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A review of the fundamental dielectric characteristics of ester-based dielectric liquids

Mark Lashbrook*, Attila Gyore, Russell Martin

M&I Materials Ltd, Hibernia Way, Manchester M320ZD, UK

Abstract

The use of alternative dielectric liquids is growing steadily, with fire safety and environmental concerns at the forefront of the reasons for switching 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.

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

Early adopters of ester-based liquids quickly identified differences in electrical characteristics which mean that standard mineral oil designs, although suitable for distribution transformers, cannot always be used for higher voltage levels. From this finding the industry has embarked on a quest for clearer understanding of the fundamental differences between esters and mineral oil and how to adapt designs to allow the use of esters at ever higher voltages.

This paper will offer a review of the published research findings over the last decade from various institutions and manufacturers around the world, focusing on the differences in dielectric behavior between esters and mineral oil. It will start with fundamental studies of streamer propagation in divergent fields, through to more realistic arrangements which are designed to simulate conditions in operating transformers.

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Keywords: ester; transformer; fire; environmental; impulse; dielectric

* Corresponding author. Tel.: +44-161-864-5429; fax: +44-161-864-5444.
E-mail address: MarkLashbrook@mimaterials.com

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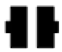
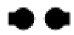
1. Introduction

For many years synthetic ester fluids were seen as specialist materials, only for use in unusual transformers, such as those in rolling stock, offshore installations and steel plants where fire safety was a prime consideration. However, in more recent times users are realizing that ester-based liquids could offer a more mainstream alternative to mineral oil and although these fluids are more expensive the overall project costs can be lower when taking into account factors such as reduced fire protection. In some space-constrained urban environments ester-based liquids may even become the preferred option, with the flammability and potential environmental impact of mineral oil making the design of modern installations extremely challenging. This type of situation has been seen with the latest 400kV projects incorporating synthetic ester fluids.

2. Standard AC Breakdown Testing

Standard test methods for assessing breakdown voltage of liquids typically employ small electrode gaps, of the order of ≤2.54mm. The electrode configuration can vary from spherical, through VDE type "mushroom" electrodes to disc electrodes. This type of testing is primarily used to give an evaluation of the cleanliness of a liquid since it gives very limited information about the actual dielectric performance. It can be seen by comparing the results in Table 1 that all the different types of liquids to be discussed in this paper give very similar results for a given electrode arrangement in this type of testing.

Table 1. Typical AC Breakdown Testing Results [1]

	Breakdown Voltage (kV)		
Method	ASTM D1816 1mm	ASTM D877 2.54mm	IEC 60156 2.5mm
Electrode Type			
Mineral Oil	47	43	>70
Synthetic Ester	46	47	>75
Natural Ester	45	47	>75

This could lead to the conclusion that all these liquids are equal in their dielectric performance, or that given a good result in the AC breakdown test one liquid is in some way superior to another. However, the true picture is more complex, since the electrical stress distribution is influenced by many factors such as electrode geometry, distance and materials types. Another key factor in the dielectric behavior is the wave shape of the applied voltage. AC voltage in the form of a clean sine wave is usually expected at frequencies of 50-60Hz depending on the geographical location. However, this is rarely the case with harmonics and other distortions of the pure waveform. In addition the prevalence of surges on the network must be accounted for; in testing this is usually characterized by two different types of event, either lightning surge or switching surge and there are standard waveforms established to test these.

So any dielectric system in a transformer must withstand AC conditions, switching impulse and lightning impulse, as well as chopped lightning impulse if this is specified. There may also be a requirement to withstand DC fields in some special cases and this adds an extra level of complexity.

When considering a new dielectric medium, therefore, all these aspects need to be tested and in the beginning researchers will look to comparisons with existing materials of known behavior to assess likely changes. As stated previously in terms of short gap AC behavior ester-based liquids are very similar to mineral oil and this gives some confidence that they can be used. For distribution class equipment up to 33kV the change to ester has required little in the way of detailed electrical design evaluation, since the electrical margins are large due to the need for excess solid insulation to provide mechanical strength. However as the voltage level rises there is less electrical margin