Effect of electrical discharge on the properties of natural esters insulating fluids

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ABSTRACT

Vegetable oils have been an alternative to mineral oil for oil-immersed transformers due to concern on less flammable, environmental-friendly, biodegradable, and sustainable resources of petroleum-based insulating oil. This paper presents the effect of electrical discharges (200 up to 1000 discharges) under 50 Hz inhomogeneous electric field on the properties (acidity, water content, and breakdown voltage) of two varieties of vegetable-based insulating oils; i) natural ester (NE) and ii) low viscosity insulating fluids derived from a natural ester (NE_{LV}). Results show the water content, acidity and breakdown voltage of NE fluctuate due to applied discharges, while NE_{LV} display insignificant changes. Hence, results indicate that the low viscosity insulating fluids derived from natural ester tend to maintain their properties compared to natural ester.

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1. INTRODUCTION

Mineral insulating oil (MO) is extensively used worldwide for over a century due to its adequate ageing behaviour, good dielectric strength, low viscosity, less susceptible to oxidation, effectively good operation in low temperature, widely available petroleum resources, compatible and reliable used in transformer as well as cost benefit [1]. Yet, disadvantages of MO such as non-biodegradable properties, enforcement of environmental laws, and limited reserves of naphthenic crude oil in future have directed to the quest for alternative fluids [2], [3].

Exploration on alternative insulating oil to replace existing MO have started nearly four decades back [4], where researches on vegetable-based insulating oil as an alternatives to MO are gaining much attention [5]-[8]. To date, vegetable-based insulating oil is being developed from edible oil. For example coconut oil, sunflower oil, soybean oil, rapeseed oil, and palm oil [9]-[15]. Other researches carried out in the field of non-edible oil. For example *Pongamia pinnata* oil, *Jatropha curcas* oil, *Terminalia catappa* oil, karanji oil, sesbania seeds oil, and castor oil [16]-[22]. According to BS EN 62770 [23], there are two categories of vegetable-based insulating oil: i) mainly triglycerides natural esters (NE) and 2) low-viscosity insulating fluids derived from natural esters (NE_{LV}). Contrast to mineral oils, NE are usually characterized by its high flash point (less flammable), yet have higher viscosity and a higher pour point. On the other hand, properties of the NE_{LV} are close to those of mineral oils (i.e., low flash point, low pour point and low viscosity). Most of the studies regarding electrical discharges in dielectric liquid are focused on mineral oil, while only few were regards to natural esters and synthetic esters [24]-[27]. Electrical discharges could be divided into; i) low; ii) medium; and iii) high energy discharges [26]. The discharge magnitude for low (e.g., corona) and medium (e.g., partial discharge) energy discharge was around 2.5 nC and 20 nC, respectively. While arcing is a high energy discharges type. This paper presents the effect of 200 and up to 1000 electrical discharges (i.e., under 50 Hz inhomogeneous electric field) on the properties (acidity, water content and breakdown voltage) of two types of vegetable-based insulating oils i) NE and ii) NE_{LV}.

2. RESEARCH METHOD

Methodology adapted in this study is summarized in a flow chart, as shown in Figure 1.

