

Insulating Liquids: Key Aspects of Today's Liquids – Differences and Similarities

by **Bruce Pahlavanpour**

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Since the beginning of the electrical age, mineral oils have been used as dielectric insulating liquids (US patent 428648 to Elihu Thomson). In the early decades, the mineral oil was minimally processed. As the refining industry evolved, processing has improved, and today's hydro processed naphthenic insulating liquids are extremely stable and in use world-wide.

Over the last 50 years, alternative products such as the synthetic esters (late 1970s), natural esters (late 1990s), isoparaffins from petroleum refining (1990s), gas-to-liquid isoparaffins (2012), re-refined mineral oils, and bio-based isoparaffinic hydrocarbons from triglycerides (2019) have been introduced. Each of these must fulfill the basic requirements for insulating liquids, i.e., effective cooling, reliable performance under HV stresses, and having sufficient oxidation stability to maintain performance – as well as low maintenance. Low viscosity, high oxidation stability, and favorable

streamer propagation behavior characterized by high acceleration voltage are key aspects of a good insulating liquid.

Also, in addition to the performance over the life of the transformers, other criteria are being considered, such as high fire point, biodegradability, sustainability, recyclability, and low carbon footprint. It is the chemical composition of the insulating liquid which determines its physical, chemical, and electrical performance as well as the other criteria. 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.

The aging rate of the insulating liquid and the paper insulation will affect the performance, efficiency, maintenance, and total cost of ownership. However, improving the performance of one criterion often decreases the performance in other areas. Each area will be examined in terms of comparison between the different types of insulating liquids.



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Innovation and evolving technology have allowed tremendous improvements over the past thirty years in the production of insulating liquids. In relation to mineral oil, the standard specification (IEC60296) has been revised three times during this period culminating in the current state of the art supply of high-quality mineral insulating oil. Alternative insulating liquids such as natural and synthetic esters, blend of esters and bio base oils have been manufactured and supplied to the market.

For the past thirty years international standards have been actively setting the appropriate specifications for natural esters, synthetic esters and blend of esters liquids. These specifications have been revised and improved constantly to make sure they meet market requirements, in line with recent equipment. Maintenance guides and standards for each type of insulating liquids are also developed and revised to facilitate the safe operation of oil filled electrical equipment and better performance.

Utilities are obliged to reduce their losses, using so-called green and environmentally friendly material. Key issues in this field include sustainability, carbon footprint and biodegradability of the liquid. This is in contrast with mineral oil, which is the most readily available and cheaper than alternative fluids. It has a proven record of excellent performance as well as being the insulating liquid that equipment owners are familiar with in terms of maintenance and performance. Furthermore, mineral oil is recyclable as it can be re-claimed and used a number of times. Whilst current trends still skew towards mineral oil, it remains to be seen what the future of insulating liquids will be.

HV Behavior

The key functions of an insulating fluid are to act as a cooling medium and to withstand high voltage stresses. Breakdown mechanisms in liquids are complex and as such the industry uses many empirical relationships, experience and proxies to ensure that a well-designed transformer combined

with a high-quality insulating oil have a long lifetime and can withstand the stresses of service.

The relative permittivity of a liquid is an important parameter that will impact the prevailing electric field distribution in the transformer. It is desirable to try and match the permittivity of the liquid and cellulose based solid insulation (which normally has higher permittivity than mineral oil). Nonetheless the reason for higher permittivity (as is the case in ester fluids for example) is polar chemistry – which may in fact lower the insulating capability of the liquid. Furthermore, surface and boundary effects (e.g. between pressboard and liquid) can influence localized electric fields. Therefore, care should be taken when modelling and determining the maximum permissible field stress in a practical insulating system.

