Next Generation Insulating Liquids

Prepared by the International working Group of IEEE DEIS Technical Committee on Liquid Dielectrics

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***Abstract*—The IEEE technical committee on liquid dielectrics (TC-LD) activities mostly include study of aging phenomena, condition monitoring, and diagnostic testing of dielectric liquids. Notably, the emphasis is laid on the environmental and sustainability factors of the dielectric liquids. The TC-LD acts in promoting research on biodegradable insulating fluids, vis-à-vis existing literature on mineral insulating fluids for applications in oil-filled electrical apparatus. Thus, to prepare the global transformer technology for the next generation, a working group is planned within the scope and framework of the TC-LD. This working group aims to understand and summarize the intrinsic nature, behavioral aspects, and challenges in using ester liquids for liquid-filled high-voltage apparatuses. The objective of fine-tuning the ester liquids as high-performance insulating liquids with enhanced workability remains the focus of the working group. The present article presents the contemporary situation prevailing with the application of ester liquids in high-voltage transformers. The key concerns to improve the workability of ester liquids are discussed. The present article may be helpful to engineers and researchers interested in alternative insulation technologies, insulation engineers, and transformer owners.**

Keywords— liquid dielectrics, transformers, synthetic ester, natural ester, insulation.

I. INTRODUCTION

Lately, ester dielectric fluids are majorly accepted for applications in high-voltage apparatuses and have been of high interest to the dielectricians and transformer engineers [1, 2]. However, with the rapid increase in the technological advancements an increase in electric power ratings is foreseen with high predicted load. The electric grid is encountered to a high severity in terms of loading and working profiles. Also, with the inclusion of the distributed power generators and deregulated conditions, this severity has triggered the need to prepare the apparatus on the power network to a wide range of vulnerable operating conditions. Hence, the power and distribution transformers are expected to be prepared for supporting such a foreseen high workability in the near future. Thus, there is a need to focus on the next generation insulating liquids, which poses a high performance to sustain a reliable operation of the high-voltage transformers.

Insulating liquids are used as an impregnant, insulant, coolant, and diagnostic media for various equipment used in the power transmission and distribution network. However, the eco-friendly nature, sustainability, and strict technical (electrical and thermal) requirements of dielectric liquids are of key concern to the utilities. Alternative liquids (ester-based) are foreseen as promising candidates to lead the future of liquid dielectrics and transform the transformer technology, in particular [1, 2]. Thus, a technical committee on liquid dielectrics is developed by the IEEE DEIS society, the focus of which is performance of insulating liquids, condition monitoring of transformers, and insulation aging phenomena [3, 4]. Inline of the above concerns, a working group is focused on to understand and summarize the intrinsic nature, behavioral aspects, and challenges of using ester liquids in liquid-filled high-voltage apparatus. The objective of fine-tuning the ester liquids as high-performance insulating liquids with enhanced workability is the focus of the working group. The objective is to emphasize and accumulate knowledge on the essential properties, challenges, and shortfalls of the ester liquids. The potential concerns include but not limited to additives, viscosity, ionization resistance, oxidation stability, gelling issues, thermal conductivity, regeneration, diagnostic-prognostic challenges, and operation in cold regions.

In addition to the above, solid insulation plays a vital role and governs the liquid insulator's service performance. Therefore, the compatibility of the high-performance liquids with upgraded solid insulants will also be a potential subject of the working group. In this line, the primary focus of the researchers and manufacturers remains inclined towards fine-tuning new alternative liquids to serve as high-performance insulating liquids in the coming generations. To deal with this, it is important to recall the following [1, 2, 5].

- The rate of degradation of ester liquids is lesser than mineral insulating liquids.

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- Ester dielectric fluids proved the possible longevity of solid insulation.
- Moisture being the number one enemy, esters are hydrophilic while mineral oils are hydrophobic.
- Esters have higher fire and flash points.
- The viscosity of natural ester liquids is challenging.
- Esters have high permittivity and less ionization resistance.
- Ester liquids are colloidal stable liquids as compared to that of the mineral oils.

