Reducing Environmental Impact and Improving Safety and Performance of Power Transformers With Natural Ester Dielectric Insulating Fluids

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***Abstract*—Natural ester fluids may be used in new transformers as well as to retrofill existing units in order to improve their performance and reliability. Designing or retrofilling power transformers with natural ester fluids requires, however, to account for a number of significant differences in properties, characteristics, and material parameters between natural ester fluids and mineral oil in order to obtain the desired performance (thermally and dielectrically). This paper gives a comprehensive review of natural-ester-fluid main properties and associated values when it comes to environmental impact, fire resistance, and overall performance of transformers filled with such fluids. The key fluid characteristics impacting the design of power transformers are also highlighted.**

***Index Terms*—Environmental impact, fire safety, natural ester, transformer performance, vegetable oil.**

Nomenclature

The ONAN/ONAF and KNAN/KNAF terminologies describe the transformer cooling system types as defined in the IEEE Standard C57.12.00, "Standard General Requirements for Liquid-Immersed Distribution, Power, and Regulating Transformers," and the International Electrotechnical Commission (IEC) Standard 60076-2, "Power transformers—Part 2: Temperature rise for liquid-immersed transformers".

I. Introduction

For over 100 years, petroleum-based mineral oil purified to "transformer oil grade" has been used in liquid-filled transformers. Nowadays, over a million tons of transformer oils are annually purchased worldwide. The success of mineral transformer oil has mainly been built on its availability and low cost associated with good dielectric and cooling performance.

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Today's escalation in power demands pushes often aging networks to their limits, causing unprecedentedly high failure rate in large power transformers, for instance. In these situations, mineral-oil-based dielectric insulating fluids have shown costly limitations. Mineral-oil-filled transformer explosions and fires causing heavy collateral damage have raised major safety concerns. There have also been major environmental concerns over the toxic effects of uncontained mineral oil spills. This has given rise to a new class of alternative dielectric insulating fluids that have historically been developed to answer these specific concerns.

Polychlorinated biphenyls (PCBs) were used in transformers as dielectric insulating fluids to solve the problem of high flammability for installations in and near buildings. As their negative aspects began to be fully appreciated (high toxicity), other fluids such as silicone oils, high-temperature hydrocarbons, tetrachloroethylenes, and synthetic esters started to be used in transformers located in many of the locations where PCBs were formerly used. These fluids possessed superior fire resistance properties compared to mineral oils, although they were not as fire resistant as PCBs with the exception maybe of tetrachloroethylenes. They did not, however, with the possible exception of synthetic esters, possess biodegradability characteristics that were markedly superior to mineral oils. In the late 1990s, natural esters, a new class of fully biodegradable dielectric insulating fluids, were developed for transformer applications. These vegetable-oil-based fluids meet all the requirements for a high-temperature insulating fluid with the addition of being manufactured from renewable raw materials.

There are, today, a number of published industry standards and guides that cover the use of natural ester fluids in transformer applications, such as the American Society for Testing and Materials standard D6871 and the IEEE guide C57.147 in North America, the Associação Brasileira de Normas Técnicas standard NBR 15422 in Brazil, and, most recently, the Cigré Brochure 436 and the IEC Standard 62770.

II. Natural Ester Dielectric Insulating Fluids

A. Development of Electrical-Grade Vegetable-Based Oils

Vegetable-based oils were seriously considered as dielectric insulating fluids for capacitors first. Castor and cotton seed oils were mentioned for use in capacitors (with cellulose insulation) as early as 1962 [1]. Later on in the 1990s, rapeseed oil became

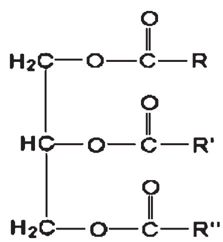

Fig. 1. Triglyceride ester molecule.

TABLE I
TYPICAL FATTY ACID COMPOSITION OF SOME VEGETABLE OILS

Vegetable oil	Saturated fatty acids, %	Unsaturated fatty acids, %		
		Mono-	Di-	Tri-
Canola oil [a]	7.9	55.9	22.1	11.1
Corn oil	12.7	24.2	58.0	0.7
Cottonseed oil	25.8	17.8	51.8	0.2
Peanut oil	13.6	17.8	51.8	0.2
Olive oil	13.2	73.3	7.9	0.6
Safflower oil	8.5	12.1	74.1	0.4
Safflower oil, high oleic	6.1	75.3	14.2	-
Soybean oil	14.2	22.5	51.0	6.8
Sunflower oil	10.5	19.6	65.7	-
Sunflower oil, high oleic	9.2	80.8	8.4	0.2

[a] Low erudic acid variety of rapeseed oil; more recently canola oil containing over 75% mono-unsaturated content has been developed.

another center of interest for use in capacitors [2]. Triggered by major utilities spending millions annually on cleaning up mineral oil spills and leaks from transformers, it is during the same decade that research efforts were started to develop fully biodegradable dielectric insulating fluids based on vegetable oils for use in transformers [3].

