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Effect of mixing ratio on the breakdown voltage of mineral and natural ester insulating oil blends

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ABSTRACT

To date, the most common insulating oil used in oil-immersed transformers is mineral insulating (MI) oil, which is derived from petroleum. Owing to the depletion of petroleum over the years, it can be anticipated that petroleum-derived products such as MI oils will also deplete in the future. MI oils are not only non-renewable, but they are also non-biodegradable, where these oils are harmful to the environment in cases of oil spillage. Therefore, the aim of this study is to investigate the potential of mixing MI oil with natural ester insulating (NEI) oil in order to reduce the high dependency on MI oil for transformer applications. The MI and NEI oils were mixed with different mixing ratios. AC breakdown voltage test was conducted on the MI-NEI oil blends according to the ASTM D1816 standard. From the results, it is found that the following mixing ratios (30% of MI oil + 70% of NEI oil, 20% of MI oil + 80% of NEI oil) result in significant improvement in terms of the AC breakdown voltage compared with unused MI oil. The flash point and corrosivity levels of the oil blends were also examined.

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1. INTRODUCTION

It is known that oil-immersed transformers are an essential piece of equipment in electric power transmission and distribution systems as they ensure reliable and efficient electricity supply [1]. Transformers are listed as the most critical high-voltage equipment. The insulating oil used in oil-immersed transformers play a dual role as an electrical insulator as well as a cooling medium. Mineral insulating (MI) oils are typically used in high-voltage oil-immersed transformers because of their low cost and favorable properties (low dielectric loss, high electric field strength), and good long-term performance. However, MI oils are non-biodegradable, and these oils can cause soil and water pollution in the event of a spillage [2]. In addition, MI oils are non-renewable because they are produced from petroleum, which is a non-renewable resource.

For the aforementioned reasons, much effort has been made to develop biodegradable insulating oils such as natural ester insulating (NEI) oils since the mid-1990s [3], [4]. NEI oils offer a few advantages over MI oils in terms of fire safety, environmental-friendliness, and insulation aging [5], [6]. NEI oils are non-toxic, biodegradable, and less flammable, rendering them suitable for use as transformer insulating oils [7], [8]. Many studies [9]–[13] have been carried out to explore the potential of NEI oils produced from palm oil.

Palm oil has high cooling stability, excellent oxidation stability, and favorable dielectric properties, rendering it a desirable substitute for MI oil. In 2006, Lion Corporation took the initiative to develop palm fatty acid ester for use as NEI oil [14], [15]. NEI oils have been proven to offer superior insulating performance in high-voltage oil-immersed transformers in addition to being environmentally friendly.

In recent years, studies have been conducted to assess the potential of mixing MI and NEI oils to exploit the advantages that each oil has to offer. Numbers of researchers have suggested by mixed MI and esters oils will enhance the stability of the insulating oil in terms of the dielectric properties, flash point, and thermal properties [16]–[22]. Blends of MI and NEI oils have been shown to have good oxidation stability, which will reduce the overall cost of transformer operation associated with frequent oil changes. The optimal mixing ratio has been shown to be 80% of MI oil and 20% of synthetic or NEI oil [23]–[25]. In this study, an attempt has been made to determine the best mixing ratio for MI-NEI oil blends in terms of the AC breakdown voltage (NEI oil is palm oil based). In addition, the effect of the mixing ratio on the flash point and corrosivity level was also assessed.

2. METHOD

The methodology adopted in this study is presented in Figure 1 (see in appendix). The methodology begins with the selection of materials and ends with analysis of the test results. The MI oil used for the tests is uninhibited mineral oil manufactured by commercial transformer oil manufacturer. The NEI oil chosen for the tests is palm fatty acid ester oil manufactured by Lion Corporation, Japan. The MI and NEI oil samples were first pre-processed by filtration and temporary heating to normalize their properties.

