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Mixed Insulating Liquids with Mineral Oil for High Voltage Transformer Applications: A Review

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ABSTRACT

Due to the growing interest in environmental concerns, synthetic, and natural esters have become the key focus of the picture in the last two decades as insulating fluids for high voltage equipment. This is because, unlike mineral oil, ester liquids are biodegradable, non-toxic, and safe for the environment and human health. These fluids are derived from renewable sources and have high fire resistance. However, synthetic and natural ester fluids are still used in a rather limited number of electrical equipment for several reasons (high cost, high viscosity and density, increased tendency towards electrostatic charge, faster propagation of streamers in an inhomogeneous electric field, etc.). Besides, a huge amount of equipment is filled with mineral oils. The massive replacement of oil-filled equipment with natural or synthetic esters may be extremely expensive to utilities and transformer owners. In addition, in the event of partial or complete retrofilling of mineral oil with an ester fluid, the equipment may evidently contain a mixture of two insulating fluids; therefore, demanding the scope for research on mixed insulating liquids. The intent of this article is to present a comprehensive review of the literature on the blend of mineral oil and other alternative dielectric fluids. The critical research progresses, highlights, and challenges related to mixed liquids along with significant tutorial elements as well as some analyses are discussed. This review should be useful for researchers, utilities, and transformer owners concerned with ester liquids and retro filling aspects.

Index Terms — **Transformer, mineral oil, insulating liquid, ester fluids, mixed liquids.**

1 INTRODUCTION

TO date, mineral oils have remained a successful dielectric liquid for power and distribution transformers and other high voltage apparatuses around the world. However, mineral oils are non-renewable resources obtained from crude petroleum stocks. Due to the fact that mineral oils are non-biodegradable with a low fire resistance and a negative impact on health and the environment, the issue of replacing mineral oil with biofluids is of high engineering importance [1-4]. Despite a fairly wide range of biodegradable ester fluids on the market, mineral insulating oils remain the backbone for insulating and cooling purposes in high-voltage transformers.

There are several reasons for this: their affordable costs, good insulating properties, low viscosity, and the availability of standardized requirements for monitoring their properties, both for unused and in service oils. Besides, with over 130 years of experience with mineral oils, many valuable methods and criteria for assessing the condition of the insulating system of oil-filled equipment have been developed [5-8]. For decades, few methods have been developed for diagnosing oil filled equipment, for restoring the insulating characteristics (in particular, methods for reclaiming or regenerating mineral oil, drying the solid insulation [6, 9-16]. In other words, the operation of power equipment filled with mineral insulating oil is quite understood, well established and does not raise

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acute questions for specialists or condition monitoring engineers.

Moreover, an increase in the production of mineral insulating oils by 7% is expected by 2025 [17]. This is associated with the increase in the world's population, with the growing industrialization and urbanization, with the introduction of digital technologies, with the replacement of old worn-out electrical equipment. The largest quantities of mineral oil are used by Asian countries, North America, and Europe [17]. Accordingly, in these parts of the world, it is planned to increase the production of insulating oils (paraffin, naphthenic, aromatic) intended for various electrical equipment. Thus, taking into account the huge volume of insulating oil (several billion liters) in global transformers, and the tendency for the availability of crude oil, methods for improving the workability and alternatives are of high importance.

Numerous researchers across the globe have emphasized the performance and workability improvement of mineral oils. Fire resistance is one of the major challenges addressed in [18] by adding various additives that increase the flashpoint. However, the proposed additives allowed an increase in the flash point by only 2-7°C. Several additives are noticed to lower the flashpoint by almost two times (from 135°C to 73°C). Also, the introduction of certain nanoparticles (TiO_2, Al_2O_3, Fe_3O_4, SiO_2, C_{60}, and etc.) in pure mineral oils have not raised any unambiguous results [19-21].