The primary cause for a transformer to meet the condition of failure is overheating, which accelerates the degradation rate of the composite oil-paper insulation [6]. Thus, the heat dissipation ability of the insulating oil and thermal conductivity of the paper are key parameters. This will facilitate rapid heat dissipation and aids to achieve a control on the decay particles and other colloidal particles in the insulating liquid [6]. On the other side, the withstand voltage of the insulating liquid also plays an important role that needs to be considered for new, aged, and heavily loaded transformers. This withstand voltage is largely attributable to the decay particles and moisture within the insulation system [7]. Thus, the stability of the insulating towards the aging by-products (water and decay particles/colloids) and heat dissipation properties are the parameters that need to be considered for a high-performance insulation system. Both of the said factors will act in extending the workability of a transformer insulation system.

Meanwhile, nanofluids are expected to play a promising role as liquid replacements for mineral oils and in improving the performance of the transformer insulation system. The application of nanofluids to large power transformers is a challenging and promising topic of research. With an effective choice of nanoparticles as additives to the insulating liquids, critical properties like, viscosity, oxidation stability, thermal conductivity (cooling), ionization resistance, dielectric strength, etc. may be significantly controlled/regulated. The performance improvement achieved through nanoparticles could be the orders of the magnitude that leads to extended workability and service life of a transformer. So, application of nanofluids may lead to drastic improvement in electrical, thermal, and chemical properties of the insulating liquid which results in enhanced workability and reduced size of the insulation system.

The future of alternative insulating liquids for transformers being the main subject of the present article, few major properties/aspects that need to be focused for improved performance of the ester liquids are discussed. The present article summarizes the state-of-the-art challenges concerning the streamer behavior in ester liquids, oxidation stability and gelling, and a brief overview on the additives for transformer liquids.

II. STREAMER BEHAVIOR IN ESTER LIQUIDS

Streamer behavior in ester liquids has been studied for many years, wherein a particular increase was observed at the beginning of the twenty-first century when synthetic esters were introduced to the dielectric liquids market for a larger scale [5].

One of the most important parameters is its propagation velocity, which is related to another parameter describing streamers - acceleration voltage [5]. For voltages below acceleration voltage, streamer velocity increases marginally, however, above this characteristic indicator propagation velocity of streamers are typically of an order of magnitude higher than these developing below acceleration voltage [8, 9]. Independently of the liquid type, streamers are generally classified as slow (1st and 2nd modes) or fast (3rd and 4th modes). Their velocities are from some mm/µs for slow developing streamers up to 10-100 mm/µs for fast developing ones. Either slow or fast propagating streamers may lead to breakdown in dielectric liquids. However, breakdown is usually noticed by a 2nd mode (slow) and/or 3rd mode (fast). The change of the streamer nature from slow to fast may be explained on the basis of the field stress at that instance. If the electric field stress is in the range of less than 10 MV/cm, it may be considered as slow streamers (in 1st mode or 2nd mode). If the electric field stress is in the range of 10 MV/cm to even 100 MV/cm, it may be considered as fast streamers (in 3rd mode or 4th mode) [10]. However, the above-quoted values may differ when taking into account the liquids of different chemical composition, electrode geometry and type of voltage.

