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Bio-based, Low Viscosity Insulating Liquid to improve transformer performance

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Abstract— *An innovative low viscosity and bio-based insulating liquid has been developed and is compared to a high-grade mineral insulating oil and ester liquids. Due to its very low kinematic viscosity, this new bio-based hydrocarbon provides improved convective heat transfer in power transformers. Depending on the transformer design, significant temperature reductions of both winding and hot spot can be obtained as shown in a simulation of a 250 MVA transformer. This achievement could become a practical and accessible solution in extending asset life by running transformers cooler, or a powerful enabler to uprate transformers while still maintaining them at their designed operating temperature.*

In addition, this liquid opens new doors to transformer designers in optimization and cost savings. For instance, as shown in the paper, this new liquid allows faster and more complete impregnation of the solid insulation, hence also ensuring there are no trapped voids or air bubbles, which are common causes of partial discharge.

Finally, this liquid is readily biodegradable and has superior oxidation stability to existing mineral oils and vegetable-based insulating fluids in the market, making this innovation ideal for all transformer types.

Keywords— low viscosity, bio-based hydrocarbon, oxidation stability, biodegradable, transformer, cooling.

I. INTRODUCTION

Most power transformers worldwide are mineral oil filled where the oil serves dual primary purposes – insulation and cooling. In the Americas it is common for mineral oil according to the standard ASTM D3487 to be used and in the rest of the world predominantly to IEC 60296. Historically such mineral oils meeting the historic standard equivalents were mainly made up of refined naphthenic distillates and, to a lesser extent, paraffinic distillates. The refining techniques used to produce such liquids were originally solvent extraction and acid clay treatment but in later years (late 1980s) severe hydrotreatment was more common – and now is the main technique for refining mineral oils for insulating applications.

Alternative liquids such as Poly-chlorinated Biphenyls (PCB), silicone fluids, synthetic esters and natural esters have also been used in oil filled power transformers. PCB being the most notorious due to major health and safety issues that became a worldwide issue and are now phased out. At present the landscape sees naphthenic mineral oils still as the majority, with some paraffinic oils also being used. Synthetic and natural ester filled transformers are also used in certain applications.

The increased commoditization of both mineral insulating oils and ester-based fluids means to the transformer manufacturer or end-user often the approach to the insulating liquid is “oil is oil”. Nonetheless – even within liquids sold to a certain standard (such as IEC 60296) there can be several differing products each with differing properties and subsequently differing performance. These differences naturally become larger when comparing liquids of significantly different chemistry (i.e. between mineral oils and ester fluids). Therefore, it is essential that when selecting the materials used in a transformer, optimizing its design and evaluating its total cost of ownership the impact of the insulating liquid is considered.

Furthermore, in this paper we will introduce a novel insulating liquid – based on bio-based hydrocarbons - with low viscosity and biodegradability, but which complies with (and exceeds) the IEC 60296 specification.

II. COOLING

The deciding factor in a power transformer’s power rating is mainly the steady state winding and oil temperature rise (see IEC 60076-2). Consequently, the cooling efficiency of a transformer is a critical design component. Oil-Natural and Oil-Directed cooling are the most common methods used today – and for both the key parameter of the liquid influencing heat transfer is the kinematic viscosity. Table I lists some viscosities of different products for reference. NYTRO BIO 300X (bio-based hydrocarbon), NYTRO Gemini X (naphthenic oil), a common soy-based natural ester and a synthetic ester are used in this paper for comparison.

Naphthenic oils such as NYTRO Gemini X and NYTRO 10XN – have typically been favored due to their low viscosity index, that is a drop in viscosity with increasing temperature. NYTRO BIO 300X provides an even lower viscosity profile. One major drawback of ester liquids is their high viscosity – which leads to reduced cooling and therefore higher winding and oil temperatures.

In figure 1 and figure 2 results from a Computational Fluid Dynamic (CFD) simulation based on the model developed by Susa [1] on a 250 MVA ONAF power transformer are shown.