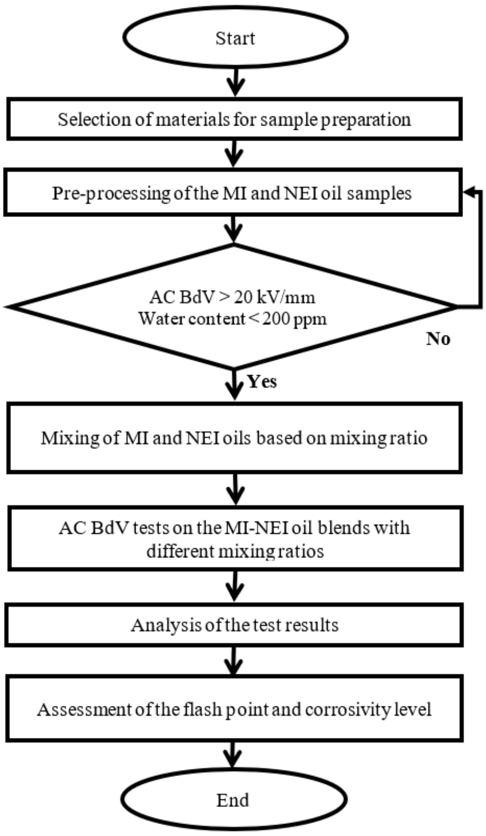


Figure 1. Flow chart of the methodology adopted in this study

Next, the AC breakdown voltage (BdV) and water content of the MI and NEI oil samples were determined to ensure that their AC BdV values were more than 20 kV and their water content values were less than 200 ppm. The AC BdV test was conducted on the MI and NEI oil samples using Megger OTS60PB portable oil tester (Figure 2), which complies with the ASTM D1816 standard. Verband der Elektrotechnik (VDE) electrodes (Shape A) were chosen and the gap between the electrodes was set at 1 mm. The oil was poured into a graduated beaker up to the 500-ml mark. The oil sample was checked to ensure that no bubbles formed within the oil sample, which can affect the results. Likewise, the temperature of the oil sample was checked to ensure it was within 20–30 °C (room temperature) and the oil sample was stirred for 3 min in the test chamber before the AC BdV test. For each oil sample, the AC BdV test was conducted 30 times to obtain 30 AC BdV data points, and the mean AC BdV was determined.

Eleven MI-NEI oil blends were prepared, each with a different composition, as listed in Table 1. For the AC BdV test, the total volume of each oil blend was set at 500 ml. Each oil blend was mixed using a hot plate magnetic stirrer with the following settings: (1) stirring speed: 400 rpm, (2) oil temperature: 90 °C, and (3) stirring time: ~1 h (Figure 3). Next, the unused MI oil, unused NEI oil, and oil blend with the best mixing ratio were tested to determine their flash points and assess the presence of corrosive sulfur according to the ISO 2719:2002 standard and ASTM D1275 Method B, respectively. The samples were tested in an accredited laboratory at TNBR QATS Sdn. Bhd. This is important owing to the lower flash point and higher presence of corrosive sulfur of the MI oil. The flash point and corrosivity level of the oil blend were assessed and the results were compared with those for unused MI oil and unused NEI oil.

Figure 2. Photograph of the oil sample in the test chamber. The gap between the semi-spherical electrodes was 1 mm

Table 1. Mixing ratios of the MI-NEI oil blends

Sample no.	Composition (by volume)
1	100% of MI oil
2	90% of MI oil + 10% of NEI oil
3	80% of MI oil + 20% of NEI oil
4	70% of MI oil + 30% of NEI oil
5	60% of MI oil + 40% of NEI oil
6	50% of MI oil + 50% of NEI oil
7	40% of MI oil + 60% of NEI oil
8	30% of MI oil + 70% of NEI oil
9	20% of MI oil + 80% of NEI oil
10	10% of MI oil + 90% of NEI oil
11	100% of NEI oil

Figure 3. Mixing of the MI and NEI oils using a hot plate magnetic stirrer

3. RESULTS AND DISCUSSION

The AC BdV was used as the parameter to determine the best mixing ratio for the oil blends prepared in this study. Figure 4 shows the AC BdV of the oil blends. It can be seen that the mean AC BdV for Sample 1 (unused MI oil) is 24 kV. In contrast, Sample 11 (unused NEI oil) has a significantly higher AC BdV, with a mean of 34 kV. In general, both oils surpass the requirement stipulated in the ASTM D3487 and ASTM D6871 standards. Based on the test results, Sample 4 (30% of MI oil + 70% of NEI oil) has the highest AC BdV (34 kV) compared with all the oil blends tested in this study. In contrast, Sample 2 (90% of MI oil + 10% of NEI oil) has the lowest AC BdV (19 kV) among the oil blends. The results can be attributed to the higher water solubility of the NEI oil, which improves the AC BdV when NEI oil is mixed with MI oil.