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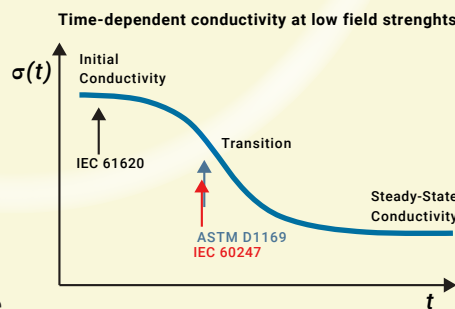


Figure 1: Oil Conductivity, measurement at a single point during transition provides little information, adapted from Cigré TB 646.

Volume resistivity commonly measured via IEC 60247 is the reciprocal of the (Direct Current) DC conductivity and some try to evaluate a liquid using this. The challenge with this test is its repeatability. As the conductive current in the liquid is being measured whilst it is behaving as an insulator - (electric field of ~250 V/mm). As there are such small quantities of conductive and quasi-conductive species contained in clean oil the current changes greatly over time (ion mobility makes these species move around) during this test and is part of the reason why the end value can vary greatly.

Figure 1, from Cigré TB 646, shows that the common tests such as IEC 60247 (for volume resistivity) are effectively measuring (with regards to duration and field strength used in the test) during the transition region of the conductivity for most oil types. Therefore, it is no surprise that great variability in the values is experienced by labs and users.

Understanding the conductivity of the liquid is more relevant in HVDC applications – due to the presence of DC stresses and polarity reversal - and in TB 646 a “three-point characterization method is proposed” that should be considered when designing equipment for HVDC.

Common breakdown voltage tests such as IEC 60156 and ASTM D877 are effective at testing the condition of liquids – namely the presence of particles, excess gases and moisture. In small gaps and quasi-uniform fields, like in IEC 60156. However, they are insufficient for comparing the intrinsic insulating capability of different liquids. As shown in table 1 below, different esters and mineral oils have very similar breakdown values. The difference in the silicone fluid (for the IEC test) is attributed to insufficient standing time due to it having much higher viscosity (bubble release).

Test	Mineral Oil	Synthetic Ester	Natural Ester	Silicone Oil
IEC 60156 2.5mm	>70 kV	>75 kV	>75 kV	50 kV
ASTM D877	55 kV	43 kV	46 kV	43 kV

Table 1: Some typical breakdown voltage values after treatment for different fluids using different methods, from Cigré TB 436.

The study of streamers in different insulating liquids, and mostly their propagation has been done quite extensively in the literature, examples are [1-5].

In "large gaps" ($\sim > 2.5\text{cm}$) and under non-uniform fields (point-plane or point-sphere electrode configurations are normally used in such tests) one generally observes greater differences in breakdown and pre-breakdown phenomena between differing liquid chemistries as well as more differences between positive and negative applied voltage.

Mineral oils, ester fluids and others have all been shown to exhibit different field dependent "modes" – whereby the streamer propagation velocity increases noticeably with each progressing mode. Of most interest is normally the transition to "fast" streamers (characterized by a sudden jump in propagation velocity normally by approximately 1 to 2, or more, orders of magnitude) which occurs at a lower voltage stress in positive streamers than for the negative.

The voltage where this transition is seen is normally referred to as the "acceleration voltage" of a liquid. As shown in figure 2 for example, ester liquids show a lower positive streamer acceleration voltage than typical mineral oils.

The reason why understanding the onset of fast streamers in insulating

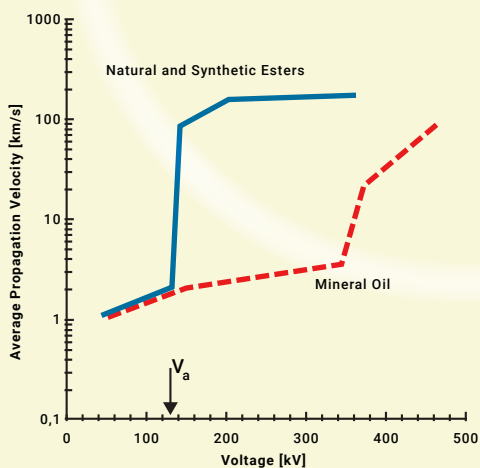


Figure 2: Approximate Positive streamers average propagation velocity in a 10cm gap, adapted from Nguyen N.M. et. Al [1], where V_a is "acceleration voltage".

liquids is important in practice is because the significantly faster streamer propagation could lead to higher probability of breakdown in practice – as potentially short lived temporary over voltages 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.

