PD Behaviors of Monoester Insulating Oil under Different Moisture Contents

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PD Behaviors of Monoester Insulating Oil under Different Moisture Contents

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Abstract

One of the problems encounters in implementing vegetable oils (natural esters) as a transformer insulating oil is their viscosity which is high. To address this problem, monoester derived from vegetable oil was introduced. This paper deals with partial discharge (PD) behaviors of dry and moist samples of a monoester type insulating oil, palm fatty acid ester (PFAE), under AC high voltage utilizing a needle plane electrode configuration. Variations of average PD charge and PD number against the variation of voltage application, as well as their polarity discrimination under both dry and moist sample conditions are analyzed. PD pulses phase distributions of both dry and moist sample oils are elaborated. Finally, a mechanism of the water molecules effect on PD behavior is proposed based on experimental results and shown schematically.

Keywords: *Insulating oil, Moisture content, Monoester, Partial discharge, PFAE*

1. Introduction

It is well known that the presence of moisture in transformer decreases both mechanical and electrical strengths of transformer insulation, thus degrades the overall performance of the transformer [1]. Water is one of a degradation product of oxidized oil as well as that of paper insulation [2]. Moisture ingression could also happen when insufficient dry air entering the transformer's tank, or when there was a leakage on the gasket [3]. In addition, natural ester was reported to attract more water than mineral oil from cellulose in oil/paper insulating system under thermal aged condition [4-5]. Therefore, the moisture content of transformer oil in service increases over the time.

The effect of moisture content on PD activities in insulating oil has been studied by several researchers. Apparent charge was reported to decrease slightly with the increase in moisture content of mineral oil due to the shorter duration of PD pulses in moist oil, whereas PD number increases significantly [6]. Partial discharge inception voltage (PDIV) decreased as the moisture content increased. The remarkable reduction in PDIV was observed in the sample with the presence of water droplet [7]. However, the different results were reported in [3]. The PDIV of synthetic ester and mineral oil of Diala S4 ZX-I type increased with moisture content, whereas that of mineral oil of Gemini X type is equal under dry and moist conditions. The PD number of both mineral oils increased with moisture content, but that of synthetic ester decreased slightly. The PD magnitude of all tested oils decreased as the moisture content rose at lower applied voltage, but that of synthetic ester and Gemini X increased with moisture content at 38 kV applied voltage or higher [3]. It is indicative from the mentioned literature that moisture content alters the PD behavior of insulating oil, although its effect, whether the increase in moisture content intensifies PD activities, or vice versa, has not been concluded.

In our previous work [8], we stated that PD activities in PFAE oils under relative moisture content varying from 10 to 17 % exhibit similar behavior to that of breakdown event. Namely, it was shown that PDIV, PD charge, and PD number do not have significant difference in those oil samples. It is well known that breakdown voltage of insulating oils does not change significantly when the relative moisture content increases up to about 10% and 30 % of unclean and clean oils, respectively, and reduces remarkably when the moisture content is further

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raised [9]. The investigation of PD behaviors of insulating oil, particularly PFAE, at higher moisture content is then important to be conducted.

This paper presents investigation results on PD behaviors of PFAE sample oils under of two different moisture content conditions; dry and moist samples. PD properties like PD number and average PD charge at different applied voltage levels are investigated and analyzed. The polarity of applied voltage at which the PD pulses occurred is discriminated and explored. The mechanism of the water molecules effect on PD behavior is proposed and shown schematically.

2. Experiment

2.1. Sample

It has been recognized from our previous work [8,10] that moisture content up to 188 ppm, or about 17% relative moisture content does not cause a significant difference in PD properties of PFAE such as PDIV, PD number, and average PD charge, as well as generated combustible gases. That 17 % level of relative moisture content is possessed by the oil without pretreatment before being used as an experimental specimen. The same sample was used in this experiment to represent a sample of dry type.

Another sample representing moist condition was prepared by adding about 0.5 ml of water into the PFAE oil having volume of 1000 ml. The sample was stirred at 500 rpm at 40 °C for about 12 hours using magnetic stirrer.

