Low viscosity over operating temperature range, high oxidation stability and favourable streamer propagation characterized by high acceleration voltage are key aspects of a good insulating liquid

ABSTRACT

This paper briefly discusses the functions of a power transformer's insulating liquid in achieving effective cooling and reliable performance under high voltage stress, and in having sufficient oxidation stability to maintain performance, as well as low maintenance. Low viscosity over operating temperature range, high oxidation stability and favourable streamer propagation behaviour characterized by high acceleration voltage are key aspects of a good insulating liquid. The efficiency of a power transformer can be partly improved by increased convective cooling, thanks to a lower viscosity of the liquid. Moreover, many established electrical design rules for oil/paper systems used in power transformers of today rely on the characteristics of "traditional" mineral oils, which typically have high acceleration voltage. Furthermore, the insulating liquid's oxidation stability and ageing behaviour will have a direct impact on a transformer's total cost of ownership for its operator.

KEYWORDS

insulating liquid, oil, power transformer

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Insulating liquid properties impacting transformer performance

1. 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 to be used according to the standard ASTM D3487, and in the rest of the world predominantly according 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 Bi-phenyls (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 paraffinic and iso-paraffinic liquids also being used. Synthetic and natural ester filled transformers are also used in certain applications.

To the transformer manufacturer or end-user, the increased commoditization of both mineral insulating oils and ester based fluids often means that 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, when selecting the materials used in a transformer, optimising its design and evaluating its total cost of ownership, it is essential that the impact of the insulating liquid is considered.

This paper provides some information on the key parameters and functions of insulating liquids that can influence the performance, reliability and efficiency of an oil filled power transformer; namely, cooling, high voltage (HV) performance, and ageing behaviour.

2. 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 1 lists some viscosities for reference, where naphthenic mineral oils 1 and 2 (NMO1 and NMO2) are naphthenic insulating oils, and iso-para is an iso-paraffinic insulating liquid. Two typical esters were tested: natural ester and synthetic ester.

Notice how Iso-Para and NMO2 have less different viscosities at 20 °C (NMO2 is around 1 % lower) than at 100 °C (NMO2 is around 11 % lower) – this is a simple illustration of the meaning behind two oils with different viscosity index (VI) [1]. A greater decrease in viscosity with increasing temperature is the reason naphthenic liquids are normally favoured for use in cooling applications – they generally have low VI. For example, NMO2 would have a VI of ≈52 and Iso-Para ≈109. It is the nature and structure of the molecules themselves that lead to differing viscous forces with changing temperature and the actual viscosity profile against temperature of the liquids in question should be measured – but the VI is a quick indication of what the viscosity change with temperature is expected to

Table 1. Typical kinematic viscosities for various insulating liquids

Temperature	Kinematic viscosity [cSt]				
	Naphthenic mineral oil 1 (NMO1)	Naphthenic mineral oil 2 (NMO2)	Iso-paraphinic insulating liquid (Iso-Para)	Natural ester	Synthetic ester
20 °C	16	19	19.2	73	70
40 °C	7.6	9.2	9.5	35	29
100 °C	2.1	2.3	2.6	8	5.25

be. It is calculated from the viscosity at 40 °C and 100 °C of a particular liquid [1]. 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, results from a Computational Fluid Dynamic (CFD) simulation based on the model developed by Susa [2] are shown. Liquids NMO1 and natural ester are compared where all other elements of the model (including the transformer parameters, load and ambient conditions) are kept constant. In this example, a 250 MVA ONAF transformer is simulated, and as such there are no pumps, only natural convection is occurring. The load input in this simulation was 1 PU to 1.5 PU overload scenario every 5 hours for 24 hours. Only the liquid's properties were changed, thereby simulating the effect of the liquid with no design modifications. Based on this simulation, if the transformer is filled with natural ester, its average LV (low voltage) winding temperature is expected to be approximately 12 K higher, and the hot spot approximately 15 K higher than if filled with the naphthenic oil NMO1. In practice, the increase in temperature due to the higher viscosity will depend on the specific design of the unit; moreover, the differences are much more pronounced in units using natural convection.

