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Transformer Lifeblood: Oils & Fluids PART I

Interview with **Javiera McGuiggan** Global Business Leader at **Cargill**

Degradation of Insulating Liquids: Myths and Facts

Interview with **Giovanni Cattani** General Manager of **Siemens Energy Transformers**, Trento, Italy

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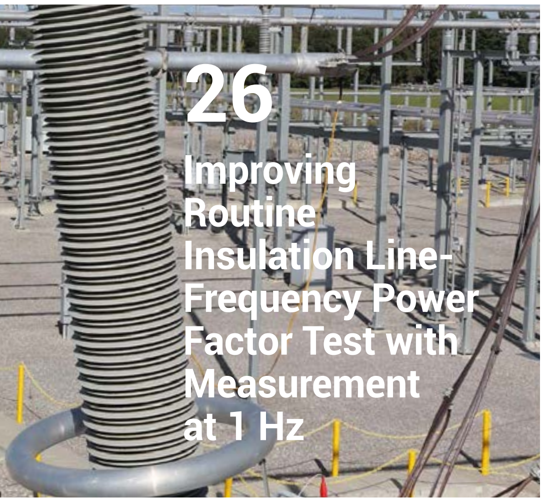
Global Business Leader at Cargill



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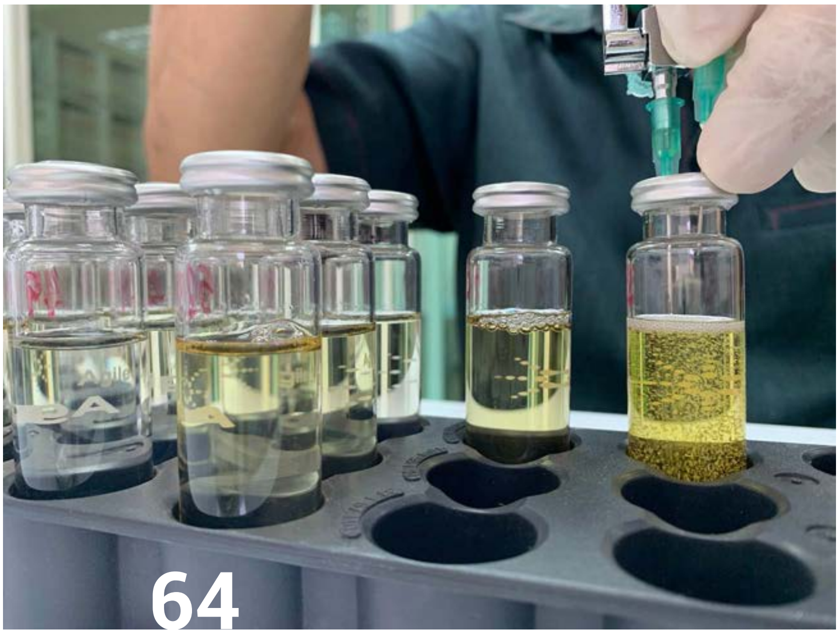

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Unique Properties of Transformer Insulating Oils Containing Hydrogen Donor Compounds

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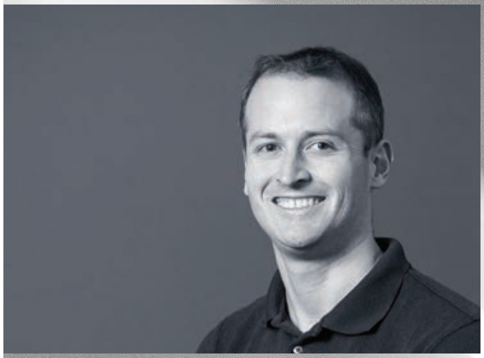

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Dear Readers,

I remember the first issue of Transformer Technology: Oils & Fluids and how we were amazed at how quickly we were able to curate the content that was the correct combination of quality and quantity. For this issue, we have been overwhelmed with both the quality, but also the quantity of articles and interviews, so much so that we are splitting Oils & Fluids into two parts, with this issue being Part 1 and in January we will publish Part 2.

As we develop our Body of Knowledge (BoK) for the TT Community, we look for several things for Oils & Fluids: a variety of technical content about the different types of fluids, whether it is mineral or vegetable, application information about how these fluids are being used, and comparative information between different types of fluids. We add in an interview that was transcribed from a video-cast we did with interesting and informative subject matter experts, all in the hopes that we inform, educate and inspire. We expect you will find that both this December issue and the future January issue will do just that.

Over the past decade, I have watched as natural and synthetic esters were changing the industry. Their unique qualities and chemistry have a growing list of applications that make for a changing landscape. But, not to be left behind, mineral oil technology is also changing to adapt to unique applications as well. What does all this change mean to the transformer fluid testing world? The way we extract condition information must change, and the way we gather and evaluate the data from that testing is changing as well. Change! I love that word.

While technology is changing rapidly to a digitalized world, you would think that the chemistry of oils and fluids would not change, but as they do, to adapt to new applications, one thing is certain: data collection and machine learning must keep up. Over time we will be gathering tremendous amounts of testing data that will determine the condition and thus, the life cycle of these critical assets. Making the right decision of which fluid to use will depend on the specific requirements of the transformer, and here is where I get most excited. Since all reliability of an asset and thus of a system in which the asset is deployed begins at design, the specification of the fluid must also begin at the design stage.

If we are to build more reliability into the electrical system, whether that be for the grid or for a data center or steel mill, then it stands to reason that the selection, testing and treatment of the fluid within the transformer is a critical decision.

If we are to build more reliability into the electrical system, whether that be for the grid or for a data center or steel mill, then it stands to reason that the selection, testing and treatment of the fluid within the transformer is a critical decision.

Alan M Ross

At Transformer Technology we are committed to give you, our community, actionable information that can help you make key decisions for all stages of the life cycle of transformers; from design, to manufacturing, to installation, to testing and finally to maintaining and disposal. With this issue focusing on Oils & Fluids and with the upcoming January 2022 Part 2 issue, we believe we are bringing insight that educates, informs and inspires. Enjoy!

Finally, our February issue of Transformer Technology is themed, Transformers: The Heart of the Generation, Transmission and Distribution System. We will also preview the upcoming IEEE PES Conference and Exhibition coming in April in New Orleans.

If you, or someone from your organization wishes to contribute to the February issue and add your voice to our BoK, please contact me at:

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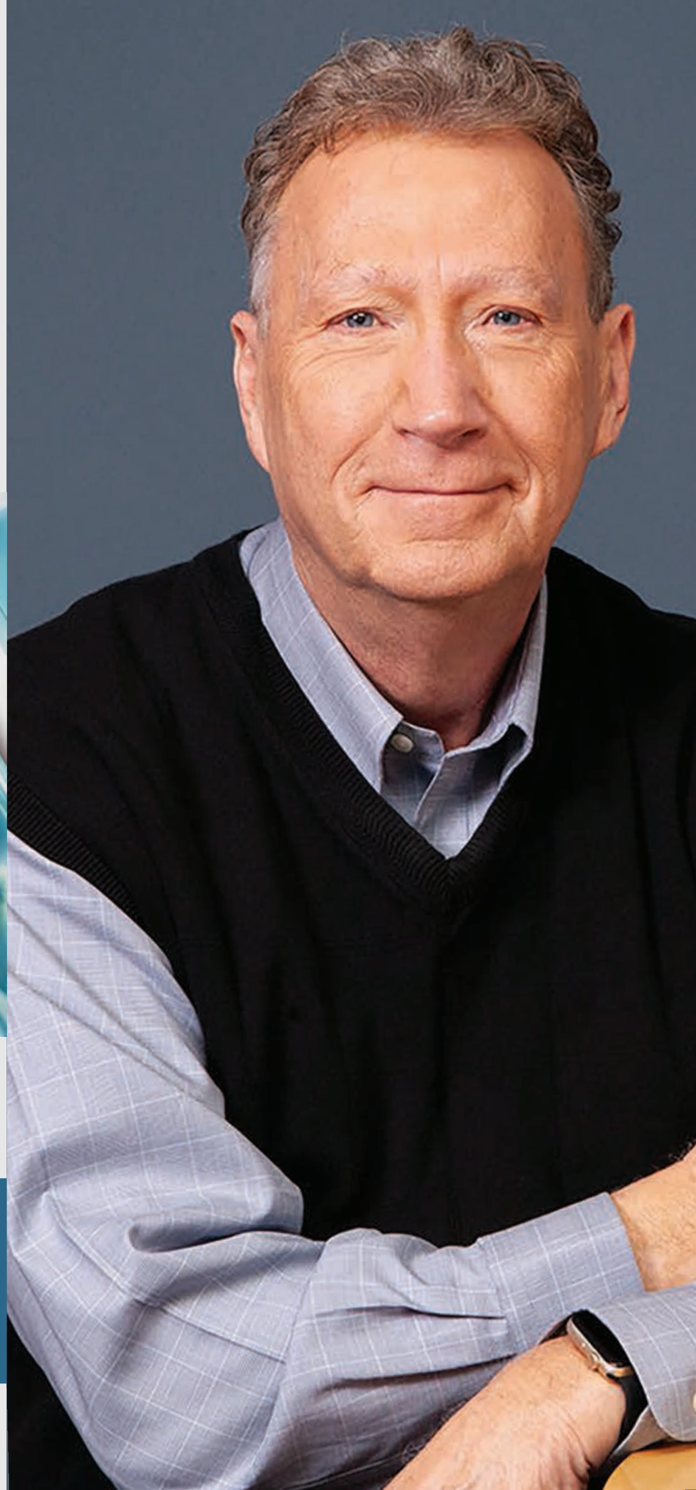

Javiera McGuiggan

Cargill

Alternative Fluids: Making Smart Choices for a Better Future

Interview with **Javiera McGuiggan**

Global Business Leader at Cargill

“

We are changing the world, one transformer at a time.

Photo: Cargill

Javiera McGuiggan is a hydraulic engineer, fluid expert and Global Business Leader in Cargill's bioindustrial business, passionate about the optimal more sustainable solutions for transformer fluids. In her interview with Transformer Technology, Javiera shares insights on the bioindustrial market and her views on the present and future of alternative transformer fluids as well as Cargill's efforts to bring the optimal biodegradable insulating solutions.

Alan Ross: Javiera, you are the Cargill's global business leader for the bioindustrial market, including the biodegradable FR3® fluid. Could you tell us about the department's mission with transformer fluids?

Javiera McGuiggan: The main mission is to take products that are either chemicals, that are not necessarily good for the world or they are petroleum-based solutions for industrial purposes, and change them into renewable bio-based solutions. I run one of the product lines in this group, but it is a broader group, with lines in consumer and other industries.

AR One of the things we realized is the importance of sustainability. Safety and environmental health are becoming a big

area, but alternative transformer fluids are still not widely accepted and there is need for more and better information. I want to talk about different industry segments. We know there is a safety issue about using FR3 fluid compared to using any mineral oil. What can you tell us about the overall cost and safety, as we see that more and more people justify the cost because of a safety issue?

JM This goes to my point that people are not seeing the broader picture of the impact that using this fluid can have. It's not just an ingredient in the transformer.

Using alternative transformer fluids can change the way transformer owners do their operations, the way they manage their assets, financial returns, and influence overall peace of mind with grid reliability and safety and protection of the environment.

It can literally change the way transformer owners do their operations and the way they manage their assets. It is influencing their overall peace of mind with the reliability of the grid, the safety and the protection of the environment. It can also strongly influence financial returns in terms of asset management, performance quality, the cost-reduction of maintenance and the asset longevity. There's a broad set of impacts that people forget to put into the equation. That is why we do a lot of education on understanding the broader picture in reliability.

AR In reliability, we focus on the total cost of ownership as opposed to the cost of an asset. What is the advantage of FR3 fluid for a

Photo: Shutterstock

total cost of ownership? Does it last longer? Is it less damaging?

JM There are two things that directly impact the long-term value equation. The main one is a property inherent to the fluid related to its behavior with water. If there is excess water in a transformer, which is generated by moisture because of usage and environmental conditions, FR3 fluid will grab that water and take it away from the paper, the solid insulation. To put it that way, transformers end up dying when the solid paper insulation dies. If you take away that moisture and the liquid takes care of it, it is protecting the paper and naturally extending the life of the asset. Depending on the size of the transformer and the type of paper used, the paper's life is extended by five to eight times. That is the first advantage, something very basic that most people aren't familiar with.

Once someone told me "I hate your fluid because when I have a mineral oil transformer, I open it and I immediately know what's going on with it just by looking at it." And my response was "Yes, that's because mineral oil kind of burns and it's nasty after a couple of years. You know exactly what it's been through."

Our fluid doesn't. We have had transformers literally working for 25 years, and, when you open them, the fluid is almost as new. Therefore, there is much less maintenance required to refresh and put additives in. Just even for inspection, there should be significant changes in maintenance.

We have never had a reported fire in a transformer using FR3® fluid. Even if it fails, there wouldn't be an explosion or a fire.

And the advantage that surprised me the most is related to understanding the possibility of your flexible loading capability, and that is that you can run your transformers a little hotter and then get some more power out of them. People don't realize that a large utilities, for example, can save huge amounts of money just by inventory management. You don't have to have every size of transformer. You can skip a size and don't have to have the whole set of inventory just in case there

Photo: Shutterstock

is a storm, or for every different unit have all the little parts and pieces that go with it. That way your inventory can be much more efficiently managed. And, of course, there are many financial benefits of using FR3 fluid.

environmental impact of using biodegradable fluids?

JM The beauty of the whole picture is that using biodegradable fluids is

AR You mentioned moisture, and you are absolutely right - the life of the transformer is the life of the paper. I call it a wicking propensity that FR3 fluid has. For those among us who are not chemists - what happens to the moisture?

JM Briefly, there is a chemical reaction with the dielectric fluid that, so to speak, disintegrates the water and separates it into its two components. That way the water doesn't stay trapped in the transformer, but it decomposes into oxygen and hydrogen, becoming neutral and has no negative effects.

AR I was once involved with a company that had six transformers located on a river running through the city - two primaries, three secondaries and one tertiary. The city decided to turn the area into a tourist destination, and the company was asked to relocate because their mineral oil-filled transformers posed an environmental risk. It was a multi-million-dollar deal and a great publicity problem for the company. They solved it by retrofilling the transformers with a biodegradable fluid, and later relocating their facility. What can you tell us about the

the smartest choice, not just because of safety concerns, but also because you don't have to compromise. You don't have to spend more money to take care of the planet and have all the other benefits. When you look at the total cost, it is actually saving money. It is an initial transformation, but you are not really compromising, you are making the smartest choice. This goes back to my point about educating people who are scared and have not tried this before - that is one of our main goals.

There is no limit on the size of the unit when it comes to using FR3® fluid. My team has even come up with a fun challenge about who is getting to work on the biggest transformer.

AR In the case of a leak, there is an environmental risk because mineral oil is considered a hazardous material.

JM Because of the lower viscosity, mineral oil could get to the waterbed very quickly.

AR When we speak of environmental hazard, we mean a hazard from a leak. And leaks in transformers are much more prevalent than a catastrophic failure. Every year we hear of some transformer explosion and when they blow up, they're like bombs, particularly bushing explosions.

JM Apart from the environmental issue, another hidden cost that people forget about is their corporate image, how the community sees your company. I am sure it is hard to put a price on your peace of mind before you have had an accident or before you have had a spill or a fatal fire. Because it isn't fire. It is a literal explosion when a transformer fails, and it keeps burning until all the oil is gone. This peace of mind is like insurance. It is just hard to get people to understand it until sometimes it is too late. And that is part of our education journey, letting people understand how you might be ignoring this or not seeing it because it is inconvenient, and you are naturally scared. People are just scared of change. Overall, it is a natural thing for people to think "If I don't do a big change in my job, if I don't put my neck out, I shouldn't get fired" rather than have the vision of "I should be the one pushing for this because I want the future to be better."

We have never had a reported fire in a transformer using FR3 fluid. It can fail, but this wouldn't result in explosion or fire.

AR I would like you to address a criticism. FR3 fluid started with smaller transformers, and some people think that the higher up you go in terms of the power of the transformer, the less likely it is that FR3 fluid is available.

How high do you go? What size of transformer is your limit for FR3 fluid?

JM Thank you, because this is a very good question. We started focusing on distribution transformers exactly because companies were driven by the fear of change. Distribution transformers are smaller, you change them more frequently, less cost is involved if anything goes wrong, and that is why this was our first window into this change. But FR3 fluid can be used in any size of transformer. There is no limitation for the use of the fluid related to the kV rating or any other aspect of the transformers. So, there is no limit. My team is almost in an internal competition about who has worked on the biggest transformer lately - it was China, then it was Brazil, etc. It is a fun challenge to see who is getting the largest transformer, but there is no limit. In fact, the larger the transformer, the greater the financial benefits you get because you are extending the life of this giant asset that you can expect to last longer.

One of our main goals is to educate people who are scared about using alternative fluids on why this is the smartest choice.

AR I believe we have just dispelled the myth about bio fluids. We have hit many reasons why FR3 fluid is a growing choice for a lot of people. If somebody is looking to make the change, especially those that are looking to retrofill their transformers or buy transformers with alternative fluids, how does your team help them?

JM We offer a lot of information, and we especially help in cases of retrofills. That is when people worry that their asset might fail and they want a warranty that the fluid won't cause any damage. We help them every step of the way - we help them understand the current status of the transformers they want to retrofill, recommend the best partners that we have to do the work, and we are present to do the change if they want to make sure that everything was done correctly. We perform trials, if you have many units that you want to retrofill, and you want to just start with one for your own peace of mind. So, we grab people's hand to go through that journey.

AR Excellent. Well, we grab hands with you, we appreciate it, and we will be following the journey of biodegradable fluids in the industry.

JM Thank you. It is a really fantastic mission we are doing. Our main focus is to keep growing, building plants everywhere so that these biodegradable solutions are accessible to everyone, and no one is missing out on understanding what this can do for them. We are changing the world, one transformer at a time. (laughs)

AR That is brilliant! Thank you so much for joining us, Javiera, and for sharing your knowledge and your enthusiasm.

JM Thank you for inviting me.