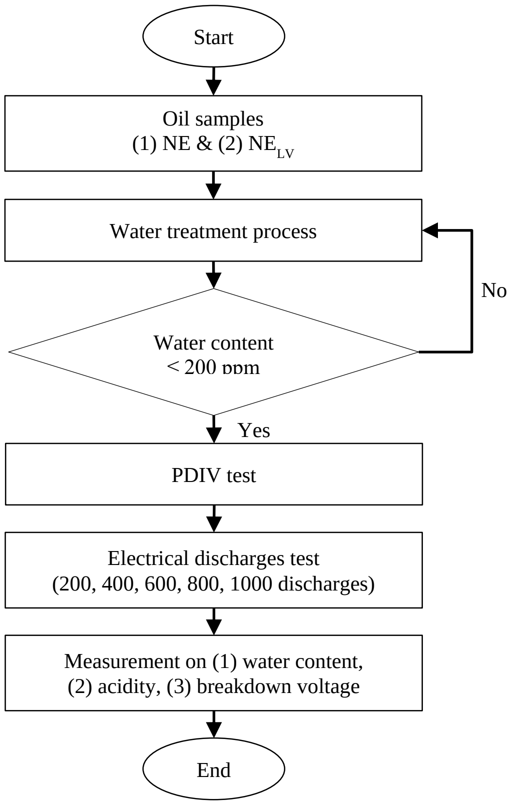

Figure 1. Flow chart of methodology adapted in this study

2.1. Sample preparation

In order to standardize the water content of oil samples to be less than or equal to 200 ppm (i.e., the stipulated limits for water content of "new natural ester fluids"), both oil samples; i) NE and ii) NE_{LV} were first treated via water treatment process. The process was done by bubbling nitrogen gas into oil samples [28] for 30 minutes or until the water content limits are fulfilled.

2.2. Partial discharge inception voltage (PDIV) test

The block diagram for partial discharge inception voltage (PDIV) measurement is as shown in Figure 2. The PDIV is defined as the voltage at which partial discharge occurs with an apparent charge equal or greater than 100 pC. The PDIV of the oil samples were measured using Omicron MPD600 partial discharge measurement device. The PDIV test setup was calibrated according to the IEC 60270 standard. The experimental apparatus was placed within a Faraday cage to minimize unwanted noise during the PDIV measurements.

After the equipment setup for PDIV measurement was free from discharges, the pre-processing sample (~ 400 ml) was filled in a test cell as shown in Figure 3. The test cell consisted of a glass vessel with a tungsten needle (tip radius: 3 µm, length: 50 mm, diameter: 1 mm) and a brass plane electrode (diameter: 40 mm, thickness: 10 mm) separated by a vertical gap (50 mm). The needle electrode acts as the high voltage electrode whereas the plane electrode acts as the grounding electrode. The sample was allowed to rest for 15 minutes before the first voltage was applied. The voltage was increased from 0 at 1 kV/s until partial discharge was occurring above the threshold of 100 pC. The voltage applied was then decreased to 0. The voltage level during partial discharge initiations was recorded. Measurement on the sample was repeated 10 times. After the measurement were completed, the oil was drained from the test cell. Following this, the test cell was cleaned, and a new needle electerode was inserted. With that, measurement of PDIV on new oil sample was take place.

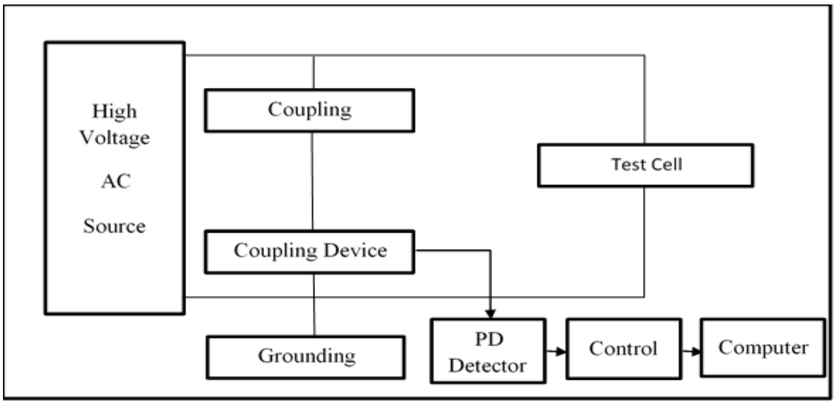

Figure 2. Block diagram for PDIV measurement [29]

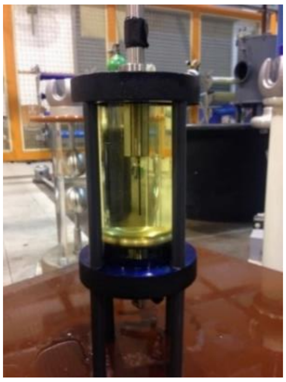

Figure 3. Test cell for PDIV and electrical discharges measurement

2.3. Electrical discharge test

Electrical discharges (i.e., the applied voltage at which partial discharge occurs with an apparent charge equal or greater than 100 pC) were applied and counted with a series of 200 successive discharges (i.e., 200, 400, 600, 800 and 1000 discharges) on the oil samples; i) NE and ii) NE_{LV}. After each series of discharges, water content, acidity and breakdown voltage of oil samples are measured.