If the transformer is filled with natural ester, its average LV winding temperature is expected to be approximately 12 K higher, and the hot spot approximately 15 K higher than for the naphthenic oil in an overload scenario

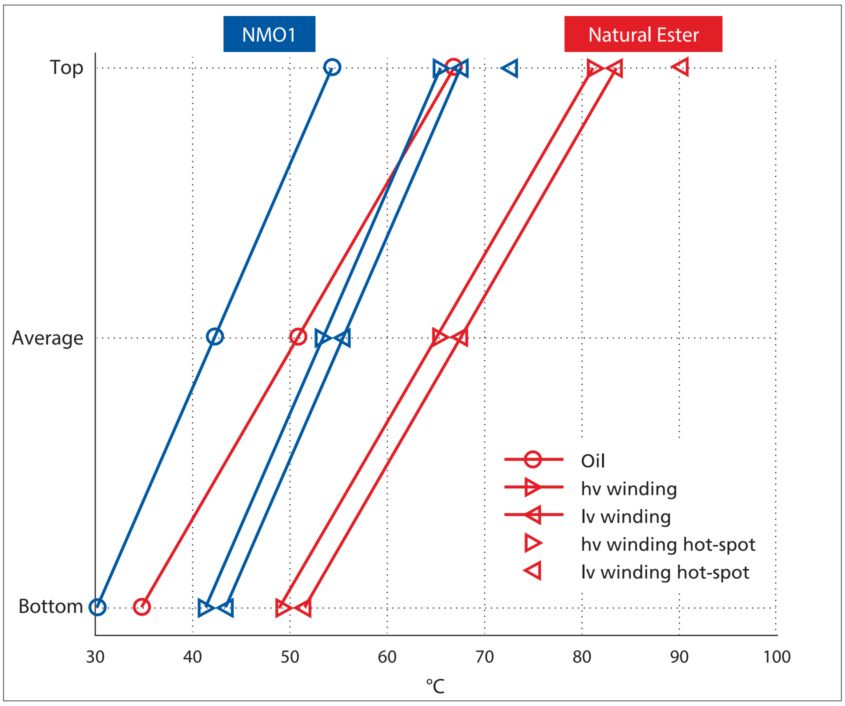

Figure 1. Comparative winding thermal profile comparing two liquids, based on work and models developed in [2], with a 250 MVA ONAF (oil natural air forced) transformer with the same load and ambient conditions used for both liquid cases. The difference in viscosity primarily leads to the difference in cooling.

From this example one can appreciate the major impact the viscosity of the insulating fluid has on the temperature profile of the transformer.

Furthermore, lower VI and indeed a greater drop in viscosity with temperature also favours 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) [3]:

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

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 $\Delta\theta$ is the oil temperature gradient.

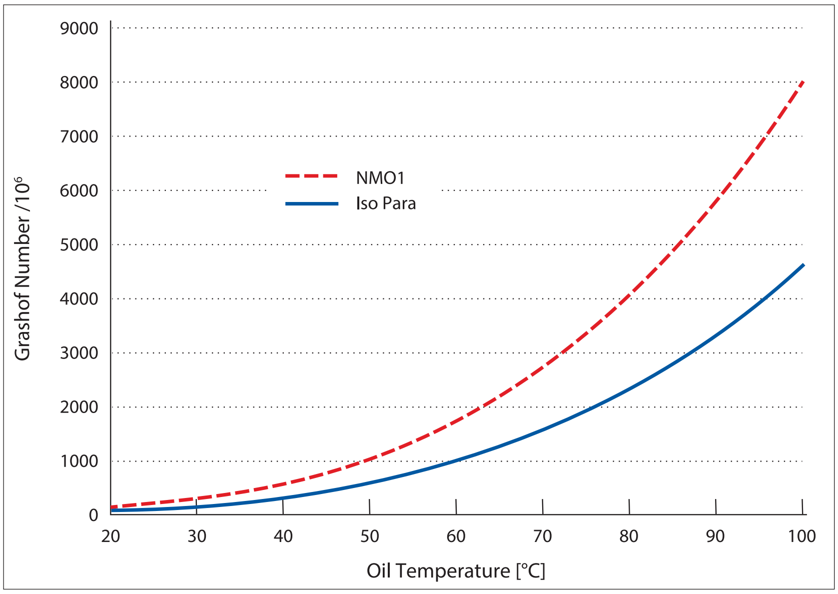

Figure 2. The Grashof (Gr) number calculated for the temperature range 20-100 °C for NMO1 and Iso-Para. An increasing Grashof number indicates higher flow due to natural convection.