2.2. Experimental Arrangement and Procedure

Oil sample was placed in a cylindrically shaped chamber made of an acrylic in which electrode pairs of a needle-plane configuration was immersed. The photograph of the chamber is depicted in Figure 1. The needle having tip radius of 10 μm was used in conjunction with a plane electrode having diameter and thickness of 68 mm and 5 mm, respectively. With an acrylic of 5 mm thick on the plane electrode surface, the gap between the needle and acrylic was 5 mm. The schematic view of electrode configuration is shown in Figure 2.

Figure 1. Oil chamber used for PD measurement

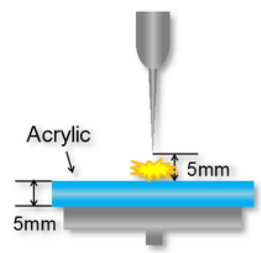


Figure 2. Needle-plane electrode configuration. An acrylic with the thickness of 5 mm was placed on the surface of plane electrode, remaining a 5 mm gap between the needle electrode and the acrylic

PD was generated in each oil sample by applying AC high voltage on electrode pairs of a needle-plane configuration. Partial discharge measurement was performed using a combined Resistor (R), Detecting Impedance (DI) and CD6 detection system to compare PD magnitude and PD phase distribution of PFAE at both positive and negative polarities of AC voltage application. The schematic diagram of the PD measurement is shown in Figure 3. R detector was used to discriminate the polarity of PD pulses, whereas combined DI and CD6 detectors were used to measure the integrated apparent charge of PD pulses.

To investigate voltage dependence of PD charge and PD number, the experiment was conducted by varying applied voltage. The application of voltage was started at 7 kV, and it was increased with the increment of 1 kV up to 21 kV. At each voltage level, the applied voltage was kept for about 2 minutes for conducting measurement. The 2 minutes measuring time was chosen to allow a relatively stable measurement while protecting the measuring device from a possible damage caused by a long exposure to the discharge.

To study phase distribution of PD pulses, R detector was removed, and PD pulses were detected by combined DI and CD6 detector. The 60 Hz AC voltage waveform taken from the tertier winding of transformer was used as reference. A voltage probe having a voltage ratio of 10:1 was used to step down the amplitude of AC voltage before being connected to the oscilloscope.

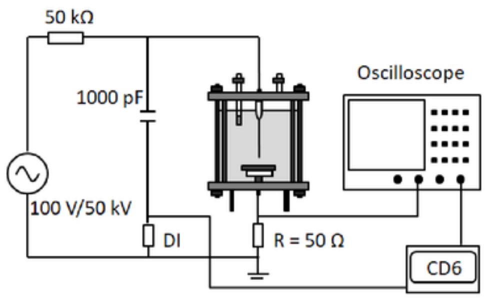
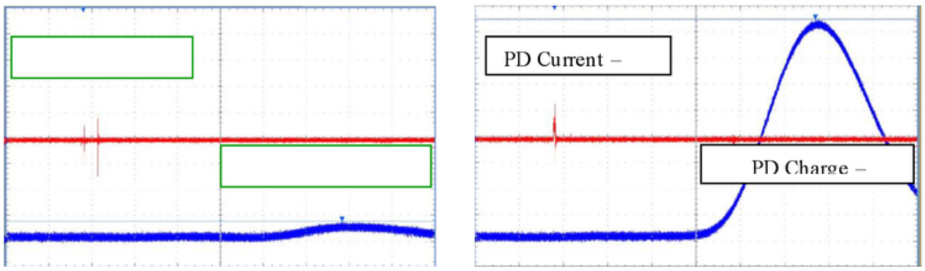


