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Safer And More Reliable Transformers Using Natural Ester Liquids

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SUMMARY

As climate change causes more frequent extreme weather conditions and surge in electricity consumption, a growing number of regions are facing restrictions for the use of mineral oil-filled transformers, mainly due to concerns over fire and environmental safety. Such situations are particularly relevant in environmentally sensitive areas, often the location for wind and solar farms, and in highly populated urban areas, where the peak demand is expected to surge during the coming years. While the emergence of new technologies in cable insulation, line spacing, and various types of failure sensors and protection devices mitigate the risks of sparks and fire ignition, the use of less flammable insulating fluids is key for mitigating the risks of fire propagation. In addition, proven advantages in grid resilience and reliability are enabled with the use of natural ester filled transformers.

The interaction between the natural ester liquids and the cellulose-based insulation differs from that of mineral oil and paper in several aspects. The water generated by paper degradation tends to accumulate in the paper in the case of mineral oil. In natural ester filled transformers more water migrates to the fluid and is consumed by the hydrolysis reaction, resulting in a continuous drying process. Keeping the insulation system dry extends the asset life, preserves the dielectric capacity, increases the loading capacity, mitigates the need of maintenance interventions for removing water and prevents the risk of dielectric failures during cold start energization processes.

The cold starting procedures were developed for mineral oil units, aiming to mitigate the risk of a dielectric failure due to the very water saturation of mineral oil on such conditions. This is not the case of natural ester liquids. While the viscosity of all esters are higher than that of mineral oil, it reduces quickly as temperature increases. As it will be better detailed in the paper the main (and only) attention point when cold starting a soybean based natural ester filled transformer is an excessive stress for mechanical moving components immersed in the liquid when its temperature reaches values lower than -25°C for prolonged periods of time.

KEYWORDS

Natural ester liquids, reliability, resilience, fire safety
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CONCERN OVER FIRE SAFETY OF POWER NETWORK

As searing hot weather becomes increasingly common in different parts of the world, not only is the risk of catastrophic wildfires getting higher but the risk to power grids is also increasing because of the greater stress on these grids due to rising levels of electricity consumption from air-conditioning and growing use of electrical devices.

Even though it is estimated by California Public Utilities Commission (CPUC) that only about 10 percent of the state's wildfires are triggered by power lines, the frequency and severity of these wildfires has caused the CPUC to expand its probe into PG&E power line safety practices and even consider breaking the utility up into smaller utilities to facilitate more management accountability for power line safety. [1] While electrical transformers are generally considered to be very reliable with an overall failure rate of about 0.53% per year [2], meaning that one in five transformers would experience a failure during its expected service life of 40 years. With the large number of transformers operating in forestry and nature reserve areas, the risk of a transformer causing a catastrophic wildfire outbreak, by its own failure or by exacerbating a fire started by other sources, is clearly still very significant.

Despite the many technological advancements made in the prevention, detection and mitigation of power grid failure following some of the serious wildfire outbreaks, the use of less-flammable dielectric fluids in transformers continues to be one of the most widely deployed options in preventing fires. Among the different types of less-flammable fluids, natural ester, continues to have the fastest growing rate in market share due to its unique properties in extending the lifespan and thermal class of cellulose paper insulation. Apart from improving the reliability and loading capacity of transformers, these properties also contribute to proactively mitigate the risks of wildfires.

The science behind less flammable dielectric fluid

Considering fire as a chemical reaction between a combustible material and oxygen, for this reaction to take place, the combustible material would need to be at its auto ignition point, or alternatively, at its fire point in the presence of a spark or ignition source. Based on the energy required to bring 5,000 liters of dielectric fluid in an operating transformer from an average liquid temperature around 90°C to its fire point, it is possible to estimate the fire safety rating of different types of fluids as shown in Table 1.

Table 1. Fire risk of different insulating fluids based on the energy to reach their fire points

Fluid	Fire point (°C)	Energy needed to bring 5,000l of fluid to fire point from 90°C (MJ)	Fire safety rating*
Mineral oil	160	733	1
Synthetic ester	315	2240	3.1
Natural ester	360	3710	5.1

*Bigger number for better fire safety

Based on the typical sequence of events taking place during dielectric failure. The benefit of using natural ester fluid with the highest fire point in reducing the risk of transformer fire becomes apparent. Dielectric failures typically begin when the insulation of transformers, particularly those in a degraded condition, fails to withstand the stress created by natural events such as lightning, switching impulse, overloading, ferro resonance, secondary short circuit and line fault, etc. Even though such failures might generate a breach and arc of very high energy intensity, in most cases only the paper insulation surrounding the arc would be destroyed, and a small volume of dielectric fluid would break down and vaporize, generating combustible gases which cause the pressure inside the transformers to build up.