For the temperature range of most interest (20 °C to 100 °C) the Grashof number was calculated for NMO1 and Iso-Para and is shown in Figure 2. L was set to 1, and $\Delta\theta$ to 5 K nominally in these calculations as it is for comparative purposes. The higher increase of the Grashof number with temperature in the case of NMO1 is clearly due to its lower viscosity and lower VI. 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).

When oil forced or oil directed cooling is applied and high flow rates are induced in the transformer, the phenomenon known as Electrostatic Charging Tendency (ECT) may become the limiting factor for maximum flow rate. Refer to the Cigré brochure [4] and [5] for more information on ECT.

In summary, in a world where more efficient transformers are desired, with lower operating temperature and lower load losses, a component that is often overlooked in providing improvement is the insulating liquid. A lower viscosity will ensure better convective cooling, which will, in turn, help reduce the size and magnitude of the winding hot spots – and indeed the overall transformer temperatures.

> **Lower viscosity will ensure better convective cooling, which is particularly important in "oil natural" cooled transformers**

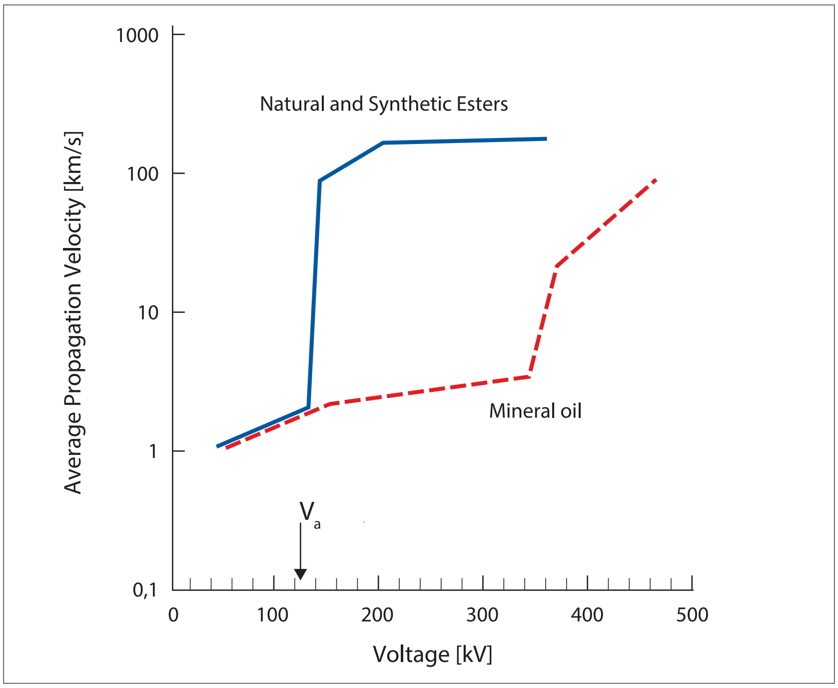

Figure 3. Approximate Positive streamers average propagation velocity in a 10 cm point-plane gap, comparing ester liquids and conventional mineral oils, adapted from Nguyen (2010), where V_a is "acceleration voltage" [11]

3. Performance under HV stress

The performance of a power transformer under HV stress depends greatly on the electrical design of its insulating system, which normally consists of cellulose based solid insulation and mineral oil [6]. Some key aspects of a good dielectric design are minimizing maximum field stress, controlling field uniformity (and avoiding sharp edges), and avoiding large oil gaps – all with the purpose of being Partial Discharge (PD) free under over voltages [6-8]. Moreover, the intrinsic properties of the insulating liquid – most notably streamer propagation behaviour [9], also play a role in many aspects of a good dielectric design. Under positive applied voltage, in non-uniform fields, positive streamers develop at lower stresses than negative ones, and therefore are normally of most concern. Moreover, one observes differences between different liquid chemistries in terms of the speeds of streamers versus applied stress [10]. Natural esters for example have a much lower acceleration voltage than naphthenic mineral oils [11], see Figure 3.

Furthermore, oils without aromatics and those with lower densities also appear to have lower acceleration voltage [12, 13]. Some useful data on streamer initiation and acceleration for different liquids is contained [14].

