The Journal of CPRI,
Vol. 13, No. 4, December 2017 pp. 615- 620

Electrical Behaviour of Ester-based Dielectric Liquids for Use in Transmission Transformers

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The use of alternative dielectric liquids is on the rise, with fire safety and environmental concerns at the forefront for the switch from mineral oil. Ester-based dielectric liquids have been in use in the power industry for almost four decades, with synthetic esters having originally been introduced as replacements for harmful PCBs in the late 1970s.

Over time the use of esters has grown steadily and the introduction of natural ester-based liquids in the 1990s has further accelerated their adoption, as in addition to being fire safe and biodegradable, these liquids provide users with a very environmentally friendly, sustainable alternative to mineral oil. Natural esters have made some significant inroads into the distribution industry, where they are used extensively for equipment such as pole-mounted transformers.

One limiting factor to the use of esters in transmission transformers in the past has been a lack of experience at higher voltages, coupled with some different behavior in standard dielectric tests. However, over ten years of concerted research effort is changing this.

Beginning with the fundamental differences in the physical and chemical properties between esters and mineral oil, this paper aims to provide an overview of the characteristics which influence the electrical design of transformers, especially for transmission voltage levels.

In addition, research from across the industry will be presented along with an examination of the implications of various findings for the design of higher voltage equipment. Furthermore the latest research conducted by the Budapest University of Technology and Economics will be presented which provides a comparative design curve between mineral oil and different types of ester-based products, both natural and synthetic organic.

THE ESTER FUNCTIONAL GROUP

The chemistry of ester-based dielectric liquids is somewhat different to that of mineral oils. The difference in some electrical behavior can be most easily explained by looking at the role of the ester functional group within the molecular structure. Mineral oils are comprised primarily of saturated hydrocarbon structures, as shown in Fig 1.

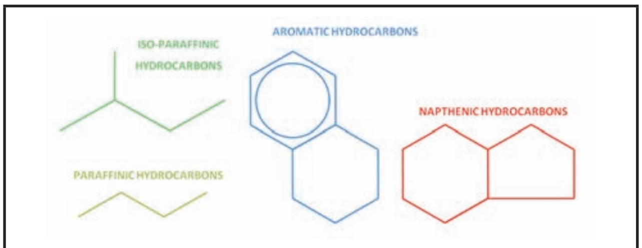

FIG. 1 CHEMICAL STRUCTURE OF MINERAL OILS

These molecules are very non-polar and this has a direct impact on properties such as resistivity and interfacial tension with water. As mineral oil ages it degrades to more polar molecules such as keytones and acids. The presence of these polar species reduce resistivity and interfacial tension.

Ester-based liquids begin with a much higher polar content when new, owing to the presence of the polar ester functional group. As shown

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in Fig.2 synthetic esters have a higher proportion of ester-functional groups per molecule than natural esters. The presence of the polar parts of the molecule cause lower resistivity and lower interfacial tension. These parts of the chemical structure may also explain why esters have different behaviour in terms of streamer propagation, as will be discussed later. This in turn causes lower levels of impulse breakdown under certain electrode arrangements, especially in very divergent fields.

In some ways the polar nature of the ester functional group brings advantages, for example esters can tolerate much higher water content than mineral oil owing to a binding of water molecules through a process known as hydrogen bonding.