If the arc lasts a sustained period, the internal pressure will eventually dislodge the bushing or other weak parts of the tank and force the volatile gases out. Following the exposure to air and ignition source, the combustible gases will explode, causing more substantial damage.

It is at this point that the type of insulating fluid would make a difference in the propagation of fire. With a typical mineral oil-based insulating fluid of low fire point, the burning of combustible gases could generate enough heat to ignite the bulk of the fluid in the tank, leading to a self-sustained pool fire. On the other hand, with its extremely high fire point, the combustion threshold of natural ester would be too high to cause an outbreak of pool fire, and any ignition caused by the combustible gases would also be quickly extinguished.

The criticality of the dielectric fluid fire point as described above was validated in a series of internal short circuit tests on small transformers conducted by Factory Mutual (FM). During the first test, a typical mineral oil-based dielectric fluid was preheated to 128°C when an internal arc lasting about 8 seconds was generated through a short-circuit fault. The resulting buildup of internal pressure caused the transformer tank's burst disk, which had been calibrated at 20psi, to rupture, and a big pool fire broke out when the spray of vaporized mineral oil from the ruptured disk contacted the hot mineral oil in open air, even though there was no external ignition source (Figure 1 top).

When the same test was repeated with a less flammable insulating fluid of over 300°C fire point preheated to 140°C, the increase in internal pressure caused by the sustained arc again ruptured the burst disk. However, when the spray of vaporized fluid from the ruptured valve came in contact with the hot less flammable fluid, it did not cause any pool fire (Figure 1middle). More significantly, even when an external flame was brought in front of the ruptured disk to ignite the spray of vaporized fluid, the preheated less flammable fluid still did not catch fire, and the initial flame was extinguished quickly (Figure 1 bottom).

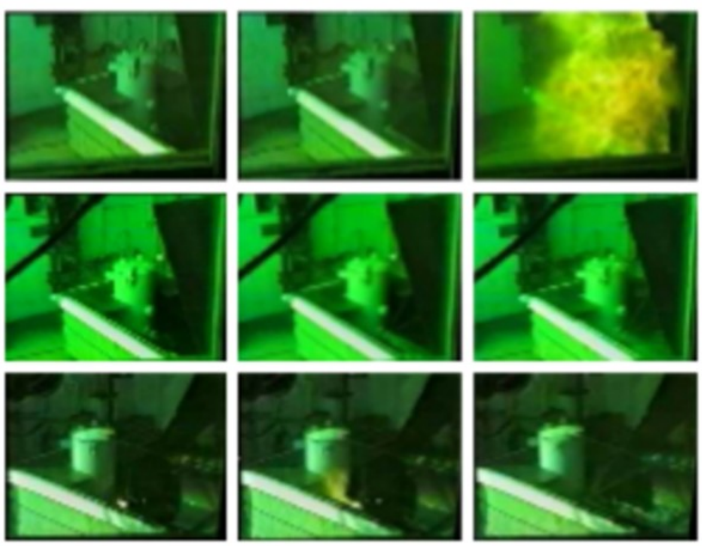

Fig. 1 Internal short circuit tests on mineral oil (top), high fire point less flammable fluid (middle) and high fire point less flammable fluid with external ignition source (bottom)

With fire point proven to be the most critical parameter for preventing outbreak of transformer fire, the net calorific valve, which have been part of the IEC classification of dielectric fluids [3-4], is no longer considered relevant to the categorization of fire safety properties of transformers in the different fire codes and product listings [5-7].

While the use of less flammable insulating fluids with high fire point is effective in minimizing the risk of catastrophic fire outbreaks in the event of transformer failure, the unique properties of natural ester in extending the lifespan and thermal class of cellulose paper insulation enables it to go one step further in mitigating the risk of transformer failure.
Unlike mineral oil and other alternative insulating fluids such as silicone oil and synthetic ester, natural ester is capable of absorbing moisture from the cellulose paper insulation and removing it chemically through hydrolysis [8].
This dual drying action is one of the most important properties that makes natural ester the fastest growing insulating fluids on the market. Proof of this process has been validated by moisture content of cellulose paper samples measurement during an accelerated ageing test in sealed vessels containing mineral oil and natural ester (Figure 2) [8].

