

Degradation of Insulating Liquids: Myths and Facts

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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.





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



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FR3 fluid sample performance under test: ageing and oxidation



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



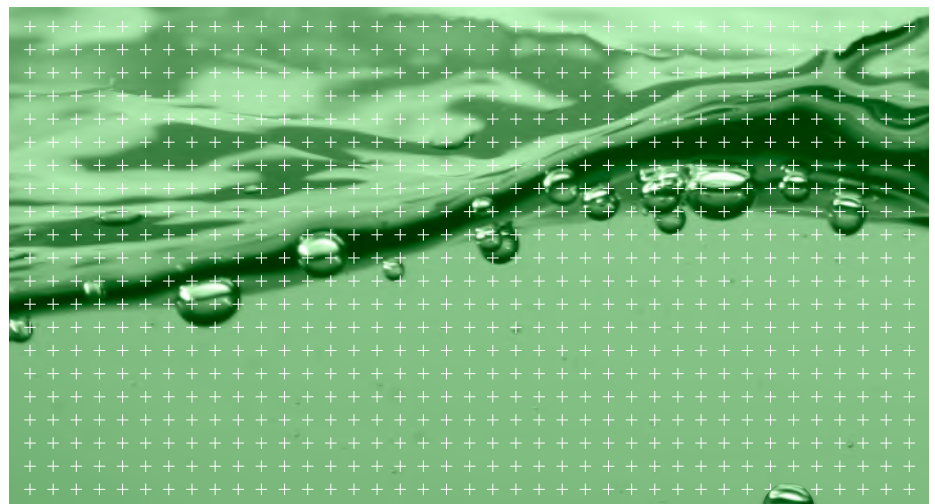
transformers have been available for years for natural ester liquids [4] [5] [6]. Conversely, there are still several discussions on which parameters would be relevant to indicate the degradation of synthetic ester liquids, with very limited published data. Having a standardized framework for fluid application 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.



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





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.

References

- [1] IEC 60076-7 Ed 2.0, "Power transformers - Part 7: Loading guide for mineral-oil-immersed power transformers," Technical Committee TC14, International Electrotechnical Committee, 2018
- [2] S. Boyde and U. Wilton, "Hydrolytic Stability of Synthetic Ester Lubricants," *Journal of Synthetic Lubrication*, vol. 16, no. April, pp. 297-312, 2000
- [3] A. Sbravati, K. Wirtz and L. B. d. Oliveira, "Insulating liquids at free breathing conditions," in *2021 Electrical Insulation Conference (EIC)*, Virtual Event, 2021
- [4] IEEE C57.147, "IEEE Guide for Acceptance and Maintenance of Natural Ester Fluids in Transformers," Institute of Electrical and Electronics Engineers, Inc, New York, USA, 2008
- [5] IEEE C57.155, "IEEE Guide for Interpretation of Gases Generated in Natural Ester and Synthetic Ester-Immersed Transformers," 2014
- [6] IEC 62975 Ed 1.0, "Natural esters - Guidelines for maintenance and use in electrical equipment," Technical Committee TC10, International Electrotechnical Committee, 2021
- [7] A. Sbravati, E. Casserly, H. Wilhelm, P. Su, A. Levin, A. Gyore, M. A. M. Cheema, K. Wirtz and N. Lukenda, "Initial investigation of a thermal performance qualification method for transformer insulating liquids," in *2021 Electrical Insulation Conference (EIC)*, Virtual Event, 2021
- [8] V. Vasconcellos, A. Sbravati, L. C. Zanetta Jr., K. Rapp, L. Lombini, S. Nazzari, F. Scatiggio and A. Valant, "Increased Loadability of Transformers Using Natural Ester and Cellulosic Materials as High Temperature Insulation Systems," *IEEE Electrical Insulation Magazine*, pp. 8-17, September/October - Vol. 34, No. 5 2018
- [9] A. Lemm, K. Rapp and J. Luksich, "Effect of Natural Ester (Vegetable Oil) Dielectric Fluid on the Water Content of Aged Paper Insulation," in *EIA/IEEE - 10th Insucon International Electrical Insulation Conference*, Birmingham, UK, May 24-26, 2006
- [10] K. Rapp, C. P. McShane and J. Luksich, "Interaction Mechanisms of Natural Ester Dielectric Fluid and Kraft Paper," in *IEEE/DEIS 15th International Conference on Dielectric Liquids*, Coimbra, Portugal, June 26-July 1, 2005
- [11] IEEE C57.154, "IEEE Standard for the Design, Testing, and Application of Liquid-Immersed Distribution, Power, and Regulating Transformers Using High-Temperature Insulation Systems and Operating at Elevated Temperatures," Institute of Electrical and Electronics Engineers, Inc, New York, USA, 2012
- [12] IEC 60076-14 Ed 1.0, "Power transformers – Part 1: Liquid-immersed power transformers using high-temperature insulation materials," Technical Committee TC14, International Electrotechnical Committee, 2013