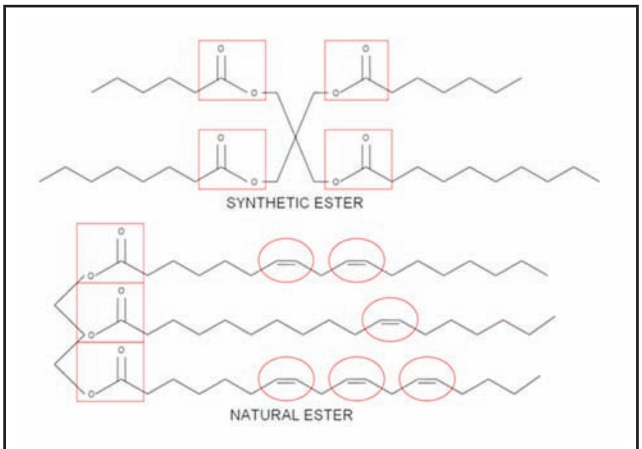

FIG. 2. CHEMICAL STRUCTURE OF ESTER-BASED LIQUIDS

Fundamental Electrical Design Differences

When designing any transformer or other electrical apparatus it is very important that the correct parameters for the insulation system are used. One key property is the permittivity, or dielectric constant, of the materials which will form the electrical insulation. Under AC the field strength will distribute in inverse proportion to the permittivity values of the insulation. Taking a simplistic view when combinations of materials are used then a better balance between the different material's permittivity will lead to a more balanced field distribution. This is true in homogeneous arrangements, but the picture is more complex when considered non-homogeneous electrodes. Taking a simple example it is possible to demonstrate this. Fig. 3 shows a simple electrode arrangement of a paper wrapped conductor spaced at distance s from an earthed plane. This could be found where a bushing is placed next to the tank wall for example. In this example the space between the conductor and the plane is filled with a dielectric liquid.

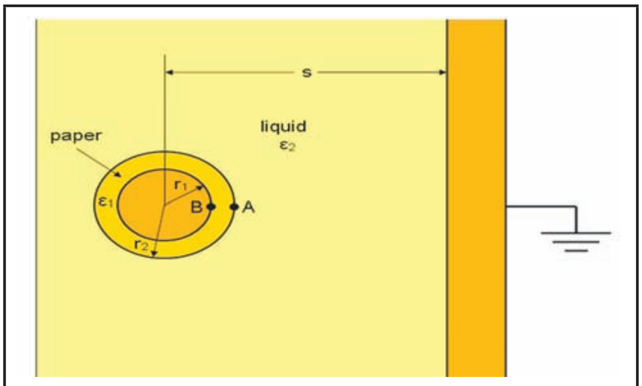

FIG. 3. SIMPLE ELECTRODE ARRANGEMENT

Taking the values of permittivity for mineral oil, mineral oil impregnated paper, ester and ester impregnated paper in table 1 a calculation can be made of the field stress at points A and B.

TABLE 1
PERMITTIVITY VALUES [1]

Fluid	Liquid Permittivity	Impregnated Cellulose Permittivity
Mineral Oil	2.2	4.4
Ester	3.2	4.7

TABLE 2
RESULTS OF SIMPLE FIELD STRESS CALCULATION

	Mineral Oil	Ester
Stress at Point A	9.35kV/mm	9.23kV/mm
Stress at Point B	5.84kV/mm	7.84kV/mm

It can be seen that although the stress at the edge of the paper wrapping is lower in the ester, the stress at the conductor is much higher. The peak stress in this arrangement is still lower, which is advantageous, but it shows that stress distribution is different with esters and must be taken account of when designing. When considering items such as condenser bushings, where electrical field is graded, this is particularly crucial; to avoid concentrated areas of stress beyond the partial discharge inception of the liquid.

Dielectric Strength Dependence on Field Divergence

To understand the difference in electrical behaviour between mineral oil and esters researchers have employed a wide variety of electrode arrangements, from extremely divergent needle-plane through to homogeneous set ups designed to simulate windings. One of the key differences that has been found is the relationship between field divergence and dielectric strength. Taking the most extreme example of this with a very sharp needle and a sphere the electrical strength of ester-based liquids can seem far inferior to mineral oil, especially as the gap size increases. Fig 5 shows impulse testing results from the University of Manchester in such a set up.

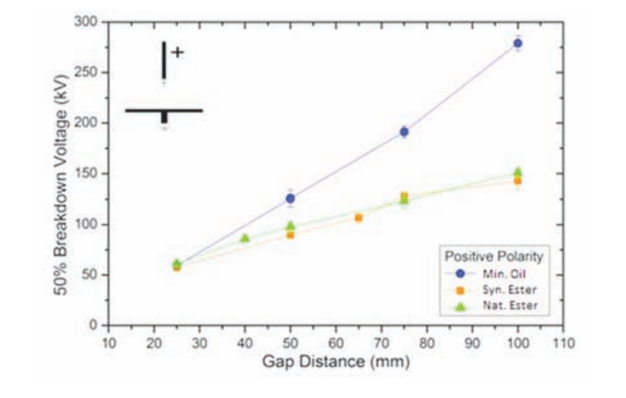

FIG. 4. IMPULSE BREAKDOWN VOLTAGE COMPARISON, NEEDLE TO PLANE ARRANGEMENT [2]

