Study on static electrification of the PFAE-mineral oil mixture

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Abstract. The natural ester of tri-ester type has been implemented on a high voltage large power transformer, rated at 420 kV, since 2014. The high voltage transformer is known prone to the static electrification risk. Palm fatty acid ester (PFAE) which is a monoester oil type has also been tried on the high voltage power transformer. For a retrofilling purpose, some portion of the previously used insulating oil (it is mainly mineral oil) will remain in the transformer. It is then demanded to study the static electrification of a mixture of PFAE and mineral oil. This paper presents an investigation results on the static electrification properties of PFAE-mineral oil mixture at various percentage ratios of PFAE. The results show that charging tendency (ECT) increase with the percentage ratio of PFAE, but then decreases for the oil containing only PFAE. On the other side, the resistivity of oil mixtures decreases with the increase of percentage ratio of PFAE but then increases for the oil containing only PFAE.

1. Introduction
The static electrification phenomenon occurs in high voltage large power transformers at the surfaces of solid insulation like paper and pressboard exposed to the oil flow. It mainly occurs in the aged power transformers [1]. Oxidation of sulfur compound and hydrocarbon molecules is responsible for the increase of electrostatic charging tendency [2-4]. Although it is not desired, the presence of a sulfur compound in mineral oil is sometimes unavoidable. The electrostatic charging seems to increase rapidly by air exposure during maintenance. An effort has been made to suppress the electrostatic charging in aged mineral oil immersed transformers, and one of the countermeasures applied is by adding 1,2,3-benzotriazole (BTA) to the insulating oil [5]. Nevertheless, static electrification problem was also observed even at the early stage of the development of 500 kV class of transformers in the 1970s [2]. Hence, the static electrification problem occurs in both aged and new high voltage large power transformers.

Natural ester has been re-investigated for application as an insulating material for transformer since the early 1990s, and it became commercially available in 1999 [6, 7]. The main application of the liquid was in distribution transformers and has been partially introduced in medium power transformers. In 2014, the first natural ester filled power transformer, rated at 420 kV was installed [7]. Naturally, the chemical structure of natural ester is trygliceride, where three fatty acid groups are
bonded together by glycerol. The structure is also known as tri-ester. Unlike another vegetable oil-based insulating liquids, PFAE is mono ester type which is chemically modified from the tri-ester through a transesterification reaction.

As a consequence, the liquid has a lower viscosity than vegetable oils in original form (tri-ester). Its viscosity is even lower than the commonly used insulating liquid, mineral oil. It means that PFAE has better cooling property than other vegetable oils and mineral oil [8, 9]. Also, PFAE contains only saturated carbon-carbon single bond in its hydrocarbon chain, so that it has better oxidation stability than other vegetable oils containing unsaturated fatty acid [7, 9].

Meanwhile, the electric utilities are experiencing a transition from time-based maintenance to the condition based maintenance regimes to reduce costs. An effort to extend the lifetime of transformers which nearly reach their technical end of life is then emerged. It is conducted by replacing the aged mineral oil inside the transformer with the fresh, natural ester [10]. The process is known as a retrofilling process. It is reasonable because the experimental evidence shows that natural ester filled transformer has a longer time expectancy than the mineral oil one [11, 12]. The natural ester is also well compatible with the mineral oil [10].

At the retrofilling process, some portions of mineral oil will remain inside the transformer. It is trapped in the pore of insulation paper and pressboard, or other locations. Hence, a mixture of natural ester and mineral oil takes place. This is the idea of the investigation reported in this paper. Although the portion of the mineral oil is remaining in the transformer after the retrofilling process is approximately not more than 7 % [10], it would still be meaningful to study the characteristics of the mixture between mineral oil and natural ester at various ratios.

Moreover, researchers have also tried to make an alternative insulating liquid by mixing the mineral oil and natural esters [13]. This paper deals with the static electrification properties of the PFAE-mineral oil mixture. The percentage of PFAE content of the oil mixtures was varied from 0 (pure mineral oil) to 100 (pure PFAE). The ECT and the resistivity of the oil mixtures are discussed. The explanation of the phenomenon of a sudden change in patterns of the ECT and resistivity from the oil mixture containing 80 % of PFAE to the pure PFAE is proposed.