Research works soon demonstrated that vegetable oils needed further improvement to be used as transformer oil. Transformer oils remain in the unit for many years (as many as 30–40 years). Only in the larger power transformer units is the oil periodically changed or reclaimed. Long-term stability is therefore of critical importance, and vegetable oils have inherently components that degrade in a relatively short time.

B. Long-Term Stability, A Key Factor

Crude vegetable oils extracted from oil seeds contain solid constituents such as proteins and fibers, and liquid (fats and oil). Both fats and oil are triglyceride esters of fatty acids (Fig. 1), but fats contain a relatively high percentage of saturated triglycerides and would solidify below room temperature. Oil usually remains as liquid above 0 °C (oils with high unsaturation may remain as liquid at −15 °C to −30 °C). Table I lists the typical fatty acid composition of some vegetable oils [4].

The degree of unsaturation of the triglyceride ester molecule or fatty acid chains is an indicator of stability to heat, oxidation, and light degradation of the oil (the higher the degree of unsaturation from mono- to triunsaturation, the more unstable). The relative instability to oxidation is roughly 1:10:100:200 for saturated, mono-, di-, and triunsaturated C-18 triglyceride, respectively [5]. In that respect, the high oleic sunflower oil provides the best stability with a monounsaturated level of above 80% (even though very stable, fully saturated fatty acids easily solidify and are therefore here not desirable).

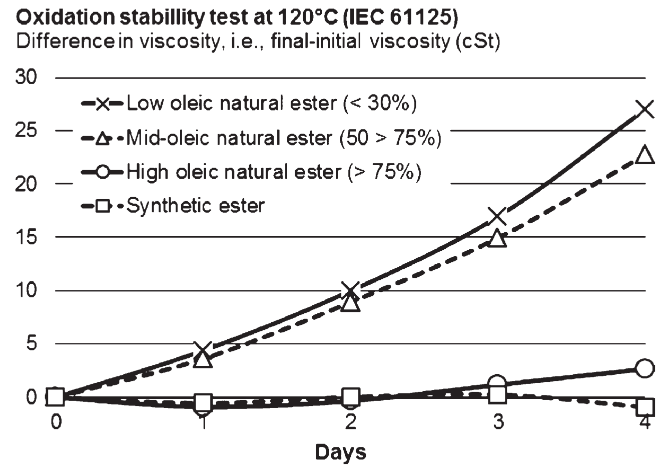

Fig. 2. IEC 61125 oxidation stability test results at 120 °C.

Oxidation stability tests have been run at 120 °C on different commercially available natural ester dielectric insulating fluids using the standard test method IEC 61125. The three natural ester fluids tested mainly differentiate themselves in the content of monounsaturated or oleic fatty acids, i.e., above 75% for a high oleic sunflower-based product, between 50% and 75% for a mid-oleic rapeseed-based product, and below 30% for a low oleic soybean-based product. The three natural esters were compared to a synthetic ester fluid which is known for its greater stability. The change of viscosity of the fluid during the test is a good indication of its degradation. Fig. 2 shows the results obtained over a test duration of 96 h or 4 days.

While the high oleic natural ester showed no degradation, both the mid- and low oleic natural esters showed sign of marked degradation at a very early stage already, with the low oleic product irreversibly polymerizing eventually. These results were further corroborated by visual inspection, infrared (IR) spectroscopy analysis, and oxidative induction time measurements [6].

In transformers, the presence of copper enhances the tendency for oxidation. Oxidation inhibitors are therefore needed for the oils used in transformers. Another factor is the purity of the oil. The oil has to be free of conducting ionic impurities to acceptable levels, and food-grade vegetable oils are not of this purity.

C. Main Characteristics

1) Preserving the Environment: Natural ester fluids are now recognized by the industry as the environmentally friendly dielectric insulating fluid of choice. By nature, these fluids are nontoxic and readily biodegradable (Fig. 3). Such properties have been verified and approved by the U.S. Environmental Protection Agency through their Environmental Technology Verification program [7]. Natural ester fluids are also classified as nonhazardous to water by the German Federal Environmental Agency (Umweltbundesamt) [8].