Table 1: Typical properties and Kinematic Viscosities for various insulating liquids

	NYTRO BIO 300X	NYTRO GEMINI X	SYN. ESTER	NAT. ESTER
Type	Bio-Based Hydro-carbon	Naphthenic	Pentaery-Thritol Ester	Vegetable Seed Oil
Density at 20°C	0.785 g/dm^3	0.870 g/dm^3	0.920 g/dm^3	0.968 g/dm^3
Biodegrad-ability (OECD 301)	Readily	Inherent	Readily	Readily
Viscosity 20°C, cSt	6.13	20.66	74.7	73
Viscosity 40°C, cSt	3.77	9.57	29.5	35
Viscosity 100°C, cSt	1.44	2.45	5.3	8

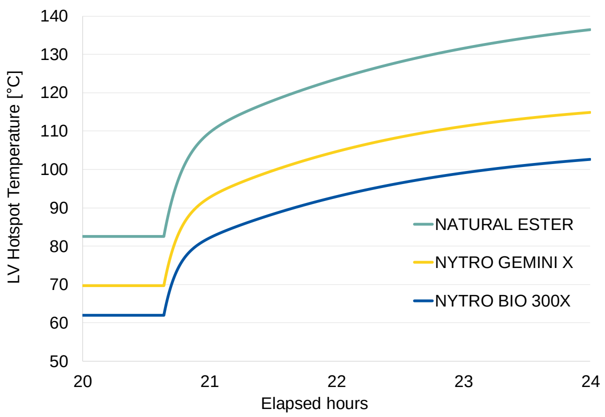

Figure 1: Simulated LV winding hotspot – based on work and models developed in [1] – a 250 MVA ONAF (Oil Natural Air Forced) transformer with the same load and ambient conditions used for all liquid cases. The difference in viscosity primarily leads to the difference in cooling. The load is set at 1PU until a step change to 1.5PU for the remainder. Ambient 20°C.

One immediately appreciates how not only the steady state LV hot spot temperature is dependent on the oil viscosity but also once equilibrium is disturbed (the load is increased to 1.5PU) NYTRO Gemini X and NYTRO BIO 300X provide better cooling during the overload scenario. This implies that insulating liquids with lower viscosity can improve the dynamic performance and overload capability of power transformers. Figure 2 compares the LV winding profiles of the transformer where changes in average winding temperature can be observed. From this example one can appreciate the major impact the viscosity of the insulating fluid has on the temperature profile of the transformer.

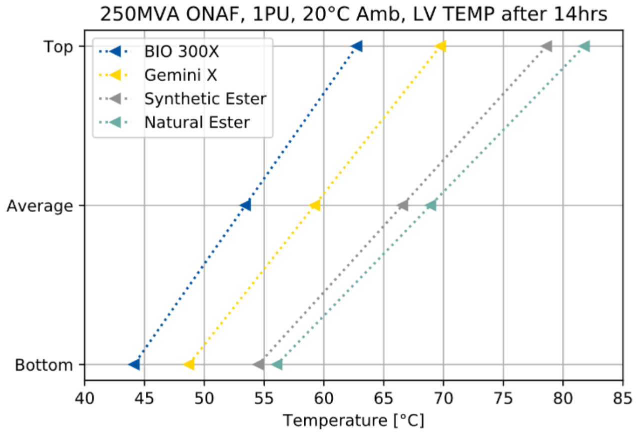

Figure 2: Simulated LV winding temperature gradient for the different liquids (with same simulation parameters kept constant). The load is set at 1 PU, ONAF, ambient 20°C.

Furthermore, low viscosity, as well as a faster drop in viscosity over operational temperature range also favors the onset of natural convection. This is particularly important in "Oil Natural" cooled transformers (without pumps). The Grashof number provides a dimensionless indication of the ratio of buoyancy to viscous forces and is given in (1) [2].

$$Gr = \frac{L^3 * \rho^2 * g * \beta * \Delta\Theta}{\mu^2} \quad (1)$$

Where L is the characteristic length, ρ is the density, μ is the dynamic viscosity, g is the gravitational constant, β is the thermal expansion coefficient, and Δθ is the oil temperature gradient.