Furthermore, in mineral oils and in pure liquids (such as cyclohexane) studies [2-4] have shown that the typical "high" acceleration voltage of "typical" mineral oils is likely due to the influence of aromatic hydrocarbons. This is supported by demonstrations that in certain cases the addition of (relatively small amounts – approximately 0.5 – 2 % ranges) of aromatic additives to, for example, white oils and cyclohexane increases the acceleration voltage for that liquid mixture [2].

Studying the Partial Discharge (PD) behavior under AC applied voltage, using test cells employing point-sphere or point-plane geometries like those in IEC 60897 to compare liquids (based on IEC TR 61294) also reveal differences between liquid chemistries. Such tests are most informative by being used to compare the differing pulse magnitude and pulse rate behavior (over time and for differing voltages) of different liquids. Lower PD activity in mineral oils than in ester liquids has been reported [6, 7]. Lower PD activity in mineral oil and ester blends containing aromatics has also been shown [8].

There is most likely a strong link between these observations and those concerning the differing acceleration voltages of esters and mineral oils containing aromatics, but further investigations are needed for the link to be explained.


Ageing Behavior

The lifetime and ageing behavior of insulating liquids is a critical factor in a power transformer. Naturally, one needs to understand how a liquid's properties, and therefore its performance, change during ageing under thermal, oxidative and



hydrolytic stress so that the design and operation philosophy of the transformer is appropriate to achieve the desired lifetime.

Mineral insulating oils are mainly divided into two main types "un-inhibited" and "inhibited" – and for the latter the inhibitors used are most commonly phenolic type anti-oxidants such as 2,6-di-tert-butyl-paracresol (DBPC) limited to 0.4% of the total



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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” (mainly consisting of sulphur compounds remaining from the original crude oil) contained in uninhibited mineral oils which are mainly peroxide decomposers.

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 [9] 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 - 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 anti-oxidants than typical mineral oils.

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Maintenance of inhibited liquids

One of the key factors to consider when dealing with inhibited liquids is the "timeous" top of inhibitor. 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 oxidising. For a specific product, it is necessary to determine the minimum sufficient concentration of anti-oxidants that prevents the onset of oxidation – and the goal of the inhibitor top up regime should be around never reaching that level.

Concerning the practicality of condition monitoring and inhibitor management, the accuracy and cost of measuring the inhibitor consumption is important. For example, the test method used to measure inhibitors in mineral oil are well developed (see IEC 60666 for example) but for new liquid types these methods must be evaluated for precision whilst the fluid ages to ensure background interferences do not result in significant errors. Furthermore, the cost and practicalities of obtaining the additives and adding them to the transformer – during the "top-up" need to be considered and added to the total cost of ownership model for that system. It is for this reason that using "high" and "super" grade

oils with high oxidation stability and low inhibitor consumption is the best engineering practice.

As illustrated in figure 3 inhibited oils will progress into developed oxidation once the inhibitor is fully consumed – or below the minimum sufficient concentration for a particular liquid. This same behavior will occur for esters and as such a detailed additive and inhibitor management strategy must be employed by users.

Furthermore, the most common proxy tests, namely Inter Facial Tension (IFT) and Dielectric Dissipation Factor (DDF), for mineral oils to detect early oxidation products such as carbonyls are extremely useful because the products are polar and the oil bulk is non-polar. One must be aware that in polar liquids such as ester-based fluids the sensitivity of such tests to early ageing products may be much lower and additional proxies may have to be used/developed to achieve an appropriate level of trending capability.