The reason why understanding the onset of fast streamers in insulating liquids is important in practice is because significantly faster streamer propagation could lead to higher probability of breakdown – as potentially short lived temporary overvoltages that are normally insufficient to cause breakdown in a liquid with high acceleration voltage may in fact be sufficient in one with a lower acceleration voltage. Therefore, if a "new" type of liquid was to be used in a certain transformer design (which was verified through a long iterative process, empirically with conventional mineral oils) then understanding if it has significantly lower acceleration voltage will help assess the risk of "unexpected" breakdowns.

Furthermore, comparative studies under AC applied voltage into the differing partial discharge behaviour of liquids also show that liquid chemistry impacts the behaviour [15, 16].

Liquid purity and condition (particles, gas and moisture) are also key factors for reliable performance and therefore quality indicators such as the "breakdown voltage" tested to IEC 60156. The Inter-Facial Tension (IFT) and Dielectric Dissipation Factor (DDF, IEC 60247) must also be considered [17], but these have a higher impact on quality and maintenance rather than design.

Ultimately, one desires an insulating liquid that has very high purity (free from contaminants), favourable streamer propagation behaviour (high acceleration voltage), a well understood PD behaviour, and a proven track record. When coupled with a good dielectric design and high quality solid insulation, power transformer reliability can be increased by using insulating liquids with higher acceleration voltage and favourable allover streamer behaviour as they help add to the safety margin by potentially being less sensitive to short lived overvoltages. Furthermore, rigorous quality control

> **Natural esters in comparison to naphthenic mineral oils have a lower acceleration voltage and faster streamer propagation, which, depending on electrode arrangement, can be associated with higher probability of breakdown**

processes both at the transformer factory and on site, as well as performing "last point" oil filtration and degassing, will help reduce the risk of contamination and therefore reduce the risk of unexpected issues.

4. Ageing behaviour

Both inhibited and uninhibited oils are available worldwide and used as insulating liquid in transformers, although uninhibited grades are produced in larger volume. From an end-user perspective, the main difference is the aging behaviour. Whereas inhibited oil goes through a long life without any oxidative change before depletion of the inhibitor, uninhibited grades oxidize at a slow rate from the beginning. Once the inhibitor in inhibited oil is depleted, the rate of oxidation takes off. However, with a suitable monitoring program and re-inhibition the life of the oil (and the transformer) can be extended far longer. For this reason, inhibited oil puts less aging strain on the solid insulation over time.

To ensure the reliable operation of a transformer, an insulating liquid which does not degrade significantly over time, in the conditions of the transformer, is desired. Moreover, transformer efficiency overall is not only about its losses, but also about the Total Cost of Ownership (TCO). In this regard, one desires low maintenance and if preferable to not have to reclaim (referring to clay treatment or similar process) or change the oil of the transformer throughout its life.

4.1. 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 most relevant in mineral oils at the common temperatures of power transformers. But for different liquids with different chemistries, different chemical reactions will occur at different temperatures, and have different activation energies and different products and by-products. When evaluating a new liquid, a holistic approach considering the service conditions and the chemistry of the liquid is necessary. The establishment of possible "type tests" framework with a reasonable level of standardization to characterize a liquid in these lines would be beneficial and is recommended future work.

Table 2. Some requirements for different insulating liquid types based on current IEC standards when evaluated to IEC 61125 to illustrate their typical relative oxidation stabilities

Fluid type	Specification	Ageing duration	Maximum acids allowed after ageing
Mineral uninhibited	IEC 60296	164 hours	1.2 mgKOH/g
Mineral trace inhibited	IEC 60296	332 hours	1.2 mgKOH/g
Mineral inhibited	IEC 60296	500 hours	1.2 (0.3)[1] mgKOH/g
Synthetic ester[2]	IEC 61099	164 hours	0.3 mgKOH/g
Natural ester[2]	IEC 62770	48 hours	0.6 mgKOH/g

[1] Special applications – met by most commercially available "high grade" oils

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

For example, esters have a much poorer hydrolytic stability than mineral oils [18] and must be considered when determining an ester liquid's ageing behaviour.

With regards to thermal stability of insulating liquids, evaluation without oxygen is necessary and becomes a practical concern as controlling and measuring oxygen content in liquids during ageing is very challenging.