The most practical way to improve some of the properties of mineral insulating oils is by mixing them with other dielectric fluids in different volumetric concentrations. Mixing mineral oil with alternative dielectric liquids during partial refilling or a complete replacement is a feasible solution [22, 23]. It is estimated that after the retro-filling process, up to 7-10% of the mineral oil remains in the cellulose insulation, but also at the bottom and the walls of the tank or on the transformer core [24]. Therefore, there is a need to understand the phenomenal behavior and changes in properties of mixed liquids. Research work in this direction has been carried out since the beginning of 2000. Different researchers have targeted various liquids mixed with mineral oils. At the same time, some researchers have focused on different proportions with the aim of understanding the optimal blending ratio. The properties (physicochemical, electrical), behavior, degradation rates, influence on cellulose insulation have been mostly focused on this topic. The detailed research findings have been organized and presented in the subsequent section of this article. The discussions in the article are spanned to studies on the blend of mineral oil with silicone oils, natural esters, and synthetic esters. The literature concerning mixing ratio, changes in various properties, and operational behavior have also been summarized in this article. The present review might be helpful for transformer owners, utilities, and researchers interested in improving the workability of mineral oils and those concerned with alternative dielectric liquids.

2 BLENDS OF DIFFERENT INSULATING LIQUIDS

2.1 MINERAL OIL AND SILICONE FLUID

Experiments on mixing mineral oils with silicone fluids (polydimethylsiloxanes) in various ratios lead to positive changes such as an increase in flashpoint and fire point [25]. But at the same time, polydimethylsiloxane added to mineral oil does not improve oxidation resistance but increases the viscosity and the cost of the mixture [26]. Moreover, the water saturation limit does not improve since neither oil nor silicone liquid has a good ability to dissolve water [25, 27]. Another disadvantages of this mixture is their extremely low degradability under the influence of microorganisms. From the point of view of environmental safety, this behavior does not meet one of the most important requirements for insulating fluids today - a high degree of biodegradability.

2.2 MINERAL OIL AND NATURAL ESTER

The most valuable are mixtures consisting in mineral oils and biodegradable esters, with improvements in some physicochemical characteristics. Mixing natural ester (esters based on glycerin and fatty acids) with mineral oil has both positive and negative effects. Among the advantages, are miscibility in any proportions, an increase in biodegradability due to the added bioester, an increase in the flash point and fire point, and an increase in the water solubility limit. The good hygroscopic nature of esters, has a positive effect on increasing the dielectric strength of the mixture at a given relative moisture content. With the increase thermal performance, the service life of the paper insulation is lengthened [28, 29]. The gas-absorbing properties of natural esters, in general, is also another positive effect on the insulating mixture. But at the same time, mixing these two liquids leads to undesirable results: an increase in the viscosity of the mixture, an increase in the pour point since natural ester itself has a high pour point. Another significant drawback of this mixture is the deterioration of one of the main properties – the oxidation stability since natural esters do not initially have a sufficient level of antioxidant stability [30-33]. Many natural esters contain additive packages consisting of pour point depressants, oxygen resistance enhancers, and in some cases, antimicrobial agents or copper deactivators. However, these additives do not always lead to the desired effect, and some of them, on the contrary, impair the physicochemical characteristics [34, 35]. The way of improving the oxidation stability of a natural ester by mixing it with mineral oil or a synthetic ester liquid also does not give a worthwhile result due to the presence of a large amount of polyunsaturated fatty acids initially contained in the natural ester [36].

2.3 MINERAL OIL AND SYNTHETIC ESTER

Synthetic ester (pentaerythritol fatty acid esters) has the highest water solubility limit among all-dielectric liquids, a low pour point, an excellent oxidation resistance, and is biodegradable. This fluid is more homogeneous in term of chemical composition since there is no need to introduce a whole complex of various additives. Synthetic ester is not inferior to natural ester in terms of fire resistance: flash point and fire point. In particular, when the flame of an acetylene-oxygen burner (with a temperature above 2000°C) is directed to the surface of the synthetic ester within 70 minutes, the liquid temperature reaches 260°C, and no ignition occurs. In contrast, under the same conditions, mineral oil ignites after 4 minutes [37]. Also, the disadvantage concerning the high viscosity may be eliminated by mixing synthetic ester with mineral oil. Thereby improving the cooling performance of the transformer without significant investment.