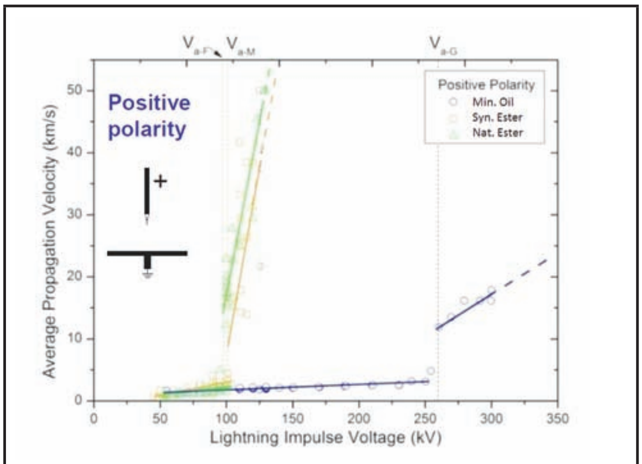

FIG.5. PROPAGATION SPEED OF STREAMERS [2]

Further studies found that the mechanism for this behaviour is a lower voltage transition to fast streamers, also known as acceleration voltage. In both natural ester and synthetic esters this change to fast streamers occurs at a much lower voltage than mineral oilin this extremely divergent case. Fig 4 shows the results of one such investigation with three different liquids mineral oil, synthetic ester and natural ester using impulse to provoke the transition from slow to fast streamer with the same sharp needle and a plane.

This may seem to indicate that esters are unsuitable for use at higher voltages, since they will tend to be more likely to flashover. However it is necessary to also think about discharge inception voltages, since without inception there is no possibility of propagation of the streamer. PDIV studies using similar arrangements of electrodes have concluded that in fact the discharge inception level for esters is very similar to mineral oil, as shown in Table 3.

TABLE 3

PDIV COMPARISON IN NEEDLE TO SPHERE ARRANGEMENT [3]

Liquid Type	PDIV (kV)
Mineral Oil	23.2
Synthetic Ester	22.3
Natural Ester	25.6

Although in very divergent fields esters have a lower level of dielectric strength than mineral oil as the electrodes become less divergent and inception begins to dominate over propagation the difference becomes smaller. An investigation into different electrode arrangements and gap sizes by MR and others demonstrates this behavior.[4]The testing of three different electrode arrangements was reported as shown in Fig. 6. The left hand arrangement used the VDE electrodes, the middle one a typical tap changer contact to a plate and the final a very divergent needle to plate.

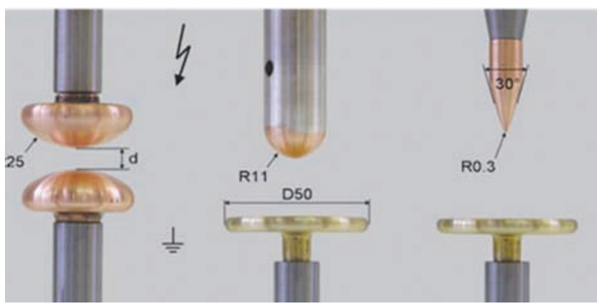

FIG. 6. TESTED ELECTRODE ARRANGEMENTS[4]

Starting with the needle to plate arrangement it is observed that the difference between the mineral oil and the esters is large, becoming more so as gap size increases.

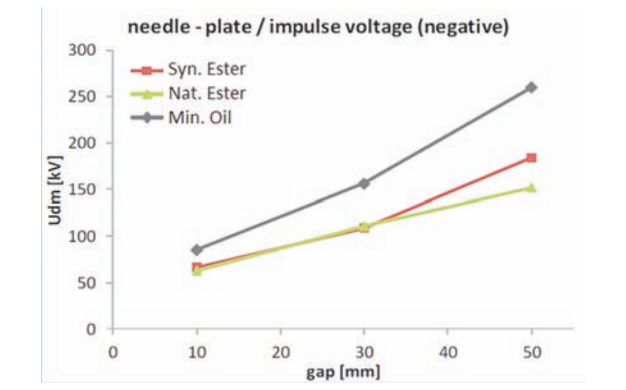

FIG. 7. NEEDLE TO PLATE IMPULSE BREAKDOWN[4]

As the electrodes change to become more homogeneous the difference in electrical strength becomes smaller, as shown in Fig 8 for the more realistic tap changer contact to plate.