2. Experiment

2.1. Sample

The oils used in the experiment were PFAE with and without additives and mineral oil, both the unused and the aged ones. The additives are usually added into the insulating oil to improve oxidation stability and to reduce viscosity and pour point of the oil. PFAE is provided by LION SPECIALTY CHEMICALS CO., LTD., Japan, the manufacturer of the liquid. The unused mineral oil is a naphthenic type supplied by JX Nippon Oil & Energy Corporation. The aged mineral oil was 30 years in service oil in a 60 kV distribution transformer, supplied by Kyushu Power Electric Company.

Four kinds of samples were prepared for the ECT and resistivity measurements. They were mixtures of the PFAE without additives and the unused mineral oil, the PFAE without additives and the aged mineral oil, PFAE with additives and the unused mineral oil, and the PFAE with additives and the aged mineral oil. For all four kinds of sample oils, the percentage ratio of PFAE in the mixture oils was varied from 0 to 100 %, so that there were 24 sample oils.

2.2. Oil Pre-conditioning

A tightly sealed stainless steel tank with the capacity of about 1000 ml, as shown in Figure 1, was used for preconditioning the oil sample before being used as a test specimen — the oil preconditioning aimed at bringing all oil samples to the relatively equal in relative moisture content. This was conducted by stirring the oil sample inside the tank using a magnetic stirrer, while the oil was being vacuumed. This procedure was conducted for 1.5 hours. The nitrogen gas was added to
the oil tank after the vacuuming process to avoid the ingestion of air into the oil tank due to the pressure difference between the inner tank and its surroundings.

![Figure 1](image1.jpg) **Figure 1.** The stainless steel tank for pre-conditioning the oil sample.

### 2.3. Electrostatic Charging Tendency (ECT)

ECT was measured by using a Mini Static Tester. This method has been standardized by the Electrical Technology Research Association (ETRA) Japan and recommended by transformer working group of CIGRE. The structure of the mini static tester is given in Figure 2.

![Figure 2](image2.jpg) **Figure 2.** Mini Static Tester

50 mℓ oil inside syringe was flown through a paper filter placed in a filter holder. Generated charges on the paper filter were measured using an electrometer (ADVANTEST, R8240) with a minimum detection level of 10 fA. A commercial paper filter was used as a static generation part. The paper filter was dried for about 24 hours at 100 °C and was kept in a closed container with silica gel before being applied for the measurement. Midpoint value \( i \) [pA] of measured current and oil velocity \( v \) [mℓ/s] were used to calculate ECT at \( t \) °C (room temperature) as in (1). Then, the ECT was corrected to a reference temperature 20 °C as in (2).

\[
ECT \ t^* C \left[ \frac{pC}{mℓ} \right] = - i [pA] / v [mℓ/s] 
\]

(1)

\[
ECT \ 20^* C \left[ \frac{pC}{mℓ} \right] = ECT \ t^* \times 3.18 \exp(-0.0589t) 
\]

(2)
2.4. Volume Resistivity

Volume resistivity (ρ) was measured based on JIS C 2101. The test circuit for the measurement is depicted in Figure 3. A DC 10 V was applied to the tested oil at room temperature for about 5 minutes. Adsorption current was measured using the electrometer (ADVANTEST, R8240) with a minimum detection level of 10 fA. 0-minute value extrapolated from the measured current was used to calculate the volume resistivity as in (3) and (4).

\[
R_x = \frac{V}{I_0} \quad (3)
\]
\[
\rho = KR_x \quad (4)
\]

Where Rx is resistance in Ohm, V is applied a voltage in Volt; Io is current at 0 minutes in Ampere, ρ is volume resistivity (2) with K = 1000 was used.

3. Results and Analysis

Figure 4 shows the electrostatic charging tendency (ECT) of PFAE-mineral oil mixtures at various PFAE percentage ratios. A sample of zero percent ratio means a mixture containing zero percent PFAE and a hundred percent mineral oil, so as the sample of one hundred percent ratio contains only PFAE oil. It can be seen from the Figure 4 that the oil mixtures containing aged mineral oil, in general, have higher ECT compared to those containing unused mineral oil, though an exception was observed on the mixture ratio of 60% and 80%. The effect of additive in PFAE oil seems to be neglectable.