For the temperature range of most interest (20 °C to 100 °C) the Grashof number was calculated for the three liquids and is shown in figure 3. L was set to 1, and Δθ to 5 K nominally in these calculations as it is for comparative purposes. The higher increase of the Grashof number with temperature is clearly due to lower viscosity. In practice fluids with higher Grashof numbers in the temperature range of operation will lead to better natural convective cooling in the transformer (due to higher flow rate).

Looking at figures 1,2 and 3 it is quite clear that the higher convective heat transfer expected by the liquids with lower viscosity during natural convection translates into lower temperatures in the transformer.

In practice a transformer manufacturer can use liquids with lower viscosity to help optimize a certain design and save money on cooling systems and conductor. On the other hand, one could rather choose to keep the design the same and effectively produce a transformer with higher overload rating and lower operating temperatures. This is particularly useful in hot climate countries where many utilities specify more strict temperature rise requirements in order to consider the higher ambient one.

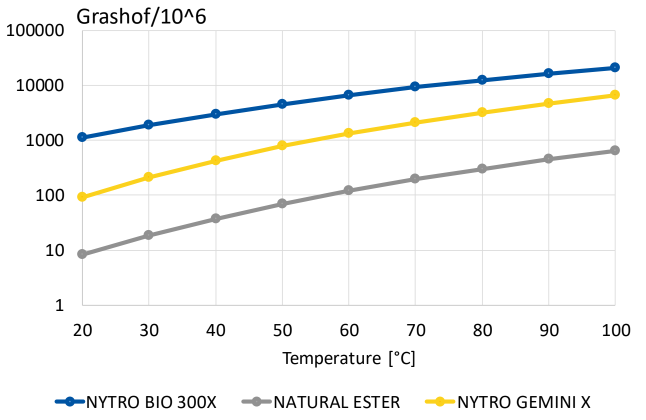

Figure 3: The Grashof (Gr) number (divided by 10^6) calculated for the temperature range 20-100°C for NYTRO BIO 300X, NATURAL ESTER and GEMINI X. An increasing Grashof number indicates higher flow due to natural convection.

Different insulating liquids and different cooling regimes of a transformer can lead to differences in thermal performance in service [3, 4]. Therefore it is important to keep the above in mind if a utility is considering to specify a particular type of insulating liquid together with the temperature rise limits on the transformer – for example if a transformer design was left unchanged and the insulating liquids were on the one hand a high viscosity natural ester and on the other a low viscosity mineral insulating oil – there would be significant differences in actual winding temperature for the same load. See [3,4] for some examples, in [3] the authors showed a 154kV 20 MVA ONAN transformer had an average LV winding temperature difference of 17°C between the mineral oil and natural ester-based liquid used in their experiment.

Another interesting aspect of lowering on-load temperatures of a transformer is the impact on load losses. The EU ECODESIGN regulations are an example of increased pressure on utilities to reduce losses from their power transformers. Although the conductor and winding design are probably the most significant aspects determining load losses- lower winding temperature will still result in lower load losses.

III. TOTAL COST OF OWNERSHIP (TCO)

The purchase price of a transformer is not the only component to consider in the TCO of a power transformer, or similar HV equipment. The cost of the energy losses over the lifetime and the cost of liquid related maintenance on the transformer are two key aspects to consider. Especially for high load factor transformers, the costs of losses can become considerable when capitalised throughout the life of the transformer. Therefore, the actual winding temperature and actual load loss are important factors to consider when specifying and purchasing a power transformer. The insulating liquid can have significant impacts on the thermal performance of a transformer (and thus on both its purchase price and load loss costs) as well as significant impacts on the maintenance requirements on the transformer.