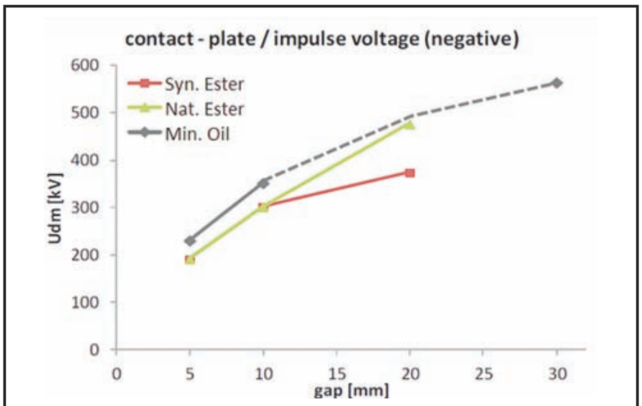

FIG. 8. CONTACT TO PLATE IMPULSE BREAKDOWN[4]

Finally looking at a homogeneous arrangement of two VDE electrodes it can be seen that the difference in electrical strength under AC is actually very small between esters and mineral oil, see Fig. 9.

This leads to the conclusion that to design for esters focus should be given more to the inhomogeneous parts of the design than to the areas where fields are not divergent. In esters propagation behaviour dominates and this means it is more critical in esters to ensure that insulation is discharge free.

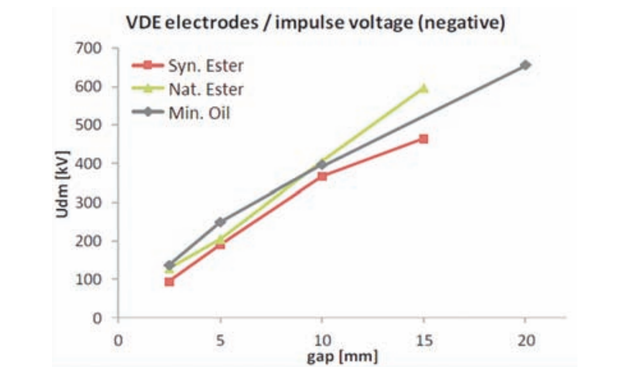

FIG. 9. VDE ELECTRODE RESULTS UNDER LIGHTNING IMPULSE[10]

Although these differences in electrical breakdown may seem to be detrimental to ester-liquid use in larger power transformers by use of the correct design parameters and enhanced margin in certain parts of the insulation esters can be made to work in large power transformers. The areas where most focus may be needed on design is in equipment such as tap changers, winding ends and between lead ends and the tank walls.

Research Under More Realistic Arrangements

In addition to open oil gaps it is also necessary to look at creepage behaviour, as pressboard surfaces can promote streamer propagation. Various electrode arrangements have been applied to investigate the flashover and partial discharge behavior of insulating liquids.Recently, arrangements creating an inhomogeneous electric field gained popularity, since they allow the testing of relatively large gaps without issues such as corona around connections to test vessels. Testing of a number of different dielectric liquids has been conducted using the arrangement shown in Fig. 10, which is based upon the method in [5].

In preparation the pressboard sample, base and crepe paper were vacuum dried at 65 °C for at least 7 days. They were impregnated with the liquid under vacuum (<0.1 mbar) and then kept for 48 hours at the same temperature before commencing the tests.

The tests themselves were conducted in a large test vessel containing more than 330 liters of the liquid at room temperature. It was possible to apply vacuum to the test vessel, which accelerated the escape of air bubbles. The vacuum was only broken for the duration of the tests and sample replacement. This minimized the contact of the liquid with free air, thus moisture content could not increase excessively. Regular tests were made to ensure that the moisture content and breakdown voltage of the liquid in the test vessel met the requirements.