3 RESEARCH PROGRESS ON THE BLEND OF MINERAL AND SYNTHETIC ESTER

3.1 MIXING RATIO

I. Fofana, A. Beroual, U. Mohan Rao, G. Dombek, and other prominent scientists have made a significant contribution to study the properties of mixtures of mineral oil and synthetic ester fluids [30, 31, 38-47]. Fofana et al were the first to pinpoint the focus on a mixture of 80% mineral oil and 20% synthetic ester. This proportion is the best compromising solution, both from a technical and an economic point of views. After all, the cost of synthetic ester liquids is several times (7 to 10 times) expensive than mineral oils. In [26, 38, 39], it was shown that the mixtures of naphthenic oil with a ratio of 10%, 20%, 50%, 90% (by volume) of synthetic ester do not delaminate at temperatures from -40°C to 105°C. In [41], it is reported that the oxidative stability of the mineral insulating oil increases with blending of 20% of mineral oil with synthetic ester. The rate of degradation of the blend is noticed to be significantly controlled with this ratio. I. Fofana and U. Mohan Rao have extensively investigated the ratio 80:20 (mineral oil: synthetic ester) for use in transformers [38-40, 43-47]. The research findings are affirmative towards the promising ratio 80:20 for usage in liquid-filled high voltage equipment.

3.2 KINEMATIC VISCOSITY

The kinematic viscosity is among the most important parameter for heat transfer inside high voltage equipment. To achieve high heat transfer in power transformers by convection, low viscosity and good specific heat are required. The viscosity of mineral oil is much lower than that of synthetic ester. Therefore, it is expected that with an increase in the proportion of ester, the viscosity of the mixture increases, which hampers heat transfer. However, the addition of ester dielectric in an amount of up to 30% does not have a noticeable effect and the viscosity of such mixture remains very close to that of mineral oil itself [26, 27, 38]. Therefore, the heat transfer efficiency of the mixture insulating liquid does not decrease too much. This is explained by the fact that the resulting mixtures, due to the chemical interaction, do not obey the simple mixing rule, which is expressed by equation (1) [26].

$$\psi_C = X\cdot\psi_A\cdot 0.01 + Y\cdot\psi_B\cdot 0.01 \qquad (1)$$

where, ψ_C - mixture characteristic; X – liquid content A (%) with parameter ψ_A; Y – liquid content B (%) with parameter ψ_B.

3.3 BREAKDOWN VOLTAGE (BDV)

Interestingly, the addition of synthetic ester in an amount of 10% to 50% increases the average value of the AC breakdown voltage versus relative moisture content, of mineral oil and slows down the decrease in its dielectric strength with aging [27, 30]. This is because, synthetic esters have a high water saturation limit, about 30 times that of oil (or 2500 ppm versus 70 ppm at 25°C). It is to be noted that the AC breakdown voltage of oil largely depends on emulsion or dispersed water content. Thus, when the polar ester is added to non-polar oil, moisture shifts from emulsion state to a dissolved one, thereby significantly reducing the effect of moisture on the breakdown voltage [39]. Also, the AC breakdown voltage remains high for the aged insulating mixture [37].

In DC voltages, the smallest breakdown voltage value of the various mixtures of oil and synthetic ester always remains higher than the highest value of that of mineral oil alone. However, the average DC breakdown voltage of mineral oil and synthetic ester oil mixtures is less than AC breakdown voltage. For example, AC BDV of mixture 80%MO + 20%SE is 85 kV, DC BDV this mixtures is 57 kV. While the breakdown voltage of mineral oil is 53 kV (DC) and 52 kV (AC). Whatever the type of voltage (DC or AC), mixtures of oil and synthetic ester always have a significantly higher breakdown voltage than mineral oil alone. The addition of only 20% of synthetic ester oil is sufficient to considerably increase the breakdown voltage (DC or AC) of mineral oil. The dielectric strength of such a mixture is much higher than that of mineral oil alone and can reach that of ester oils [30].

3.4 RELATIVE PERMITTIVITY

The relative permittivity of mineral oil is about 2.2, and that of the synthetic ester is 3.2. The relative permittivity of paper insulation is approximately 4.2 [42, 49]. The use of dielectrics with different relative permittivity leads to a change in the distribution of the electric field strength in multilayer insulation. As you know, breakdowns will occur in the place where the electric field strength is greatest. In other words, the violation of the electrical strength of the oil barrier insulation begins with the breakdown of the oil channel.

The use of mineral oil mixtures with a synthetic ester content of more than 20% by volume as a liquid dielectric in combination with paper insulation leads to a decrease in the field strength in the liquid and paper layers. The electric field in the "ester-oil mixture - paper" system is more uniform than with mineral oil. In general, this has a positive effect on increasing the electrical strength of the “paper-ester-oil” insulation and greater resistance to the effects of a discharge on the surface of electrical cardboard (sliding discharge) impregnated with insulating mixtures of mineral oil and synthetic ester. It has been established that the relative

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permittivity practically does not change with the aging of the mixtures (less than 5% changed) [38].