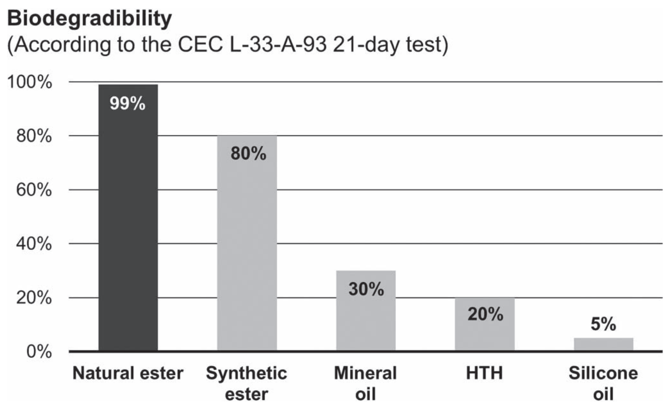

Fig. 3. Twenty-one-day aquatic biodegradability test results.

This environmental friendliness of natural esters may lead to substantial benefits for the transformer end user. For instance, when such fluids are used, FM Global[1] allows a much larger oil volume before containment is required and a much smaller containment when required in some installations [9]. Although local laws and regulations are still applicable, spills of natural esters can be disposed through normal means since they are not characterized as hazardous waste. This can also lead to potential relief from local environmental regulatory penalties (soil contamination mitigation after spills).

In addition, natural esters have a near neutral carbon footprint due to the negative carbon footprint of a vegetable oil production. The by-products of natural esters after combustion are also much less toxic than the ones of mineral oils, which further minimizes their overall impact on the environment.

2) Preserving Life and Properties: Natural ester fluids have a flash and fire point above 300 °C (versus 160 °C–180 °C typically for mineral oil). As such, they meet the U.S. National Electric Code definition of and are listed as “less flammable” dielectric fluids by both FM Global and Underwriters Laboratories[2] (UL). They are also classified as K-fire-hazard-class dielectric insulating fluids as per the IEC Standard 61100 [8].

Consequently, natural-ester-filled transformers meet fire safety requirements for indoor applications and outdoor areas of heightened safety sensitivity without additional safety equipment. According to FM Global, for example, active fire suppression and barrier walls can essentially be eliminated when minimal spacing is maintained between the different equipment (for transformers with ratings 10 MVA and lower) [9]. This, again, can lead to nonnegligible savings on initial installation costs as well as rehabilitation and maintenance costs for the transformer end user.

Overall, natural ester fluids greatly reduce the risk of transformer fire and explosion, hence greatly mitigating collateral damage of such dramatic events and potentially lowering insurance premiums. This is illustrated in Fig. 4, which displays the results of high-energy arcing faults simulated in pole-mounted distribution transformer tanks using pointed conically shaped rods as electrodes.

[1]FM Global is a global insurance company for commercial and industrial properties.

[2]UL is a global independent safety science company.

(a)

(b)

Fig. 4. High-energy arcing fault test results with (a) mineral oil and (b) a high oleic sunflower-based dielectric insulating fluid.

A current source was used to supply up to 8000 A through a short circuit across the electrodes for up to three cycles. At the highest energy level, the lid of the mineral-oil-filled setup blew apart, and a fire started after the hot oil was exposed to the atmosphere [Fig. 4(a)]. In the corresponding test with a high oleic sunflower-based dielectric insulating fluid, the lid simply vented, and a small amount of carbonized and vaporized oil spewed out of the tank; however, there was no fire [Fig. 4(b)].

3) Enhancing Performance: Natural ester fluids are also hydrophilic (water-loving substances) by nature and have a water saturation limit of five to eight times greater than that of mineral oil at normal transformer operating conditions (Fig. 5). Testing has shown, however, that, even at a level of 500-ppm moisture content in the oil, the dielectric breakdown strength of natural esters is still within the standard limits. Because of the natural esters’ greater water saturation limit, less moisture is held into the cellulose insulation materials (water moves between cellulose and oil to reach the same relative saturation in each material). The result of this lower moisture content in the insulation paper is a reduction in its degradation rate over time by up to a factor of four as compared to standard