The current state-of-the-art in this field shows that in the case of some streamer characteristics the differences between mineral oil and esters are of minor while some other are remarkable. The first group includes among others the streamer inception voltage. However, it is reported that, in a non-uniform field, the streamers in esters (natural and synthetic) and mineral oils are initiated at similar magnitudes of testing voltage. Furthermore, the influence of the radius of curvature of the needle electrode on streamer inception in esters and mineral oils was assessed to be of the same order [11]. Minor difference also concerns streamer shape. The photographically recorded streamer shapes in general do not differ from each other whether ester or mineral oil is considered [5, 10]. A significant parameter of streamers is their stopping length. Both for positive and negative voltage polarity, the stopping length of streamers propagating in ester liquids was identified to be longer than that of the streamers in mineral oil. In addition, having in mind that the stopping length increases with applied voltage, this should be pointed out that this increase is observed as faster for esters. The major difference between streamers developing in esters and mineral oils is acceleration voltage. Especially for longer gaps (> 25 mm) the fast streamers in ester liquids appear at much lower testing voltage than in the case mineral oil. Thus, this may be said that transition from slow (2nd mode) to fast (3rd or 4th mode) streamers in esters occurs relatively faster than mineral oils. This may be attributable to the chemical structure of esters, which contain the polar molecules (ester groups) that are characterized by lower ionization potential than the hydrocarbon groups in mineral oil [5, 10, 11]. Thus, concerning the streamer behavior in ester liquids, the further challenges may be focused on further analyzing the streamers in esters to find the way allowing for improvement their properties, especially in the field of partial discharge inception voltage and acceleration voltage. The influence of degradation aspects on the streamer behaviour is still a posing challenge to the researchers. Importantly, the influence of additives (added to improve the performance) also needs to be investigated.

III. OXIDATION STABILITY AND GELLING

Ester dielectric fluids are divided into two main types namely synthetic esters and natural esters. Both types of esters offer distinct advantages over mineral insulating oils. Synthetic esters are chemically made from a reaction between and alcohol and short chain fatty acids, whilst natural esters are extracted from naturally grown seed crops such as soybean and rapeseed/canola. This leads to both ester types having different chemical structures which impact their oxidation stability. Given the structural differences in the two types of esters, standards have been adopted and modified to test the oxidation stability of each ester type. The oxidation stability tests are typically performed to check the quality of the ester liquid rather than determine the deterioration rate of the ester liquid over a prolonged period. The details of which are discussed below:

A. *Synthetic esters*

The main oxidation stability test referred to in the ester specifications is IEC 61125 Method C (1992, originally developed for hydrocarbon oils). In this method, a sample of the ester is maintained at 120°C for 164 hours whilst air is bubbled through the sample in the presence of a copper catalyst. At the end of the test, the following are determined and reported:

- Sludge (%w/w more appropriate to mineral oils)
- Soluble acidity (acids dissolved in the ester)
- Volatile acidity (acids formed which exit the sample as vapor, captured in a separate flask)
- Total acidity (sum of volatile and soluble acidity)
- Dielectric Dissipation Factor @ 90° (DDF, post oxidation)

However, there is an option to test at 500 hours to allow one to understand the extra stability of synthetic esters, but this is not mandatory as per the above said specification.

B. *Natural Esters*

Whilst drafting the specification for unused natural esters (IEC 62770, 2013), the experts found that it was impossible to set sensible oxidation parameter limits for natural esters based on IEC 61125 Method C, as the results of the round robin tests from several laboratories showed too much variation and poor repeatability. Ultimately, the solution was to modify Method C to only 48 hours instead of 164 hours. This gave a test method which was acceptable and more robust for natural esters. As with synthetic esters, the same post oxidation parameters are reported, with the addition of viscosity (reported a % increase over the initial un-oxidized viscosity). In 2018, an optional test method variation was added to IEC 61125 as Appendix C. In this method a sample of fluid is sealed in a tube with a copper catalyst, and the sample maintained at 150°C for 164 hours. However, the post oxidation analysis is different as shown below:

- Soluble acidity (acids dissolved in the ester)
- Dielectric dissipation Factor @ 90° (DDF, post oxidation)
- Kinematic viscosity (reported a % increase over the initial un-oxidized viscosity)

It is worth mentioning that this method is purely optional and has not yet been adopted in any ester specifications. The IEEE C57.147-2018 standard lists IEC 61125, Method C as a test that can be performed for oxidation stability, however, it is not a mandated tests as it is not listed or recommended in the ASTM D 6871 standard.

