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Proceeding Paper

Performance Enhancement of Aged Mineral Oil by Blending Synthetic Ester for Transformer Insulation Applications †

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Abstract: Mineral oil derived from petroleum is the most preferred liquid insulation and coolant in power and distribution transformers because of its stability at high temperatures, as well as its excellent electrical insulating properties. Since it is non-biodegradable and inflammable, an alternative insulating liquid should be developed, or a possible approach should be established, to further utilize the aged mineral oil in the existing transformers to avoid the problem of discarding the oil. Though natural esters look like a promising alternative, they suffer from excessive oxidation which makes them unsuitable for transformer insulation applications. This work presents the feasibility of blending aged mineral oil with synthetic ester to extend its life. Both fresh and aged mineral oil were blended with synthetic ester separately using ultrasonication after the removal of moisture content. The electrical, thermal, and physiochemical characteristics of the blended oil were studied by measuring breakdown voltage, flash and fire points, and viscosity, respectively. These characteristics varied depending upon the ratios of mineral oil and synthetic ester. The optimum ratio of synthetic ester and mineral oil for enhanced performance was found as 1:4 for both fresh and aged mineral oils. This adds an advantage of reduced synthetic ester requirement and, thus, reduced cost. A comparison of results also revealed that the optimum ratio of mineral oil and synthetic ester depends on the ageing condition of the oil, electrical, physiochemical, and thermal properties of the blended oil. The results also proved that the aged mineral oil can be reused after blending it with synthetic ester, which avoids discarding the oil.

Keywords: mineral oil; synthetic ester; transformer liquid insulation; breakdown voltage; viscosity

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1. Introduction

High-performance dielectric materials are required as the electric power transmission system is moving toward extra and ultra-high voltage transmission. A power transformer is the most important equipment of the electrical power system. The liquid insulation used in such transformers should have high breakdown strength, as well as enhanced thermal conductivity, for higher ratings at smaller sizes due to better heat dissipation [1]. Therefore, improvement of electrical, physiochemical, and thermal characteristics of insulating materials is a major concern in the current situation. Mineral oil derived from petroleum is the most preferred insulating fluid in transformers because of its better dielectric and thermal properties. Mineral oil, which is nonbiodegradable and combustible, is becoming unpopular as environmental concerns develop [2]. This necessitates the search for alternative insulating liquids for transformer applications.

Several research articles have been published on the use of nanoparticles to improve the dielectric and thermal properties of mineral oil. Various nanoparticles such as SiO_2, Al_2O_3, TiO_2, Fe_3O_4, ZnO, etc., were added to the mineral oil with different weight proportions that enhanced the dielectric and thermal properties of the base mineral oil [3–5]. The addition of silica and fullerene nanoparticles increased the partial discharge inception voltage, and reduced the discharge magnitude of mineral oil [6]. However, the optimum concentration of nanoparticles to be used varies for different materials. As well, the cost of nanoparticles is very high. Further, the stability of nanoparticles in the base mineral oil for long-term usage, and the interaction of nanofluid with transformer solid insulation, are a few topics that need to be addressed [7,8]. These issues forbid the application of nanofluid as transformer liquid insulation.

Natural esters synthesized from vegetable oils, on the other hand, appear to be a viable alternative for mineral oil due to their rapidly biodegradable and non-flammable character. Natural esters such as palm oil, coconut oil, etc., have shown good dielectric and thermal properties [9–11]. The effect of adding nanoparticles in natural esters was also investigated and comparable results were achieved [8,12]. The blending of natural ester and mineral oil also proved to be a promising substitute [13]. The ageing studies revealed that natural esters enhance the life of paper and pressboard insulation by absorbing moisture [14]. However, the double bond present in the R chain of the natural ester becomes broken when the liquid comes into contact with the oxygen and results in oxidation. This reduces the life of natural esters and limits their application for transformer insulation [15].