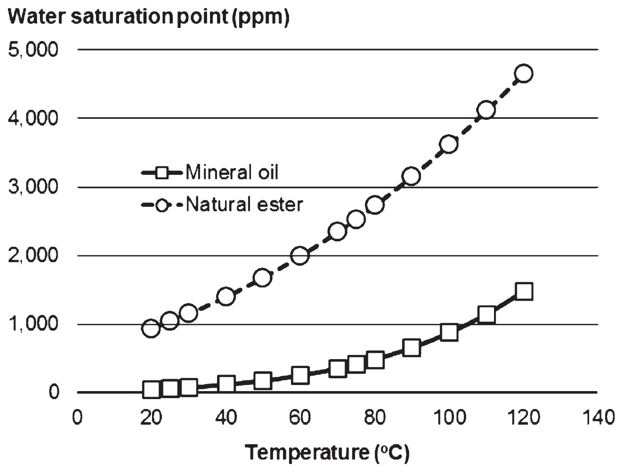

Fig. 5. Water solubility test results as a function of temperature.

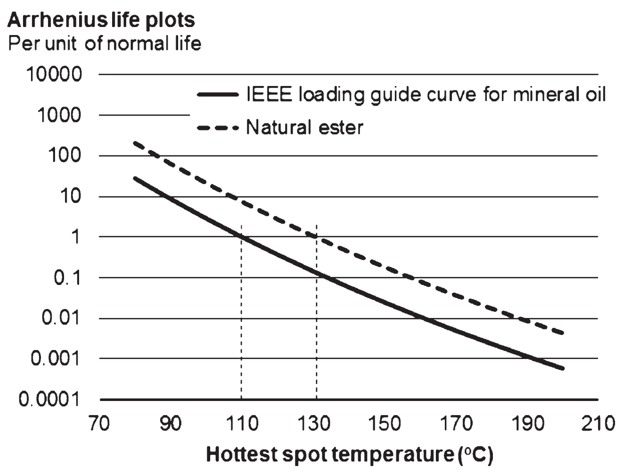

Fig. 6. Arrhenius life plot according to IEEE guide C57.91.

mineral-oil-impregnated paper [10]. The chemical reaction of water generated during the cellulose aging process with natural esters (hydrolysis) producing free fatty acids and a change in the cellulose structure through another chemical reaction with these free fatty acids (transesterification) have shown to also contribute to improve the life performance of cellulose insulation when aged in natural esters [11].

These phenomena can lead to either a life extension of the insulation system at normal operating conditions or, alternatively, to the ability of operating the transformer at a 20 °C higher hot-spot temperature while maintaining the same life expectancy than that of an equivalent mineral-oil-filled transformer operating at normal conditions (Fig. 6).

Several actual references illustrating the benefits of the higher thermal capability of cellulose paper immersed in natural ester fluids are given in the next section.

III. Practical Examples

There are several applications where energy utility and process industry asset managers have opted for a natural ester fluid in substitution to mineral oil in their transformers. From environmental impact to insulation life extension, some of the most common applications of natural ester fluids are reported as follows.

Fig. 7. 138-kV compact mobile substation filled with a high oleic sunflower-based dielectric insulating fluid.

A. Additional Power and Overloadability

In [10], the authors presented a survey of several tests performed by different research laboratories worldwide and comparing the aging behavior of cellulose immersed in mineral oil and in natural ester fluids.

This survey shows that higher temperatures and temperature rise limits can be allowed with transformers filled with natural ester fluids when compared to similar transformers filled with mineral oil.

When designing a new transformer, this increase in temperature limits can be translated in either increase in power rating or a more compact transformer.

The ultimate approach that is to reduce the transformer footprint in a substation would also imply the use of a high-temperature insulation material. By using the latter in combination with natural ester fluid, the authors in [12] have resolved their customer space limitation and capacity expansion requirements by designing a 40/50-MVA (KNAN/KNAF) transformer with the same physical dimensions as the original 20/30-MVA (ONAN/ONAF) unit, while in [13], the authors reported a power capacity increase from 15 to 25 MVA using the same transformer tank and core. Those examples illustrate the real potential in transformer size reduction (ranging from up to 50%) when compared to conventional transformer technology.

Along the same line, compact mobile substations can also be designed even more compact with less risk when a high-fire-point biodegradable fluid is used and hence transported (Fig. 7).

B. Life Extension

Alternatively, the same survey [10] also shows that the transformer cellulose insulation life can be extended. Cellulose paper used to insulate the transformer windings is the main determining factor of the transformer lifetime. It is wrapped around the wires where it cannot be easily maintained or substituted. While in operation, cellulose paper is subject to thermal, electrical, and mechanical stresses. The retaining of its mechanical strength, which is related to the transformer capacity to withstand strong faults, is the most used parameter to monitor the transformer aging state.