![Figure 3. The test circuit of volume resistivity measurement](image)

![Figure 4. The charge density of PFAE-mineral oil mixture at various percentage ratios of PFAE.](image)
It can also be seen from the Figure 4, the ECT of the oil mixture increases with the percentage of PFAE up to the 80%, and then it decreases when the sample contains only PFAE (the PFAE ratio is 100%). The explanation we propose to deal with this is that the phenomenon is caused by a property of PFAE that can hold much higher water than mineral oil due to the polarity nature of PFAE molecules. It should be noticed that molecules of mineral oils are nonpolar. Also, the existence of oxygen atom in its molecular structure makes the PFAE molecules tend to attract moistures (moisture affinity). During the mixing process, moistures are extracted from the mineral oil and are directed toward the PFAE. It is suspected that under the current investigation, the rest time between the mixing process and the measurement was not long enough to have the extracted moistures dissolved completely in PFAE. The moistures are temporarily dispersed in the oil mixture. This moisture dispersion was suspected to be responsible for the increase in ECT of mixture oil until the PFAE content of the oil mixture reaches 80%. The moisture dispersion did not occur in the oil containing only PFAE. Consequently, the ICT of the oil containing only PFAE is lower than the oil mixture containing 80% PFAE.

Figure 5 shows the resistivity of PFAE-mineral oils mixture at various percentage ratios. The pattern of the change in the resistivity concerning the increase in the percentage of PFAE in oil mixtures coincides with the pattern of the variation of ECT in the opposite way. The resistivity of the oil mixtures decreases as the percentage of PFAE increases up to 80%, and then it increases when the sample contains only PFAE (the PFAE ratio is 100%). This confirms the relationship between the ICT and the resistivity of an insulating oil which is inversely proportional [11]. Therefore, the phenomenon of the sudden change in the resistivity of oil containing only PFAE could also be explained as that of ICT but in the opposite way.

As can be predicted from the ICT and resistivity relationship, the resistivity of oil mixtures containing aged mineral oil, in general, are lower than those containing new mineral oil. This can be seen in Figure 5. Unlike the effect on the ECT, the presence of the additive in PFAE oil slightly decreases the resistivity of oil mixture.

Charging potential is determined by both the density of charges deposited on the surface of cellulose and the ability of the cellulose-oil system to evacuate or neutralize the deposited charges which are represented by the resistivity of the oil. Therefore, it describes the net accumulated charges, thus represents the risk of occurrence of discharge. The higher amount of accumulated charges, the higher possibilities of the occurrence and the severity of the discharge are. It is then desired to have a lower ECT for high resistivity oil or to have a lower resistivity for the high ECT

![Figure 5](image-url)
oil. The most desirable oil is that having low ECT and low resistivity [11]. However, it must be compromised with the need for the high resistivity oil to minimize the electrical loss [12]. Table 1 indicates the desired and the undesired oils from the study of static electrification view.

| Oil’s ECT | High | Low |
|-----------|------|-----|
| Resistivity | undesired | tolerable |
| High     | tolerable | desired |

Table 1. Oil classification from the study of static electrification view.

In this experimental work, the density of charges are those accumulated by the paper filter during the process when the oil flows passing it. The resistivity of the oil was measured separately by the resistivity measurement system. The charging potential of all tested oils is depicted in Figure 6. As can be seen from Figure 6, the charging potential of mixture oils containing aged mineral oil, in general, are lower than those containing new mineral oil. This indicates that the resistivity has a higher contribution in affecting the charging potential of oil mixture than that of ECT. The presence of additives in PFAE oil which decreases the resistivity of oil mixture, therefore, contributes to decrease the charging potential of oil mixture.

4. Conclusion
Properties of static electrification of PFAE-mineral oil mixture have been studied to simulate the retro-filling condition of the oil-filled transformer. It was found that the ECT of oil mixture increases with the percentage ratio of PFAE to 80% but then decreases when the oil contains only PFAE. On the other hand, the resistivity of the oil mixture decreases as the percentage ratio of PFAE increases but then increases when oil contains only PFAE. It is suggested that these phenomena are caused by the moisture affinity property of PFAE and that the PFAE can hold much higher water than mineral oil. The limited time between the mixing process and the measurement creates dispersed moistures which are suspected to be responsible for the tendency of the ECT and the resistivity of tested oils. This should be further clarified by adding the rest time between the mixing process and the measurement in the future.
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