2.4. Water content

Water content of oil sample was determined based on the oxidation of sulphur dioxide by iodine in methanolic hydroxide solution. Measurement of water content in oil was done based on ASTM D1533 standard [30] by using 899 Karl Fischer coulometer (Metrohm). Firstly, hydranal-coulomat (100 ml) was injected into an electrolysis cell. Next, a 5 ml syringe filled with 1 ml of oil sample was weighed using a precision balance. Then the oil sample was injected into the electrolysis cell. The wighted of oil sample were keyed into the coulometer, where titration process was initiated. The water content of the oil sample shown on the display monitor was recorded. The water content measurement was repeated three times for each oil sample in order to ensure consistency of the results.

2.5. Acidity

Acidity or total acid number (TAN) test is a measurement of acidity that determines the sum of all acid compounds present in insulating oil samples. TAN was measured based on the amount of potassium hydroxide (in mg) required to neutralize hydrogen ions (H^+) in 1 g of oil sample. TAN is expressed in mg KOH/g. In this work, TAN was measured using a compact titrator (Model: 848 Titrino plus, Metrohm) according to the ASTM D974 standard [31]. Before any measurement wants to be conducted, the electrode was calibrated first with three buffer points, pH 4, 7 and 9 at room temperature. The calibration assessment was repeated twice by using new buffer solutions. Next, a standardization step was conducted to examine the actual concentration of potassium hydroxide in isopropanol (IPA) with a molarity of 0.1 mol/L by weighing around 0.1 g of potassium hydrogen phthalate (KHP) and added approximately 80 mL of distilled water into a same beaker. This step was repeated twice with new KHP and distilled water in a new clean beaker. After that, 20 mL of solvent was inserted into another beaker and its acidity was measured as a blank solvent. This step was repeated two times with fresh 20 mL of solvent into another clean beaker. For acidity measurement on oil sample: Firstly 5 g of oil sample was weighted using a syringe. Then, the oil sample was poured into a beaker with 20 mL of solvent. After that, the solvent-oil sample mixture is titrated IPA to obtain the TAN. Each sample was tested for three times in order to ensure consistency of the results.

2.6. Breakdown voltage

Breakdown voltage of oil sample was measured according to ASTM D1816 standard [32] by using OTS60PB portable oil tester (megger). The equipment is capable to measure breakdown voltage up to 60 kV. The electrode configuration for the test setup were two semi-sphere electrodes of the Verband Deutscher Elektrotechniker (VDE) with the gap distance of 1 mm. Firstly, a minimum volume of 350 ml oil was slowly poured into a test cell, to ensure no bubble trap in the oil. Then, the temperature of the oil sample was measured prior to the test. The test was conducted within range temperature of 20°C to 30°C. After the electrode immersed into sample oil and left to rest, voltage was increased gradually at a rate of 0.5 kV/s ± 5% until breakdown occurs. The voltage at which breakdown occurs was recorded as the breakdown voltage. A settle-down period of 1 min was set between repetition tests to assure the result obtained for the next test is not affected by the previous test. Based on ASTM D1816 standard, one breakdown cycle consists of five individual tests in sequence, where the mean values of the breakdown voltage for five individual tests were determined.

3. RESULTS AND DISCUSSIONS

The oil samples; i) NE and ii) NE_{LV} were firstly treated via water treatment process. As the water content is satisfying the limit as stated in standard, the PDIV on both oil samples were then determined. The PDIV levels will be a reference for executing the electrical discharges tests. After electrical discharges experiment on oil samples were done, its properties (water content, acidity, and breakdown voltage) were measured, presented and discussed.