Dielectric and thermal properties of artificially modified synthetic esters are comparable with those of mineral oil and natural esters [16]. They are free from oxidation which makes them better than natural esters. However, their higher cost compared to mineral oil and natural esters makes them unfavourable. All these issues make the mineral oil a better option for transformer liquid insulation, which is undesirable. Hence, a trade-off between the unwanted characteristics of mineral oil and desired characteristics of synthetic esters should be made. Blending mineral oil and synthetic ester is proved to be a good choice to achieve the above-said objective. A few studies have reported on the enhancement of dielectric and thermal properties through the testing of blending fresh mineral oil and synthetic ester [13].

This study reports on the enhancement of dielectric and thermal properties of aged mineral oil via its blending with synthetic ester. The results would help give insight into the reusing of the aged mineral oil and the prolonging of its life. The same study was conducted on the blend of fresh mineral oil and synthetic ester for comparison purposes.

2. Materials and Methods

The optimum ratio of synthetic ester and mineral oil suggested was 1:4 [17]. However, this is applicable only to fresh mineral oil, and the proportion may vary when the mineral oil is aged. Hence, different ratios of synthetic ester and mineral oil chosen for blending were 1:4, 2:3, and 4:1 to determine the optimum ratio.

2.1. Blending of Oils

The mineral oil, aged for 16 years, was collected from an 11/66 kV, 16 MVA power transformer for this study. The aged oil was drained from the bottom of transformer tank. Though it was drained from the tank bottom, the circulation of oil during the transformer operation over a long period resulted in equal aging of the oil throughout the tank. All three oils viz., synthetic ester, fresh mineral oil, and aged mineral oil were heated in a microwave oven at 120 °C for 30 min to remove the moisture content. The microwave heating resulted in uniform distribution of heat throughout the oil, and avoided the generation of gas bubbles. Heated oils were allowed to cool down to ambient temperature.

Ultrasonication was done for 30 min to blend the oils at different ratios after the heated oils reached the ambient temperature. Ultrasonication provided homogeneous blending of oil without generation of gas bubbles. On the other hand, mechanical stirring and magnetic stirring would produce gas bubbles in the oil. Synthetic ester was blended with fresh mineral oil and aged mineral oil, separately, at 1:4, 2:3, and 4:1 ratio. Once ultrasonication was over, breakdown voltage, flash point, fire point, and viscosity were measured.