3.5 DIELECTRIC DISSIPATION FACTOR

With an increase in the proportion of ester, the mixture's dielectric dissipation factor or tg δ (DDF) increases. Thus, in comparison with pure oil, the DDF in fresh mixtures increases by 1.5-4.0 times [50]. The tendency of an increase in dielectric losses is also observed with the aging of mixtures (see Table 1) [38, 49]. Thus, having a scope for reducing the dielectric losses with that of the mixed insulation system.

3.6 WATER CONTENT

Due to the hygroscopic nature of synthetic ester, the moisture saturation limit also increases in the resulting mixture of synthetic ester and mineral oil (see Table 1) [37]. It was also noticed that during aging, the water content in the mixtures increases [51]. This is due to the moisture absorption in form of water vapor from the air, especially if the aging experiments were carried out under unsealed conditions. Since ester are hydrophilic, and mineral oils are hydrophobic, there is a significant difference in both the liquids' water holding ability. Adding an ester group to mineral oil improves the water saturation limit of the mixture.

Table 1. Properties of mixed liquids (naphthenic oil and synthetic ester - pentaerythritol fatty acid esters) [38, 41, 50, 51]

Properties	Proportion of ester in the oil, %			
	0	10	20	50
Relative permittivity at 25°C (fresh blend)	2.20	2.29	2.40	2.66
Dielectric dissipation factor *(tg δ)* (10^{-4}) at 90°C (fresh blend)	7	8	12	17
Dielectric dissipation factor *(tg δ)* (10^{-4}) at 90°C (old blend)	17	22	26	28
Water content, ppm at 20°C at 100°C	 40 650	 100 940	 310 1600	 830 2900

3.7 FLASHPOINT

Flashpoint (closed cup) of insulating mixtures of mineral oil and synthetic ester increases with increasing proportion of ester. Thus, the flashpoint of the mixture of mineral oil and synthetic ester ratio of 80% to 20% is about 180°C, which is almost 30% higher than the flashpoint of mineral oil [27]. Accordingly, there is an increase in the fire-resistant properties of the mixed liquids [42, 44, 50, 52]. A significant increase in the fire-resistant properties of the mixture is achieved when the content of ester in the oil is more than 80% [42, 52]. This is because synthetic esters have a flashpoint greater than 300°C.

3.8 OXIDATION STABILITY

The oxidation stability of mineral oil and synthetic ester mixtures is monitored in [26] by the change in the tangent of the dielectric dissipation factor (tg δ) and acidity. These indicators are the most suitable properties for assessing the oxidation condition of a liquid. The acidity and tg δ were measured before and after the aging process. The oxidation of the mixtures was carried out under conditions close to those existing in free breathing power transformers with air inlet (according to the ASTM D1934 standard, which regulates the exposure of oil for 96 hours with circulating air at 115°C). Another oxidation experiment of the mixtures was performed out in the presence of copper (8.8% by weight) and kraft paper (15% by weight) IEC 61125 (A). After checking pertinent indicators, the authors conclude that the addition of 20-50% ester liquid to mineral oil slows down it is aging [38], but with a slight increase in acidity and the dielectric dissipation factor (tg δ) [26]. However, the early indication of oxidation is the formation of colloids and reduction in the interfacial tension. This process further continues to increase the acid number and sludge formation. Therefore in [41, 47], extensive degradation of mineral oil and blend of mineral oil and synthetic esters (80:20) was performed. It is reported that sludge appears in mineral oil at an early stage than the mixture of mineral oil and synthetic ester. Even though mixed oil's interfacial tension is low compared to mineral oils, higher sludge formation at an early aging factor in mineral oils is questionable. In contrast, evidence of no sludge in esters is a potential merit in adding ester liquids to mineral oil. Recently, it is reported that esters have a tendency to dissolved sludge colloidal particles [53].