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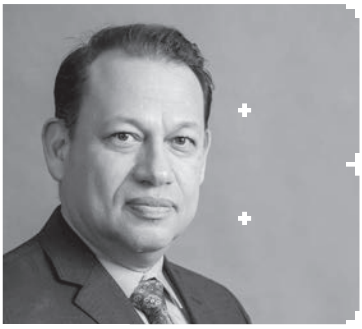
Improving Routine Insulation Line-Frequency Power Factor Test with Measurement at 1 Hz

by **Diego M. Robalino**
Vince Oppedisano
and **Kenneth Petroff**

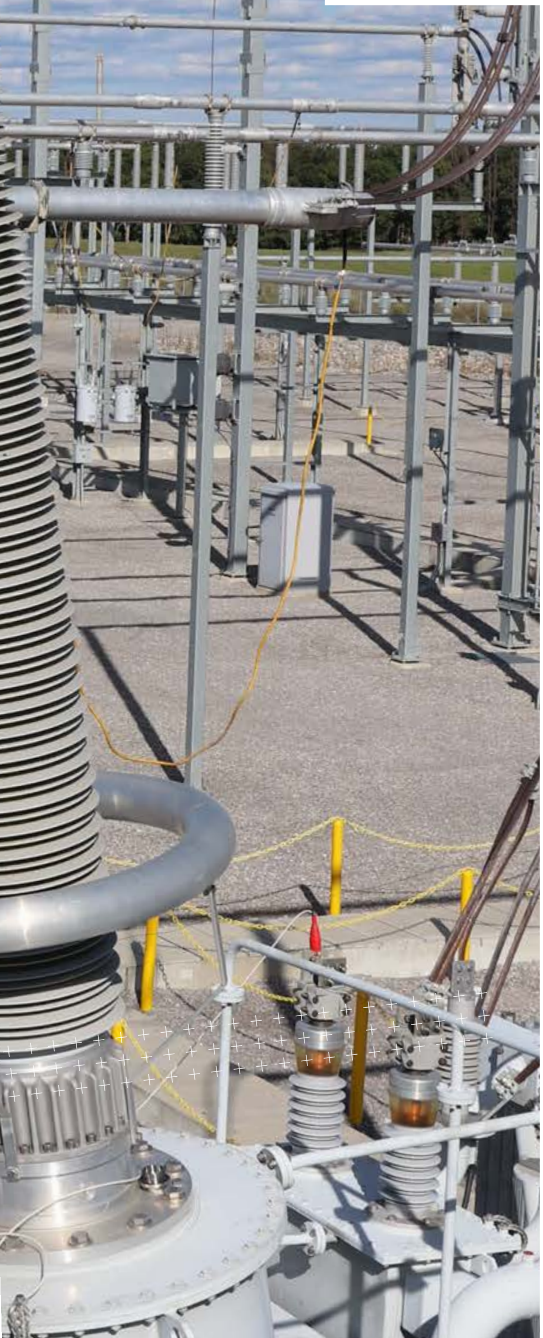
Photo: Megger



Diego Robalino is the Business Development Director – Power Transformers at Megger. Diego is a Senior Member of IEEE, a member of IEEE/PES Transformers Committee, a certified Project Management Professional with the Project Management Institute (PMI), and the General Chairman for the IEEE/DEIS 2022 40th Electrical Insulation Conference. He is the author and co-author of over 40 technical articles related to power, distribution, and instrument transformer condition assessment. Diego received his Ph.D. in Electrical Engineering from Tennessee Technological University.

Kenneth Petroff is a Product Manager for Transformer Products at Megger in Valley Forge, PA. Ken is a graduate of Western Michigan University, and brings both field experience as well as unique skills related to the modern requirements of testing methods and the complex computer operations needed to perform them efficiently. Ken is a product quality champion with a wide understanding of the transformer testing challenges and needs of testing personnel in the field.

Vince Oppedisano is the Transformer Product Specialist at Megger in the Valley Forge, PA factory. Vince has dedicated more than 35 years to the electrical testing industry. He has represented Megger at several technical and commercial events worldwide. He is a dedicated product development leader devoted to power and instrument transformer testing and diagnostics.



Introduction

Line-frequency (50/60 Hz) insulation dissipation factor (DF) or power factor (PF) is commonly used in the field for general insulation condition assessment of substation equipment. This common approach to measure dielectric losses in the insulation and quantify as a percentage PF or DF has been performed using portable field equipment with a voltage source up to 12 kV. Measurement of dielectric losses depends on dielectric properties of the insulation material, insulation temperature, geometrical design, as well as aging and contamination that might be present within the insulating medium. Most important to consider is that the insulation system is not perfect, and some losses will be identified.

General limits have been established for line-frequency (LF) PF/DF measured in liquid-impregnated power and distribution transformers and guidelines have been given to field users. It is important to mention that PF/DF test equipment does not only measure %PF but also provides a measurement of capacitance, watt losses, and resultant current. All of them are important for overall condition assessment.

Nevertheless, field users from different parts of the world have encountered situations where a transformer or bushing with a recently tested good %PF value failed in the field shortly thereafter.

Then the question for most asset managers is: What methods are available to improve the quality of assessment of line-frequency power/dissipation factor (LF PF) without affecting the productivity and efficiency of maintenance and field staff? Can this new method be easily adapted within routine testing practices?

Line-frequency insulation dissipation factor or power factor (LF PF) is commonly used in the field for general insulation condition assessment of substation equipment.

Line-Frequency Power Factor (LF PF)

In a liquid-immersed transformer, LF PF is measured

winding-to-winding and winding-to-ground, typically at 10 kV (or below rated voltage of the winding under test) and at line-frequency or at frequencies very close to it.
As mentioned above, LF PF is temperature-dependent which leads to an additional requirement in the assessment process – normalization to a base temperature value (20°C).

In the last 25+ years, the electrical power industry has seen added value provided by the analysis of dielectric losses at frequencies different from 50 or 60 Hz (Dielectric Frequency Response).

Is DFR a viable path to help clarify doubts related to LF PF measurements? What are the lessons learned and how can this tool be used to support routine testing in the field?

Looking into the alternatives and the physical capabilities of the PF/DF test set, the ability to measure dielectric losses in a spectrum of frequencies from 1 Hz and up to 500 Hz was implemented. Measurement in this spectrum of frequencies does not imply significant addition of testing time but opens the opportunity to also measure PF/DF at any other frequency in this range as part of the routine LF PF test.

Now that the test set can measure dielectric losses within this frequency spectrum, the traditional LF PF test takes a major step further towards improvement and ease for condition assessment. LF PF/DF is not any more a one-point/single reference that may or may not be influenced by degradation or contamination in the complex insulation system under test. Between 10 and 100 Hz, the dielectric response is typically very linear (especially at temperatures between 0 and 25°C) whereas the range between 1 and 10 Hz is at least

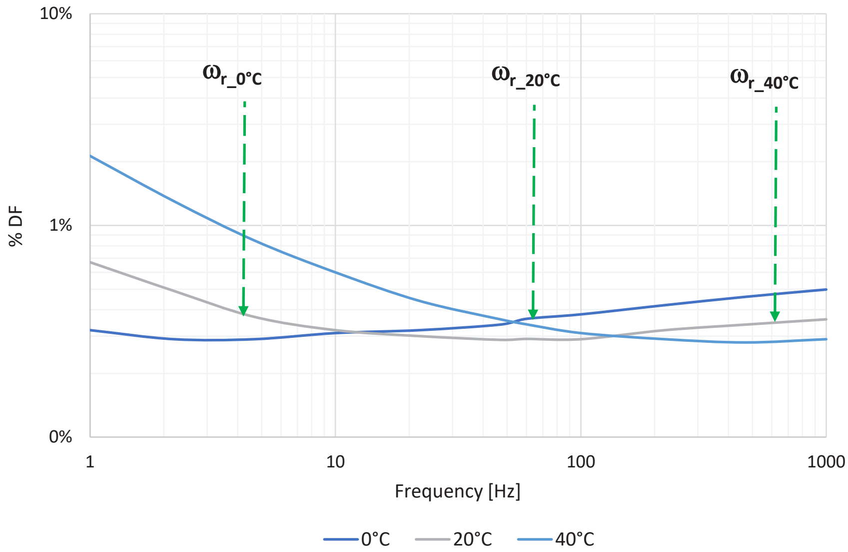


Figure 1.
Resonant frequency shift in a dielectric response at different temperatures

10 times more sensitive to insulation degradation. For dielectric analysis, the amount of information in each logarithmic decade (1 Hz to 10 Hz; or 10 Hz – 100 Hz) is of similar importance.

Therefore, the use of an additional frequency value while performing the LF PF/DF test is a practical approach to leverage technical assessment on two points within the dielectric spectrum of the insulation under test.

The use of an additional frequency value while performing the LF PF/DF test is a practical approach to leverage technical assessment on two points within the dielectric spectrum of the insulation under test.

Power Factor at 1 Hz

For liquid-immersed systems tested at or close to 20°C, the frequency range between 10 and 500 Hz displays a very linear characteristic when losses are low. Measuring PF at lower frequencies, the dielectric response encounters a frequency range represented by high losses and greater dispersion. The point of transition is called resonant frequency and it will shift depending on temperature (see Figure 1), insulation materials, and level of contamination or degradation of the insulation.

The variation of LF PF as a function of temperature is very small as compared to that observed at 1 Hz, especially for a healthy and dry specimen (<0.5% moisture in the solid insulation) immersed in good liquid insulation (conductivity <0.37 pS/m). When the condition of the insulation changes, the thermal response of LF PF also changes, and these changes may be overseen when temperature correction is not performed properly.

The research work carried out in liquid-immersed transformers and

OIP bushing insulation condition	1 Hz DF/PF at 20°C
As new	0.2 – 0.5
Good	0.5 – 0.75
Aged	0.75 – 1.25
Investigate	>1.25

Table 1. OIP bushings assessment for 1 Hz DF/PF at 20°C

OIP transformer insulation condition	1 Hz DF/PF at 20°C
As new	0.2 – 0.75
Good	0.75 – 1.25
Aged	1.25 – 2.0
Investigate	>2.0

Table 2. OIP transformers assessment for 1 Hz DF/PF at 20°C

Insulation tested	Measured %LF PF	20°C %LF PF	Measured 1 Hz PF	20°C 1 Hz %PF
CHG	0.52	0.39	11.7	4.25
CHL	0.42	0.39	10.6	3.54
CLG	0.45	0.35	10.6	3.56

Table 3. Overall LF and 1Hz PF results for 1978 Tx

Bushing tested	Measured %LF PF	20°C %LF PF	Δ% LF PF at 20°C	Measured 1 Hz PF	20°C 1 Hz %PF
H1	1.04	0.88	0.6	15.1	12.3
H2	0.72	0.63	0.34	8.77	7.12
H3	0.73	0.64	0.35	9.69	7.92

Table 4. HV bushings C1 capacitance LF and 1 Hz DF/PF results

bushings using wide spectrum dielectric frequency response testing techniques is extensive. From this research, recommendations were made for 1 Hz PF limits for OIP transformers (Table 1) and OIP HV bushings (Table 2).

Field Experience
Routine testing on a service-aged transformer

A 1978, 20 MVA, 69/13.09 kV, Dyn1 transformer was taken out of service to repair a pump in the cooling system. The technical maintenance team completed the required repairs and conducted a complete protocol of routine commissioning tests including a regulatory 10 kV line-frequency (LF) power factor (PF) test.

The overall capacitance and line-frequency power factor (LF PF) test at 10 kV is carried out using Megger's DELTA4000 power factor (dissipation factor) test set at a top-oil temperature (TOT) of 30°C.

The overall line-frequency PF results are normalized to 20°C using the individual temperature correction (ITC) algorithm showing a "Good" overall condition of the insulation (Figure 2). Without any additional information, it would be assumed that no additional work needs to be performed on the transformer to improve its lifespan.

As part of the routine test, 1 Hz PF was measured and corrected at the same time LF PF was carried out. The 1 Hz PF values obtained are much greater than those considered in Table 2 for service-aged transformers and the system calls for Investigation [I] as presented in Table 3.

Capacitance C1 of the HV bushings are tested at an estimated bushing temperature of 22.5°C (as an average between ambient and top-oil temperatures).

Line-frequency power factor (LF PF) on all HV bushings shows values doubling or nearly tripling the nameplate reference values (see Table 4). These elevated values warrant investigation.

Again, ITC is used to normalize LF and 1 Hz PF results to 20°C in Table 4.

Results in Table 4 lead to a decision to replace the HV bushings. The transformer oil was drained and the HV bushings were removed from the unit. Figure 2 shows a layer of contamination on the bottom section of the bushings.

Based on these findings, the owner decided to filter the oil to ensure the removal of all particulates.

New bushings were installed on the HV side of the transformer, and they tested at an estimated bushing temperature of 24.5°C. Excellent LF and 1 Hz PF values were obtained on the C1 capacitance as presented in Table 5.

With the HV bushings replaced, the oil filtered, and under the same test conditions, the overall LF PF test was carried out and results show clear improvement, as presented in Table 6.

As with LF PF values, 1 Hz PF did improve but assessment indicates that the unit requires further

Photo: Megger

*Figure 2.
HV bushing removed from the transformer – surface contamination*

investigation. Why would the 1 Hz PF values still be high after HV bushings replacement and oil filtering?

To answer this question, and based on the 1 Hz PF results, the owner of the equipment requested a definitive analysis of the insulation system using Megger's Insulation Diagnostics Analyzer IDAX300S to obtain a wide spectrum (1 mHz – 1 kHz) dielectric frequency response (DFR) and determine the condition of the entire insulation system inside the transformer.

Full-spectrum DFR shows that the interwinding solid insulation contains a typical % moisture (1.7%) for a service-aged transformer but the liquid insulation reports high conductivity (11.8 pS/m).

Further internal inspection of the unit shows that tank walls and paper insulation retained contamination material in areas difficult to be removed. It was recommended now to flush the core-coil assembly several times to remove contamination. Sampleswere taken and sent to the laboratory for analysis.

It is important to mention that historical DGA data did not alarm the operator. In Duval Triangle 1, values fluctuated within the T1 region.

Bushing tested	Measured %LF PF	20°C %LF PF	Measured 1 Hz PF	20°C 1 Hz %PF
H1	0.24	0.25	0.11	0.19
H2	0.24	0.25	0.14	0.18
H3	0.24	0.25	0.1	0.12

Table 5. HV Bushings (new replacements) C1 capacitance LF and 1 Hz PF results

Insulation tested	Measured %LF PF	20°C %LF PF	Measured 1 Hz PF	20°C 1 Hz %PF
CHG	0.36	0.26	10.8	1.75
CHL	0.45	0.33	13.6	2.19
CLG	0.51	0.34	13.7	2.29

Table 6. Overall LF PF results after oil process and HV bushings replacement

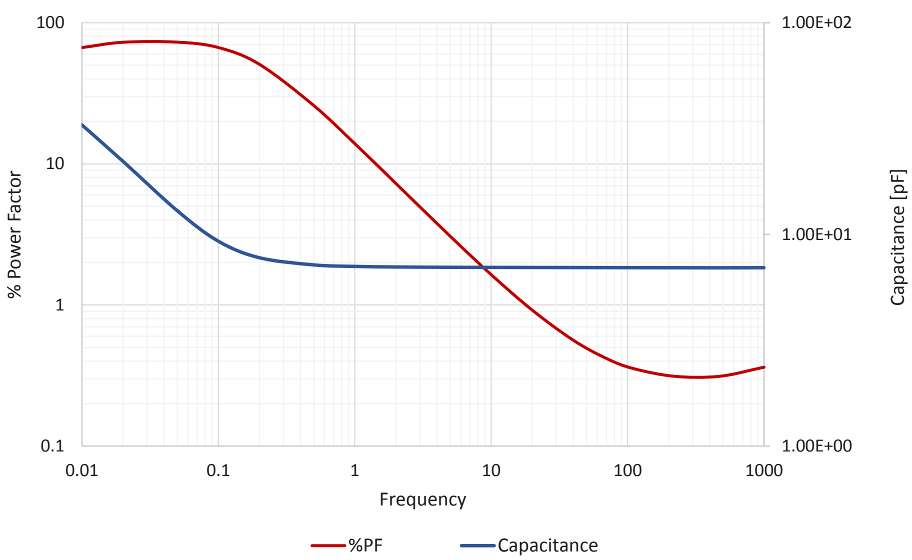


Figure 3.
Dielectric Response after oil-processing

Conclusions and Recommendations

Line frequency PF (DF or tangent delta) measurements by themselves may or may not reflect the true condition of the insulation system inside a transformer.

- It is a fundamental practice to record a benchmark signature of the dielectric condition of a power transformer before any maintenance work is carried out.
- Identify deviations from practical references besides LF. 1 Hz complements, confirms, and verifies the information obtained by LF PF.

The use of LF DF together with 1 Hz DF results properly corrected to 20°C using the Individual Temperature Correction (ITC) algorithm provides higher sensitivity to changes in the insulation system of HV equipment.