Aging of cellulose paper is determined by several factors related to the maintenance as well as operation of the transformer. Considering proper maintenance practices, the load profile of the transformer and the resulting temperature profile are the

Fig. 8. 69-kV transformer being prepared for retrofilling in the field with a high oleic sunflower-based dielectric insulating fluid.

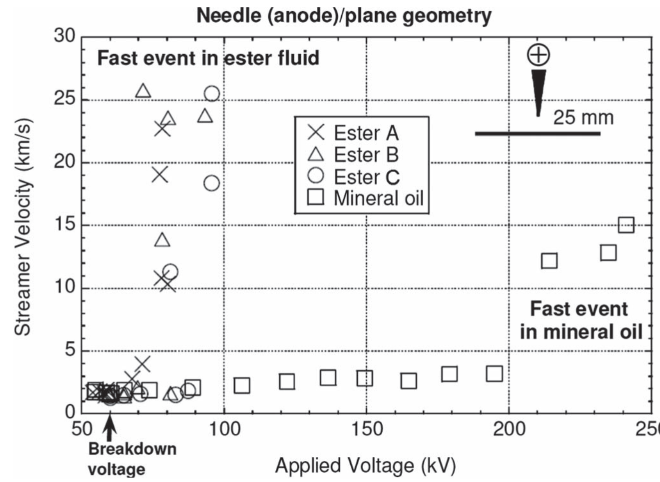

Fig. 9. Dependence of positive streamer velocity on lightning impulse (LI) overvoltages in needle/plane geometry with an electrode gap distance of 25 mm for mineral oil and ester fluids [17].

most important variables that govern the aging of cellulose paper.

The Arrhenius relationship shows, for example, that cellulose life can be doubled for every 6 °C–7 °C decrease in hot-spot temperature when in the transformer operation range of 80 °C–100 °C, while such a doubled life rate can range from 5.9 °C to 9.7 °C in the 80 °C–180 °C range [14]. Therefore, if a natural-ester-filled transformer operates at similar temperatures as a mineral-oil-filled unit, the higher thermal capability of cellulose paper immersed in natural ester fluids will result in a much lower aging rate, i.e., the substitution of mineral oil by a natural ester can extend the remaining life of an old equipment by more than four times in ideal conditions.

C. *Reduced Risk of Fire*

A fire point above 300 °C classifies natural ester fluids as “less flammable” dielectric insulating fluids, and IEC identifies transformers filled with liquids that meet this requirement with the letter K instead of the traditional O in the description of the cooling code [15].

Depending on local regulations, those transformers can be used in fire-sensitive areas or have reduced installation requirements for fire protection and spill containment. Insurance companies that make use of engineering risk assessment established lower installation requirements when “less flammable” fluids are used [9].

Improved fire safety can be a determining factor to keep old substations operating according to more modern regulations. Therefore, retrofilling becomes an interesting option when the fluid exchange can be performed in the field for existing units (Fig. 8).

Although natural-ester-fluid unique properties and their implications in the transformer real life have been presented separately, they are all connected whether it is for a new or retrofilled unit. In [13], a transformer end user presented how the solution met his original expectation when it comes to increased overload capacity and fire safety, while addressing his concerns about soil and water contamination, for which a biodegradable fluid did certainly contribute positively.

IV. Impact in the Transformer Design

While natural-ester-fluid biodegradability, fire behavior, and cellulose paper aging characteristic do benefit greatly transformer end users, designers and manufacturers do have, however, to accommodate for the differences in fluid properties in their design models and processes.

A. *Oxidation Stability*

The most important functions of an insulating liquid are dielectric insulation and cooling capacity. The development of free-breathing transformers in Europe pushed, however, for more and more stringent oxidation stability criteria for mineral oil [16].

Natural ester fluids are known to not be as stable as mineral oil, and therefore, the same standards are generally not accepted as references. Free-breathing applications are usually not recommended for natural ester fluids either.

The IEC Standard 62770 for the use of natural ester fluids in transformer applications defines specific methods and limit values as well as relevant control parameters when it comes to oxidation stability that will allow users to perform the right selection among the different natural ester fluids commercially available in that respect.

B. *Dielectric*

In a needle/plane geometry experimental setup with transient voltages, the breakdown voltage of ester fluids is comparable to that of mineral oil at positive polarity and in short gap distances (25 mm). However, at longer distances (100-mm gap), the breakdown voltage of ester fluids is noticeably lower than that of mineral oil [17].

