at a rate of approximately 4 liters for every 100 liters at a temperature difference of 50°K. Hence, an expansion device, such as a stainless-steel bellow becomes necessary. Gasses (especially hydrogen) evolved due to high moisture or partial discharges also expand the bellow. Such a stainless-steel bellow should be designed with a sufficient inner diameter so that speed of its expansion is higher.

When the bellow is connected to the high voltage tube of the instrument transformer, any abnormal expansion of the bellow can be used to disconnect it from the tube connected at high voltage. This will lead to its de-energizing and the transformer can then be taken out of service for diagnostics. Hence, the stainless-steel bellow serves a very important function to relieve the excessive pressure build up in oil and could prevent premature explosion.

Oil over-pressure switch

In case of a fault due to electrical discharges inside the transformer, or

an internal arc fault, the oil pressure will rise. In most cases, the rise is usually a slow event which can take from few minutes to even few days. If the excess pressure can be detected, the transformer can be de-energized and taken for examination before it can lead to an explosion.

Depending on the height of the instrument transformer, a suitable oil overpressure switch is fitted at the bottom of the transformer. This detector is provided with Normally Open/Closed (N.O./N.C.) contact at the normal, predefined hydrostatic pressure of the oil. In case of excessive pressure rise in the oil beyond the set point of the detector, the detector will close with one end connected to the metal tank body which is grounded in service. The potential contact of the detector could be connected to the visual and/or audio alarm to allow the operator to de-energize the instrument transformer.

Composite Insulators

Composite insulators are an alternative to porcelain insulator for the external insulation and are manufactured with a high strength inner FRP tube and external silicone rubber sheds. The physical properties of the FRP tube material does not allow it to shatter like porcelain. In the event of any fault, expected failure mode is rupturing or bursting which eliminates the

occurrence of hazardous condition to personnel and surrounding equipment.

Equipment using hollow core composite insulators can withstand seismic acceleration stresses up to 1 g without damage due their lower weight, high damping factor and high strength design characteristics. The hydrophobic properties of the silicone rubber sheds have a better electrical performance in contaminated condition.

Water on the surface of hydrophobic materials forms water beads, so the conductive contamination dissolved within the water beads is discontinuous. This condition results in lower leakage current flow and the probability of dry band formation, which in turn requires a higher impressed voltage to cause flashover. The higher resistance of silicone rubber helps to limit the arcing and minimizes the flashover.

Oil with Negative Gassing Tendency

Due to thermal or electrical stress through partial discharges, the oil-paper insulation can be degraded and release various gases, such as hydrogen. Since mineral oil is gas-evolving, the gases could accumulate and make partial discharges persistent. This could eventually lead to an explosion of the transformer and the risk of fire. By adding 3-10% of Mono/dibenzyltoluene (M/DBT) to the mineral oil, it can become gas absorbing from gas evolving. Such an oil is modified to behave with negative gassing tendency which helps eliminate the gaseous channels and thus suppress the probability of discharge occurrence.

Conclusion

Not only are better materials for both oil and paper available today, but the knowledge gained in insulation design over the past decades is also of advantage to implement stress optimized designs. Despite introductions of dry type instrument transformers, the advantages of oil-paper insulation are too difficult to ignore and will remain relevant for the foreseeable future.



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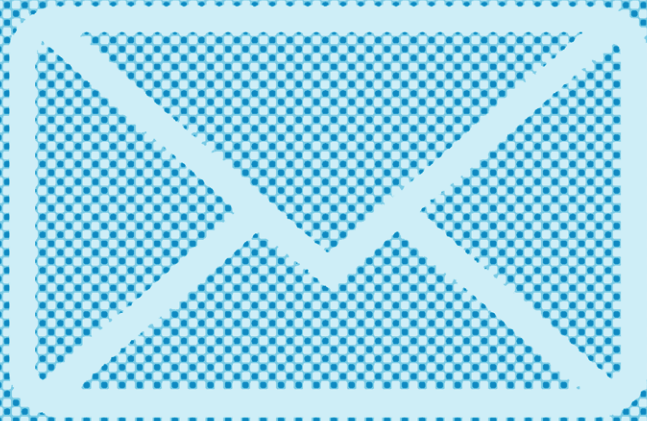


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