Figure 3. Experimental Setup

3. Results and Analysis

3.1. PD Pulses Shape

Figure 4a shows an example of negative PD pulse burst containing 4 discreet pulses (detected by R detector) and the corresponding integrated charge (detected by DI), obtained in a dry PFAE sample at 15 kV. This kind of negative PD pulse burst was also obtained in [11]. Figure 4b shows an example of positive PD pulse and the corresponding integrated charge, also obtained in the dry PFAE sample at the same condition as that of the negative one. The difference in PD pulses shapes between the negative and the positive PD is due to the difference in the formation mechanism. Under negative polarity of applied voltage electrons required to trigger PD are injected from the field enhancement site at the tip of the needle electrode, resulting in PD pulse burst containing one to several discreet PD pulses [11]. When the needle is positive, the initial electron comes from the oil side through a field ionization mechanism [12], resulting in a more irregular and erratic PD pulses, having a duration between 0.5 to 6 µs [11]. It can also be seen from the Figure 4a and 4b that magnitude of positive PD is much larger than the negative one. This behavior applies to both dry and moist samples, as will be further elaborated in the next section.

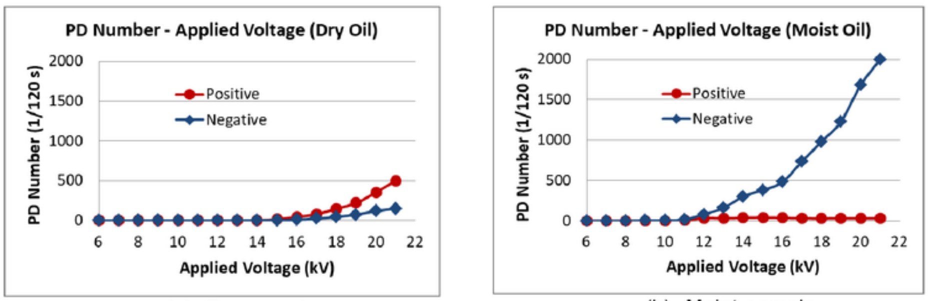


(a) Negative PD (b) Positive PD

Figure 4. Examples of PD Pulses Shape and integrated PD charge; (a) Negative PD, and (b) Positive PD. The time difference between PD pulses and the peak of integrated pulses is due to the time delay of the amplifier of DI [13]

3.2. Voltage Dependence

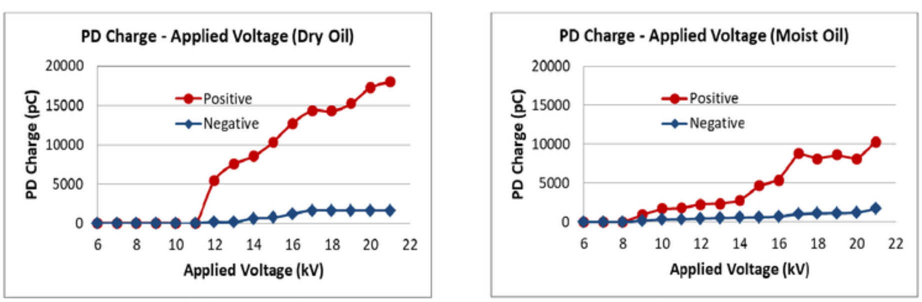
Figures 5a and 5b show the dependency of PD number on applied voltage in dry and moist oils samples, respectively. Under dry condition as shown in Figure 5a, the PD numbers of both polarities increase with applied voltage, and the increase of positive PD number (circle) is much larger than the negative one (diamond). The situation is different in moist sample as shown in Figure 5b. PD number of negative polarity increases drastically with the increase of applied voltage, whereas that of positive polarity remains constant. The effect of the increase of moisture content can be seen by comparing Figures 5a and 5b, especially at higher applied voltage. It significantly reduces positive PD number and drastically increases the negative one.