3.9 AGING OF THE MIXTURES

The work reported in [38] present the results on the aging of mixtures of synthetic ester and naphthenic mineral oil. The authors showed that accelerated aging of mixtures in an open vessel at a temperature in the presence of catalysts (steel, aluminum, and zinc each 3g/l) leads to a change in the color of the liquids. The ester liquid's color changes slightly, while the mineral oil becomes almost black. For mixed liquids containing 10, 20, and 50% ester, the darkening effect is less pronounced with increasing ratio. The darkening of the color of the liquid indicates thermo-oxidative destruction of the insulation components with the formation of carbon dioxide, resinous substances, and other compounds. The color of the filter paper, in which the metal catalysts were wrapped, also changed after aging. In oil, the paper becomes almost black, while the color of the paper immersed in ester is slightly yellow. For the mixtures, the paper filter are less brown with increasing amount of ester in the oil. These observations indicate a decrease in the rate of decomposition of the mixed liquids relative to the amount of synthetic ester added. Extensive degradation studies of mineral oil, natural ester, synthetic ester, and a mixture of synthetic ester and mineral oil (80:20) are reported in [44-47]. Critical measurements include UV spectral curves, interfacial tension, flashpoints, color, sludge monitoring, and functional group changes with aging. The degradation of the mixed fluids is reported to be lesser than that of the mineral oil.

3.10 THE GASSING TENDENCY

In service conditions, under the influence of elevated temperatures and partial discharges, the liquid is subject to chemical decompositions. As a result, light gases with initial traces of hydrogen are formed. Gas bubbles are weak dielectrics, and their presence favors partial discharges or initiate breakdown. The higher the tendency to gassing, the higher the risk of breakdown of the insulation system is. For mineral oil, the first noticeable gas bubbles appear at temperatures between 250°C and 300°C. This means that at this temperature the oil begins to boil and gas bubbles are released from the oil volume. Whereas synthetic ester in direct contact with the heating coil starts to boil at a higher temperature - from 350°C to 400°C [38]. At this temperature, the total amount of gas generated by mineral oil is much higher than the amount of gas generated in synthetic ester. A similar trend is observed for a mixture of oil and ester in a ratio of 80:20, namely when the mixture is heated to 600°C for 3 minutes, the volume of the evolved gas is 5 times less than the volume of gas generated by only oil [38, 40].

It is worth noting that the gassing tendency characterizes the resistance of an insulating liquid to decomposition when exposed to high temperatures without the presence of a spark. And such an indicator as the flashpoint indicates the presence of explosive and flammable substances that form a mixture with air, which ignites when a spark is applied.

3.11 ELECTROSTATIC CHARGING TENDENCY

Electrostatic charging tendency describes the property of a liquid to acquire a charge when moving on a solid surface. Friction electrification leads to electrostatic charging and potential breakdown of equipment insulation. A. Beroual et al. [26] reported that the addition of 20% ester increases the level of electrostatic charge of the mixture relative to base mineral oils. It is known that the streaming electrification of an insulating mixture decreases with an increase in the concentration of water [54, 55]. As reported by authors in [55, 56], the higher the resistivity, the lower the tendency towards electrostatic charging of the oil. When liquids are mixed, the resistivity of the insulating mixture decreases, which partly explains why ester liquids and mixtures with mineral oils have a higher electrostatic charging tendency.

M. Zdanowski and M. Maleska [57] showed how the magnitude of the electrification current in the mixtures of oil and ester changes when they flow at a speed of 0.34 m/s (gravitational flow) through pipes made of different materials (iron, aramid, and cellulose). Few studies [26, 57, 58] have shown that the electrification of the prepared mixtures strongly depends on their composition, or rather on the ratio of oil and ester in the mixed oil. The mixtures of the synthetic ester with fresh mineral oil exhibit electrostatic properties that are significantly different from those with aged mineral oil. In the first case, the electrification current increases with an increase in the proportion of ester, reaching a maximum value at 40% of ester content in a mixture and then decreases. In the case of a mixture of synthetic ester with oxidized mineral oil ranging from 10% to 80% (by volume), the electrification current decreases. After 80% of the ester fraction in the mixture, an increase in the electrification current is observed [57]. The trend described above is observed for mixtures when they move, regardless of the pipe material. However, the largest streaming electrification is observed when the mixtures are passed through a metal pipe, and the least - through a cellulose pipe while the aramid material occupies an intermediate position.