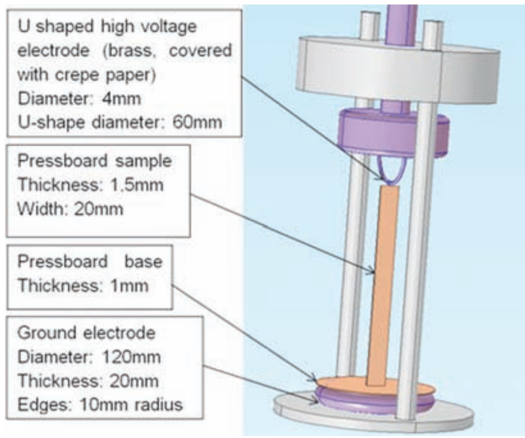

FIG.10. ELECTRODE SYSTEM APPLIED IN THE TESTS

The high voltage was generated by test transformers, considering causing minimal degradation of the liquid after flashover. The shorter samples (5 to 35 mm) were measured with a 250 kV/40 kVA transformer limited with a 300 kΩ water resistor, while the longer samples with a 550 kV/500 kVA transformer, which was switched off by an under-impedance protection immediately after flashover. In the first case, partial discharges were measured by a conventional device (40-200 kHz); noise and corona was kept below 10 pC, while PDIV was recorded at 20 pC. In the second case, partial discharges were detected by a high frequency current transformer (90 kHz-21 MHz, transfer impedance 3.8Ω); noise and corona was kept below 25 mV and PD inception was recorded at 50 mV.

Results from 25 samples for each liquid and length were recorded and from this fitted plots of average PD inception voltage and AC flashover were produced, as shown in Fig. 11and 12. A comparison was made between the five different tested liquids, to evaluate the likely differences that may occur and whether designs need to be adjusted to accommodate flashover behaviour.

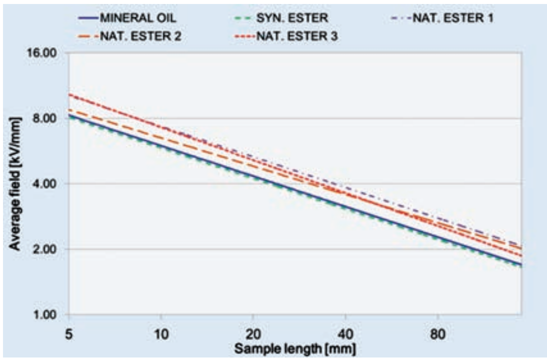

FIG. 11. PARTIAL DISCHARGE INCEPTION FILED – AVERAGE OF THE RESULTS

The results of the PDIV study match many other investigations in that they show similar levels of PDIV for synthetic ester and mineral oil, with slightly higher partial discharge inception for the natural ester products. This also concurs with the very divergent needle-sphere study quoted above.

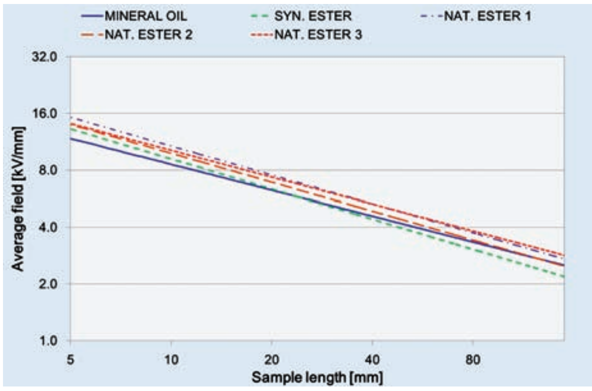

FIG. 12. AC FLASHOVER FILED – AVERAGE OF THE RESULTS

The AC flashover values taken from this study show similarities in behaviour between all the natural ester liquids, with higher flashover voltages and a slightly lower flashover strength for the synthetic ester. This is in contrast to the situation with very sharp needles and suggests that in a more realistic divergent set up the difference between the liquids is not so large.

CONCLUSIONS

There are a number of factors that must be taken into account when designing transformers for use with ester-based liquids. Owing to their high fire point these liquids will have higher viscosity than mineral oil and this will lead to increased temperature rise for a given design. The designer then has the option to either adjust the thermal aspects, such as cooling channel widths, or to agree a higher temperature rise with the customer.

On the electrical design the most key factor to take into account is the difference in permittivity between esters and mineral oil, since this substantially changes the stress distribution in the insulation structure. There is also evidence that esters are weaker under impulse voltage, especially over long very divergent gaps. This leads to a need to take care around divergent parts of the design and also to ensure that manufacturing defects are avoided. The electrical margins may be increased by the designer to take account of this.

Overall the design of ester filled transmission voltage transformers needs some more attention and the designs for mineral oil may not be suitable. However testing in more realistic electrode arrangements shows that the differences may not be so large and the latest 400kV+ transformers in the field demonstrate that any changes are possible to apply. In fact even considering extra work and design adjustments an ester filled transformer may still provide lower overall project costs once aspects such as fire protection savings are taken into account.

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