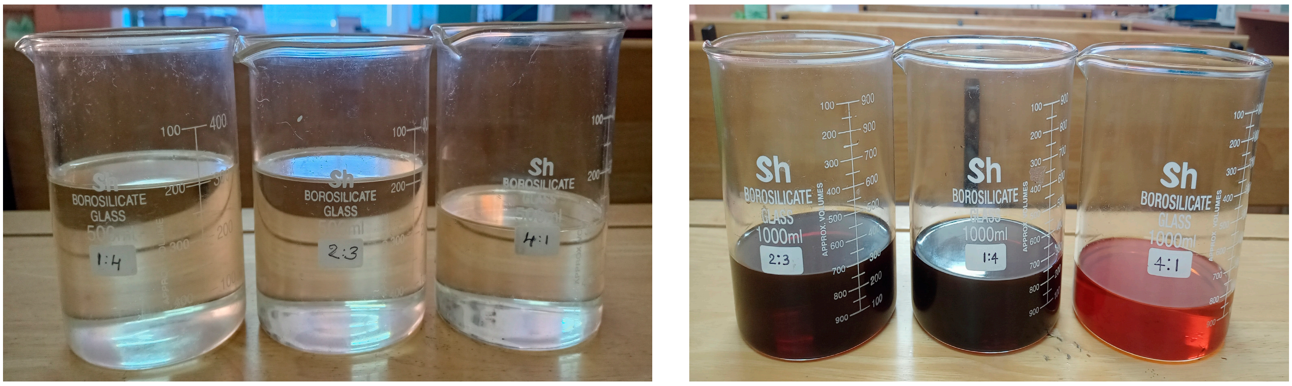
2.2. Characterization

The breakdown voltage of the different oil mixtures was measured using an oil breakdown test kit. The oil was filled in the test cell, and the applied voltage was increased at the rate of 2 kV/s until breakdown was observed. Each sample was tested six times with a time interval of 3 min between tests. The breakdown voltage determined the ability of the insulation to withstand high electrical stress in terms of voltage. The flash point and fire point of the mixtures were measured using Pensky–Martens closed cup tester according to ASTM D445. Flash and fire points determined the safest maximum temperature at which the transformer could be operated without any thermal hazard. The Redwood viscometer method was used to measure the viscosity according to ASTM D92. The lower viscosity of the liquid showed that it can flow easily so that effective temperature reduction can be achieved.

3. Results and Discussion

3.1. Appearance of the Blended Oil

As both the fresh mineral oil and synthetic ester are transparent, their mixer also appeared transparent as shown in Figure 1a, once they were blended. However, the colour of aged oil became dark brown. Once it was blended with the synthetic ester, its colour changed as shown in Figure 1b. It was observed that the transparency improved with increased synthetic oil quantity.



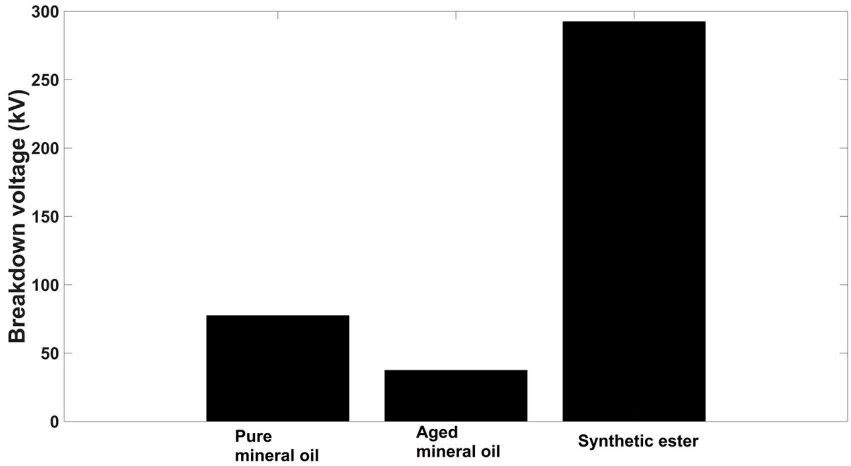
(**a**) (**b**)

Figure 1. Appearance of (**a**) fresh mineral oil and (**b**) aged mineral oil after blending with synthetic ester.