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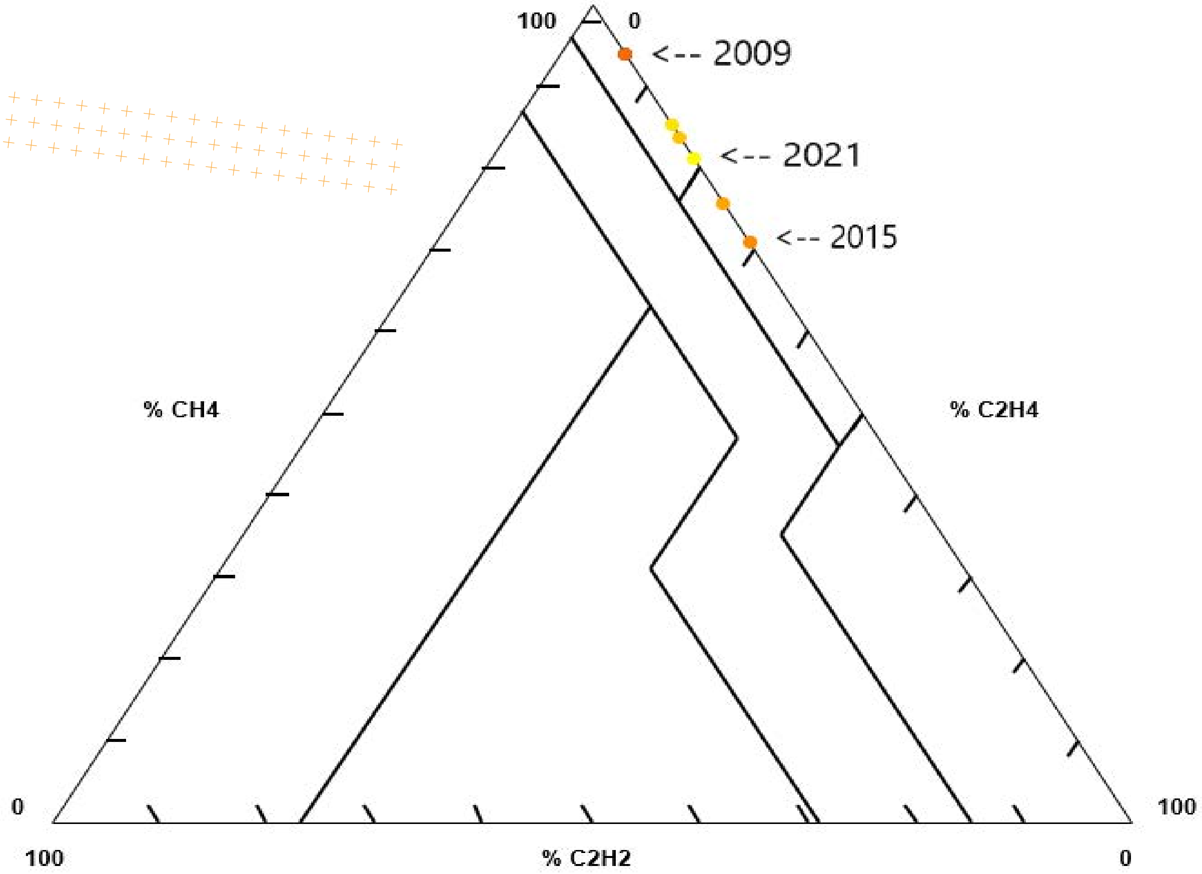

Figure 4.
DGA Trending - analysis in Duval triangle 1

1 Hz measurement is a valuable addition to the "ROUTINE" testing procedure for insulation condition assessment of liquid-impregnated transformers and bushings.

The combined analysis of LF DF + 1 Hz DF (ITC corrected) allows for numerical condition assessment of new and service-aged transformers and bushings as suggested by the authors in Tables 1 and 2. The 1 Hz DF with ITC assessment does not require trending analysis, although it is also possible to trend this value. Moreover, average factors used for temperature correction which are obtained from generic tables do not represent theimmediate dielectric condition and thermal behavior of PF. End-users should consider the implementation of the ITC algorithm for reliable assessment of results and proper trending over time.

The traditional 10 kV LF DF together with the 1 Hz DF (ITC corrected) marginally increases the testing time (les than one minute). The testing approach presented in this paper helps extend the life of HV and EHV assets providing sufficient support for future sound technical and financial decisions or future investigation and definitive analysis using DFR technology.

1 Hz measurement is a valuable addition to the "ROUTINE" testing procedure for insulation condition assessment of liquid-impregnated transformers and bushings.

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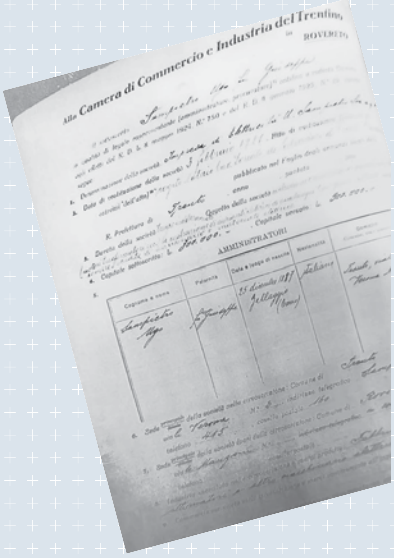
Q&A

INTERVIEW WITH GIOVANNI CATTANI

GENERAL MANAGER
OF SIEMENS ENERGY
TRANSFORMERS S.R.L.
TRENTO, ITALY

Photo: Siemens


Alla Camera di Commercio e Industria del Trentino
AMMINISTRATORI

Giovanni, thank you for taking the time to share your knowledge and insights about Siemens Energy Transformers factory in Trento and your very successful career in the industry.

First of all, congratulations to Siemens Energy Transformers in Trento on 100 years of history. You became General Manager in 2014. Tell us a little bit about the Trento factory, which is one of the oldest factories, isn't it?

Giovanni Cattani: That's right, I became General Manager in 2014 and together with my team I manage the business, driving the factory towards the future. We're a long-established factory with a 100-year tradition of delivering high-quality transformers across the world

The factory was founded in Trento (Northern Italy) on the **3rd February 1921**, and it kept its name of S.T.E.M (Società Trentina Elettro Meccanica) until 1986. In 2005 it became part of Siemens AG and starting from 2020, after the spin-off of Siemens AG, we've been part of Siemens Energy.

We are an international company with a strong local connection with the Trentino territory, but at the same time, we are highly oriented to foreign markets with more than 85% of our orders coming from the export market – mainly Europe, USA and Middle East.

Our highly motivated workers, employees, technicians and engineers are **our real asset** that helped us achieve this level and thanks to them we will successfully overcome the challenges of the new century.

I'm proud to work for a company that is innovating, looking for new technologies and helping customers in the energy transition in a more sustainable way. It's a factory with strong competences, local roots and international vision and breadth that is contributing to a better energy distribution, making a real difference in the world.

Giovanni, what is the specialty focus of the Trento plant? What range of transformers are manufactured there?

GC: Our main business is the development and production of innovative power transformer solutions for special customer demands. Nearly every transformer delivered out of Trento is **unique and tailor made** according to the customer specifications.

The products that we manufacture are:

- Single/three-phase transformers (generator step-up transformers, unit auxiliary transformers, grid network transformers, mobile substation transformers)
- Single/three-phase autotransformers
- Railway feeder transformers

Our design range comprises transformers, both mineral oil as well as synthetic and natural ester filled units, from 10 MVA to 150 MVA and up to 300 kV.

One of the changes we see taking place in our industry is the focus on reliability engineering by design. How does Siemens Energy Trento integrate all aspects of the process from design to engineering, and from engineering to integrating production, quality control, testing and commissioning?

GC: We know that reliability of our products is extremely important to our customers, so we have invested a lot over the years to improve all processes.

It all starts with reliable design, which is ensured by using consolidated and harmonized solutions that are developed by central R&D teams and subjected to test programs. The feedback is collected before and after their applications on dedicated platforms.

Technical risk evaluation is performed at different levels, with suitable methodologies (such as Complexity Matrices, FMEAS, etc.) for detecting problems before they happen. Safety and environmental aspects are also evaluated.

Check, review and validation points are well established (according to ISO), as well as the entire process from design, through manufacturing (including manufacturing, engineering and quality experts) up to the final tests. Analyses are performed, in case of failures in the factory or claims from the field, by interdisciplinary teams (e.g. with 8D technique). Non-conformities (NC) are constantly monitored, and statistics are maintained for feeding a continuous improvement loop and increasing reliability.

What are some of the biggest challenges that the global transformers market will be facing in the years and decades ahead and what is Siemens Energy Trento doing to overcome those challenges?

GC: One the biggest challenges will be, of course, the **decarbonization**, which will play a central role in the decades to come. At Siemens Energy, there is a clear commitment to carbon-neutral operations.

At our Trento facility, decarbonization and the **carbon-footprint** of our products is seen as a step of upmost importance towards sustainability. In 2019, we obtained a certification for our systematic approach according to the latest ISO 14067: 2018 (Annex C), and thanks to this, we can respond to our customer's requests ON TIME because we are able to autonomously create a carbon-footprint register of our power transformers and monitor the environmental impact, the CO_2 emissions, without the necessity of providing each time a third-party verification statement.

Another challenge that I see is the integration of energy generated by **renewables** in the existing power grids and providing solutions for a smooth transition to a more decentralized power supply.

We've been actively working on this challenge for years because we are convinced that renewables are the right path towards a sustainable electrical system, as the world seeks long-term economic solutions. At Trento, we started manufacturing power transformers for renewable applications back in 1997, and since then, we have successfully delivered about 500 units to more than 40 different countries all around the world.

Finally, the areas that are seeing growing development are **digitalization** and **resiliency**. We are focusing on these areas together with Siemens Energy, including the innovative solution called **"Sensformer"**. Thanks to this innovation, we equipped our products with a new device developed by Siemens Energy which allows real-time and remote monitoring of transformer parameters with units connected to the Cloud service. Using this technology, we can collect the data to analyze and simulate the operating condition of the transformers, allowing our customers to make informed decisions about asset management, predictive maintenance planning and improving operation of their electricity network to ensure continuity of service.

You must have seen a great deal during your career with Siemens and Siemens Energy. What would be one or two of the significant highlights of your career thus far?

GC: I started working at the Trento factory in 1990 and for Siemens in 2005, holding different positions.

My personal highlight was in 2012, when I started my position with Siemens as **Global Commodity Manager** for grain-oriented steel, negotiating volumes for all power transformer factories. It was a great opportunity for me to deal with worldwide supplier base and international teams who supported me in reaching ambitious goals.

Another significant highlight was in 2014, when I was appointed **General Manager** of the Trento factory, where I started my carrier after university and where now I see implemented and realized many of the ideas that I developed over the years with my teams and colleagues.

I'm proud to work for a company that is innovating, looking for new technologies and helping customers in the energy transition in a more sustainable way – a factory with strong competences, with local roots and international vision and breadth, which is contributing to a better energy distribution making a real difference in the world.

How has Covid-19 affected or changed the approach you are taking regarding these challenges?

Photo: Siemens

GC: As you well know, Italy was one the countries that suffered a lot in the beginning of the outbreak of COVID-19. Nevertheless, even during the lockdown that was imposed by the Italian Government in March 2020, our business was classified as "essential", so we did not close the factory. We have implemented stringent measures to stay fully operational through the crisis.

In the past we introduced the remote inspection and FAT, and we took the occasion to additionally improve this technology. Our clients appreciate this huge advantage that gives them the possibility for home office inspection.

Additionally, before COVID-19, we had introduced the smart-working activities which allowed us to adapt easily to the "new normal" and successfully deal with this challenging situation.

How do you advocate for diversity, equity, and inclusion in your company?

GC: Siemens Energy believes that inclusion and diversity create more opportunity for success. Regardless of gender, age, ethnic or other differences, everyone has an equal part to play in the energizing society.

At Trento we believe that through diversity we generate power, and this is the belief and practice supported by our headquarters. We are proud to have in our factory employees coming from 11 different countries and some of the key positions are headed by women, such as CFO, Head of HR, Head of Business Administration and Head of Logistics.

Giovanni, what is your vision for the future?

GC: We have six topics that we are putting at the core, which can be translated into real actions as a partner and driver of the green energy transition. They include:

Digitalization: Focus on customer value from information via application on demand and anywhere from connected grid assets in a secure manner.

Efficiency: Providing products and solutions with state-of-art technologies to enable a highly efficient grid ensuring affordable energy.

Decarbonization: Becoming $C0_2$ neutral by building renewable and environmental power grids.

Resilience: Delivering high quality products and solutions for uninterrupted power supply, independent of the operating environment.

Innovation: Continuing to innovate together with our customers, creating a sustainable and greener world.

People: Investing in people and their capabilities, knowledge, competence and expertise, because our employers are the real asset of the company.

Any final thoughts or advice that you would give to young engineers just starting their careers, thinking back to when you had just graduated from the University of Padova?

GC: The advice that I usually give to young engineers at University conferences that we participate in is to stay curious and have a flexible mindset to cope with ever faster evolution of technologies and markets.

The real asset of our company are the workers, employees, technicians and engineers. We highly believe in this and for this reason we started years ago direct collaboration with universities promoting our field of business and looking for new graduates willing to accept challenges and to improve their skills directly in the factory.

We invest a lot to make them grow with us, learning directly on the job and preparing the base for our future.

Degradation of Insulating Liquids: Myths and Facts

by **Alan Sbravati**

With the main focus today shifting to strengthening of the electrical grid, natural ester filled transformers can provide advantages for both the reliability and resilience of electrical power networks.

Photo: Cargill, Incorporated

Alan Sbravati started his career working for a transformer manufacturer, mainly developing calculation and design tools for power transformers. After almost 9.5 years in the same company, he was the R&D&E manager for power transformers in Brazil and responsible for two global R&D projects directly related to transformer design and thermal calculation. After three years in a commercial role, he moved back to a more technical position at Cargill. Over the last six years he has been working with the development and application of alternative insulating liquids, especially natural ester fluid (FR3® fluid), holding the position of Global Technical Manager since 2018. Alan chaired the Brazilian Standards Committee from 2012 to 2016, prior to moving to USA. He participates in IEC TC 14 and Cigre working groups. Currently he is a member of IEEE Transformers Committee, as chair of task forces and secretary of the Insulating Fluids Subcommittee.

Paraphrasing Cindy Joseph quote "Ageing is just another word for living", all materials inside a transformer start ageing and degrading the moment the transformer is built. While much of the ageing process can be influenced by the transformer design and use, it cannot be stopped.

Insulating materials are some of the most critical components of a transformer. Typically, they are divided into solid and liquid insulation. The life of a transformer is often defined by the life of the solid insulation since its replacement is practically non-viable. And the liquid insulation plays an essential role in the ageing process of the solid insulation, especially the cellulose-based materials (paper). Although it is possible to recondition the liquid insulation, there are aspects of its interaction with the solid insulation that need close watching.

While most people associate the degradation of liquid insulation with oxidation, the wide use of sealing systems and a potential impact of other degradation processes challenge this direct link.

It is a common understanding that water is a transformer's worst enemy. Its presence has a range of undesirable effects, affecting the dielectric capacity, and thus the reliability of the transformer, and leading to the degradation of other materials, such as the insulating paper. A rule of thumb says that the rate of paper degradation doubles as the moisture content in paper doubles, starting at 0.5%. Thus, the degradation rate in a transformer where the moisture content is 2%, which is not an uncommon condition for mineral oil filled transformers that have been in service for a couple of years, will be four times higher than that estimated by the Arrhenius curve. The second enemy is oxygen, which leads to oxidation of liquid and paper. The latest revision of IEC 60076-07 [1] brings charts and more accurate data on the influence of water and oxygen on paper degradation.

Early degradation processes in a transformer can also be identified by the laboratorial analysis of the insulating liquid. Generating mostly polar byproducts, tests such as Interfacial Tension (IFT) and Dielectric Dissipation Factor (DDF, also associated with Power Factor – PF) can accurately measure the effects of the presence of polar compounds in the insulating liquid. Within a range of variation, these properties have no impact on transformer's performance, being exclusively early indicators of other degradation processes.

How Does a Fluid Degrade?

Degradation processes are not the same for all insulating liquids. The chain of reactions usually included in the oxidation process have several similarities when occurring in mineral oils and ester fluids. The differences are in the final step of the reaction, where the natural ester molecules – having a free electron – bond to each other instead of generating non-soluble/polar byproducts. Thus, the main effect of oxidation in natural ester is an increase of fluid viscosity, which is prevented by the actuation of the oxidation inhibitor additive. Even in a free breathing transformer, the increase of viscosity should not exceed 10% within 10 years of continuous operation.

However, there are other degradation processes whose timeframe is much shorter than that of oxidation. For all insulating liquids, the most relevant one is the absorption of moisture from the ambient air. Water is the main enemy of insulation systems because it typically leads to a depletion of the dielectric capacity.

In a mineral oil immersed transformer, being fluid "hydrophobic", moisture tends to accumulate in the paper insulation. While the water content in the paper in a new transformer is expected to be around 0.5%, it may quickly reach values of 2-3% in a free breathing unit and after 10-15 years in a sealed mineral oil unit, as water is a byproduct of cellulose degradation. A wet insulation system leads to high power factor (and dielectric dissipation factor – DDF), accelerated paper degradation and low dielectric capacity.

As a rough estimation, we can consider an equivalent relative moisture content as the equilibrium condition for the balance of moisture between the paper and the fluid. Considering moisture saturation in the paper to be around 6.5-7%, a 2% water content would represent a relative content close to 30% (2% divided by 6.5%). Applying the same relative saturation to the insulating liquid would lead to 18 ppm, as the water saturation of mineral oil at 40°C is around 60 ppm. In a free breathing unit, a typical moisture content would be in the range of 25-30 ppm in the fluid, and about 3% in the paper.

In the case of synthetic ester liquids, whose saturation point is around 1800 ppm at 40°C, the water content in the fluid could be as high as 800-900 ppm in free breathing units. This would lead to very high DDF values (also known as *tan delta* or fluid power factor), and, potentially, to increased acidity through the hydrolysis reaction. In synthetic ester liquids, the ester groups are hindered in the molecule structure, typically leading to a lower rate of hydrolysis reaction in comparison to the natural ester liquids. Due to the absence of double bonds in the typical molecules, the oxidation will lead to polar byproducts also affecting other fluid properties.

In natural ester liquids, the rate of hydrolysis reaction is expected to be higher [2], since the ester groups are more exposed. As the long-chain free fatty acids generated by the consumption of water are completely soluble in natural ester and mild (low reactivity/corrosiveness), this fluid "degradation" process has a positive outcome of preventing the increase of water content in paper.

In a recently published paper [3], samples of the three fluids – mineral oil, synthetic ester and natural

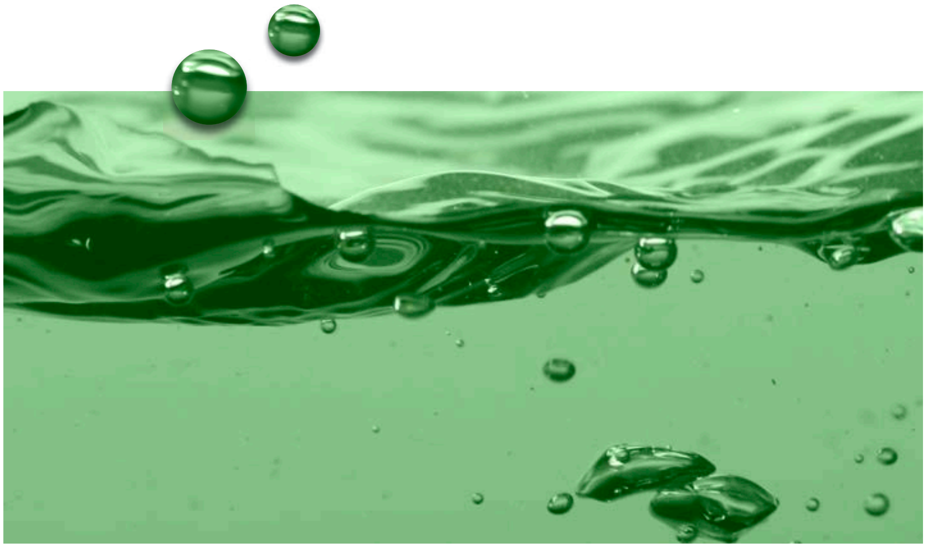
Two years ago, over 2.5 million transformers were estimated to have already been produced with just one brand of natural esters. The expectation is that today this number would have exceeded 3 million units.