Moreover, an oxidation stability test must be performed at a relatively representative temperature to that in service (for example, in IEC 61125 it is performed at 120 °C where a common "maximum" transformer top oil temperature of ≈105 °C is a common norm). Performing an accelerated ageing test at substantially higher bulk oil temperature than expected in service (a justification for this is usually to shorten the duration of the test) may result in a poor estimation of the actual ageing behaviour at a lower, more reasonable temperature. The reason for this is that other reactions with higher activation energies could take over and thus could have a substantial impact on the ageing products and the rate of production. This aspect must be taken into consideration, based on the liquid's chemistry, when characterizing a liquid's oxidative, hydrolytic or thermal stability.

Based on current standards, as shown in Table 2, the typically relatively poorer oxidation stability of natural and synthetic esters is evidenced by the less stringent requirements on them for oxidation stability.

4.2 Antioxidants and other additives

Mineral insulating oils are most commonly divided into two main types: "uninhibited" and "inhibited", and for the latter the inhibitors used are most commonly phenolic type antioxidants such as 2.6-di-tert-butyl-paracresol (DBPC) limited to 0.4 % of the total weight of the product in IEC 60296 and 0.3 % in ASTM D3487.

DBPC is a primary antioxidant, in that it is mainly "radical destroying". This is different from secondary antioxidants, such as the "natural antioxidants" (consisting of sulphur compounds remaining from the original crude oil) contained in uninhibited mineral oils which are mainly peroxide decomposers [19].

Natural esters typically have much poorer oxidation stability than mineral oils, naturally depending on the vegetable oil and the degree of unsaturated groups, and as such they often contain primary antioxidants at higher (approximately around 1 % or above) concentrations to achieve "reasonable" oxidation stability. Furthermore, most commercially available natural esters often may contain metal passivators, antifungals, dyes and pour-point depressants [20], which may impact the oxidation stability or participate during oxidation and hydrolysis reactions, and therefore the consumption of them, in any liquid where they are employed – this is an important factor to understand as well.

Synthetic esters typically have better oxidation stability than natural esters, due to higher degree of saturation; however, they are still likely to contain higher levels of antioxidants than typical mineral oils.

The establishment of possible "type tests" framework with a reasonable level of standardization to characterize new liquids would be beneficial and is recommended future work

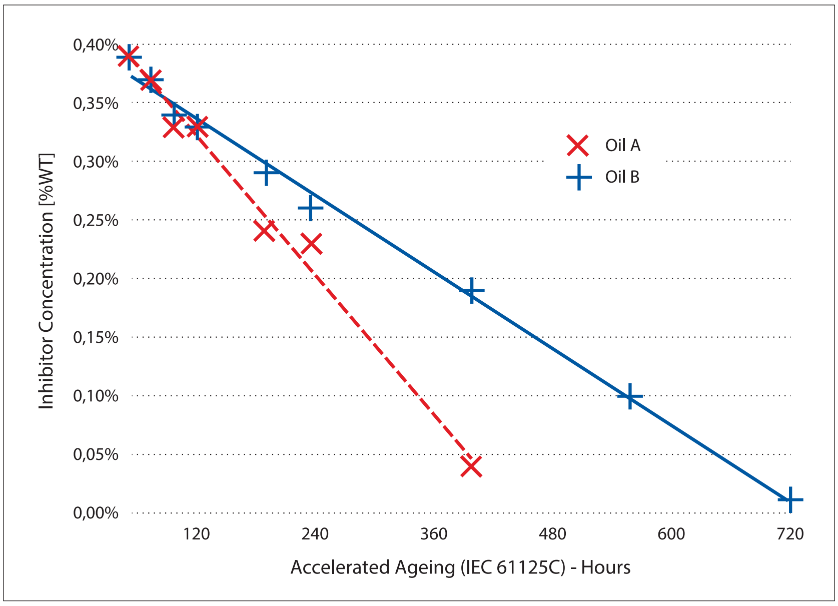

Figure 4. Under the accelerated ageing conditions of IEC 61125, the inhibitor consumption of an oil of lower refining degree (Oil A – aromaticity ≈13 %) was compared to an oil with a higher one (Oil B – aromaticity ≈5 %). The inhibitor consumption rate was lower for the more refined oil.