Using the same experimental setup, differences can be also found in streamer velocity, acceleration voltage, and transition to fast event (Fig. 9).

The main factor which governs streamer propagation velocity in ester fluids and mineral oil is the amplitude of the applied voltage. With increasing voltage, streamer propagation can switch from a slow mode with a velocity of less than 5 km/s to a fast mode with a velocity greater than 10 km/s and up to the order of 100 km/s. The acceleration voltage for transition to fast streamer in ester fluids is noticeably lower than that in mineral oil [17].

The transformer manufacturer must acknowledge the similarities and differences in the dielectric behavior of the different fluids and must address them with proper design rules—as well as with design assessment in the case of retrofills. Neglecting those differences increases the risk of dielectric failures during the final tests or while in operation. While those differences do impact the design of a new or renewed transformer, once the transformer is designed with the correct rules, the dielectric performance of a transformer filled with natural ester fluids is as good as that of a conventional transformer filled with mineral oil, and no additional protection is required.

C. Viscosity

Viscosity of natural ester fluids is greater than that of mineral oil and also requires some consideration in the design of a transformer. When compared to mineral oil, the flow of natural ester fluids through the transformer windings, core, and cooling equipment is slower, leading to a relative increase of top oil, windings, and core temperatures. At the same time, natural ester fluids have higher thermal conductivity and slightly higher heat capacity than mineral oil. However, these better thermal properties only slightly compensate for the impact of the higher viscosity of natural ester fluids [18].

Viscosity also varies with temperature. The higher the temperature, the closer the viscosity of natural ester fluids to that of mineral oil. At lower temperatures however, the difference in viscosity is increasing until the fluids solidify. The pour point of a standard mineral oil is typically lower than -40 °C, while natural-ester-fluid pour point is rather in the range of -15 °C down to -25 °C. Despite the fact that natural-ester-fluid dielectric behavior is not influenced by the change of state, special cold start procedures may be required at higher subzero temperatures than for mineral oil.

It is also worth mentioning that the increase in viscosity observed in the oxidation process of natural ester fluids can be used to determine the degree of deterioration of the fluid with time. The fatty acid composition of each specific natural ester fluid will determine its long-term stability. Depending on the application considered, it may be worth assessing the effect of heat, oxygen, and/or light (ultraviolet and IR) on the fluid viscosity in order to select the most suitable product.

D. Temperature Rise Limits

The benefit of cellulose paper life extension when aged in natural ester fluids has motivated several researchers to quantify and investigate its origin as well as to evaluate its potential in the design and manufacturing of power transformers. A way to quantify this benefit is by means of temperature increase for the equivalent life expectancy. Recent measurements show a temperature advantage up to 20 °C for natural-ester-impregnated cellulose insulation [10]. Based on these data, upper temperature rise limits for natural-ester-filled transformers could be selected up to the values given in Table II.

TABLE II
TEMPERATURE RISE LIMITS FOR TRANSFORMERS FILLED WITH NATURAL ESTER FLUIDS AS IN THE IEEE STANDARD C57.154 [19]

Top liquid temperature rise (°C)	90
Average winding temperature rise (°C)	85
Hot-spot temperature rise for solid insulation (°C)	100

In this case, even without the use of high-temperature insulating materials, transformers filled with natural ester fluids could be more than 20% smaller than equivalent mineral-oil-filled units when designed for continuous operation at higher temperatures. Alternatively, it can add more flexibility to a transformer designed for standard temperature limits when operated above its nameplate.

V. CONDITION ASSESSMENT

Higher operating temperatures associated to natural-ester-fluid different chemical composition and characteristics result in a different interpretation of the traditional tests used for condition assessment.

For an acceptable transformer performance during factory tests and/or during the transformer lifetime, both mineral oils and natural ester fluids need to meet and maintain certain characteristics. Properties that directly impact the performance of the transformer should then remain stable over time and therefore be addressed in the design of the apparatus and monitored during the transformer lifetime to identify deviations and subsequently apply corrective actions. Examples of those properties are dielectric breakdown strength and viscosity.

On the other hand, some mineral oil properties commonly monitored due to their direct correlation with the actual transformer performance may have reduced importance for natural ester fluids, for example, interfacial tension, dissipation factor, moisture content, and the neutralization number [20].