Day 0 Day 1 Day 2 Day 3 Day 7 Day 14

FR3 fluid sample performance under test: ageing and oxidation

Day 0 Day 1 Day 2 Day 3 Day 7 Day 14

Mineral oil sample performance under test: ageing and oxidation



ester – were artificially aged in the lab under two different conditions, both simulating free breathing transformers. Open bottles of the fluids were aged in hot-air circulation ovens at 130°C (an ambient moisture) in one case, and in a "climatic chamber" at 80°C and 80-100% moisture content. While the higher temperature in the first case increased the thermal degradation/oxidation, the lower temperature in the climatic chamber favored moisture absorption.

The conclusions of the study clearly indicated that oxidation, by far, is not the priority concern for any of the liquids. Variations in other properties reached continuous operation limits much faster. Natural ester was, in most cases, the last fluid to exceed the maintenance thresholds, proving to be the most robust solution for sealed units which may get some eventual exposure to ambient air.

Standardization Framework

Being the most traditional solution, mineral oil has the advantage of the availability of information of its long-term behavior and valid international standards. Nevertheless, occurrences such as the presence of corrosive sulfur are still causing significant financial losses to many utilities around the world, so the assumption of "no surprises" has been proven to be biased.

Natural ester liquids were developed in the early 1990s as the latest generation of *less-flammable liquids*, also known as *alternative liquids*. Although synthetic ester liquids were developed in the early 1980s, based on market estimations, the number of transformers produced with natural ester liquids exceeds the number of synthetic ester filled transformers by approximately one order of magnitude. Two years ago, over 2.5 million transformers were estimated to have already been produced with just one brand of natural esters. The expectation is that today this number would have exceeded 3 million units.

International standards applicable even to higher voltage classes of transformers have been available for years for natural ester liquids [4] [5] [6]. Conversely, there are still several discussions on which parameters would be relevant to indicate the degradation of synthetic ester liquids, with very limited published data. Having a standardized framework for fluid application is a major aspect for such highly regulated markets because this removes uncertainty or unclear responsibilities when it comes to transformer assessment.

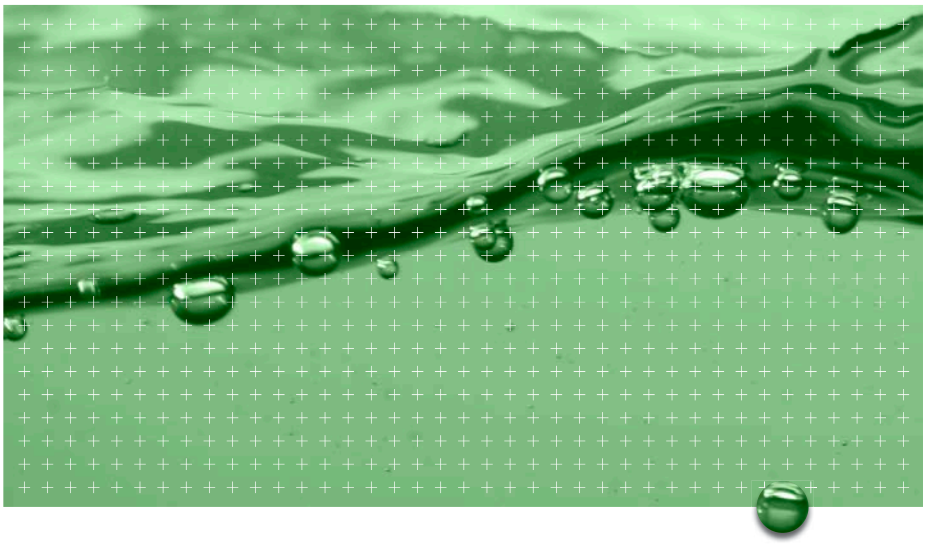
A task force within the IEEE Transformers Committee is performing a study, doing rounds of accelerated thermal aging of the three insulating liquids. Renown laboratories and institutions are participating in this investigation, and the results of the first round of tests have been published [7]. The test results clearly indicate that ester fluids can be subjected to a significantly higher continuous operating temperature in comparison to mineral oil.

Long-term Behavior

A large service provider in the United States has reported in a webinar that approximately 50% of the insulating liquid samples they have been testing are samples of FR3 fluid. Even if we were to consider that this percentage may vary according to the type of customer each service provider focuses on, it indicates that the number of datapoints of fluid properties is growing exponentially. Some of the largest transformer service providers of lab analysis in the U.S. have shared their databank of fluid testing with the IEEE working groups that are reviewing and developing natural ester standards, allowing for a significant improvement of the assertiveness of the defined limits.

The very first natural ester filled commercial transformer, sold by Cooper Power System (currently Eaton) back in 1997, remains in continuous operation in a large amusement park in Florida.

Photo: Cargill, Incorporated



This 1,500 kVA, 12.47 kV – 480/277 V transformer has remained in service under continuous operation without any maintenance intervention since installation. Confirming the expected behavior, the results of the laboratorial analysis confirmed all properties are still within the acceptance limits for a sample of natural ester in a new transformer, prior to energization. Not bad for a transformer which is getting close to 25 years in service. This data is included in a paper to be presented in 2022.

Application in Power Transformers

Possibly due to the focal market of the transformer manufacturer that developed the FR3 fluid, the use of this fluid has been developed with more focus on distribution transformers than power transformers. Yet, the estimated number of power transformers using this fluid is between 30,000 and 50,000 units. Natural ester power transformers are in operation in almost every climatic condition, including extremely cold and extremely hot locations, even remote locations, and under very different maintenance practices. The same good practices applied in traditional transformers are recommended for the same-sized natural ester units, which may eventually be subjected to internal inspections, maintenance interventions and even refurbishment, only with minor adjustments when the duration of the intervention exceeds two weeks of coils exposure to ambient air.

The first ever transformer in the voltage class of 420 kV (in Europe, which would be similar to a 550 kV unit in the U.S.) filled with ester used a natural ester FR3 fluid, back in 2013. It is a 300 MVA unit, with forced circulation of the insulating liquid (KDAF, which would correspond to the ODAF in a mineral oil unit). This transformer remains in continuous operation and the transmission system operator (TSO) already installed additional units which are also filled with natural ester.

Other TSOs also adopted natural ester liquids for their transformers

Photo: Cargill, Incorporated

in the same voltage class, including some single-phase transformers of 200 MVA (three-phase bank of 600 MVA) and more than two dozen of 250 MVA autotransformers [8]. In the United States, the highest voltage class transformers filled with ester liquids are also using natural ester, and they are generator step-up transformers in a large hydropower dam. They are single-phase, two-winding, 13.8 kV to 345 kV, 125 MVA power transformers.

The most significant advantage of using natural ester liquids in power transformers is the continuous drying of the insulation system, as described in [9] and [10]. As the moisture migrates from the paper to the liquid, the excessive moisture is consumed by the hydrolysis reaction thus keeping the moisture content of the coils (insulating paper) in the range of approximately 0.5 to 1%, throughout the transformer life.

Over the years, the benefits of continuous drying on paper degradation rate have been widely explored. International standards that support the increase of the thermal class of thermally upgraded paper to 20°C were published almost a decade ago [11] [12]. However, most significantly, continuous drying for power transformers helps avoid deterioration of the insulating system dielectric capacity and reduces the need for maintenance and removing moisture.

Careful drying of the coils in a new transformer is performed to ensure the required dielectric capacity for the high voltage tests, such as applied and induced voltage and, especially, the impulse voltage test. When moisture content in the insulating paper exceeds 2%, the probability of withstanding an impulse test is severely reduced in comparison to a transformer where the moisture content is preserved at the 0.5 – 1% range.

Conclusions

The excellent history of application of natural ester liquids in both distribution and large power transformers confirms not only their suitability for use, but also the effectiveness of the claimed advantages over traditional units.

Today, the triggers for utilities to adopt natural ester liquids go beyond the initial motivations for the use of alternative liquids, which were improved fire safety and environmental benefits.

With the main focus today shifting to strengthening of the electrical grid, natural ester filled units can provide advantages for both the reliability and resilience of electrical power networks.

While the improved reliability results from the preservation of the dielectric capacity, the higher resilience is deployed from the superior loading capacity since both paper insulation and the natural ester itself can ensure continuous operation at higher temperatures compared to those in traditional units.

Simply put, the engineers adopting natural ester are seeking peace of mind.

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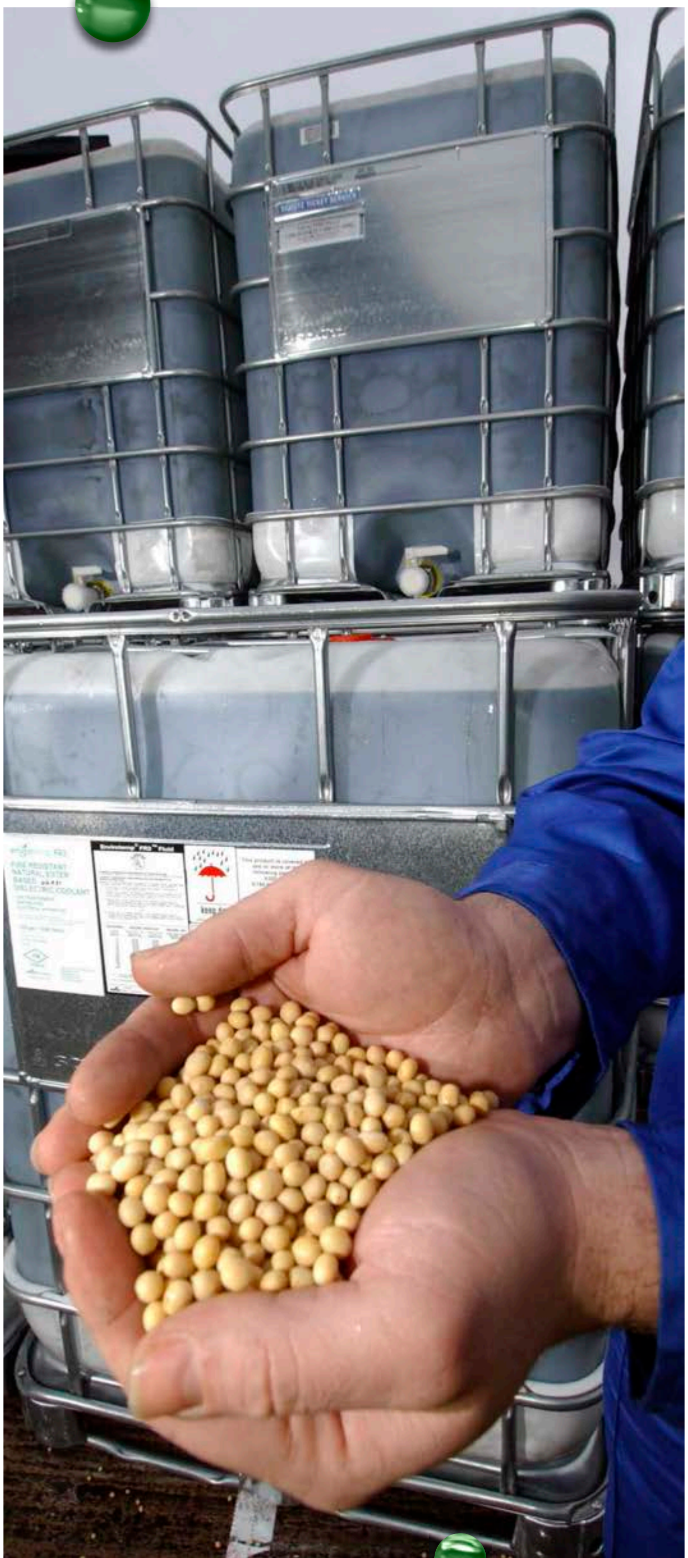

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Photo: Cargill, Incorporated

MELISSA CARMINE-ZAJAC

Melissa Carmine-Zajac is the Director of Laboratory Services for Doble Engineering Company and is based at the corporate headquarters in Marlborough, Massachusetts. A self-proclaimed "super nerd", Melissa is passionate about all things science and knew from a young age that she wanted to be a scientist someday.

Originally studying pharmaceutical chemistry, Melissa realized the best way to figure out what she wanted to do when she "grew up" was to get into a lab immediately and learn from experience.

Melissa started her career in environmental science and hazardous materials, working both in the lab and in the field. Within the first year of her career, she was promoted to a supervisory role which would introduce her to her next career goal - leadership. **She eventually moved into an analytical chemist role, but quickly began to miss the excitement of fieldwork and was inspired to take on a very challenging consulting role.** She was hired to revamp a floundering laboratory, which proved quite a challenge. Instead of backing down, Melissa dove head-first into the work, successfully completing the lab rebuild project within weeks. **Unfortunately, the rebuilt lab was destroyed in a flood and Melissa believed her career to be both literally and figurately under water.** She was then offered a different role within the same organization at a chemical plant in New Jersey. **For the next few years, she managed the plant lab, becoming increasingly involved in process engineering and plant operations.** In 2015 this journey led Melissa to Doble Engineering Company where she started as a Laboratory Manager. **After proving a strong work ethic, technical aptitude, and an extraordinary ability to handle complex managerial issues, she made the transition to Laboratory Director in 2019.** In her current role, she is responsible for the operations of four US laboratories that perform critical lab testing and advanced diagnostic services for the power industry. **She works directly with electric utility clients around the world, ensuring that all people have reliable energy.** Melissa understands the impact of a good mentor and the importance of developing young talent. **She often works directly with her lab team to encourage learning and career growth.** Leading by example, promoting career transparency, and supporting women in STEM are a few of her current passions. **When Melissa is not in the lab, you can find her partaking in hobbies like endurance sports, traveling, and making deserts.** In addition to her work at Doble, Melissa is also a publicly elected official in her hometown and an advocate for mental health awareness.

Source: **Melissa Carmine-Zajac**

Photo: Melissa Carmine-Zajac, rawpixel.com

Photo: Shutterstock

The State of Ester Filled Transformers in Europe's Transformer Market: An Overview and Outlook

by **Aleena Ahmad**

Technology has taken huge leaps in the previous decades and the advancements have benefitted all spheres of life with the biggest impact on economic development. In the recent years, however, there has been a growing concern about the environmental impact of certain technological advances with effects becoming more and more pronounced through rising temperatures, floods, droughts and more. As the world tackles the growing problem of climate change, there is an urgent need for shift in our processes to make them more sustainable. Electrical industry is also playing its role in this transition. Among other green initiatives and directives, the development of SF_6 alternatives in switchgear and vegetable ester oil as an insulation fluid for transformers, and their slow but increasing adoption by utilities and manufacturers, is a step in the right direction.

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Although the percentage of installed ester filled transformers is still low, this number is expected to rise in the future as countries race towards achieving their 2030 climate goals.

Ester Fluids vs. Mineral Oil as an Insulating Fluid

Ester fluid is derived from 100% renewable vegetable oil or inorganic feedstock. It was originally developed in 1996 as an alternative to polychlorinated biphenyl (PCBs) and high molecular weight hydrocarbons but has gradually become the fluid of choice for transformer insulation and an environmentally friendly alternative to mineral oil due to its properties. Table 1 compares the properties of natural and synthetic esters with mineral oil indicating the advantages of ester oils over mineral oil as an insulating fluid across different parameters.

Ester has an improved environmental footprint owing to biodegradability. This means that the cost of the clean-up procedure and spill prevention mechanisms that is associated with the use of mineral oil is considerably reduced. In case of a spill or breakdown, ester fluid will not contaminate the surrounding environment as is the case with mineral oil. Mineral oil oxidizes readily, leaving behind sludge precipitates that give rise to the need for periodic cleaning and maintenance, but ester is resistant to oxidation degradation, which is another added advantage.

With mineral oil, fire safety is a concern because temperature of the oil rises with transformer loading. Ester fluid has almost twice the fire point making it relatively better than mineral oil in that aspect. This reduced risk of fire in turn lowers the need for fire protection equipment and fire safety systems. Since ester oil has a high fire and flash point, it can perform better in higher temperatures and has better loading capabilities as well. Ability to withstand higher temperatures means that ester has a longer life span than mineral oil. Life cycle expansion in turn directly relates to cost and maintenance optimization.

Despite its advantages over other transformer fluids, initial capex for ester can still be up to 20% higher than for mineral oil.

Cost of Ownership and Current Applications

Despite ester having the above stated advantages, its initial capex can still be up to 20% higher than for mineral oil, which can be a concern for companies adopting this technology. It should be noted, however, that this high capital cost is compensated by the lower maintenance costs and longer life spans in the long term.

Although most of the discussions around ester filled transformers focus on replacing mineral oil transformers, these transformers are also gradually replacing dry type transformers because of their enhanced fire safety and ecofriendly properties. In addition to this, ester is not only being adopted for new installations, but existing oil immersed transformers that have reached their end of life or are overloaded are being retro-filled with ester fluids to improve grid reliability and stability until replacements can be carried out.

Globally, more and more electric utilities are installing ester filled transformers to complement the efforts that are being made to make their operations more environmentally sustainable and to achieve the ambitious climate goals being set out by their respective countries. Europe has a well-developed grid infrastructure and is in the position to take the lead in this regard, which it has been taking with numerous laws and initiatives in place.