However, the focus of this study is to determine the best mixing ratio for the MI-NEI oil blends without significantly reducing the quantity of the MI oil. Thus, the following mixing ratio (50% of MI oil + 50% of NEI oil) was chosen as the reference to analyze the percentage of AC BdV enhancement. Samples 7–

10 were not considered because they contained more than 50% of NEI oil. The AC BdV values for Samples 2–6 are tabulated in Table 2. It can be observed that the mixing ratio for Sample 4 (70% of MI oil + 30% of NEI oil) and Sample 3 (80% of MI oil + 20% of NEI oil) has the same percentage of AC BdV enhancement, with a value of 16.67% relative to that for Sample 6 (50% of MI oil + 50% of NEI oil). In contrast, Sample 5 (60% of MI oil + 40% of NEI oil) does not show a marked percentage of AC BdV enhancement (4.17%). More importantly, Sample 2 (90% of MI oil + 10% of NEI oil) shows a decline in the AC BdV relative to that for Sample 6, as indicated by the negative value of 20.83%. This is likely due to the high percentage of MI oil in Sample 2, which reduces the AC BdV. It is interesting to note that adding small amounts of NEI oil (20–30%) is adequate to enhance the AC BdV. The NEI oil has high water solubility, which compensates for the low water solubility of the MI oil.

To determine the best mixing ratio for the MI-NEI oil blend, the effect of mixing ratio on the flash point and corrosivity level was investigated. The flash points of the MI-NEI oil blends were determined in accordance with the ISO 2719:2002 standard test method using Pensky-Martens closed cup tester. The flash points for Sample 1 (unused MI oil), Sample 11 (unused NEI oil), Sample 4 (70% of MI oil + 30% of NEI oil), and Sample 3 (80% of MI oil + 20% of NEI oil) are shown in Figure 5. It is apparent that the flash point for Sample 3 is only slightly higher than that for Sample 4, with a value of 158 and 156 °C, respectively. The highest flash point is attained for Sample 11, with a value of 186 °C, which is a stark contrast to the flash point of Sample 1, with a value of 135 °C. It is evident that blending NEI oil with MI oil can increase the flash point of the MI oil, which is desirable for transformer insulating oils.

The ASTM D1275 Method B was used to assess the presence of corrosive sulfur of Sample 1 (unused MI oil), Sample 11 (unused NEI oil), Sample 4 (70% of MI oil + 30% of NEI oil), and Sample 3 (80% of MI oil + 20% of NEI oil). The corrosivity levels of the oil samples due to the presence of corrosive sulfur were evaluated according to the ASTM D130 standard test method. In general, the more the copper strip is tarnished after being immersed in the oil sample, the more corrosive the oil sample. The results of the copper strip corrosion test are presented in Figure 6 (see in appendix). Based on the results, the copper strip immersed in Sample 1 (unused MI oil) has a higher corrosivity level than Sample 11 (unused NEI oil), where the former results in a dark tarnish (3a) whereas the latter literally results in no tarnish, similar to that for a freshly polished copper strip. This apparent difference is likely due to the fact that the unused MI oil contains corrosive sulfur species. In contrast, the unused NEI oil is derived from natural resources, and thus, it is free from sulfur compounds. It can be observed that Sample 3 (80% of MI oil + 20% of NEI oil) results in a dark tarnish (3a), indicating that its corrosivity level is the same as that for Sample 1. Sample 4 (70% of MI oil + 30% of NEI oil) gives a different result, where there is only a slight tarnish (1b) of the copper strip immersed in this oil blend. This shows the benefit of adding a higher amount of NEI oil into the oil blend. Based on the results (flash point and copper strip corrosion tests), it is deduced that the best mixing ratio is 70% of MI oil and 30% of NEI oil.

Table 2. Percentage of AC BdV enhancement for Samples 2–5. The AC BdV for Sample 6 serves as a reference value to calculate the percentage of AC BdV enhancement

Sample no.	Composition	AC BdV (kV)	Percentage of AC BdV enhancement (%)
6	50% of MI oil + 50% NEI oil	24	Reference value
2	90% of MI oil + 10% of NEI oil	19	−20.83
3	80% of MI oil + 20% of NEI oil	28	+16.67
4	70% of MI oil + 30% of NEI oil	28	+16.67
5	60% of MI oil + 40% of NEI oil	25	+4.17