4.3 In-service performance and maintenance

In practice, well refined inhibited mineral insulating oil normally remains free from acidity and sludge for decades and accelerated ageing is normally associated with excessive temperatures. Likewise, good quality uninhibited oils normally experience only a minor increase in acidity over several years unless they are in excessive contact with air and experience excessive temperatures. A number of tests are used to assess the condition of in-service oil and within the industry IEC 60422 is used as guideline for maintenance of in-service insulating oil.

In general, well established tests such as breakdown voltage, moisture, resistivity, dielectric dissipation factor (tan-delta), interfacial tension and acidity are good indicators of oil deterioration which may be related to overheating or contamination. The limits for each test for oil in high voltage transformers (i.e. >170 kV) and action limits are documented in IEC 60422.

One of the key factors to consider when dealing with inhibited liquids as above is the "timeous" top of inhibitor as referred to above. In mineral oils, as described in the maintenance guide IEC 60422, topping up the inhibitor before 40 % of its starting value is reached is a good "rule of thumb" to ensure the oil does start readily oxidizing. For a specific product, it is necessary to understand the minimum sufficient concentration of antioxidants that prevents the onset of oxidation – and the goal of the inhibitor top-up regime should be around never reaching that level.

Figure 4 illustrates how a more refined oil with lower aromaticity in turn consumes less inhibitor. Figure 5 illustrates how once the aromaticity and refining degree are optimized, the inhibitor response is such that the progression of oxidation and the formation of acids will only occur at very low inhibitor levels.

Moreover, in this example the point of complete consumption (sometimes referred to as the induction period) is at >650 hours, while the benchmark for oils for special applications IEC 60296 is 500 hours (under the conditions of IEC 61125).

In practice, "high" and "super" grade mineral insulating oils are fit-for-purpose as they have an optimal aromaticity and refining degree such that they maintain the good insulating properties, but also have sufficiently low inhibitor consumption to provide long life in service.

A transformer operator can reduce their expected total cost of ownership by selecting an insulating liquid which will have a predictable and well established maintenance regime – and that will require the least amount of maintenance interventions. For example, as has been illustrated above, with inhibited liquids one should select a liquid with optimized refining degree, and using a well understood and available inhibitor, so that its inhibitor consumption will be very slow in service and that the inhibitor is not too costly. The consequence will be that occasional inhibitor monitoring (every few years) will allow for good scheduling for when (if required) inhibitor top-up must be done in order to prolong the life of the liquid.

When selecting the materials used in a transformer, optimising its design and evaluating its total cost of ownership, it is essential that the impact of the insulating liquid is considered

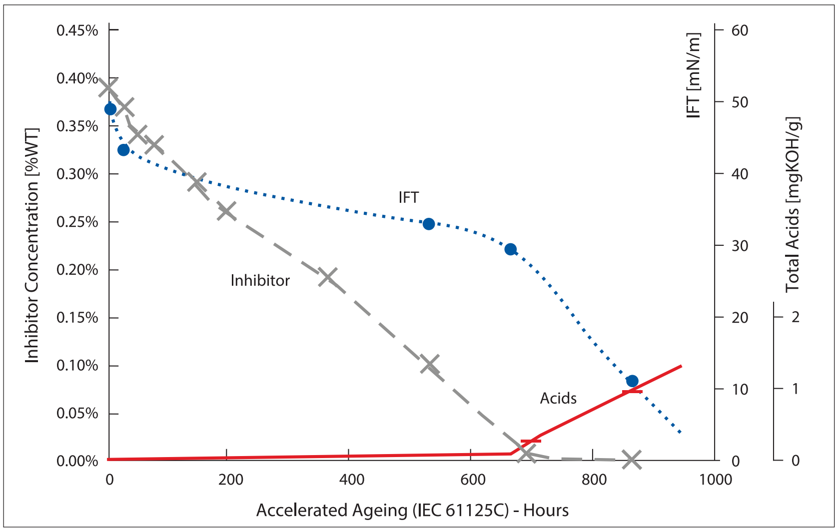

Figure 5. An example of how a well refined inhibited oil (Oil B) would behave – in this case when aged under the conditions of IEC 61125

Conclusion

The role of a power transformer's insulating liquid in achieving effective cooling, reliable performance under HV stresses and having sufficient oxidation stability to maintain performance, as well as be low maintenance, have been briefly discussed in this paper. Low viscosity, high oxidation stability, and favourable streamer propagation behaviour characterized by high acceleration voltage are key aspects of a good insulating liquid.

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