Dissolved-gas analysis in oil has, for years, been the most effective tool for diagnosing incipient faults and troubleshooting other problems in power transformers. The same set of gases associated with various fault conditions in mineral oil is also generated in natural ester fluids. However, the proportions of the generated gases in natural ester fluids are somewhat different than in mineral oil, requiring different interpretation rules [21].

Reliable transformer service providers can support users with the condition assessment of natural-ester-filled transformers. International bodies, such as Cigré [8], [22] or the IEEE Power and Energy Society Working Group PC57.155—"Guide for Interpretation of Gases Generated in Natural Ester and Synthetic Ester Immersed Transformer," are also collecting users' experiences in order to provide broader tools for end users.

VI. RETROFILL OF EXISTING UNITS

For a number of reasons that range from environmental benefits to compliance with fire safety regulations, natural ester fluids have been used to retrofill transformers already in operation. Retrofilling of power transformers requires qualified engineering assessment as it would probably require design considerations to accommodate the differences between mineral oil and such alternative fluids [8].

TABLE III
NATURAL-ESTER-FLUID BENEFITS AND TRADEOFFS VERSUS CONVENTIONAL MINERAL OILS

Benefits
• Readily biodegradable and non-toxic – mitigating soil and water contamination after transformer oil spills
• High fire point (K class) and explosive limits – reducing the risk of transformer fire and explosion
• High water saturation limit – improving the life performance of cellulose insulation and allowing higher temperature rise limits
Trade-offs
• Faster streamer propagation over long distances and higher viscosity – requiring proper design criteria consideration as well as possible special cold start procedures at higher sub-zero temperatures
• Lower oxidation stability – limiting use to sealed applications

When the details of the transformer design from the original equipment manufacturer are available, one can apply the knowledge, tools, and rules developed for designing new natural-ester-filled transformers to exactly predict the performance of the transformer retrofilled with the alternative fluid. However, design information is typically confidential and not always readily available. In such a case, engineering judgments must be made to estimate the performance of the transformer when filled with natural ester fluids. One possibility, for example, is to use the data from the factory tests to estimate the internal heat flow distribution among the windings and, hence, to predict the impact of the different fluid properties on the winding and oil temperatures.

Before retrofilling, it is also critical to verify the overall condition of the transformer as well as the reliability of the installed components. Oil analysis and additional field tests are required in that respect and will also provide a new baseline for future monitoring and maintenance operations of the transformer. The fluid exchange process needs to be well controlled in order to minimize the volume of residual mineral oil in the transformer. Although mineral oil and natural ester fluids are fully miscible, too much residual mineral oil (typically over 6%–7%) can reduce natural-ester-fluid fire point below 300 °C and hence have them losing their "less flammable" listing and K fire hazard classification.

VII. CONCLUSION

Natural ester fluids have originally been developed as a high-fire-point environmentally friendly alternative to mineral oil in liquid-immersed transformers and have demonstrated to have additional characteristics that address current challenges in the power industry beyond the safety and environmental aspects. Longer lifetime of the equipment to delay reinvestment, higher power ratings to increase profitability or to consistently meet the growing power demand, and extra compact transformers to increase capacity without expanding substation footprint (particularly useful for offshore platform) and improve the substation overall safety are just some examples of the performance improvements provided by the use of natural ester fluids as transformer oil.

Natural-ester-fluid main properties and characteristics have been presented in this paper and are summarized in Table III. Actual references of natural ester applications addressing a variety of users' concerns and needs have also been given. The impact of these unique characteristics in the transformer performance and the considerations that need to be taken when designing the transformer as well as selecting the right natural ester fluid for long lasting transformer application has also been discussed. This discussion should support transformer end users to evaluate the value of natural ester fluids compared to other alternative fluids as well as to understand the differences between the different natural ester fluids available on the market in order for them to adequately specify and select the right product.

Finally, it has been shown that reduced environmental impact and improved safety and performance with natural ester dielectric insulating fluids are also options for aged transformers when driven by an appropriate handling and specialized engineering assessment.

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REFERENCES

[1] F. M. Clark, *Insulation Materials for Design and Engineering Practice*. New York, NY, USA: McGraw-Hill, 1962.

[2] I. Moumine, B. Gosse, J. P. Gosse, R. Clavreul, and C. Hantouche, "Vegetable oil as an impregnant in HV AC capacitors," in *Proc. IEEE 5th Int. Conf. Breakdown Solid Dielect.*, 1995, pp. 611–615.

[3] T. V. Oommen and C. C. Claiborne, "Biodegradable insulating fluid from high oleic vegetable oils," in *Proc. Cigré Gen. Session*, Paris, France, 1998, pp. 15–302.