3.12 INFLUENCE OF THE MIXTURES ON THE CONDITION OF THE INSULATING PAPER

One of the main requirements that new insulating fluids must meet is the compatibility with construction materials, including the solid insulation. In [39], the electrical insulating characteristics of cellulose (PSP 3010) and aramid paper impregnated with a mixture of synthetic ester (proportion in the mixture 10, 20, and 50%) and naphthenic insulating oil (the proportion in the mixture is 90, 80 and 50%, respectively) are reported. The authors conclude that the electrical strength of cellulose paper impregnated with the mixtures made of different content of ester does not differ significantly from each other (variation less than 4%). In the case of impregnation with aramid paper, an increase in the dielectric strength of up to 10% is observed when compared to paper impregnated with mineral oil. Regarding the relative permittivity of paper, both for cellulose and aramid, this indicator increases with an increase in the proportion of ester in the impregnating liquid. A similar trend is observed for the dielectric dissipation factor *($tg\ \delta$)* of insulating papers [39].

To assess the long-term effects of insulation mixtures, the authors performed the aging of insulation materials immersed in mixtures with different ester content. As a result, it was found that with an increase in the proportion of ester, the aging rate of cellulose, and especially aramid paper, decreases. Besides, there is a slight increase in the dielectric loss tangent, but this aspect does not affect the performance of the transformers. It is also concluded that oil and ester mixtures with a content of 20% and higher, have a positive effect in increasing the thermal and oxidative stability of insulating paper and insulating board at higher temperatures [27, 59]. In [43, 46], the authors emphasized the degradation of cellulose kraft papers in various liquids along with mixed oil. Direct and physical degradation of cellulose papers aged in different liquids is measured using dilatometry analysis and X-ray diffraction analysis. The paper elongation/shrinkage, change in cellulose crystal size are controlled with the addition of ester liquid to mineral oil.

4 CONTEMPORARY CHALLENGES

The enhancement of the performance of the power transformers insulating system may be achieved by improving the properties of an insulating liquid. An engineering and material perspective of this may consist in mixing it with other liquids and introducing pertinent additives. The present section focuses on the potential challenges to address when improving the properties by mixing with other insulating liquids.

Table 2 summarizes the changes in the characteristics of the mixtures of mineral oil with silicone fluid, natural ester, and synthetic ester. The analysis of the data reported in the literature shows that the most promising mixtures for use in

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high-voltage equipment are mixtures consisting of mineral insulating oil and synthetic ester. This is because, many parameters of the blend formed, improved. According to [26, 38-41, 44-47], the most appropriate proportion of mineral oil and synthetic ester liquids is the ratio of 80% mineral oil and 20% synthetic ester.

Table 2. Changes in the characteristics of naphthenic oil when mixed with various insulating liquids [26, 27, 30, 32, 36, 38 - 52, 57, 58, 59].

No	Property	Added liquid from 20 % to 90 %		
		Silicon fluid*	Natural ester**	Synthetic ester***
1	Miscibility	In any proportion	In any proportion	In any proportion
2	Breakdown voltage	↓-	↑+	↑+
3	Dielectric dissipation factor	=	↑-	↑-
4	Relative permittivity	=	↑+	↑+
5	Resistivity	↓-	↓-	↓-
6	Kinematic viscosity	↑-	↑-	↑-
7	Density	↑-	↑-	↑-
8	Flashpoint	↑+	↑+	↑+
9	Fire point	↑+	↑+	↑+
10	Water solubility	↓-	↑+	↑+
11	Acidity	=	↑-	↑-
12	Oxidation stability	=	↓-	↑+
13	Gassing tendency	=	↑-	↓+
14	Electrostatic charging tendency	=	↑-	↑-
15	Service life of paper insulation	=	↑+	↑+
16	Biodegradability	↓-	↑+	↑+
	Total (number of «+»)	2	7	9

Note: «↑» : the value increases; «↓» : the value decreases; «+» : the property of the mixture is improved; «-» : the property of the mixture deteriorates; «=» : the property of the mixture does not change or changes slightly; * - polydimethylsiloxanes; ** - esters based on glycerin and fatty acids; *** - pentaerythritol fatty acid esters.

The characteristics of this mixture/blend meets the requirements of IEC 60296 [60]. The latter means that such a mixing ratio is the criteria for use in electrical equipment without limiting the loads and making any design changes. The design and monitoring aspects of the blend of mineral oil and synthetic ester are listed in [44, 47]. The specific properties of mineral oil and the blend of mineral and synthetic ester liquids are reported in [38, 39, 44]. Albeit, the design aspects do not require demanding changes in the existing design. There is a need to understand the thermal dynamics of a transformer filled with mixed liquids. This should allow a better understanding of the cooling behavior, thermal dynamics, moisture behavior, and viscosity changes with aging. In addition, several parameters such as gassing tendency, dissolved gas analysis, moisture migrations, water uptake and relative saturation need to be investigating while considering the influence of aging and aging byproducts.