Property	Mineral Oil	Natural Ester	Synthetic Ester
Fire Point	180°C	360°C	310°C
Flash Point	160°C	330°C	260°C
Biodegradability	No	Ultimately	Readily
Toxicity	Toxic	Non-Toxic	Less Toxic
Viscosity	12	37	29
Thermal Aging	Good	Better	Best

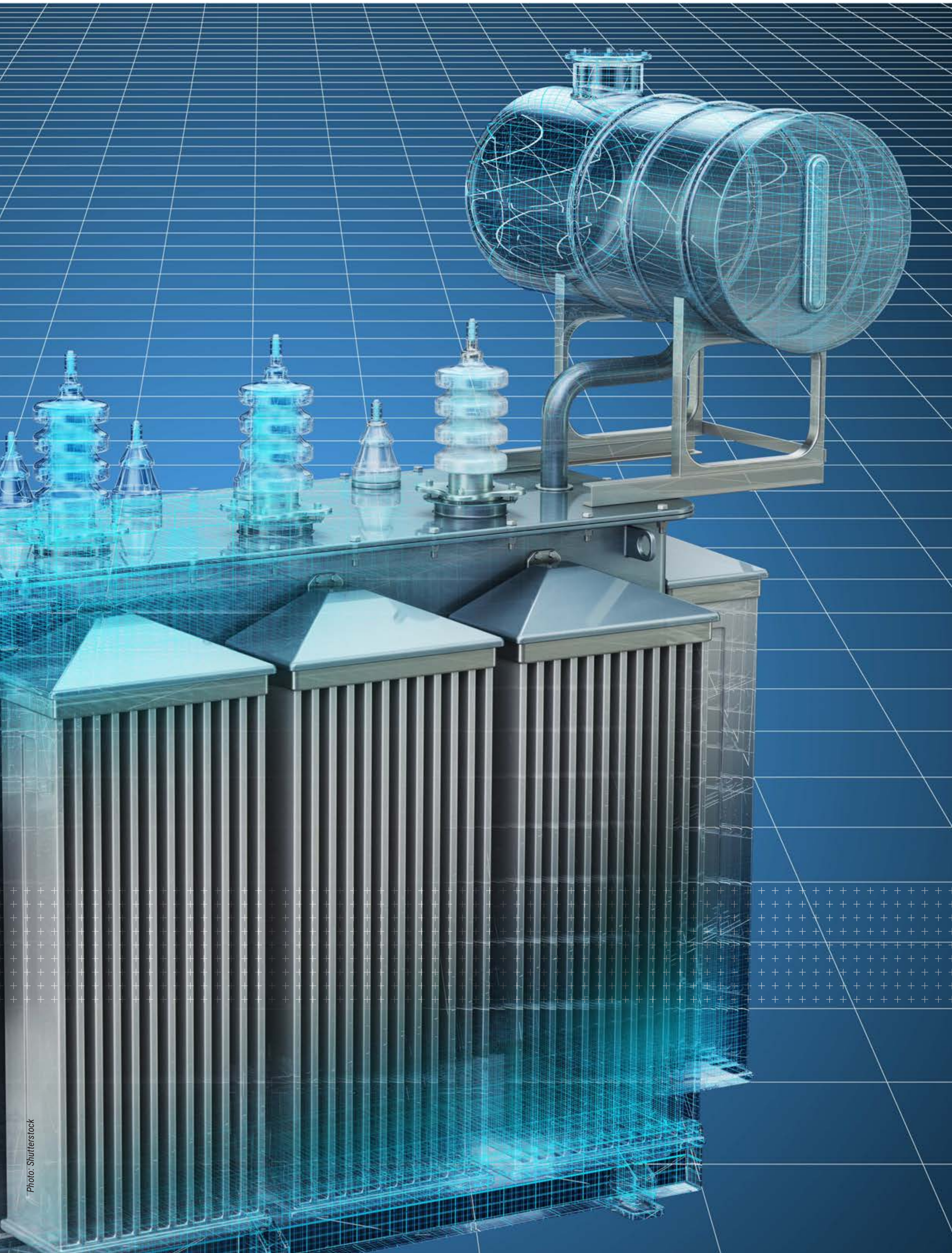
Table 1. Comparison of ester oils vs mineral oil properties

EU claims that the bloc will reduce its carbon emission by 55% by 2030 and become climate neutral by 2050.

For instance, UK has announced that it intends to achieve 65% clean energy by 2030 and zero carbon emissions by 2050. Similarly, Germany plans to reduce its emissions by 65% by 2030 as compared to the 1990 level and 88% by 2040. France's current law states that it will decrease emissions by 40% by 2030 as compared to the 1990 level. Talking about the entire region, EU claims that the bloc will reduce its carbon emission by 55% by 2030 and become climate neutral by 2050.

There are several green initiatives being adopted by European utilities that include the decarbonization of economy: an initiative by Endesa, a Spanish DSO, to develop 23 renewable hydrogen projects; Green Finance Framework by the Norwegian DSO Elvia plans on adding new hydro and wind power infrastructure to increase renewable capacity in the system; and Fluvius in Belgium plans to install EV charging infrastructure to facilitate the penetration of zero-emission vehicles.

Adoption of ester filled transformers is in line with the direction that the utilities in Europe are taking to achieve environmental sustainability. The increase in renewable power generation and the penetration of electric vehicles has given rise to a lot of gaps in the distribution grid with areas for improvement in the existing infrastructure as well as potential for expansions and additions to cater with this increased and dynamic load. The renewable installed capacity has grown with a CAGR of 5.4% from 2015-2020. With regards to EVs, Europe accounted for 30% of the global electric vehicle passenger fleet which amounts to approximately 3.1 million electric vehicles.



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State of Adoption in Europe

Europe has always been keen at adopting and manufacturing latest technologies and the same is being observed when it comes to the environment friendly and sustainable insulation fluid for transformers. Some of the top OEM markets for ester filled transformers in the region are Turkey, Poland, and Switzerland. UK, Germany, and France are some of the user markets in the region with ester oil transformers constituting a growing percentage of the total installed base of distribution transformers.

According to Power Technology Research, in Europe, the ester filled transformer market capacity accounts for about 1.29% of the total installed base, with UK, Netherlands and Spain being the top countries adopting ester fluid (Figure 1).

Although the percentage of installed ester filled transformers is low, this number is expected to rise in the future as countries race towards achieving their 2030 climate goals. UK, however, is breaking away from the generally slow adoption rate observed in the region with a comparatively higher percentage of ester filled transformers. Some utilities in the UK are exclusively installing ester filled transformers and others are using ester to retro-fill existing mineral oil transformers that have reached their end of life. Furthermore, ester filled transformers are being installed in historical buildings to ensure safety, prevent fire risk and to avoid fire suppression costs. Another observation is that utilities are more inclined towards adopting synthetic ester in comparison to natural ester since the former can be tailored to specific needs of the customers. Another statistic of importance is that utilities are adopting ester oil transformers in underground substations where the risk of mineral oil fires in transformers is higher than outdoors. 86.65% of the total installed base of ester filled transformers is installed indoors and underground.

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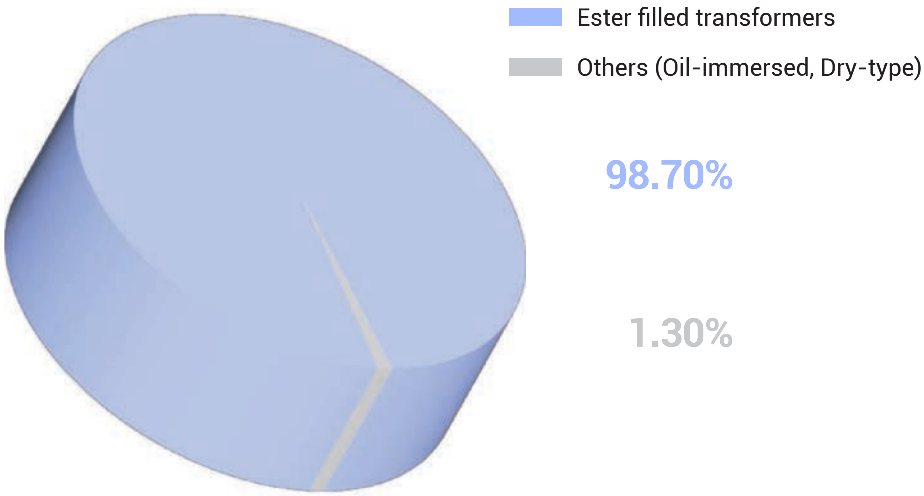

Figure 1. Ester filled transformers penetration in Europe

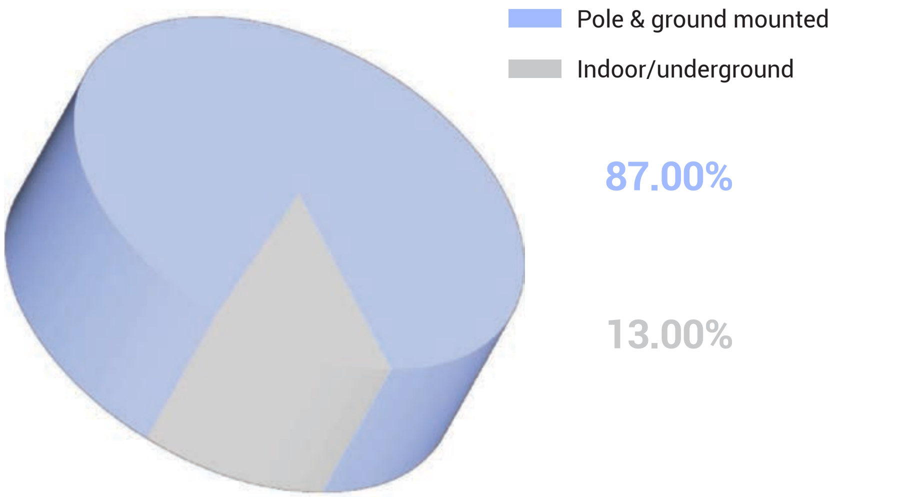

Figure 2. Segmentation of ester filled transformers by installation type

> **Utilities are more inclined towards adopting synthetic ester than natural ester since the former can be tailored to specific needs of the customer.**

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Future Outlook

Looking ahead, according to Power Technology Research, the penetration of ester insulated transformers will continue to increase, especially in Western Europe. Even though the installed base of these transformers is quite low at the moment with some utilities even reporting no ester insulated transformers in their grid, their market is expected to grow in the future. This increase is directly tied to utilities upgrading their infrastructure to incorporate the additional renewable power generation and install new charging facilities for the growing market of electric vehicles, which will consequently result in a rise of the installed base of distribution transformers, especially sustainable options like ester filled transformers.

86.65% of the total installed base of ester filled transformers is installed indoors and underground.

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TECHNOLOGY INSIGHTS BY CORNÉ DAMES

Condition Monitoring of Transformers Using Oil Analysis Data, Vital Parameters and Critical Values

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Condition monitoring is the frequent collecting, measuring, recording and analysis of relevant data. If we interpret the data correctly, it can give us great insight into the condition of an asset.

This frequent monitoring of a transformer can result in less maintenance required, or more extended periods without any maintenance required at all.

It is crucial to identify the key parameters that are needed to give us a complete picture of the actual status of the transformer and the actions we need to take to ensure the continued reliability of the transformer to achieve and maximize its life cycle.

It is vitally important to identify clear goals as part of your transformer monitoring strategy.

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.

What is the data telling us?

- Has the condition of the unit changed since the last maintenance or testing period?
- Is it safe to operate the unit?
- Are there signs of deterioration?
- Is it safe to load the unit above the nameplate rating for some period?
- Am I required to implement action to ensure the continued reliability of the unit?
- How long can we use the unit before considering replacement?
- Are the identified problems of a recurring nature?

Effective condition monitoring outline

It is vitally important to identify clear goals as part of your transformer monitoring strategy. What do you want to achieve by implementing this condition-monitoring plan? Is it in-service failure prevention, life extension or maintenance deferral? By stipulating the outcome and what you want to accomplish, it would be much easier to identify the required parameters.

Health indexing of assets is becoming an important tool to obtain a clearer picture of the condition of your transformer. Test parameters carry a numerical value-adding to the total value of the Health Index Value of the transformer. These parameter weight values were calculated based on the international standards for mineral oils, indicating the critical values stipulated in the various standards.

Category	Type of equipment
Category O	Power transformers/reactors with a nominal system voltage of 400 kV and above
Category A	Power transformers/reactors with a nominal system voltage above 170 kV and below 400 kV. Also, power transformers of any rated voltage where continuity of supply is vital and similar equipment for special applications operating under onerous condition.
Category B	Power transformers/reactors with a nominal system voltage above 72.5 kV and up to and including 170 kV (other than those in Category A)
Category C	Power transformers/reactors for MV/LV application: e.g. nominal system voltages up to and including 72.5 kV and traction transformers (other than those in Category A). Oil-filled circuit breakers with a nominal system voltage exceeding 72.5 kV. Oil-filled switches, a.c. metal-enclosed switchgear and control gear with a nominal system voltage greater than or equal to 16 kV.
Category D	Instrument/protection transformers with a nominal system voltage above 170 kV
Category E	Instrument/protection transformers with a nominal system voltage up to and including 170 kV
Category F	Diverter tanks of on-load tap-changers, including combined selector/diverter tanks
Category G	Oil-filled circuit breakers with a nominal system voltage up to an including 72.5 kV, Oil-filled switches, a.c. metal-enclosed switchgear and control gear with a nominal system voltage less than 16 kV.

NOTE 1. Separated selector tanks of on-load tap-changers belong to the same category as the associated transformer.

NOTE 2. Oil-impregnated paper bushings and other hermetically sealed equipment may be placed in Category D or E if a routine monitoring program is desired. The manufacturer's instructions should be referred to.

NOTE 3. Regardless of size or voltage, a risk assessment may justify condition-monitoring techniques usually appropriate to a higher classification.

NOTE 4. For practical and economical reasons, some electrical utilities may decide that their small transformers up to 1 MVA and 36kV are not included in this classification. Routine monitoring may not be considered economical for this type of equipment. Where a monitoring program is required for these transformers, the guidelines in category C should be adequate.

Table 1. Equipment categories [1]

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Property	Group[a]	Subclause	Method
Color and appearance	1	5.2	ISO 2049
Breakdown voltage	1	5.3	IEC 60156
Water content	1	5.4	IEC 60814
Acidity (neutralization value)	1	5.5	IEC 62021-1 or IEC 62021-2
Dielectric dissipation factor (DDF) and resistivity	1	5.6	IEC 60247
Inhibitor content[b]	1	5.7.3	IEC 60666
Sediment Sludge	2	5.8	Annex C of this standard
Interfacial tension (IFT)[c]	2	5.9	ASTM D971 EN14210
Particles (counting and sizing)[c]	2	5.1	IEC 60970
Oxidation stability[c]	3	5.7	IEC 61125
Flash point[d]	3	5.11	ISO 2719
Compatibility[d]	3	5.12	IEC 61125
Pour point[d]	3	5.13	ISO 3016
Density[d]	3	5.14	ISO 3675
Viscosity[d]	3	5.15	ISO 3104
Polychlorinated biphenyls (PCBs)	3	5.16	IEC 61619
Corrosive sulphur[c]	3	5.17	IEC 62535 ASTM D1275, METHOD B DIN 51353
Dibenzyl disulfide (DBDS) content	3	5.18	IEC 62697-1
Passivator content[b]	3	5.19	ANNEX B OF IEC 60666:2010

[a]Group 1 are routine tests, Groups 2 are complementary tests, Group 3 are special investigative tests.
[b]Restricted to inhibited and or passivated oils.
[c]Only needed under special circumstances, see applicable subclause.
[d]Not essential but can be used to establish type identification.

Table 2. Tests for in-service mineral insulating oil oils [1]

Property	Category	Good	Fair	Poor
	O, A, D	>60	50 to 60	<50
	B, E	>50	40 to 50	<40
Breakdown voltage (BV)	C	>40	30 to 40	<30
	F	<30 kV for OLTC in star point application <40 kV for OLTC in delta or line-end application		
	G			<30

Table 3. Breakdown voltage test

The scope of oil analysis, interpretation of the data and critical values

It is important to realize that we deal with different size transformers in the industry, where transformers are divided into classes according to the kV ratings of the equipment (see Table 1 [1]). It is up to the reliability or asset manager to use the guidelines for larger equipment, thereby implementing shorter increments of oil analysis and electrical testing. Table 2 explains which oil analyses are recommended, how often or under which circumstances [1].

Color and appearance

This is a routine inspection applied to every oil sample. When an oil sample arrives at the laboratory, one of the "tests" is a visual inspection of the oil sample in a clear vessel to determine the color, turbidity and possible particle identification.

Dark oils might indicate chemical degradation or contamination of the oil. When there is a lot of turbidity, it might indicate high-water content in the oil.

If the drain valve was not wiped clean by the sampler, the dirt particles in the drain valve might be incorporated into the sample. If particles are identified as carbon, this might indicate a possible electrical fault in the unit. The DGA analysis of the oil will confirm if this is the case.

Clear oils without contamination will indicate a good condition, and no action is recommended.

When oils are dark or turbid, further analysis will confirm if there are any problems. The oil analysis results will also determine the degree and type of action.

Breakdown voltage

This is a routine inspection.

Breakdown voltage (Table 3) will indicate the water content or the presence of foreign particles, or both in the oil being analyzed. As the oil in transformers acts as an insulation

Property	Category	Good	Fair	Poor
Water Content (mg/kg at transformer operating temperature)	O, A	<15	15 to 20	>20
	B, D	<20	20 to 30	>30
	C, E	<30	30 to 40	>40
	F	Action necessity >40		
	G	Not a routine test		

Table 4. Water content test

medium to avoid flashover in the unit, the breakdown voltage must be high.

If the values are **Good**, it is recommended to continue with the current sample interval action plan. If the values are **Fair**, more frequent sampling is recommended in collaboration with other parameter results like the water content, DDF, and acidity. If values are **Poor**, it is recommended to recondition the oil via oil reconditioning processes.

If alternative tests indicate severe aging, the oil can be replaced with new or reclaimed oil. Another option would be to perform on-site reclamation of the oil using a reclamation plant.

Reclamation of oil has the advantage that the color of the oil is restored, and the polar components are removed from the oil. This process will remove acid and water as well as some other compounds. Another advantage is that the oil can be re-used, and in most situations, this can be done without switching off the unit, which contributes to cost-saving. If in doubt – switch off the unit during this treatment process.