In this paper the contribution of the losses on the total cost of ownership will be briefly discussed. Generally, the cost of energy losses is the most significant portion, assuming good reliable equipment of course. The cost of Losses is made up of the combined contribution of No-load Losses and Load Losses.

An example of the loss evaluation of a power transformer is given herein. An example of a 40 MVA power transformer of nominal voltage (highest voltage of equipment) of 132/22 kV will be used. A 60K oil rise and a 65K winding rise will also be assumed. In this example the same temperatures will be assumed in both the LV and HV winding.

The nominal no-load losses are taken at 14kW and the nominal load losses (at full load) at 75°C are given to be 165 kW. The following formulae are used to calculate the cost of losses of a power transformer over its design life. These formulae are based on best-practice regarding estimating loss capitalisation in power transformers [1].

No-load losses per year:

$$kWh_0 = P_0 * nHUYear \qquad (2)$$

Where *kWh0* is the total energy (kWh) consumed by the no-load losses in one year, P_0 *is the* no-load losses of the transformer, and *nHUYear* is the number of hours of use per year, taken conventionally at 8760 hours.

Load losses per year:

$$kWhk = Pk * nHUYear * K^2 \qquad (3)$$

Where *KWhk* is the total energy (kWh) consumed by the load losses per year, *Pk* is the Load losses of the transformer, and *K* is Load factor of the transformer.

Depreciation of the cost of the electricity:

$$Yrs_{equiv} = \frac{1-(\frac{1}{1+I})^{Yuse}}{I} \qquad (4)$$

Where Y_{use} is the actual number of years of use of the transformer (usually estimated as the design life), *I* is the discount rate (interest rate related, assuming inflation and depreciation of money over time) and Yrs_{equiv} is the equivalent number of years to be used to calculate the total cost of losses.

Total losses per year:

$$kWhT = kWh_0 + kWhk \qquad (5)$$

Where is total consumed energy from the losses per year.

Total cost of losses over transformer life:

$$L = kWhT * kWhPrice * Yrs_{equiv} \qquad (6)$$

Where *L* is the total cost of losses over the transformer life, kWh_{Price} is the cost of electricity for the energy losses (kWh) in EURO (€) and Yrs_{equiv} is the equivalent years from (4).

In the example the life of the transformer is to be taken at 40 years and a cost of electricity of **0,28 EUR / kWh** will be used in the loss evaluation. Due to the depreciation of money over time a discount rate of 2% is considered – in practical terms this changes the 40 year period to an effective 27.355 years for the costs of the electricity associated with the losses (in line with formula 4 above and a 2% discount rate).

Table 2: Comparison of the load losses energy per year for the 40 MVA transformer used in the abovementioned example, with a load factor of K = 0.95 but considering different actual winding temperatures. This results in different total cost of losses over the 40-year period.

Cost of losses over 40 years, different average winding temperatures at full load. Cost of electricity 0.28 EUR/kWh
Load Factor K = 0.95. Nominal cost of losses EURO 10 931 024,64.

Average Winding Temperature at full load	Load Loss Energy per year	Change to the cost of total losses 40yrs
80°C (+5K)	1 327 302 kWh/yr	€ 174 854.04
75°C (+0K)	1 304 474 kWh/yr	€ 0.00
65°C (-5K)	1 281 645 kWh/yr	-€ 174 854.04
60°C (-10K)	1 258 817 kWh/yr	-€ 349 708.08
55°C (-15K)	1 235 989 kWh/yr	-€ 524 562.12

Table 2 and figure 5 provide an illustration of the effect of a reduced winding temperature on the cost of losses.