It is important to understand that natural esters tend to polymerize on oxidation making the liquid more viscous. It is quite possible for the natural ester liquid to develop thin films over the large surface of the core winding assembly (solid insulation) and sols and gelling within/over the bulk of the liquid. A view natural ester subjected to thermal stressing under open beaker aging is illustrated in Fig. 1. A detailed impact of the gel formation and its impact on the insulation system will be reported in the further articles of the working group.

Fig. 1. Gelling of natural ester under open beaker aging conditions in laboratory.

The formation of which leads to several unavoidable consequences. However, manufacturers have come up with suitable modifications to avoid this peculiar situation. It is reported that natural esters are serving well in the global transformers with an effective condition monitoring and maintenance planning policies..

IV. ADDITIVES IN TRANSFORMER INSULATION

Historically, additives in dielectric liquids are introduced into the liquid to improve the performance and serviceability of the liquid. The typical additives may be seen as two-fold, added by the liquid manufacturer (while producing the liquid) and condition monitoring engineers (on-site). The earlier is helpful to improve the performance of the new insulating liquid and the latter is added to rejuvenate and improve the serviceability of the aged/reconditioned liquid. The additives typically include oxidation inhibitors. Lately, the additives also include, depressants, and dyes along with inhibitors. Despite the above said additives, service life extension and performance improvement are continuous elements that are within the interest of the transformer industry. The potential uses of nanofluids have been reported by many researchers. A review of the works on this topic can be found in [12]. Various nanoparticles have been widely used for preparing transformer liquids -based nanofluids. Most of the researchers have investigated Fe_3O_4, Fe_2O_3, TiO_2, Al_2O_3, ZnO, CuO_2, CuO, SiO_2, BN, fullerene (C60), graphene, etc. for improving the properties of transformer liquids (mineral oils and ester liquids). The majority of the researchers have focused on the properties like viscosity, breakdown voltage, flash-point, and degradations aspects using various nanoparticles [12]. However, a few researchers have also reported the pre-breakdown investigations using nanofluids [13]. It seems that investigations in this field of research on nano-additives are affirmative, which initially showed potential in improvement of the breakdown characteristics of the esters. The propagation of streamers in ester liquids may also be controlled by adopting suitable electronic scavengers [5, 10].

Apart from the adding nanoparticles for property enhancements, oxidation inhibitors and pourpoint depressants are also other additives that need to be investigated. Despite being the fact that, pourpoint and oxidation stability are challenging aspects for natural esters, a very limited literature is available on the these aspects. The critical challenge in this line concerning alternative liquids include finding suitable antioxidants and pourpoint depressants. Recently, few manufacturers have come up with low pourpoint insulating liquids.

Meanwhile, high thermal conductivity and stability of the cellulose material is another important parameter. It is possible to achieve high performance solid insulation (paper/pressboard) with involvement of suitable nanoparticles. Also, it is to be recalled that transformer life is generally designed for few decades and a huge number of transformers are connected to the power grid. Thus, a huge potential of challenge and research scope is underlined within the investigation of suitable additives that will rejuvenate the insulation system.

V. CONCLUSION

In this paper, key concerns foreseen to improve the workability of ester liquids are discussed. The main concerns include characterizing, comparing and studying the various stabilization against oxidation by additives (antioxidants) or improving the thermal and electrical properties by nano-structuring (considered as the object of the next industrial revolution). The behaviour at low temperatures is crucial too. These alternative oils being more viscous, their capacities as coolants as well as the consequences on the conceptual aspect of transformers are to be evaluated. In fault diagnosis of power transformers filled with biodegradable liquids is another actual limiting factor.

The proposed activities under the umbrella of the TC-LD is consequently, expected to prepare utilities for the wide use of esters in the next generation of transformers, which is of industrial / economic importance and of critical academic significance. The planned activities may also have an impact on international standards.

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