If the values are Poor, it is advisable to take action as soon as possible and not delay the maintenance process. Excess water in the transformer system decreases the projected transformer lifetime significantly; extremely high water content can cause flashover in the unit resulting in loss of the asset.

Water content (mg/kg at transformer operating temperature)

This is a routine test for all classes of electrical equipment, except class G (Table 4). The results of this test should always be considered in collaboration with the breakdown strength. If it is found that the water content is high and the breakdown strength is low, further action needs to be taken. It is recommended that a second sample from the same unit is tested to confirm the results.

In the case of switching equipment, where there is no paper present, the breakdown voltage is the determining factor.

It should be noted that the limits indicated by IEC 60422 Edition 4 [1] apply to transformers with operating temperatures between 40 and 70°C. If it is found that the unit's operating temperature is outside this temperature range, it is best to refer to Annex A of the standard.

When the value obtained through analyses is **Good**, the normal sampling interval can be maintained, requiring no further action.

When the value returns a **Fair** result, more frequent sampling is recommended. It is also helpful to consider other parameters like the breakdown voltage, particle content and DDF/resistivity, and acidity to decide the action to be implemented.

A **Poor** result will require immediate action from the asset manager. This might include taking another sample to confirm the results from the first analysis. If it is confirmed that the water content is high, the oil should be filtered; a process that can remove a large portion of the moisture from the oil if applied correctly. *(Editor's Note: It is recommended that passive drying over a prolonged period of time is a better solution than filtering, since there is more moisture in the paper than in the oil.)*

Follow-up samples need to be taken to ensure that the moisture content is still within the required limits. The reason is that the most significant portion of the water is caught up in the paper system in the transformer. This moisture will move from the paper into the oil under conditions that favor this movement. It might be found later that the oil in the water has increased again without

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any apparent reason, but the source would be the paper in the transformer.

A visual inspection is also recommended to determine if any water might move into the transformer or electrical equipment through leaks. This problem might be more severe if the transformer or electrical equipment is outside and not in a covered area.

Acidity (mgKOH/g oil) neutralization number

This is a routine test for all classes except F and G (Table 5).

Property	Category	Good	Fair	Poor
Acidity mgKOH/g oil	O, A, D	<0.10	0.10 to 0.15	>0.15
	B, E	<0.10	0.10 to 0.25	>0.20
	C	<0.10	0.15 to 0.30	>0.30
	F, G	Not a routine test		

Table 5. Acidity test

The acids in oils are formed due to chemical reactions between the oil, water, and paper. Higher temperatures or increased load will increase the formation of these acids. Because acids are polar compounds, it will adversely affect the insulation properties of the oil and will increase paper degradation. If left untreated in transformers, this can lead to sludge formation, usually around the lower parts of the transformer core. The sludge will eventually form a semi-solid substance that is extremely difficult to remove.

If the result is **Good**, the regular sampling interval can continue.

In case of a **Fair** result, the sampling interval should be increased to fit the situation. Future analysis should include a visual inspection of the oil for sediment and sludge. If the result is **Poor** according to the prescribed values in IEC 60422 Edition 4.0 [1], the asset manager may decide to reclaim the oil or replace it with new or reclaimed oil, whichever option might suit their requirements the best.

Dielectric dissipation factor at 40 Hz to 60 Hz at 90°C

This is a routine test for all classes of electrical equipment, except F and G (Table 6).

The dielectric dissipation factor or tan delta test provides information regarding the extent of the dielectric losses in transformer oil. This test measures the inefficiency of insulating material.

When oil ages, we have the formation of polar compounds, leading to phase displacement and dielectric losses. Some other impurities that might influence the dissipation factor include water, dissolved insulating resin, and paper. When the result is **Fair**, more frequent sampling and checking additional parameters is recommended. When the result is **Poor**, reclamation or an oil change is recommended.

Resistivity (GΩm) at 20°C or 90°C

This is NOT a routine test (Table 7). DC resistivity of the oil is one of the key parameters to assess the transformer insulation condition; this is based on the fact that DC resistance is sensitive to oil degradation.

When the result is **Fair**, more frequent sampling and checking additional parameters is recommended. When the result is **Poor**, reclamation or an oil change is recommended.

Inhibitor content %

This test is restricted to oils with inhibitor added (Table 8). It would be advisable to contact the oil supplier to verify the details regarding additives.

The two most common oxidation inhibitors for transformer oils are 2,6-di-tertiary-butyl para-cresol (DBPC) and 2,6-di-tertiary butyl-phenol (DBP). The purpose of the inhibitor is to prevent oxygen from reacting with the oil. This significantly slows the aging process in the oil as well as in the solid insulation.

If the result is **Fair**, it is advised to top up the inhibitor level to the prescribed level per supplier instructions.

Property	Category	Good	Fair	Poor
Dielectric dissipation factor at 40 Hz to 60 Hz at 90°C	O, A	<0.10	0.10 to 0.20	>0.20
	B, C	<0.10	0.10 to 0.50	>0.50
	D	<0.01	0.01 to 0.03	>0.03
	E	<0.10	0.01 to 0.30	>0.03
	F, G	Not a routine test		

Table 6. Dielectric dissipation factor test

Property	Category	Good	Fair	Poor
Dielectric dissipation factor at 40 Hz to 60 Hz at 90°C	O, A	>200	20 to 200	<20
	B, C	>60	4 to 60	<4
	D	>800	250 to 800	<250
	E	>60	7 to 60	<7
Resistivity (GΩm) at 90°C	O, A	>10	3 to 10	<3
	B, C	>3	0.2 to 3	<0.2
	D	>50	10 to 50	<10
	E	>3	0.4 to 3	<0.4

Table 7. Resistivity test

Property	Category	Good	Fair	Poor
Inhibitor content %	All	Restricted to Inhibited oils, consult oil supplier	40% to 60% of original value	<40% of original value

Table 8. Inhibitor content test

It is advisable to use a field professional trained in the procedure to perform this task.

If the result obtained is **Poor**, the recommendation for this scenario would suggest that the end user continue to use the oil "uninhibited", but this may lead to more rapid degradation of both the liquid and solid insulation. It should be noted that some transformers already have a built-in oil preservation system; this is designed to keep dissolved oxygen at levels below 1000 ppm. This would be in the form of a nitrogen system, a nitrogen tank or generator, or a conservator tank equipped with a rubber diaphragm (bladder). Using inhibited oils under these circumstances is not required, although it might add additional protection against oil oxidation if the preservation system ever fails [2].

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Passivator content

Passivators, also known as metal deactivators, react with reactive metal surfaces and dissolved metals such as copper and silver and reduce their rate of reaction with compounds in the oil. This includes oxidation reactions with organic compounds and reactions with corrosive sulfur. Passivators are composed of two basic types: sulfur-based and nitrogen-based. The first suggested use of passivators in transformer oil, which the author is aware of, was in 1967 by J.J. Melchiore and I.W. Mills of the Sun Oil Company [3].

As the oil ages, the passivator might deplete more rapidly; this depletion might accelerate when the oil is un-inhibited.

With **Good** results, regular sample intervals can be maintained (Table 9). With **Fair** results, maintain regular monitoring. When the results are Poor, it is advised to remove the oil or remove the source of corrosivity from the oil via special oil treatment.

Property	Category	Good	Fair	Poor
Passivator content (mg/kg)	O, A, B, C, D, E, F	>70 and stable (rate of decrease <10/ mg/kg/year)	50-70mg/kg or <70 mg/kg, with a significant rate of decrease of >10 mg/ kg/year	<50 and decreasing at >10 mg/kg/year

Table 9. Passivator content test

The results need to be less than 0.02% by mass to be negligible. If the results return a value of more than 0.02% by mass, it is suggested that it be reclaimed. Otherwise, an oil change is recommended.

Sediment and sludge

This is not a routine test. It is advised that this test is performed when the oil results indicate a high acid value and the dissipation factor is near the acceptable limit.

Interfacial tension

This is not a routine test (Table 10).

During the aging process, the interfacial tension between transformer oil and water reduces. What this means in practical terms is there is more polar compound present in the oil, decreasing the ability of an oil to serve as an insulator in the transformer system. There is a direct correlation between interfacial tension and neutralization number. Therefore, the interfacial tension becomes a quality criterion: the oil must be changed below a predefined limit.

If the results are **Good**, continue the regular sampling interval. If the results are **Fair**, increase the sampling interval. If the results are **Poor**, Check the oil for sediment and/or sludge.

Property	Category	Good	Fair	Poor
Interfacial tension (mN/m)	O, A, B, C, D Inhibited	>28	22 to 28	<22
	Uninhibited	>25	20 to 25	<20
	E	Not a routine test		
	F, G	Not Applicable		

Table 10. Interfacial tension test

Corrosive sulfur

This is not a routine test.

Oil is either corrosive or non-corrosive. The presence of corrosive sulfur in transformer oil and its effect on the transformer system can be significant. The extent of the corrosion damage caused by the sulfur can be so severe that it might cause the failure of the equipment if not checked. The addition of a copper passivator can reduce the impact of this compound on the transformer system.

CIGRE Brochure no. 378, 2009 stipulates the necessity of corrective actions based on this institute's risk assessment study [4].

Particles counting and sizing

Table 11 outlines typical contamination levels (particles) encountered on power transformer insulating oil as measured using IEC 60970 [5].

Flashpoint °C

This is not a routine test.

If there is a maximum decrease in flashpoints by 10%, the equipment might require further inspection.

Adoption of ISO 4406 (Edition 1999) class [7]	ISO 4406 (Edition 1987) class [8]	Maximum count per 100 ml		Contamination designation	Notes
		5 µm (equal to 6 µm (c))	15 µm (equal to 14 µm (c))		
Up to 10/8/5	Up to 8/5	250	32	Background contamination	Cleanliness requirement for sample bottles filled with clean solvent
11/9/6 to 13/10/7	9/6 to 10/7	1,000	130	Low	Oil cleanliness encountered during factory acceptance test and transformer commissioning*
14/11/8 to 17/15/12	11/8 to 15/12	32,000	4,000	Good	Contamination level typical for transformer in service
18/16/13 to 19/17/14	16/13 to 17/14	130,000	16,000	Fair	Contamination level found on a significant number of transformers in service
20/18/15 and above	18/15 and above			Poor	Contamination level rare and usually indicative of abnormal operating conditions

NOTE: Considering the field measurements reported by various countries, it is recommended that the contamination level encountered in service should be classified as indicated in this table. A more refined classification would not be realistic in view of the variations that can occur in this type of measurement.

*Statistical survey has shown that values 15/11/9 are more realistic. The cleanliness requirements may depend on the rating and shall be clarified between the customer and the manufacturer.

Table 11. Typical contamination levels (particles) encountered on transformer insulating oil as measured using IEC 60970 [5]. Source: CIGRE Technical Brochure 157, June 2004 [6]

This value might differ in different countries.

It is advised to perform this test when an unusual odor is noticed, the unit has been refilled, or an internal fault has occurred.

PCB

This test is not to determine the condition of the transformer. It is a health and safety impact test. PCB is hazardous to both humans and the environment, and it is therefore vital to test for PCBs after the retrofill of a transformer. The test is also required whenever any maintenance has been done on the unit and the possibility of contamination is present. If PCB content is exceeding the recommended limits, the appropriate action needs to be taken.

The limits are defined by local regulatory bodies.

DGA

As DGA (Dissolved Gas in Oil) is an intricate science with a lot of data and interpretation, we will discuss this phenomenon in part II of the article. The limits for the different gases and the interpretation of this data according to international standards will be discussed in detail, forming part of the overall health rating determination of the transformer.

Conclusion

This is an interlaced, highly exciting field of study. In this article, we focused on the types of tests to determine the condition of the transformer, the critical values, and the recommended actions. In the future articles, we will focus on determining the Health Index for each unit using the test data results and each test's weight in the Health Index determination.

The Health Index indication will make it possible to see the supposed reliability of a specific unit at that specific date and time. This will make it possible to ensure best practice application and optimized maintenance. With this information, it would be easier to draw up a maintenance plan and action plan.

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Photo: Camlin

Importance of Proper Test Protocols and Procedures for Ester Liquids

by **Rosie Lawton**
and **Andrew Glanville**

Natural and synthetic esters used as transformer dielectric liquids are established alternatives to mineral oil, but there is a need in the industry for better understanding of these liquids and how they are analysed.

Photo: M&I Materials

Rosie Lawton is an Application Scientist at M&I Materials. Her role involves providing technical support to customers regarding the quality of the MIDEL range of ester transformer liquids and their compatibility with other materials. Rosie holds a Master's in Chemistry from Manchester Metropolitan University, UK and is pursuing a PhD in Tribology at the University of Leeds, UK. Prior to working for M&I Materials, Rosie worked as a Development Chemist at Offshore Environmental Oils; a company producing environmentally friendly fluids for subsea applications.

Andrew Glanville is a Development Chemist at M&I Materials. He holds a Bachelor of Science in Biochemistry from the University of Manchester as well as a PGCE in Secondary Chemistry with QTS. His previous roles include the development and deployment of Specialised Industrial Products at Infineum UK, and Metalworking Fluid technical roles at Afton Chemical.

Although both mineral oil and ester liquids are now established in the transformer industry, it is important to note that their chemistries are quite different. As such, testing procedures outlined in various standards must be taken into consideration. Even subtle differences between synthetic and natural esters must be considered. Furthermore, variation in results provided by different laboratories can often be seen. Some of the key areas for these discrepancies include flash and fire point, dielectric dissipation factor (DDF) and dissolved gas analysis (DGA).

In the case of DDF, cleaning and sample preparation is significant in producing reliable results. Relatively small amounts of contamination can lead to changes in flash and fire point. In addition, inadequate cleaning leads to a build-up of carbonaceous material on the sample holder that may cause a depression in the flash and fire point. This article aims to review the differences, and the similarities, between the liquids in terms of testing and results interpretation to ensure that it is appropriate to the dielectric liquid being assessed.

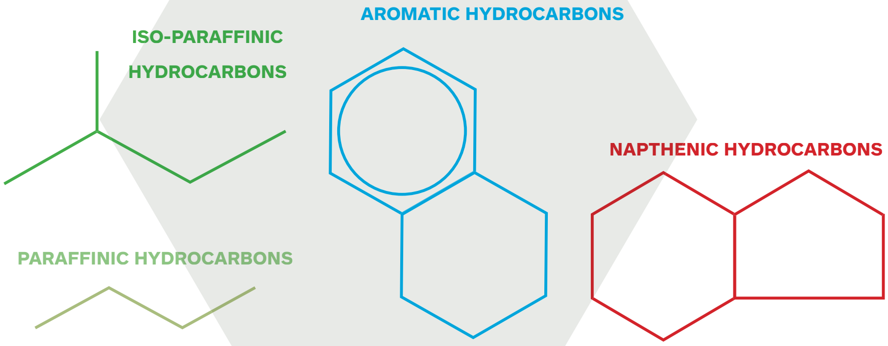

Figure 1. Structure of mineral oils

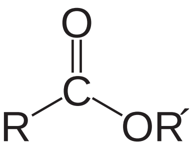

Figure 2. Structure of an ester

Introduction

High fire safety and biodegradability are some of the key properties that have successfully established ester liquids in the transformer industry, but their chemical differences compared to mineral oil are not always fully recognised and understood. This article will highlight how care is required to ensure the test method and results interpretation are appropriate to the dielectric liquid being assessed.

Mineral oil is a mixture of paraffinic, naphthenic, or aromatic hydrocarbon structures (Figure 1), and the ratio of these structures varies leading to property differences including viscosity, oxidation stability and more. New mineral oil has minimal polar molecular content, however, during the aging process, acids and ketones are produced, increasing the overall polarity of the liquid. This leads to changes in the liquid properties such as the dielectric dissipation factor (DDF) and interfacial tension.

An ester is a chemical compound containing carbon, hydrogen and oxygen bonds arranged as in Figure 2, where R represents a hydrocarbon chain. Unlike mineral oils, ester liquids are polar to begin with, which gives esters beneficial properties such as their excellent water tolerance.

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High fire safety and biodegradability are some of the key properties that have successfully established ester liquids in the transformer industry, but their chemical differences compared to mineral oil are not always fully recognised and understood.

Ester liquids can be synthetic or natural, and there are differences in their chemical structures.

Natural esters are also known as triglycerides, containing a glycerol backbone and three fatty acid chains, with the structure of the fatty acid chains influencing the ester properties. The degree of saturation of an ester refers to the amount of double bonds present in the fatty acid chain, and these double bonds are susceptible to oxidation. Saturation also influences pour point, with highly saturated natural esters such as coconut oil having a pour point too high for use in a transformer. Currently, canola, soybean and sunflower oils are most commonly employed for use in transformers (Figure 3) [1].

Synthetic esters are a popular choice as dielectric liquids. They are created by reacting select acids and alcohols by the process of esterification. Using a synthetic ester provides a high fire point and readily biodegradability, and they have better low temperature behaviour without the oxygen stability weakness when compared to natural esters. Synthetic ester can also offer higher water tolerance due to its additional ester linkage in the structure, as shown in Figure 4.

Interpretation of test results based on insulating liquid type

With multiple liquid types now in widespread use, correct identification of the type of insulating liquid is vital to obtaining meaningful results. This section outlines some common tests and highlights the importance of liquid identification. A small range of tests is commonly used to evaluate the quality of both unused and in-service insulating liquids for transformers. The results generated are an invaluable diagnostic tool.