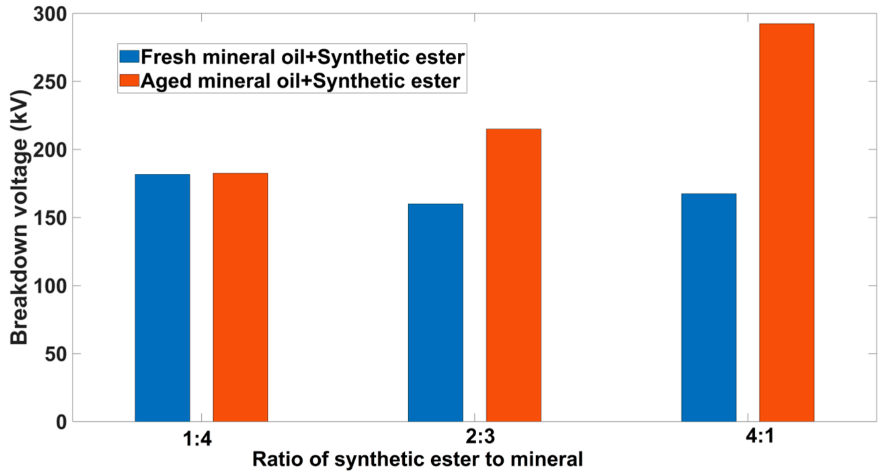
3.2. Breakdown Voltage

The breakdown voltages of unmixed oils and different oil mixtures are shown in Figures 2a and 2b, respectively. It can be seen that the breakdown voltage was the highest for the pure synthetic ester, and the lowest for the pure aged mineral oil. There was an increase of 2.34 times and 4.86 times in the breakdown voltage of both fresh and aged mineral oil when they were blended with synthetic ester. The higher values of breakdown voltage for the oil mixture also showed the efficacy of ultrasonication for blending oils without gas bubbles. As reported in the literature, 1:4 ratio of synthetic ester and fresh mineral oil resulted in higher breakdown voltage. This would help in reducing the cost of synthetic ester required. As the proportion of synthetic ester increased, the breakdown voltage of the oil mixture changed randomly, and it was lesser than that of 1:4 ratio.

The breakdown voltage of aged mineral oil and synthetic ester was the same as that of synthetic ester and fresh mineral oil when their ratio was 1:4. However, it could be observed that the breakdown voltage increased when the proportion of synthetic ester was increased in aged mineral oil. At the ratio of 4:1, the breakdown voltage of the mixture was almost equal to that of pure synthetic ester. However, the suitable ratio of synthetic ester and aged mineral oil could be decided based on the other characteristics. The increase in the breakdown voltage of the blended oil would reduce the size of the transformer, or would allow the transformer to operate at elevated voltage levels.



(**a**)



(**b**)

Figure 2. Breakdown voltage of (**a**) unmixed oils and (**b**) oil mixtures.

3.3. Flashpoint and Fire Point

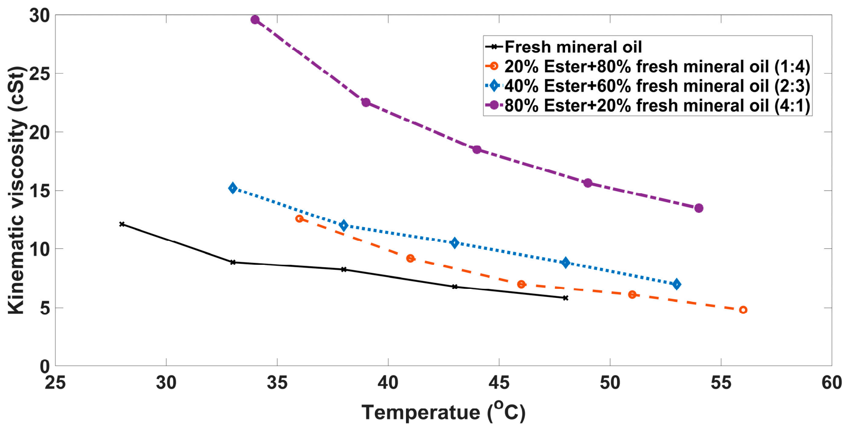
Flashpoint and fire point represent the thermal withstanding capability of the insulating medium, and the flashpoint of the mineral oil should be at least 140 °C to use it as an insulating medium for transformers. The flashpoint and fire point of mineral oil reduces with aging. Table 1 shows the flashpoint and fire point of pure and aged mineral oils and their mixtures, respectively. It can be noticed that the flashpoint and fire point of pure synthetic ester was much higher than that of mineral oil and its mixture. As the proportion of synthetic ester increased in the oil mixtures, the flashpoint and fire point increased proportionally. This clearly indicates that the blending of synthetic ester improves the flashpoint and fire point proportional to its quantity. Interestingly, the flashpoints and fire points of the mixtures containing synthetic ester and aged mineral oil were higher than those of the mixtures containing synthetic ester and fresh mineral oil at 1:4 and 2:3 ratios. The improvement in the flash and fire point of the blended oil would help the transformer to operate at higher temperature safely.

Table 1. Flashpoint and fire points of various pure oils and mixtures.