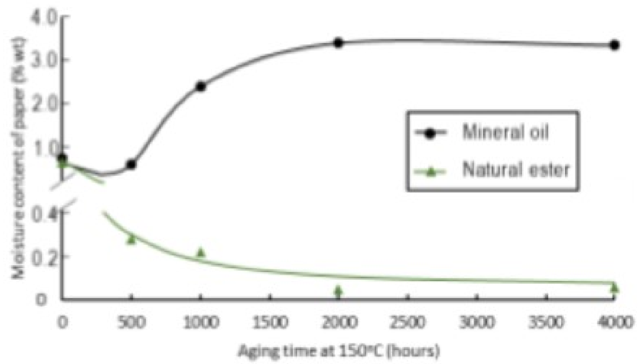

Fig.2 Water content on cellulose paper as measured during the accelerated ageing test

Effective removal of moisture not only extends the life expectancy of the paper insulation by 5-8 times [9-11], but it also helps to significantly reduce the risk of dielectric breakdown and transformer failure, as moisture is the main culprit in the reduction of dielectric strength in the paper insulation [12] and the formation of bubbles on the paper surface [13]. The improvement in transformer reliability based on the extended paper insulation life with natural ester was quantified in an extensive study with a major American utility company [14]. Based on the nominal lifespan of mineral oil-filled transformer at 180,000 hours (20.55 years) as per the IEC loading guide [15], the corresponding annual transformer replacement rate should be about 4.87%. According to the utility's statistic from a fleet of 96,000 distribution transformers, about 80% of the replacement cases are due to transformer failure, which means the annual failure rate would be about 3.89% for transformers filled with mineral oil.
Referencing the transformer failure modes and respective case percentages stated in the CIGRE Transformer Reliability Survey [2], the annual failure rate of mineral oil-filled transformers for each failure mode was obtained accordingly in Table 2. For each failure mode, the benefit of using natural ester fluid was estimated based on relevance to the higher longer lifespan and higher thermal class of the paper insulation. Comparing the estimated annual failure rates for mineral oil and natural ester-filled transformers, as summarized in Tables 2, concluded that the overall transformer failure rate can be reduced by about 36% with natural ester dielectric fluid.
The above-mentioned results therefore demonstrate the unique properties of natural ester in enhancing the reliability of transformers, which effectively enables it to combat both the consequences and causes of transformer fires.

Table 2. Estimated annual failure rates of mineral oil and natural ester-filled transformers by failure modes

Failure mode	Percentage of cases [i]	Impact of natural ester on failure (a) [ii]	Reduction in degradation rate (b) [ii]	Rate of failure for mineral oil-filled transformers (c) [iii]	Rate of failure for natural ester-filled transformers [iv]
Dielectric	36.62%	85%	7.4x	1.43%	0.38%
Electrical	16.49%	0%	0	0.64%	0.64%
Thermal	10.89%	100%	4x	0.42%	0.11%
Physical chemistry	3.32%	75%	2x	0.13%	0.08%
Mechanical	20.02%	0%	0	0.78%	0.78%
Unknown	12.66%	0%	0	0.49%	0.49%
Total	**100%**	-	-	**3.89%**	**2.48%**

i. Figures from CIGRE Technical Brochure on Transformers Reliability Survey [2]
ii. Benefits of using natural ester fluid based on each failure mode's relevance to insulation degradation
iii. Based on the total annual failure rate of 3.89% and the percentage of each failure mode
iv. Rate of failure of natural ester-filled transformers calculated from: c(1-a) + ac/b

HOW NATURAL ESTER FLUID IS DRIVING SUSTAINABILITY

As environmental regulations and the desire to reduce carbon emissions continue to push the sustainability agenda in the energy market, utility companies everywhere are following suit and increasingly turning to environmentally friendly, bio-based products to complement the shift towards renewable energy sources with low greenhouse gas emissions. As a bio-based material derived from plants, natural ester fluid is effectively free of harmful substances such as PCB's, heavy metals, sulfur compounds, and volatile or semi-volatile organic compounds that may be found in other insulating liquids. This gives natural ester fluid (as compared to mineral oil and other types of transformer fluids) the following distinctive properties contributing to its outstanding environmental benefits:
Results obtained from the well-established biodegradability tests (Fig 3 and 4) confirm that natural ester fluid biodegrades at a rate similar to the reference substance. Its biodegradability is also superior to that of synthetic ester liquid and mineral oil.