3.1. Sample preparation

Table 1 shows the properties (water content, acidity, viscosity, breakdown voltage) and PDIV of oil samples (NE and NE_{LV}) used in this study after being treated through water treatment technique (i.e., nitrogen bubbling in the oil samples). It can be seen that the properties of both NE and NE_{LV} satisfying the limit stipulated in ASTM D6871 standard [33], where; i) water content should be ≤ 200 ppm; ii) acidity should be ≤ 0.06 mg KOH/g; iii) viscosity should be ≤ 50 mm^2/s; and iv) breakdown voltage should be ≥ 20 kV. Noted that the viscosity of NE_{LV} (8 mm^2/s) is lower than viscosity of NE (35 mm^2/s). At the same time, the viscosity of NE_{LV} is also close to those of mineral oils, as according to ASTM D3487 standard [34], where viscosity should be ≤ 12 mm^2/s. As for PDIV, it shows that PDIV of NE_{LV} is higher than PDIV of NE. Similarly, breakdown voltage of NE_{LV} is higher than PDIV of NE. One reason of NE_{LV} having higher PDIV and higher breakdown voltage compared to NE is might be due to its low viscosity.

Table 1. The properties of oil samples after water treatment

Properties	Unit	Natural ester oil samples	
		NE	NE_{LV}
Water content	mg/kg	150.20	141.60
Acidity	mg KOH/g	0.0056	0.0304
Viscosity	mm^2/s	35	8
Breakdown voltage	kV	24.92	26.66
PDIV	kV	15.42	17.87

3.2. Water content

Figure 4 shows the water content of NE and NE_{LV} samples after subjected to electrical discharges. It can be said that the water content of both NE and NE_{LV} oil samples were unchanged up to 400 discharges. However, water content of NE started to fluctuate (decreased, and increased) for the remaining discharges. Initial water content of NE is 150.20 ppm but decrease to 73.74 ppm after 1000 electrical discharges. The reduction in water content with the application of discharges on NE might be due to evaporation of water traces that are present in the zone of discharges occurrence. Moreover, NE contain unsaturated fatty acid, where easily influence by stresses. On top of that, when there are increase of electrical discharges applied to the oil sample, it will allow free radical to cut the molecules in the oil, known as autocatalytic reaction. In addition, NE has superior water tolerance that can absorbs large amounts of water indicating a high saturation limit making precipitation of free water virtually impossible.

On the other hand, the water content of NE_{LV} was not affected by the electrical discharges, where it shows value of water content in the range of between 141.56 ppm and 147.54 ppm. The water content of NE_{LV} is firstly decreased to 140.76 mg/kg at 200 electrical discharges, then increased slowly with increment of the remaining electrical discharges (200 to 1000 discharges). The reults is might be due to NE_{LV} structure that consist of mainly saturated fatty acid hydrocarbon chain with hydrogen, where its not easily gave up it hydroxyl group to absorb water.

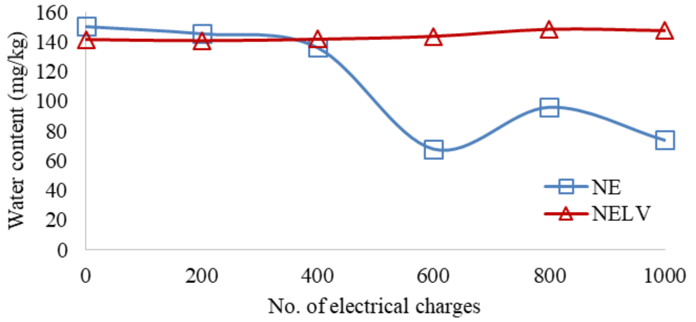

Figure 4. Effects of electrical discharges to water content of NE and NELV samples

3.3. Acidity

Figure 5 shows the changes in acidity of NE and NE_{LV} after subjected to electrical discharges. The acidity of NE was gradually increase up to 400 discharges, but decreases afterwards with the number of discharges. In contrast, insignificant changes is detected for the acidity of NE_{LV}, indicating that NE_{LV} is not much affected by electrical discharges. The different changes of acidity might be contributed to the stability of monoester (NE_{LV}) compared to triglyceride (NE). Though the acidity of NE increased above 0.06 mg KOH/g (i.e., the prescribed limit of "new natural ester fluids"), the level is 0.30 mg KOH/g (i.e., within the stipulated limit for "continued use of in-service natural ester fluids"). In chemical point of view, the acidity (degradation by-products of natural ester) are mostly high molecular weight acid (HMA). HMA is not detrimental to cellulose material (e.g. paper and pressboard).