(a) Dry sample (b) Moist sample

Figure 5. Variation of the PD Number of Oil Samples with the Increase of Applied Voltage

Figures 6a and 6b show the dependency of average PD charge (from now on called PD charge) on applied voltage in dry and moist samples, respectively. PD charge of both polarities increase with applied voltage, and again, the increase of positive PD charge (circle) is much larger than the negative one (diamond). No polarity reversal tendency of PD charge was obtained when the moisture content of the sample increased. The change only affects PD charge in the way that the increase in positive PD charge is slightly less in moist sample than that in dry sample, while negative PD charge in both dry and moist samples increase to a comparable level. The results of PD charge are in line with the observation on mineral oil reported in [5]. There, it is stated that the increase in moisture content leads to a slight reduction in PD charge of mineral oil.

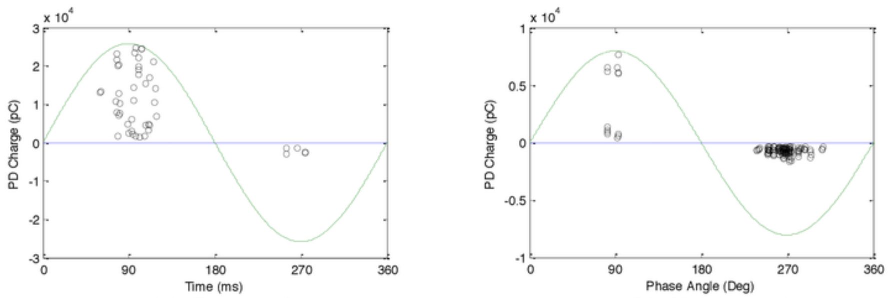


(a) Dry sample (b) Moist sample

Figure 6. Variation of the PD Charge of Oil Samples with the Increase of Applied Voltage

3.3. Phase Distributions

Figures 7a and 7b show phase distribution of PD pulses for 120 cycles of applied voltage, taken at 20 kVrms, in dry and moist PFAE samples, respectively. It is clear from the Figure 7a that for dry sample, most PD pulses with large PD charge take place at positive polarity of applied voltage. Very few pulses with small charge take place at negative polarity. On the other side, under moist sample (Figure 7b), PD pulses dominantly occur at negative polarity of applied voltage with significantly low in magnitude. Though PD pulses still occur at positive polarity of applied voltage, the magnitude is significantly lower than in dry sample and much less in number.



(a) Dry sample (b) Moist sample

Figure 7. Phase distribution of PD pulses in two different moisture contents of PFAE sample for 120 cycles of applied voltage, taken at 20 kVrms

3.4. Analysis

Far below saturation level, under dry condition, water molecules present in the form of being bonded to carbonyl group and etheric oxygen atoms of ester molecules, or are trapped between two ester molecules [14]. At this level, the presence of water does not give a significant effect on dielectric behavior of ester oils [9]. Moisture content up to 188 ppm or about 17% relative moisture content does not cause a significant difference in PD properties of PFAE [10]. When the concentration of water is high, water molecules are distributed randomly in oil or join together forming water cluster. Under this condition, PD activities are enhanced, which is indicated by the drastic increase in number of PD. These intense PD activities mostly occur at the negative polarity of applied voltage.

These behaviors may be attributed to the electronic affinity property of water molecule (water molecule contains oxygen atom which has high electron affinity). The reason for this comes from the conclusions in [15] that the PD observed in dielectric fluids are associated with the appearance of streamers and represent discharges occurring within these streamers, and in [16] that PDIV and streamer inception voltage (SIV) are interrelated. Then, the argument for propagation of streamer could also be used to explain the PD behavior.

The existence of fluorine atom having high electron affinity in Galden D-40 fluid was suspected to be the main reason for the different behavior of Galden D-40 from Ugilec C 101 and Baylectrol 4900 liquids. Unlike two other fluids, PDIV and SIV of Galden D-40 are lower and took place at negative polarity of applied voltage [15]. In cyclohexane, addition of electron-attaching additives was proven to increase the negative streamer velocity [17]. In mineral oil, addition of electron scavenger additives accelerates negative streamer. Polyaromatic components of the mineral oil increase velocities of both positive and negative streamers. The effect on negative streamer is due to their electron scavenger property, whereas the effect on positive streamer is due to the low ionization potential characteristic of aromatic compounds [12]. The existence of oxygen atom which is highly electronegative is suspected to be the reason of the faster and the further propagation of negative streamer in esters than in mineral oil at the same level of applied voltage [18]. Finally, it is highlighted in [19] that molecular structure has a significant effect on the streamer propagation. The main parameter affecting streamer propagation is the electronic affinity of the liquid molecules.