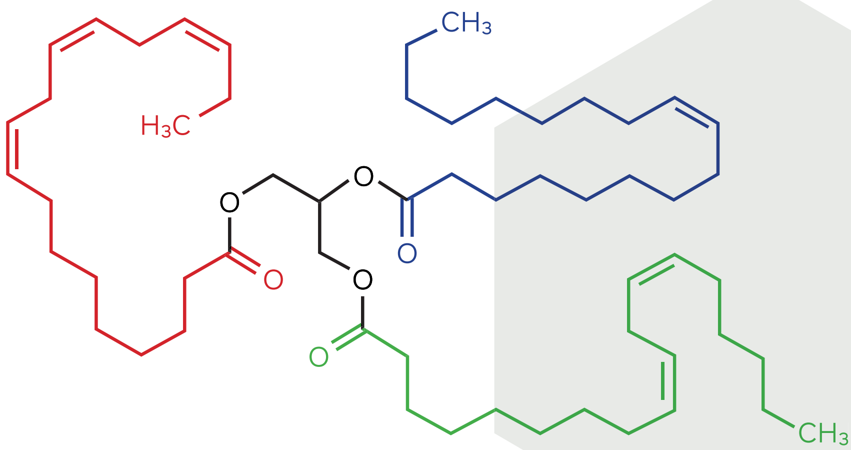

Figure 3. Structure of natural ester

Common diagnostic tests for transformer liquids include:

- Water content
- Acid value
- Dielectric breakdown strength
- Dielectric dissipation factor (DDF)
- Dissolved gas analysis (DGA)

Flash point and fire point analyses are elaborated on below as they have significant safety ramifications. Other tests, which are performed less frequently for esters, will not be explored in this article. These include interfacial tension, polychlorinated biphenyl (PCB) content, corrosive sulphur content and viscosity.

Water content is typically analysed via Karl Fischer titration instrumentation and expressed in parts per million (ppm). Due to their differing chemical structures, mineral oil and esters behave markedly different in the presence of water. Mineral oil does not readily interact with water, so relatively low levels of water negatively impact the dielectric properties of the liquid. In comparison, esters readily absorb water, and therefore higher levels may be detected (especially in service) before the same effect is apparent. For example, at 20°C, the same loss of breakdown strength is seen in mineral oil at water levels below 50 ppm, compared to over 300 ppm for natural esters, or over 600 ppm in synthetic esters [2].

Acid value is expressed as the quantity (mg) of Potassium Hydroxide (KOH) needed to neutralise 1g of the liquid. Therefore, liquids with a higher acid value (mgKOH/g) contain higher levels of acidic components. As discussed previously, the chemical structures of mineral oil and esters are different, affecting the way in which these liquids age. Mineral oil produces short chain (<C4), water soluble carboxylic acids in service that migrate with water into the solid insulation where they can cause harm. Esters produce longer chained carboxylic acids with very low water solubility.

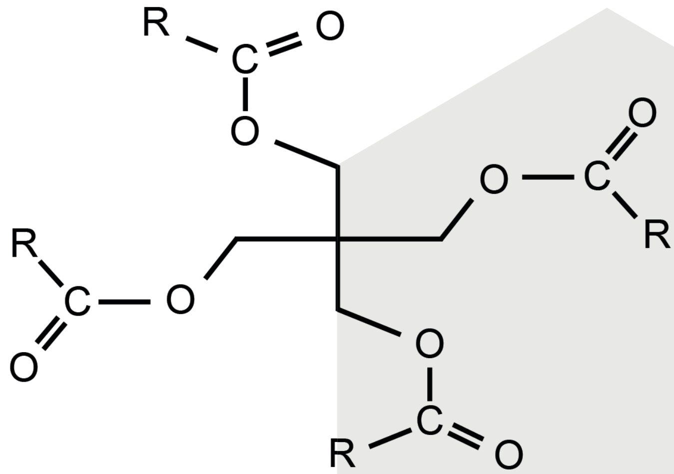

Figure 4. Structure of synthetic ester

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With multiple liquid types now in widespread use, correct identification of the type of insulating liquid is vital to obtaining meaningful results.

This benefit alongside the superior water tolerance of esters has been demonstrated to be less harmful to cellulose materials resulting in an increased transformer lifespan, and led to a revision of industry standards so that higher levels of acid are acceptable inside ester filled transformers versus those filled with mineral oil [3].

Dielectric breakdown strength is the minimum voltage, typically expressed in kilovolts (kV), at which the liquid is forced to conduct electricity between two electrodes at a specified distance apart (e.g., 1 or 2mm for ASTM D1816). Despite their chemical differences this breakdown voltage of mineral oils and esters is similar. However, to ensure the integrity of results generated, liquid-specific differences in the testing protocols must be followed. For example, ASTM D1816 states that esters require a 15-minute stand time prior to testing whereas mineral oils require only five minutes. Failure to follow this test method requirement due to misidentification of the liquid could lead to misleading results and unnecessary maintenance intervention.

DDF, or tan delta, is a measure of the dielectric losses in an electrical insulating liquid in an alternating electric field and of the energy dissipated as heat. Any contaminants present such as cellulose fibres, polar breakdown compounds, water, etc. increase the tendency of the liquid to conduct electricity seen as an increase in tan delta. Esters are more polar and much more hygroscopic than mineral oil, hence have inherently higher DDF without compromising dielectric performance.

DGA quantifies the level of atmospheric and fault gases dissolved in transformer liquids. Levels of these gases serve as a powerful diagnostic tool to track the health of transformers whilst in-service. The transformer liquid type has an impact on the interpretation of results as the chemistry of mineral oils and esters dictates that they interact differently with different gases. Whilst some general trends are true for the various types of liquid, other results are liquid specific. For example, in mineral oils certain levels of carbon oxides is indicative of cellulose paper degradation whereas for esters the presence of these gases is possible even in the absence of cellulose paper from the breakdown of the ester linkage in the liquid itself, so as with other analysis care needs to be taken and the liquid

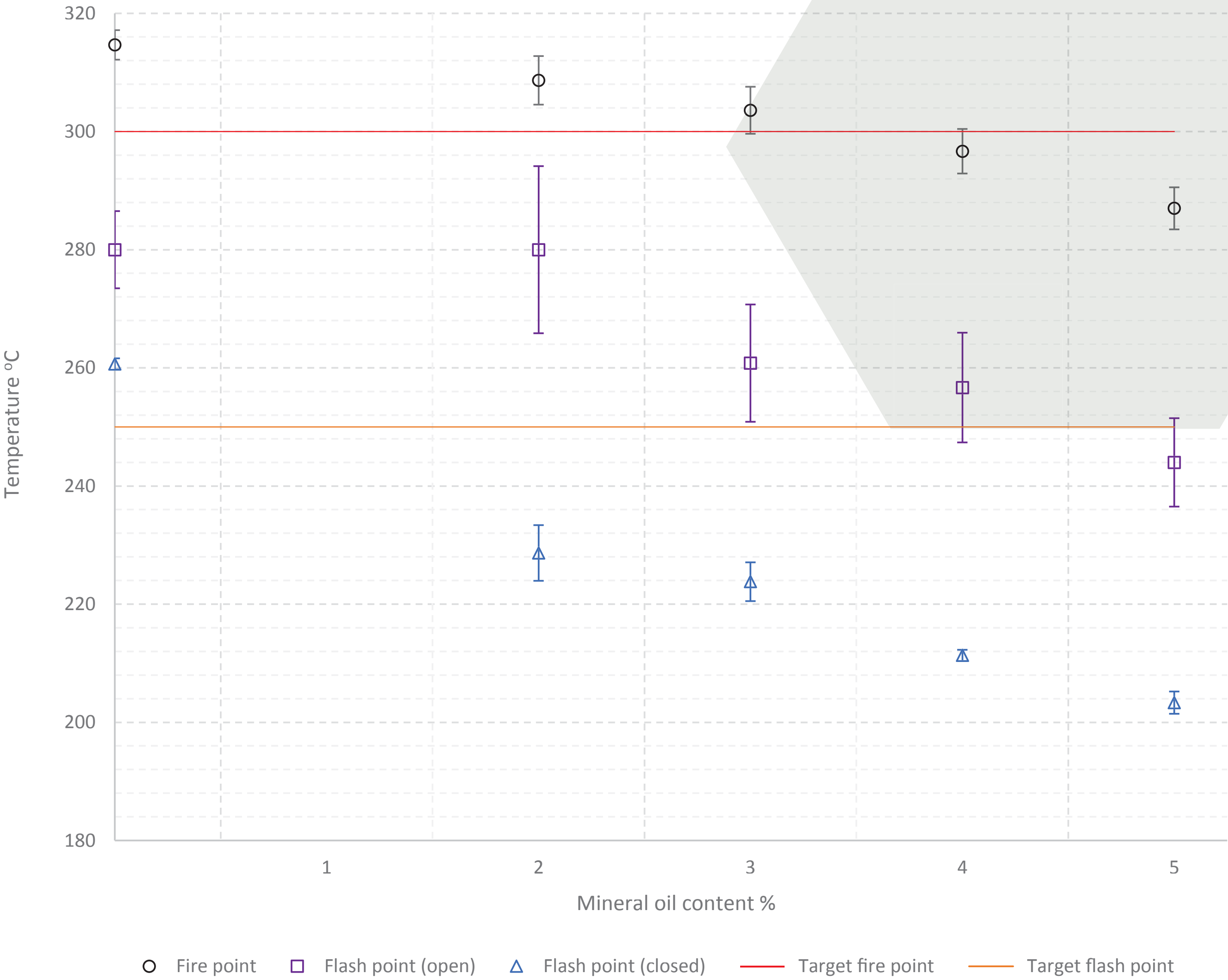

Figure 5. Fire point and flash points of MIDEL 7131 with mineral oil contamination at low concentrations

type given high precedence when interpreting results [3]. This has led to ester specific revisions to Duval's triangles and pentagons – well-established diagnostic tools which plot levels of gases simultaneously to aid interpretation of results.

Flash point is the lowest temperature at which vapours ignite in the presence of an ignition source whereas fire point is the lowest temperature at which vapours continue to burn for five seconds after the ignition source is removed [4]. Due to chemical differences in structure the flash and fire points are significantly lower for mineral oil than that of natural and synthetic esters. This is an important safety consideration. As discussed in the following section, excessive amounts of mineral oil cross-contamination can reduce the flash and fire point significantly. In retrofilling situations where mineral oil is replaced with an ester, residual mineral oil above recommended levels can impact the inherent safety benefits of an ester liquid and so must be managed accordingly.

Test procedure, repeatability, and reproducibility

In addition to interpretation of results, testing procedures are important in differentiation between different insulating liquids. Repeatability and reproducibility are also extremely important terms in the world of science and engineering. The amount of error considered acceptable greatly depends on the test and the application in question. For example, large error is not acceptable when under strict legislation or where there may be concerns for safety. By definition, repeatability of measurements refers to change measured for tests conducted under the same conditions and over a short time. On the other hand, reproducibility refers to change measured for results obtained under varying conditions, for example different testing laboratories, instruments or even an extended timeframe.

+ Strict adherence to test procedures including cleaning and sample preparation can be crucial for producing reliable results.

Strict adherence to test procedures including cleaning and sample preparation can be crucial for producing reliable results. Transformer liquid test laboratories commonly analyse more than one substance – mineral oil, synthetic ester, natural ester, silicone liquid or less flammable hydrocarbons. Low levels of residual contamination between consecutive tests could easily lead to variation in results. An investigation into the effect of mineral oil contamination in synthetic ester on flash and fire point was recently carried out. Interest was shown around the lower concentrations of mineral oil, particularly around the concentration that determines less flammable (fire point ≥300°C) or K class (fire point >300°C) specification. The repeatability of these investigations was also considered. A mineral oil, used for transformer applications, was mixed with MIDEL 7131 synthetic ester at increasing concentrations. The fire and flash point were measured on both open and closed cup apparatus and each mixture was tested three times. The results in Figure 4 shows that MIDEL 7131 fire point falls below less flammable liquid specification between 3% and 4% residual mineral oil content. Previous work using a different mineral oil with higher flash & fire point indicated that up to 3.5% mineral oil contamination was acceptable in retaining a fire point above 300°C. The repeatability in this study was very good overall. The repeatability of the flash point measured on the closed cup apparatus is much better than when measured using the open cup. This is expected and likely why the measurement using the closed cup is often suggested in various standards. In some situations, the margin of error due to the test procedure or equipment, 8˚C as stated in ISO 2592, may explain why the flash point and/or fire point result is lower than anticipated. In that situation, it would be recommended to retest the sample to confirm the analysis and interpretation [4].

Flash and fire points of unused synthetic ester are often not tested however low results have been reported on several occasions, thought to be caused by improper cleaning of the pans. Contrary to expectation, no difference was found in fire point measurements of fresh synthetic ester when the cup was not cleaned in between tests, even after excessive use seen in Figure 5. On the other hand, fire point measurements were depressed by ~7°C when cups containing mineral oil had been tested but had not been cleaned before changing liquid type. A similar effect may be seen if any sample material is left on the cup rim during the analysis. Test methodology, or various apparatus brands could be responsible for the inconsistencies seen among different test sites.

Users often test DDF in new mineral oil or used dielectric liquids, which may have a detrimental effect if they then test unused ester. The polarity of ester enables the liquid to be extremely tolerant of water, but the presence of water may increase DDF values which can be falsely viewed as poor liquid condition. It is known that DDF values can be higher in ester liquids even when other testing parameters such as breakdown voltage indicate the insulating liquid is in good working condition [5].

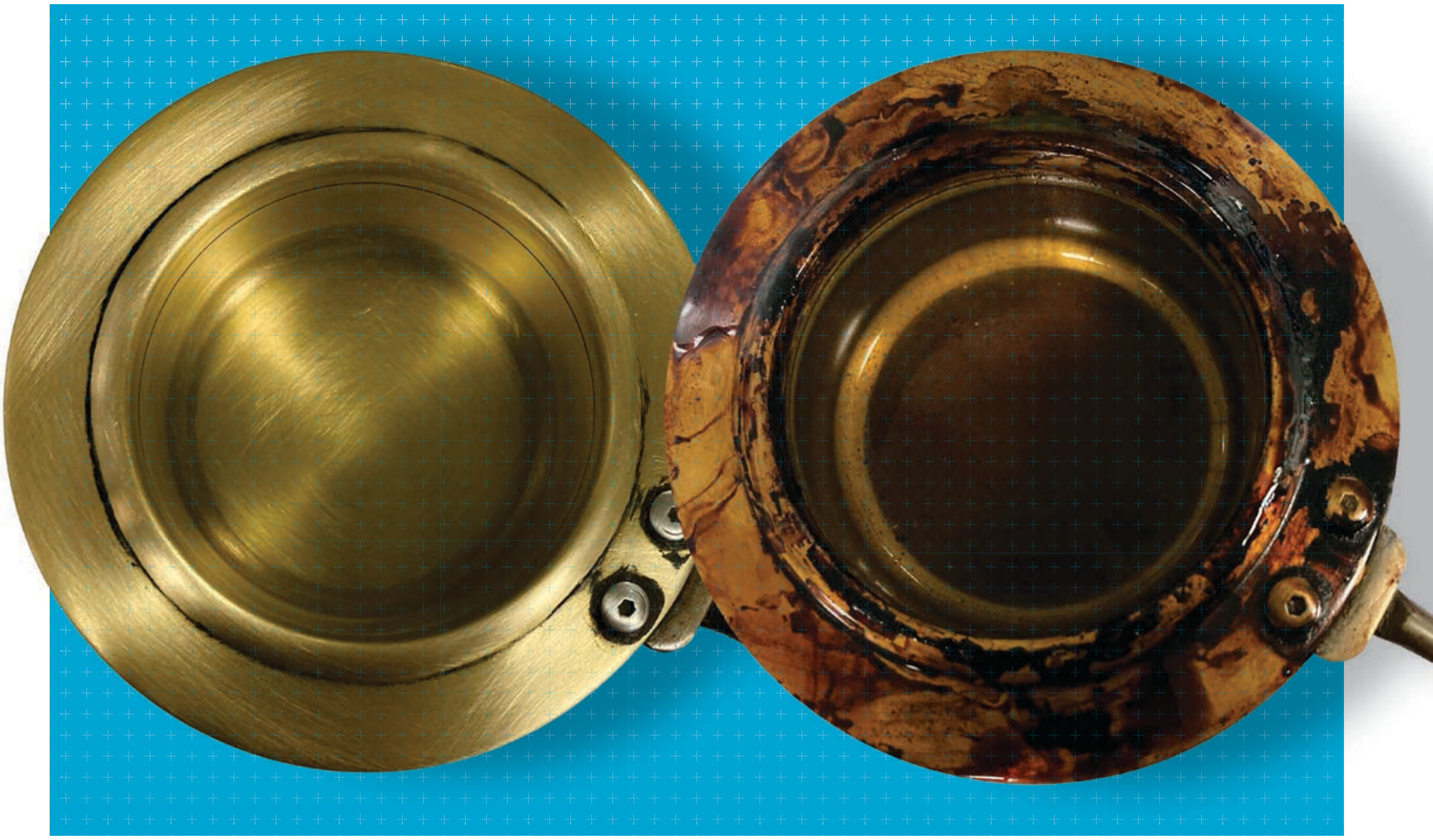

Figure 6. Left: Cup cleaned using wire wool and solvent. Right: No cleaning of cup in between tests

Gas	Mineral oil	Synthetic ester	Natural ester
Nitrogen N_2	0.091	0.091	0.074
Oxygen O_2	0.172	0.152	0.134
Hydrogen H_2	0.0504	0.0479	0.0471
Methane CH_4	0.423	0.378	0.341
Ethane C_2H_6	2.88	2.2	2.14
Ethylene C_2H_4	1.81	1.85	1.67
Acetylene C_2H_2	1.25	4.26	2.58
Carbon monoxide CO	0.125	0.13	0.108
Carbon Dioxide CO_2	1.1	2.08	1.54

Table 1. Gas solubility coefficients in insulating liquids from CIGRE Technical Brochure 443 [8]

The small sample volume of the test cell makes the liquid susceptible to unreliably high results as even trace contamination will affect the DDF. Recent investigations [6] showed that mixture of esters with oxidised aromatic oils resulted in abnormally high DDF. No explanation for this phenomenon was provided though it emphasises how DDF values could be unreliable when tested alongside used and different insulating liquids, especially esters. For these reasons, DDF is not recommended for monitoring the condition of an ester as a stand-alone test.

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Although standards specifically designed for ester liquids exist, care must be taken to adhere to the correct liquid method for some testing parameters, while other parameters should be considered cautiously.