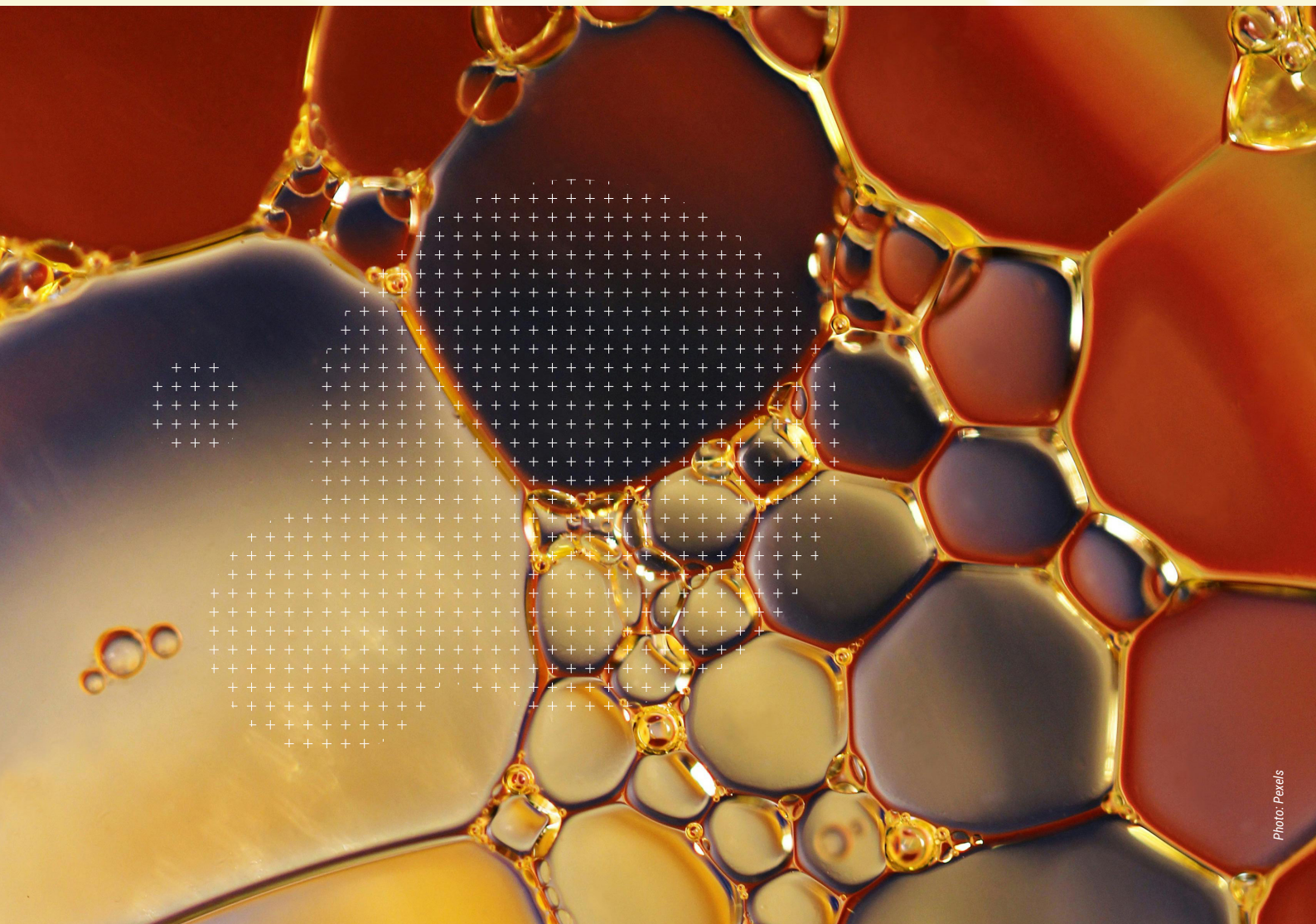


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