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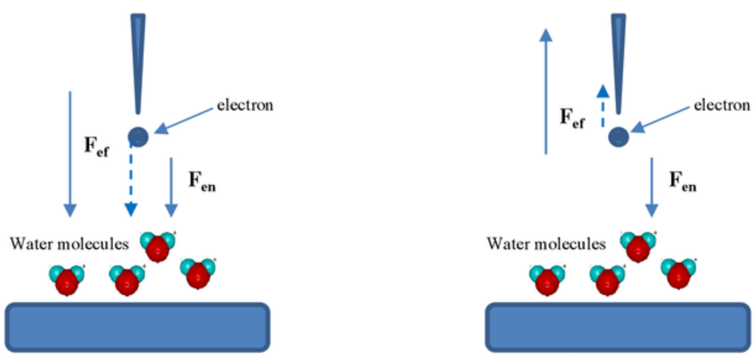
3.5. Mechanism

Based on our experimental results and literature review, then a mechanism of the effect of water molecules on PD behaviors of PFAE oil is proposed, as shown schematically in Figure 8. Under dry condition, free water and water cluster do not exist in oil. The move of electrons is merely influenced by forces due to the electric field, and restriction by oil molecules.

Under moist condition, neglecting the restriction force by oil molecules, the move of electron is controlled by two types of forces, namely, the force resulted from electric field (F_{ef}), and the force resulted from the attraction of water molecules due to their electronegativity nature (F_{en}). When the needle is negative, electrons are injected from the needle through field emission process. The electrons are accelerated into the oil side due to the superposition of F_{ef} and F_{en} as shown in Figure 8a. This acceleration enhances PD activities of moist oil under negative polarity. When the needle is positive, electrons are extracted from the oil side through field ionization process. The electrons are decelerated toward needle electrode since accelerating force (F_{ef}) was diminished by water molecules attractions (F_{en}) as shown in Figure 8b. This deceleration reduces PD activities of moist oil under positive polarity.

Moreover, since the relative permittivity of water (80) is much larger than that of oil (2.9), water molecules under high voltage tend to move into the high electric field area between the needle and plane electrodes. This will enhance the effect mentioned in the previous paragraph.



(a) Negative polarity (b) Positive polarity

Figure 8. Schematic demonstration of mechanism of the effect of water molecules on PD behavior of PFAE oils

→ Direction of force.

⇢ Direction of the move of electron

3.6. Practical Implication

It has been shown that the increase in moisture content intensifies PD activities in PFAE sample which is indicated by the drastic increase in PD number. The PD pulses in moist sample mostly took place at negative polarity of applied voltage. The average charge of these negative PDs is remarkably lower than that of positive ones. The positive PD pulses still occurred, but with the significant reduction in the PD charge and with the drastic reduction in PD numbers. It can be said that the increase in moisture content, under our experimental condition, is not hazardous to the PFAE oil. The drastic increase in PD number at negative polarity in moist oil is compensated by the remarkably lower PD charge compared to that at positive polarity under dry condition.

4. Conclusion

PD behaviors of PFAE sample oils under dry and moist conditions have been investigated. The effect of moisture content can be summarized as follows:

a. Under positive polarity, PD charge reduces significantly, whereas PD number reduces drastically. Under negative polarity, PD charge remains constant, but PD number increases drastically. The reason is due to the electronic affinity property of water molecules which in negative polarity accelerate electrons triggering PD, whereas in positive polarity decelerate them.

b. The drastic increase in PD number under negative polarity is compensated by the small average PD charge. As a consequence, the change in moisture content is not hazardous to PFAE oil.

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