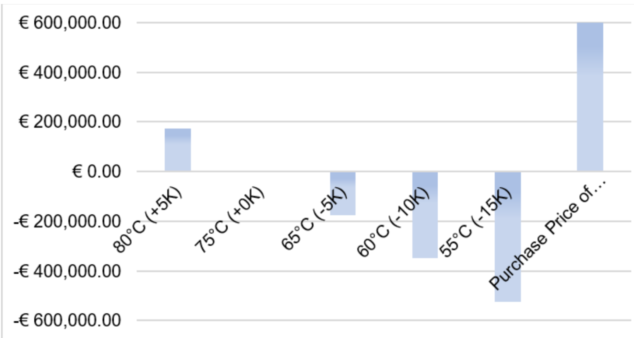

Figure 5: Bar chart comparison of the change in total cost of losses from Table 1 based on changes on the average winding temperature. The potential savings in cost of losses from improved winding temperatures can be comparable to the purchase price of the transformer.

In summary, the above example shows that especially for high load factor transformers one must weigh up the design temperature limits of a transformer together with what insulating liquid is chosen. If a low viscosity liquid like NYTRO BIO 300X is chosen on a transformer design with the standard temperature rise limits then improvement in average winding temperature can be expected and then these will translate into load loss savings in service. Likewise, if a natural ester is used and the utility allows higher temperature rise limits than the standard IEC 60076 requirements then they should consider load loss increases in service.

IV. PAPER IMPREGNATION

A critical role of the insulating liquid in a cellulose/porous media based high voltage insulation system is impregnation. In order to ensure there are no voids in the insulation or micro-bubbles (which can lead to catastrophic failure due to weakened dielectric strength) power transformers are filled under vacuum and the oil heated. Moreover, there needs to be enough settling time/impregnation time to ensure sufficient impregnation before commencing HV testing or commissioning the transformer. The impregnation time of solid insulation depends predominantly on the density of the solid insulation, the amount of solid insulation and the viscosity of the liquid. One of the reasons insulating oil is normally heated during filling is exactly for this reason – in order to reduce the viscosity – and in turn improve the rate of impregnation. In a previous study [5] it was clearly shown that in terms of physio-chemical properties viscosity of the liquid has the most effect on impregnation times. The Lucas-Washburn Relation shown in (7) is often used to model the penetration of liquids into porous media.

$$l^2 = \frac{r * \gamma * cos\Theta}{2\eta} * t \quad (7)$$

Where l is the length of solid insulation, r is the effective capillary radius, η is the dynamic viscosity, Θ is the contact angle, and t is the time to impregnate.

As shown in [5] in a practical oil/cellulose based insulating material case it is sufficient to relate the impregnation time to the amount of insulation and the dynamic viscosity – as shown in (8).

$$t \propto l^2 * \eta \quad (8)$$

Figure: 6: An example of a winding with paper-wrapped conductor and pressboard structures – the impregnation of the insulating material's pours with insulating liquid is critical to ensuring the absence of voids and high effective dielectric strength.

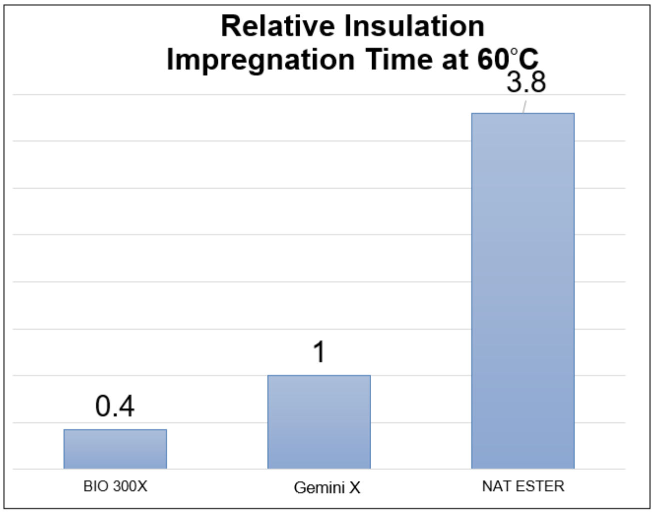

Figure 7 – An example of the approximate relative duration of insulation impregnation at 60°C. The natural ester will take 3.8 times longer than NYTRO Gemini X.