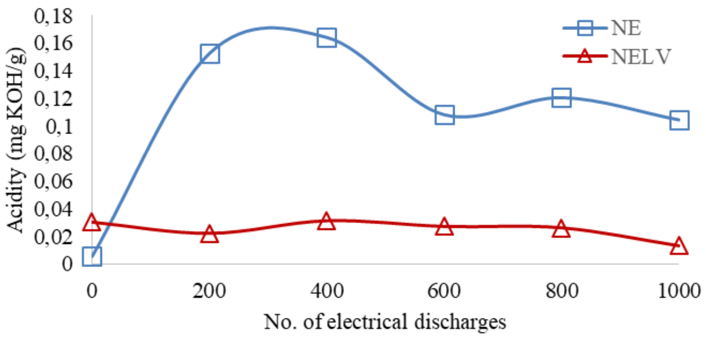

Figure 5. Effects of electrical discharges to acidity of HVNE and NELV samples

3.4. Breakdown voltage

The dielectric breakdown voltage of an insulating liquid is vital as it represents the liquid's ability to withstand electric stress without failure. The dielectric breakdown voltage serves to indicate the presence of contaminating agents such as water, dirt, cellulosic fibers, or conducting particles in the liquid. Figure 6 show the breakdown voltage of NE and NE_{LV}. Generally, the breakdown voltage of NE is increase after electrical discharges were applied. The reason is because water content is also reduced at the sime time. The breakdown voltage of NE is initially decrease from 24.92 kV to 16.77 kV, but then gradually increased to 46.87 after 1000 discharges. On the other hand, breakdown voltage of NE_{LV} is firstly almost unchanged, up to 200 discharges. Then the breakdown voltage fluctuated (i.e., decrease from 25.47 kV to 21.20 kV, but then gradually increased to 30.73 at 600 discharges and reduced again until 24.67 kV after 1000 discharges. This might due to the presence of water in NE_{LV}, because water is one of the leading causes of electrical breakdown because it increases the ionic conductivity of the oil hence dropping the breakdown voltage. On top of that, electrical discharges could also change the molecules structures where number of electrons increased.

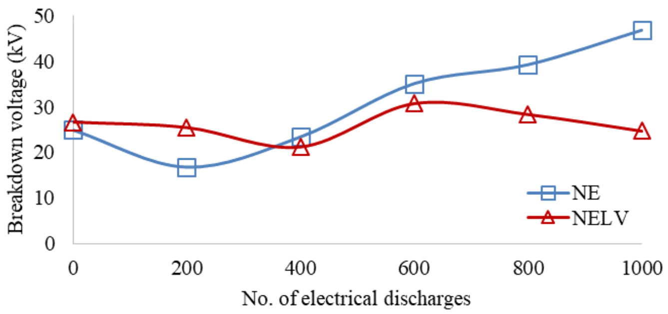

Figure 6. Effects of electrical discharges to breakdown voltage of NE and NELV samples

4. CONCLUSION

In this study, the effect of electrical discharges on two types of vegetable-based insulating oils; i) NE and ii) NE_{LV} were investigated in terms of water content, acidity, and breakdown voltage. The applied electrical discharges were from 200 to 1000 discharges. It is found that NE (contain unsaturated fatty acid) can absorbs large amounts of water indicating a high saturation limit. Decrement of water content in NE resulting in increment of breakdown voltage of NE with the number of discharges. Other than that, the acidity of NE decreases with the number of discharges, which also indicating the changes on molecules structures of oil. In contrast, NE_{LV} is found to be a stabil oil because its properties (water content, acidity and breakdown voltage) are not much affected by the electrical discharges. It is because NE_{LV} is mostly contain saturated fatty chain thus not easily to form free radical from its molecules.

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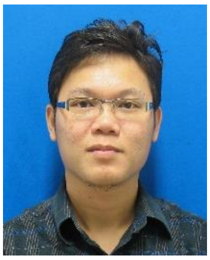

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