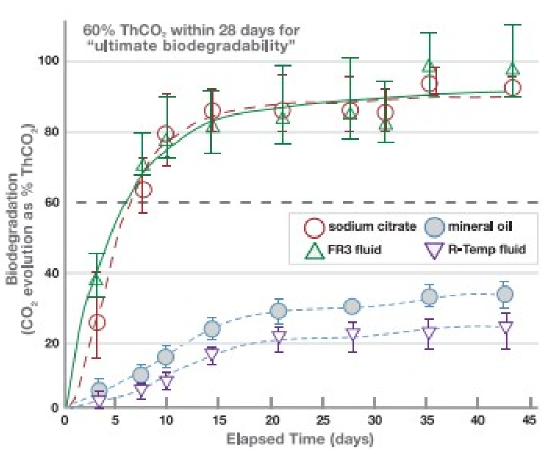

Fig 3 Ultimate aerobic aquatic biodegradation according to EPA OPPTS 835.3100

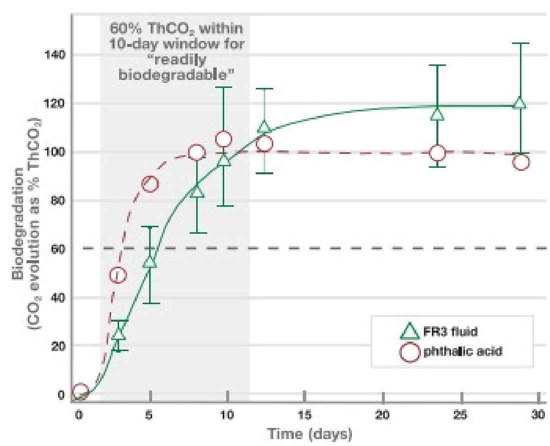

Fig 4 Fluid Ready Biodegradability per OECD 301

End users should not be concerned about a potential problem of microbial growth in natural ester transformers because of its exceptionally high biodegradability. This has been studied extensively in sealed and free breathing transformers ranging from 15-225kVA over a period 8 years with no microbial activity detected.
Transformer grade natural ester fluid typically contains over 95% vegetable oils and all the performance enhancing additives are approved for food contact. The absence of oil sheen on water surfaces and the high level of biodegradability also mean that the fluid can be broken

down without significant depletion of the oxygen level in water. Due to its higher viscosity and natural tendency to polymerize when thin layers are exposed to oxygen, the infiltration rate of natural ester fluid in the soil is much slower than that of mineral oil, thereby mitigating the risk of the material reaching tap water. The use of secondary spill containment is still recommended, especially for preventing entry into waterways, but the containment is highly simplified. Should a spill happen, natural ester fluid's biodegradability and non-toxicity in soil and water minimize the remediation costs.

Zero Carbon Footprint

Life Cycle Analysis (LCA) conducted on FR3 fluid in accordance with the Building for Environment and Economic Sustainability (BEES 4.0) method shows that CO2 absorption by the crops grown for natural ester fluid equals the CO2 emissions during the production, transportation and operation of the transformers. Thus, allowing natural ester fluid to be classified as a carbon neutral product. In addition, the total greenhouse gas emission is 56x lower than that of mineral oil, and significantly lower than that of other synthetic transformer liquids and gases.

NATURAL ESTER BEHAVIOR IN COLD TEMPERATURE ENVIRONMENTS

A transformer dielectric liquid must be a good electrical insulator at all usual service conditions. Natural ester fluid maintains its dielectric performance down to -50°C (-58°F).
Various factors impact dielectric strength, but typically the most common and important contaminant is water. For all dielectric liquids, the dielectric strength decreases as water content increases proportionally to the relative saturation.
Water in excess of the dielectric fluid's saturation point at a particular temperature, the point where the fluid cannot hold any more water, becomes "free" water. At 25°C (77°F) mineral oil saturates at about 70 mg/kg (ppm) and natural ester fluid at about 1000 mg/kg. However, at -20°C (-4°F), mineral oil saturates at about 8 mg/kg, while natural ester fluid saturates at about 425 mg/kg.
Therefore, natural ester fluid is less likely to reach saturation in cold ambient conditions, preventing the presence of free water and maintaining the dielectric strength during transformer start up.