As such the differences in viscosity between liquids are directly proportional to the rates of impregnation. See figure 7, which illustrates the relative impregnation time comparing the liquids.

Insulation impregnation remains a key factor of the oil filling and transformer commissioning process. Compared to ester liquids, which will require longer impregnation times, NYTRO BIO 300X will be more rapid and effective, due to its lower viscosity [6].

V. OXIDATIVE, HYDROLYTIC AND THERMAL STABILITY

In a power transformer heat, oxygen and water are the main factors that influence ageing of the liquid insulation.

Oxidation stability is the most relevant in mineral oils at the common temperatures of power transformers currently – but since different chemical reactions will occur at different temperatures, have different activation energies, as well as different products and by-products for different liquids with different chemistries.

For example, esters have a much poorer hydrolytic stability than hydrocarbon based insulating liquids [7] and must be considered when determining an ester liquid's ageing behavior. Based on current standards, as shown in Table 3, the typically relatively poorer oxidation stability of natural and synthetic esters is evidenced by the less stringent requirements on them for oxidation stability.

Table 3: Some requirements for different insulating liquid types based on current IEC standards when evaluated to IEC 61125 showing relative oxidation stabilities of them.

Fluid Type	Specification	Ageing duration	Maximum acids allowed after ageing
Mineral Uninhibited	IEC 60296	164 hours	1.2 mgKOH/g
Mineral Inhibited	IEC 60296	500 hours	0.3 mgKOH/g
NYTRO BIO 300X	IEC 60296	500 hours	*Typical* <0.1 mgKOH/g
Synthetic Ester[1]	IEC 61099	164 hours	0.3 mgKOH/g
Natural Ester[1]	IEC 62770	48 hours	0.6 mgKOH/g

[1] Most commercially available natural and synthetic esters should be regarded as inhibited fluids.

The bio-based hydrocarbon liquid NYTRO BIO 300X is an inhibited oil meeting IEC 60296 and meets and exceeds the special application requirements for oxidation stability and as such is fully appropriate for free-breathing transformers.

VI. BIODEGRADABILITY

Sometimes the use of a power transformer in an environmentally sensitive area is unavoidable – for example, an offshore wind farm or near a protected area. For this reason – in line with local regulations - the classification of a liquid as readily biodegradable using OECD 301B or F (most commonly) certification can help secure the required permits for the use of the equipment in that area. NYTRO BIO 300X is classified as "readily biodegradable" [8]. Commonly used naphthenic oils such as NYTRO Gemini X do however biodegrade – but at a slower rate and require the microbes to be adapted for rapid biodegradation. As such most naphthenic insulating oils are regarded as "inherently biodegradable". local regulations must always be consulted to see if by using an insulating liquid which is readily biodegradable environmental impact assessments can be improved as well as potential cost savings due to less requirements on the oil containment infrastructure of the sub-station or power station. By using NYTRO BIO 300X, end users can employ a readily biodegradable liquid, but with the specification compliance of mineral oils IEC 60296 and thus many similarities to mineral oils.

VII. CONCLUSION

Viscosity of insulating liquid plays an important and critical role in the cooling ability of liquid and hence cooling of power transformers. Convection – especially natural convection, which is critical in Oil-Natural (ON) cooling type transformers, almost entirely depends on the liquid's viscosity. Ultimately, a transformer's dynamic rating may be increased – without a significant increase of the hot spot temperature. There is also potential for design optimization thanks to improved heat transfer offered by the liquid. Low viscosity liquids are very promising innovations to enhance better thermal performances of a transformer. Transformers with higher load factors will have much higher cost of load losses over their design life and henceforth a higher TCO, comparing to those with low load factors. Load losses and power efficiency are intimately related to the winding temperature and cooling system of the transformer, in which the choice of (a low viscosity) insulating liquid is an integral component of the electrical equipment (transformer).

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