It is worth noting that the 80/20 ratio (oil/ester) is applicable only to work for naphthenic oils. This is because various researchers have carried out studies on this ratio. A large number of experiments with naphthenic oils are reported since most utilities and transformer owners mainly use naphthenic based oils. This does not mean that paraffinic liquids are not miscible rather, potential investigations are required before recommending this to the industry. It should also be understood that some utilities do operate high-voltage equipment filled with paraffinic oils, and very few with aromatic oils. For paraffinic and aromatic oils, the chemical composition of which is different from naphthenic-based oil, the optimal mixing ratio of oil-ester may be different.

Despite numerous studies in the field of mixing naphthenic mineral oils with ester liquids and the listed challenges, there are other research gaps including: pre-breakdown phenomena, the appearance and distribution of streamers, the characteristics of streamers and partial discharges, the formation of combustible and non-combustible gases, and the behavior of insulating mixtures during long aging or real life aging. The compatibility of insulating mixtures with other components of the transformer (varnishes, paints, metals, solid insulation, rubber seals, etc.) also may serve as valuable information for their practical application. With the aim of a successful "cold" start of the transformer, it is necessary to know exactly how the mixtures may behave at very low temperatures, typical for cold climate regions. Therefore, there is an urgent need to establish aging markers (such as acidity, interfacial tension, dissolved gas analyses interpretation, etc.) of the mixed fluids. Another significant aspect of the potential use of mixed liquids in power transformers is the determination of procedures allowing maintaining the operational properties of the insulation system in pristine conditions (efficiency of sorbents in adsorption and thermosyphon filters, regeneration, replacement, refilling, retro-filling, and etc.).

In general, it is worth noting that investigations on the study of the electrical insulating properties of insulating liquids and their mixtures are of great practical importance since they are useful for insulation engineers. To improve the reliability of a transformer, reduce environmental hazards, and improve fire safety, the knowledge gained must also be taken into account when modernizing power equipment to be filled with ester liquids (including blending with mineral insulating oil). Particularly, the condition monitoring aspects of the mixed liquids and service experience are to be established.

With the growing electricity demand, and, consequently, with an increase in the operating voltage of power grids, the requirements for insulating fluids are increasing. They must have excellent electrical insulating properties, high chemical stability, high biodegradability and high fire-resistant. Mineral oil, which has been used for over 130 years in electrical equipment, does not meet the two last properties. Therefore, the development of an insulating liquid that would maximize the required properties is an important task.

5 CONCLUSION

With the large number of power equipment filled with mineral oil around the world, a possible solution would be to retrofill or improve the performance by admixture with other liquids or appropriate additives.

According to the results published in the literature, the mixing of mineral oil with silicone fluids leads to an improvement in such indicators as flashpoint and fire point. At the same time, other important characteristics deteriorate, such as water solubility, breakdown voltage, resistivity, and biodegradability. That is, the main goal of improving the insulation system of high-voltage equipment by mixing oil with silicone fluid - is not achieved.

An analysis of the literature has also shown that mixing mineral oil with natural esters in different proportions improves several characteristics: water solubility, breakdown voltage, relative permittivity, flash point, fire point, the service life of cellulose insulation, and biodegradability. However, adding a natural ester to oil does not improve one of the main properties of an insulating liquid - oxidation stability. That means that such mixtures, like the natural ester itself, are subject to accelerated oxidation under the influence of oxygen, high temperature, high voltage, etc. And as some studies show, such mixtures (MO+NE), like the natural ester itself, can only be used in sealed equipment.

The results of multilateral studies show that the best technical solution to improve the properties of the insulating system at present is the mixing of mineral oil with synthetic ester. When a synthetic ester is added to the oil, a significant improvement in many indicators occurs (Table 2). In particular, oil mixtures with a synthetic ester content of 20% or more by volume have good dielectric properties and high oxidation stability. The mixed oil is also proved to aid the longevity of the solid insulation. The mixing ratio of 80%MO:20%SE is the limit for use in electrical equipment without limiting loads or making any design changes. However, to guarantee the use of these mixtures or to retrofill existing units, additional concerns listed in this review paper should be addressed.

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