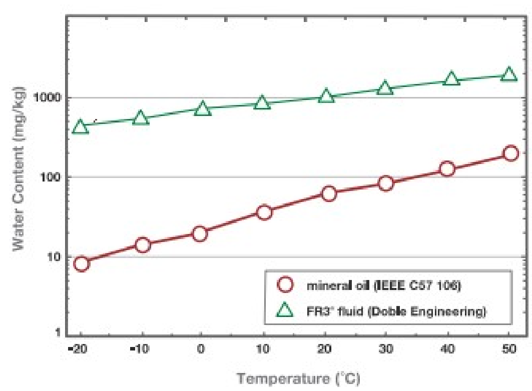

Fig 5 Water saturation in mineral oil and natural ester liquids as a function of temperature

Figure 5 shows how temperature affects the fluid's saturation point. The hotter a transformer operates the more moisture migrates from its paper into fluid. The fluid can absorb more moisture driven off the paper due to significant increases in its saturation point as temperature increases. Additionally, the hotter a transformer operates, the faster the insulation paper ages,

producing more moisture. This water migration continues until both the paper and fluid are at relative saturation equilibrium at the current temperature.
In general, moisture content above 40% of relative saturation is detrimental for the breakdown voltage. Energizing mineral oil filled transformers at temperatures around -20°C (-4°F) would require a moisture content not more than 3 mg/kg, an extremely low level. For natural ester fluid filled transformers, up to 160 mg/kg would be acceptable.
Pour point is defined as the lowest temperature at which a fluid is observed to flow under specified conditions (ASTM D97 and ISO 3016 are commonly used test methods). The pour point does not provide information about the undergoing process with the liquid and can be influenced by the effect of viscosity or previous thermal history of the specimen. Therefore, the pour point may provide a misleading view of the liquid handling properties and demands additional fluidity tests for transformer cold start purposes.

Cold start recommendations

Natural ester fluid behaves differently at low temperatures compared to mineral oil. Its pour point is much higher than mineral oil (-21 °C (-6 °F) versus -40 °C (-40 °F) respectively), but this does not represent any limitation for transformer operation or energization under the defined "normal conditions" both in IEC 60076-2 and in IEEE C57.12.00. A transformer filled with natural ester fluid does not require special procedures for cold start (energization) within the lower temperature limits of the standards. Limitations defined by manufacturers of accessories should be observed.
The most critical aspect for the cold start of a transformer is the overall dielectric capacity. Mineral oil may shrink, crack, and create voids as it cools beyond its pour point temperature, representing a risk of dielectric failure. Additionally, and even more critical, is the tendency to condense out water since mineral oil has a very low water saturation limit at low temperatures. Natural ester fluid shows a reduced tendency to develop voids when cooled beyond its pour point temperature compared to mineral oil. Natural ester fluid has a high water saturation point and it is less likely that water will condense out of the natural ester fluid upon cooling because of natural ester fluid's higher water saturation point. About 425 mg/kg (ppm) moisture in natural ester fluid is required to saturate it at -20°C (-4°F), while mineral oil is saturated with just 8 mg/kg at the same temperature. The breakdown voltage of dielectric liquids is proportional to the relative moisture content, being typically considered a maximum limit of about 40% for the safe operation of the transformer.
There are other parameters aside from pour point to take into consideration for assessing the applicability of the dielectric fluid in transformers operating in cold regions. Effectively, at temperatures near -25˚C (-13˚F), natural ester fluid becomes increasingly more viscous and slushy. The total volume of natural ester fluid and the proportion of volume to external contact surfaces are key parameters to estimate how many days of an average temperature lower than the liquid pour point would be required to affect the flow of natural ester fluid inside a transformer. For example, even for a small distribution transformer (single phase 15kVA -25˚C (-13 ˚F)), more than three days would be required for its natural ester fluid content to become slushy.
The use of Natural ester fluid in both power and distribution transformers in regions with very low temperature yields a similar concern as that which already exists for mineral oil transformers: the proper cold starting of the equipment. However, the difference is the type of risk involved. For a natural ester fluid-filled transformer, the concern is related to reduced flow and possible damage caused by mechanical movement of equipment, while in a mineral oil-filled transformer the concern would be the possibility of dielectric failure caused by low dielectric strength.

The important primary statement for safe energization is: “apply the same cold start procedure to a natural ester fluid-filled transformer that is currently practiced for a mineral oil filled transformer. The concept is to preheat any dielectric liquid until the top oil temperature reaches a range of -10°C (14°F) ~ 0°C (32°F), using no-load losses or a liquid processing machine (external source of heat) before applying load.
The thousands of natural ester fluid-filled transformers such as those in operation in Norway and the upper Midwest of the US since the early 2000’s, supports the applicability of natural ester fluid in such climates.

CONCLUSION

With over three (3) million installations across the globe natural ester fluid continues to grow in their use displacing mineral oil. Offering significantly improved fire safety, increased grid resiliency and reduced environmental impact provides a safer grid and delivers peace of mind to both electricity providers and end-users.

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