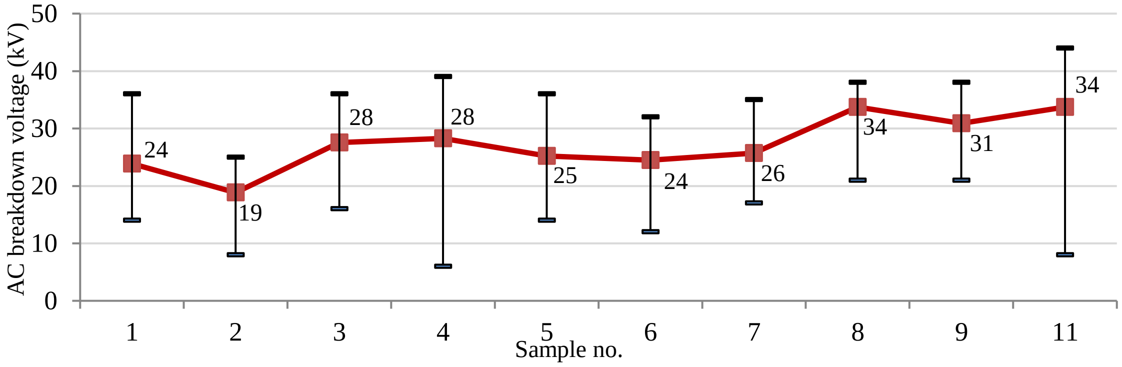


Figure 4. AC BdV values of the eleven MI-NEI oil blends tested in this study

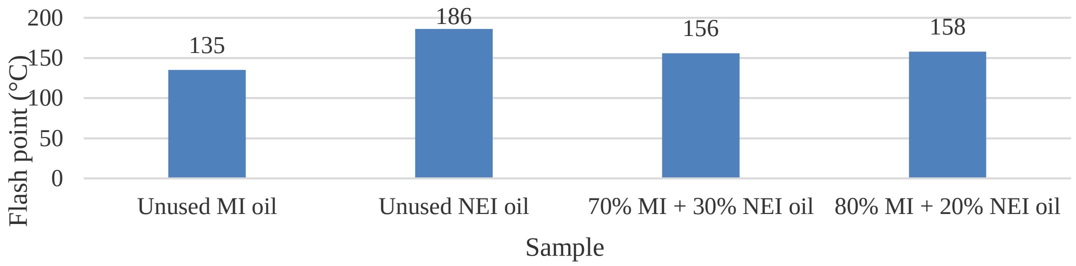
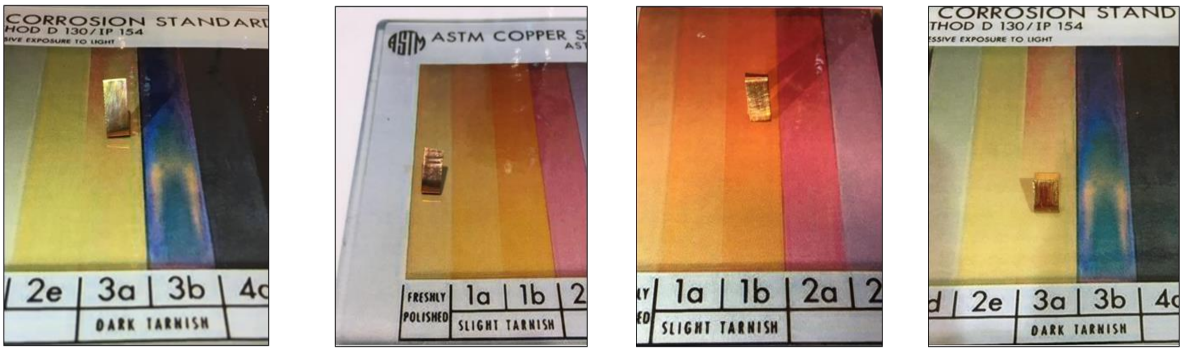


Figure 5. Flash points of Sample 1 (unused MI oil), Sample 11 (unused NEI oil), Sample 4 (70% of MI oil + 30% of NEI oil), and Sample 3 (80% of MI oil + 20% of NEI oil)



(a) (b) (c) (d)

Figure 6. Photographs of the corrosivity levels of the oil samples: (a) copper strip immersed in Sample 1 (unused MI oil), (b) copper strip immersed in Sample 11 (unused NEI oil), (c) copper strip immersed in Sample 4 (70% of MI oil + 30% of NEI oil), and (d) copper strip immersed in Sample 3 (80% of MI oil + 20% of NEI oil)

4. CONCLUSION

Based on the results, in terms of the AC BdV, Sample 4 (70% of MI oil + 30% of NEI oil) and Sample 3 (80% of MI oil + 20% of NEI oil) were found to be the best MI-NEI oil blends. These oil blends were chosen for the flash point and copper strip corrosion tests as they did not contain more 50% of NEI oil since the objective was not to significantly reduce the amount of MI oil in the blend. The results of the flash point and copper strip corrosion tests reveal that the best mixing ratio is attained for Sample 4 (70% of MI oil + 30% of NEI oil), where the flash point (156 °C) is higher than that for unused mineral oil (135 °C). Sample 4 is also less corrosive than Sample 3, where a slight tarnish is observed for the former whereas a dark tarnish is observed for the copper strip immersed in the latter.

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