[4] E. W. Lucas and K. C. Rhee, "Animal and vegetable fats, oils and waxes," in *Riegel's Handbook of Industrial Chemistry*. New York, NY, USA: Van Nostrand, 1992.

[5] S. S. Lin, *Introduction to Fats and Oils Technology*. Urbana, IL, USA: AOCS Publications, 1997, pp. 211–231.

[6] J. Viertel, K. Ohlsson, and S. Singha, "Thermal aging and degradation of thin films of natural ester dielectric liquids," in *Proc. IEEE Int. Conf. Dielectr. Liquids*, Trondheim, Norway, 2011, pp. 1–4.

[7] "Environmental Technology Verification report on BIOTEMP, vegetable oil-based insulating dielectric fluid," California Environmental Protection Agency, Department of Toxic Substances Control, Office of Pollution Prevention and Technology Development, Sacramento, CA, USA, DTSC R-02-03/EPA 600/R-02/043, Jun. 2002.

[8] *Experiences in Service With New Insulating Liquids*, Cigré Brochure 436, Working Group A2.35, Paris, France, Oct. 2010.

[9] *FM Global Property Loss Prevention Data Sheets, Transformers*, FM Global, Johnston, RI, USA, May 2010.

[10] G. K. Frimpong, T. V. Oommen, and R. Asano, "A survey of aging characteristic of cellulose insulation in natural ester and mineral oil," *IEEE Elect. Insul. Mag.*, vol. 27, no. 5, pp. 36–48, Sep./Oct. 2011.

[11] L. Yang, R. Liao, C. Sun, J. Yin, and M. Zhu, "Influence of vegetable oil on the thermal aging rate of Kraft paper and its mechanism," in *Proc. ICHVE*, New Orleans, LA, USA, Oct. 2010, pp. 381–384.

[12] M. Hrkac, P. Papageorgiou, I. Kosmoglou, and G. Miatto, "BIOTEMP transformer technology for innovative compact substation," in *Proc. 7th Med. Conf. Exhib. Power Gen., Transmiss., Distrib. Energy Convers.*, Agia Napa, Cyprus, 2010, pp. 1–6.

[13] J. C. Mendes, A. S. G. Reis, E. C. Nogawa, and C. Ferra, "Advanced application of a natural ester vegetable oil in a HV power transformer," presented at the Cigré Gen. Session, Paris, France, 2008, Paper A2-101.

[14] T. V. Oommen and T. Prevost, "Cellulose insulation in oil-filled power transformers: Part II—Maintaining insulation integrity and life," *IEEE Elect. Insul. Mag.*, vol. 22, no. 2, pp. 5–14, Mar./Apr. 2006.

[15] *Power Transformers—Part 2: Temperature Rise for Liquid-Immersed Transformers*, IEC Std. 60 076-2, 2011, Ed.3.0.

[16] I. Höhlein, P. Heinzig, W. Knorr, and R. Asano, “New properties of old transformer materials,” in *Conf. Rec. IEEE Int. Symp. Elect. Insul.*, Toronto, ON, Canada, 2006, pp. 81–84.

[17] R. Liu, C. Törnkvist, V. Chandramouli, O. Girlanda, and L. A. A. Pettersson, “Fast streamer propagation in transformer oil and ester liquids,” in *Proc. Nord-IS*, Gothenburg, Sweden, 2009, pp. 217–220.

[18] R. Girgis, M. Bernesjo, and G. K. Frimpong, “Detailed performance of a 50 MVA transformer filled with a natural ester fluid versus mineral oil,” presented at the Cigré Gen. Session, Paris, France, 2010, Paper A2-107.

[19] *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*, IEEE Std. C57.154, Oct. 2012.

[20] R. Asano, C. Claiborne, and S. Singha, “Diagnostic methods for biodegradable oils,” presented at the Proc. CIGRE, Paris, France, 2010, Session Group Ref.: D1, Pref. Subject: PS2, Question, N:2.4.

[21] G. K. Frimpong, T. V. Oommen, and C. C. Claiborne, “Interpretation of dissolved gases in high oleic, high fire point ester dielectric fluids,” presented at the Proc. CIGRE SC A2 D1 Joint Colloq., Kyoto, Japan, 2011, Paper PS2-P-7.

[22] *DGA in Non-Mineral Oils and Load Tap Changers and Improved DGA Diagnosis Criteria*, Cigré Brochure 443, Working Group D1.32, Paris, France, Dec. 2010.

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