Although DGA is not a novel technique, it remains a topic of great interest. As with other analyses, it must be recognised that the chemistry differences between mineral oil and esters will influence results and their interpretation. As with mineral oil, correct sampling, storage, and handling is required to avoid losing hydrogen or introducing air bubbles. It has been shown that air bubbles >8% volume can reduce the hydrogen value by 35% [7]. The same test methods are used for the different insulating liquids; however, analysts must ensure the correct calibration standards are used. The gas solubility of the liquid is an important parameter related to the extraction method (headspace analysis) and later determination of the gas concentrations. The solubility of most of the gases listed in Table 1 are relatively similar for each of the insulating liquid types however it should be noted that the solubility of acetylene and carbon dioxide is much higher in ester liquids. Incorrect calibration may ultimately lead to misdiagnosis of faults in the transformer which may prove costly. A recommendation would be to have online monitoring in conjunction with periodic laboratory testing to generate a reliable trend to support operational decisions.

Conclusion

Natural and synthetic esters used as transformer dielectric liquids are established alternatives to mineral oil. The industry calls for better understanding of these liquids and how they are analysed. DDF is highly sensitive in esters and should only be considered together with other liquid properties. DGA is a useful tool to detect and prevent potential faults in transformers however the right calibration is important to account for differences in gas solubility. Although standards specifically designed for ester liquids exist, care must be taken to adhere to the correct liquid method for some testing parameters, while other parameters should be considered with a cautious approach.

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Unique Properties of Transformer Insulating Oils Containing Hydrogen Donor Compounds

by **Maryam Mohagheghi**

Photo: HollyFrontier

In transformers, oil in combination with paper is used to provide insulation to the transformer's windings and other internal components. The majority of transformer insulating oils are composed of base oils and specific performance additives. Gassing inhibitors may be added to higher quality base oils to improve the gassing properties of the finished insulating oil. An insulating oil with a negative gassing tendency reduces hydrogen gas bubbles which result from electrical and thermal fault conditions in the transformer. A negative gassing tendency also reduces the risk of transformer failure and explosion due to hydrogen gas generation, providing an extra margin of safety. As a chemical class, gassing inhibitors are also known as hydrogen donors. Structurally, chemical compounds containing H_α protons, protons attached to non-aromatic carbon atoms that are attached directly to an aromatic ring structure, are potential hydrogen donors. In this study, the H_α content of a number of gassing inhibitor/hydrogen donor compounds were measured using ^{1}H-NMR. The correlation between Hα proton content and the gassing tendency of a transformer insulating oil was then studied using the ASTM D2300 test method.

Introduction

Transformers are critical and expensive pieces of equipment in the power generation and distribution network. Any failure could have drastic consequences to an entire electrical network. To protect and increase the life of transformers, insulating oils are used in combination with solid insulation. Together, they provide dielectric insulation to the transformer's windings and internal components and, also, dissipate heat generated by the transformer's windings and core [1, 2]. Different types of insulating liquids exist, including petroleum derived mineral oils, natural and synthetic esters, silicone, and synthetic hydrocarbons. Mineral oil based transformer/ insulating oils are commonly composed of base oil and additives that enhance oxidation stability, cold temperature performance, and gassing properties of the base oil. The base oil may be an isoparaffinic oil or naphthenic oil. Isoparaffinic oils are produced through a severe hydrotreating process; as a result of the process, deleterious sulfur, nitrogen, and oxygen compounds are eliminated, and undesirable aromatic compounds are converted to more stable compounds. This study used isoparaffinic mineral transformer oils for their superior dielectric and oxidative stability, as well as established performance with gassing inhibitors.

The tendency of an oil to absorb or evolve gas under electrical stress can be measured by ASTM D2300 (standard test method for gassing of electrical insulating liquids under electrical stress and ionization).

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Although the hydrocarbons in finished mineral oils are carefully refined and highly stable, the molecules may decompose through thermal or electrical stresses. During a thermal or electrical fault, energy is released and absorbed by the mineral oil's hydrocarbon molecules. This excess energy breaks down chemical bonds in the hydrocarbons, producing hydrogen gas alongside low molecular weight hydrocarbons [3]. It's these characteristic hydrocarbons that are monitored by routine dissolved gas analysis (DGA) testing to monitor the health and performance of the transformer. The remaining part of the decomposed hydrocarbon is a free radical, which can react with a similar free radical and produce higher molecular weight species which are no longer soluble in the oil (i.e. sludge). When this process happens, the evolved hydrogen gas exacerbates oil aging, and is a potential threat to the operational safety of the transformer.

The tendency of an oil to absorb or evolve gas under electrical stress can be measured by ASTM D2300 (standard test method for gassing of electrical insulating liquids under electrical stress and ionization). In this test method, electric stresses are simulated by ionic bombardment of the oil molecules producing hydrogen and other breakdown species. Should they be present, gassing inhibitors can absorb the generated hydrogen gas in the insulating oil.

The value reported by ASTM D2300 is the net value of these two competing reactions. A positive result indicates gas is evolved following electrical stress. If gas is absorbed, however, the result is a negative gassing tendency. During this equilibrium, saturated hydrocarbons are mainly responsible for the hydrogen gas produced. On the other end, aromatic molecules, or unsaturated bonds within a molecule, tend to absorb ree hydrogen.

Since isoparaffinic mineral oils are highly refined to enhance their oxidative stability, they tend to evolve hydrogen under stress as they lack reactive unsaturated and aromatic molecules. To improve the gassing tendency of stable isoparaffinic mineral oils without compromising their oxidation stability, gassing inhibitors are added to the oil.

Negative gassing tendency is a unique property for the transformer oil because it reduces the risk of transformer failure and explosion due to hydrogen generation, providing an extra margin of safety and performance.

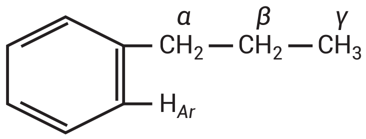
*Table 1.
Hydrogen types and chemical shift*

Parameter	Chemical shift, ppm	Type of Protons
H_{Ar}	6.0-9.0	Aromatic hydrogen
H_α	2.0-4.0	Aliphatic hydrogen on C_α to aromatics rings
H_β	1.0-2.0	Aliphatic hydrogen on C_β and the CH_2 beyond the C_β to aromatic rings
H_γ	0.5-1.0	Aliphatic hydrogen on C_γ and the CH_3 beyond the C_γ to aromatic rings

Gassing inhibitors, also known as hydrogen donors, are used to improve the gassing tendency of stable isoparaffinic mineral oils without compromising their oxidation stability.

As mentioned, gassing inhibitors are also known as hydrogen donors, as they can donate a hydrogen bond with free hydrogen molecules. A hydrogen donor may be any compound which contains labile or easily displaced hydrogen. By readily displacing existing hydrogen bonds, the gassing inhibitor is able to absorb new, free hydrogen.

*Figure 1.
Hydrogen types in a molecule*



Examples include partially saturated aromatic compounds such as tetrahydronaphthalene, alkyl substituted tetrahydronaphthalenes, and alkylated benzenes [4]. The ability of a donor material to donate a hydrogen bond can be expressed in terms of specific types of hydrogen content. There are four hydrogen types according to the ^{1}H-NMR (Nuclear Magnetic Resonance) spectral analysis of hydrocarbons, as shown in Table 1. For a better visualization, the four hydrogen types are shown in Figure 1 [5, 6].

The H_{Ar} protons are attached to aromatic rings and are a measure of the aromaticity of a material. H_α protons are labile and are potential hydrogen donors. They are attached to non-aromatic carbon atoms attached directly to an aromatic ring structure.

H_β -protons are attached to carbon atoms in a second position away from an aromatic ring. Protons attached to carbon atoms three or more bonds away from an aromatic ring structure are H_γ protons.
As such, the performance of any hydrogen donor was expected to be linked to the type and amount of aromatic structures, alongside higher Hα proton content [5].

Experimental

To study the effectiveness of different hydrogen donor compounds as gassing inhibitors, [1]H-NMR was first used to measure H_{Ar} and H_α proton content in four different compounds. The gassing tendency of transformer oils made with each compound was then measured using the ASTM D2300 test method to assess the correlation between the two properties.

Table 3. Gassing tendency results

	Transformer oil 1 with HD1	Transformer oil 2 with HD2	Transformer oil 3 with HD3	Transformer oil 4 with HD4
Gassing tendency, μL/min	-13	25	17.2	-4
H_α percentage, %	33.0	5.2	12.2	28.9
H_{Ar} percentage, %	32.0	0.3	12.6	22.6

Four hydrogen donor streams (HD1 to HD4) were assessed in this study of which three were pure compounds and one was a mixed hydrocarbon refinery byproduct. [1]H NMR spectra were recorded at room temperature on a Bruker Avance II 400 spectrometer. Approximately 5-10 mg of sample was dissolved in approximately 1 mL of CDCl3 (Cambridge Isotope Laboratories, 99.8% D, w/ 1% V/V TMS) in a 5 mm NMR tube. [1]H (400.32 MHz) experiments were run with an interscan delay of 4.83 s and 32 scans were collected. Figure 2 shows the [1]H-NMR spectra for each hydrogen donor.

Results and Discussions

For [1]H-NMR interpretation, the typical [1]H-NMR signal positions reported in Table 1 were used. The percentage of H_α and H_{Ar} protons was calculated for the hydrogen donor compounds tested in this study and is shown in Table 2. Three different samples of the HD4 stream were tested to check the variation between different production batches.

The gassing tendency of transformer oil blends made using each hydrogen donor as the gassing inhibitor were then measured by the ASTM D2300 test method.

The elevated amount of H_{Ar} for the compounds with higher H_α content indicates the link between hydrogen donor performance and aromatic structures, alongside with higher H_α proton content. Figure 3 shows the correlation between H_α content of a hydrogen donor and the gassing tendency of an isoparaffinic transformer oil containing 2 vol.% hydrogen donor material.

Table 3 shows the gassing tendency results. The treat rate of the hydrogen donor/gassing inhibitor was the same in all the blends at 2 vol.%. Results show that hydrogen donor material with H_α content greater than 28% provides the blend with a negative gassing tendency.

Results confirm that the addition of a superior hydrogen donor additive, based on H_α content, provides superior negative gassing properties to the oil.

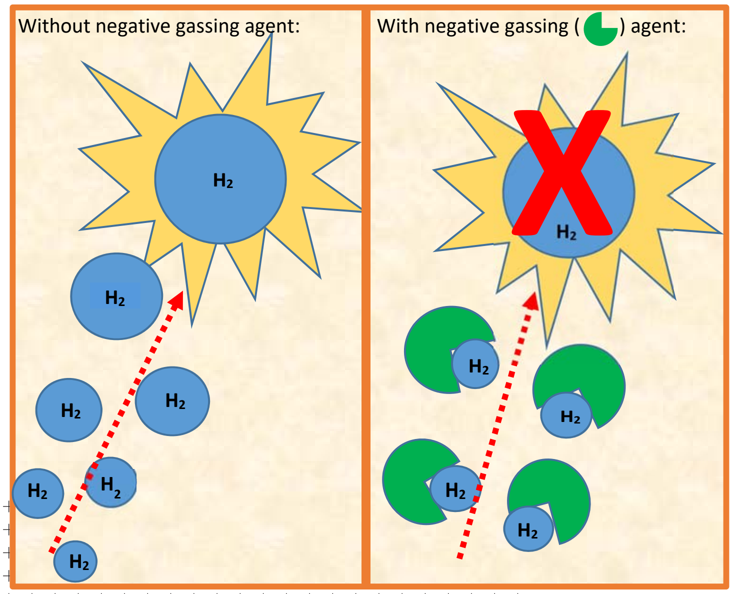


Figure 2.
¹H-NMR Spectra

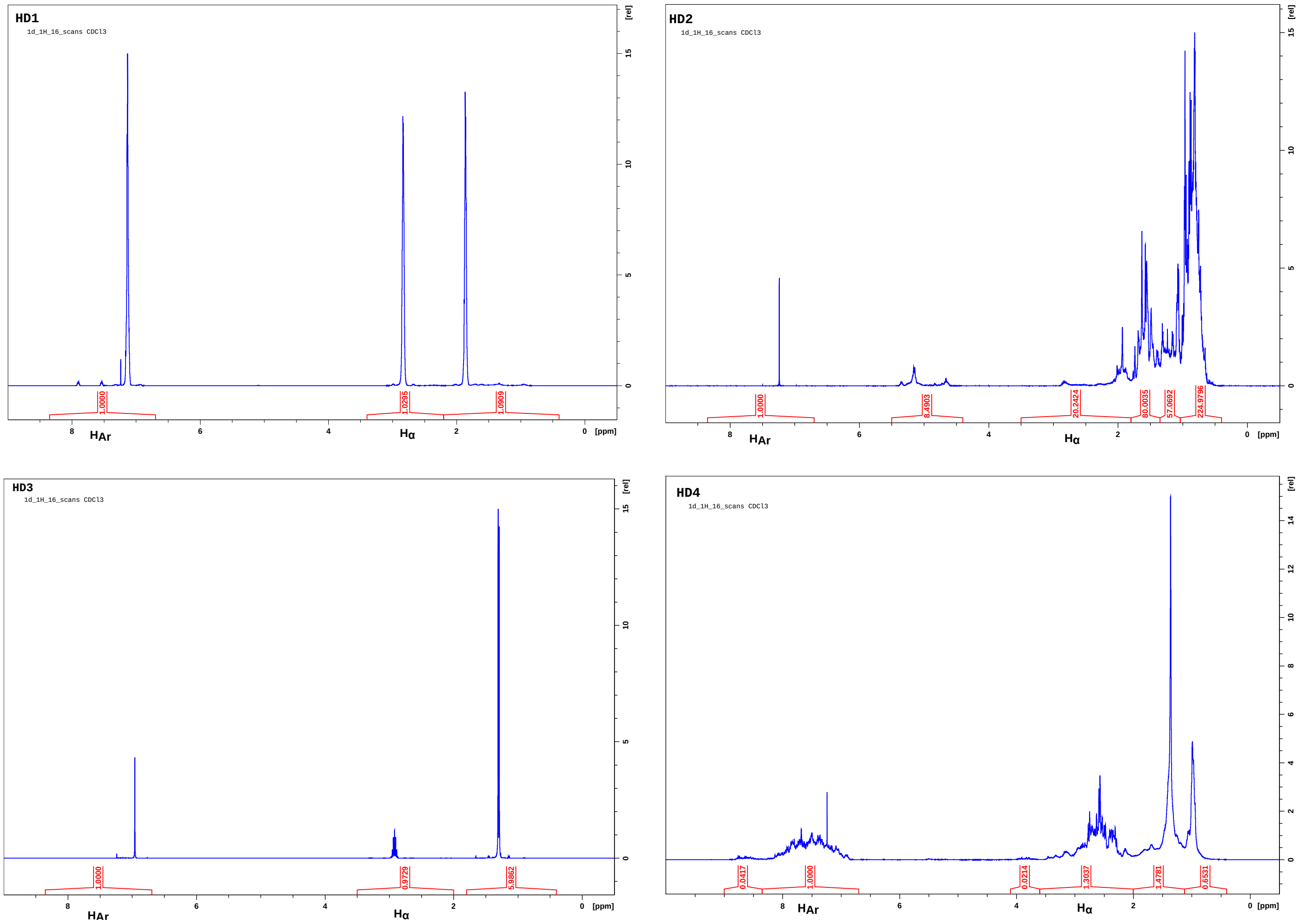
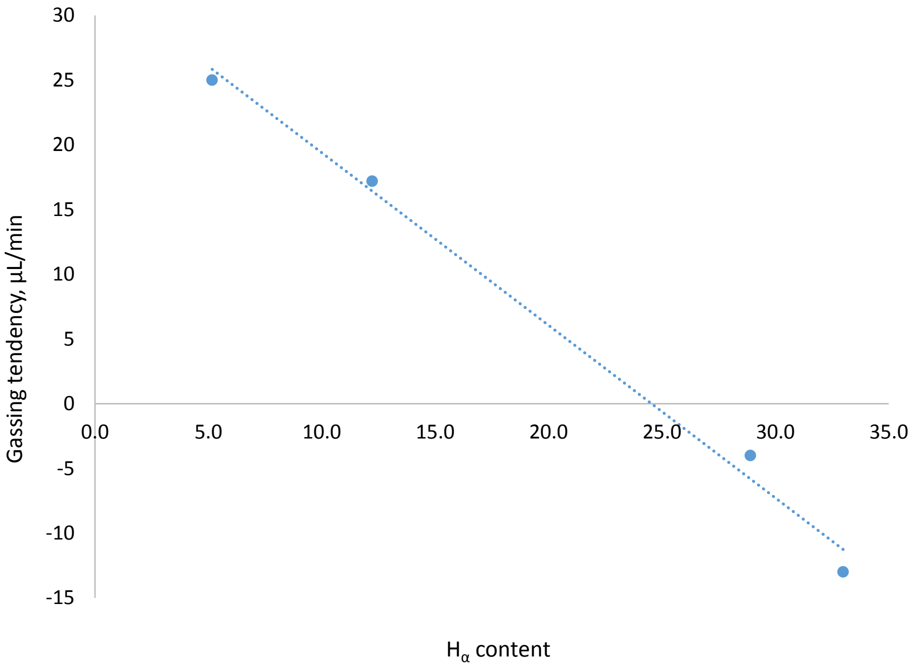


Table 2.
Hydrogen content of four different hydrogen donor compounds using ¹H-NMR data

	HD1	HD2	HD3	HD4		
				HD4-1	HD4-2	HD4-3
H_α content, protons integration	1.030	20.242	0.973	13.251	12.597	13.077
H_{Ar} content, protons integration	1.000	1.000	1.000	10.417	10.000	10.000
Total Hydrogen, protons integration	3.120	391.785	7.959	44.98	44.412	45.338
H_α percentage, %	33.0	5.2	12.2	29.5	28.4	28.8
H_{Ar} percentage, %	32.0	0.3	12.6	23.2	22.5	22.1

Figure 3.
Gassing tendency of a transformer oil vs H_α content of hydrogen donor compound used in the transformer oil



Conclusions

The effectiveness of different hydrogen donor compounds as gassing inhibitors in isoparaffinic transformer oils was studied. The ^{1}H-NMR technique was used to assess the Hα and H_{Ar} content of different hydrogen donor compounds. The gassing tendency of a representative transformer oil blend containing 2 vol% of each hydrogen donor was then measured using the ASTM D2300 test method. The correlation between H_α content and gassing tendency indicates higher H_α content provides negative gassing tendency to the transformer oil. Negative gassing tendency is a unique property for the transformer oil because it reduces the risk of transformer failure and explosion due to hydrogen generation, providing an extra margin of safety and performance.

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