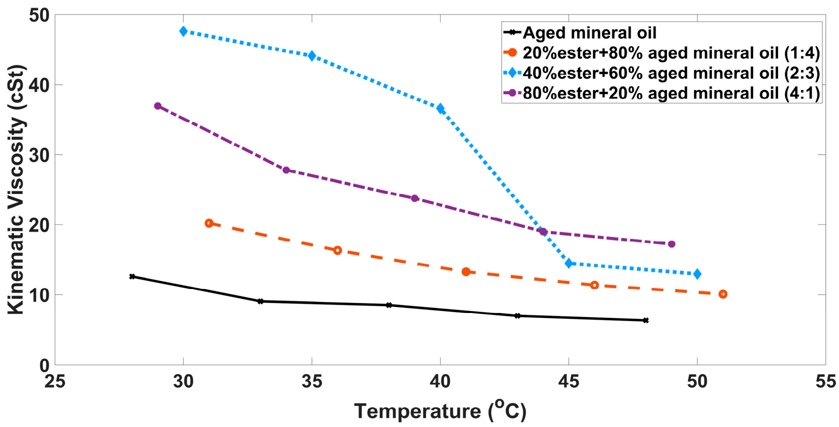
Oil Type	Flash Point (°C)	Fire Point (°C)
Fresh mineral oil	150	170
Aged mineral oil	145	165
Synthetic ester	260	316
	Synthetic ester + Fresh mineral oil	
1:4	150	180
2:3	180	200
4:1	226	244
	Synthetic ester + Aged mineral oil	
1:4	190	200
2:3	212	220
4:1	260	316

3.4. Viscosity

The variations of viscosity, with respect to temperature, are plotted in Figures 3a and 3b for synthetic ester and fresh mineral oil, and synthetic ester and aged mineral oil, respectively. The viscosity should be minimum for good heat transfer characteristics. It can be observed that the viscosity of synthetic ester and fresh mineral oil increased with the quantity of synthetic ester. However, the viscosity value remained good for the 1:4 and 2:3 ratios, and it was higher only for the 4:1 ratio. The increment in the viscosity can be attributed to the higher viscosity of synthetic ester that increases the oil mixture viscosity with its proportion.



(**a**)



(**b**)

Figure 3. Viscosity of (**a**) fresh mineral oil and synthetic ester mixtures and (**b**) aged mineral oil and synthetic ester mixtures.

The viscosity of pure aged mineral oil was almost equal to the fresh mineral oil. However, its viscosity increased when it was blended with synthetic ester, and this increment was much higher compared to that of synthetic ester and fresh mineral oil mixture. The viscosity of the 1:4 ratio of synthetic ester and aged mineral oil mixture was within acceptable limit. Contrastingly, viscosity of higher synthetic ester proportion increased abruptly to very higher and unacceptable values. This makes the 1:4 ratio of synthetic ester and aged mineral oil mixture more optimum for transformer insulation applications.

4. Conclusions

The nonbiodegradability of mineral oil forces the industry to look for alternative oils for transformer insulation applications. As the discarding of mineral oil is a difficult task, an alternative way should be determined to use the aged mineral oil effectively. The blending of mineral oil with synthetic ester seemed to be a promising method to maximize its life as it enhances electrical, physiochemical, and thermal properties of both fresh, as well as aged, mineral oil. The optimum ratio of synthetic ester and fresh mineral oil for enhanced properties is 1:4, and is determined based on breakdown voltage and viscosity. Contrastingly, the optimum ratio of 1:4 for synthetic ester and fresh mineral oil mixture is determined based on viscosity. This reveals that the optimum ratio of synthetic ester and mineral oil for improved performance depends on the ageing condition of the mineral oil, and the electrical, physiochemical, and thermal properties of the blended oil. Further studies on the ageing characteristics of blended oils and their impact on the transformer solid insulation would help in maximizing the utilization of existing mineral oil in transformers.

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