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Partial Discharge Phase Distribution of Palm Oil as Insulating Liquid

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Abstrak

Mengingat sifat minyak mineral yang sulit terurai secara alami dan rentan terhadap bahaya kebakaran, minyak sawit diusulkan sebagai minyak isolasi alternatif. Makalah ini membahas pelepasan sebagian (PD) dalam minyak sawit di bawah tegangan sinusoidal dan perbandingan dengan minyak mineral. PD dibangkitkan dengan menggunakan elektroda jarum-plat, yang memungkinkan peninggian medan listrik di ujung elektroda jarum. Pulsa-pulsa PD dideteksi dengan detector RC dan diukur menggunakan sistem pengukuran berbasis komputer. Hasil-hasil menunjukkan bahwa karakteristik PD dalam kedua minyak adalah sama. PD terjadi pertama kali pada polaritas negatif. PD terjadi pada kedua polaritas tegangan dengan jumlah PD lebih besar pada polaritas negatif. Beberapa penomena peluahan mengindikasikan kehadiran muatan ruang yang mengubah medan listrik dan mempengaruhi aktivitas PD disamping medan utama dari aplikasi tegangan.

Kata kunci: *minyak sawit, minyak isolasi, partial discharge, PD pattern, muatan ruang.*

Abstract

Due to the low biodegradability level of mineral oil and its susceptibility to the fire, palm oil was proposed as alternative insulating liquid. This paper discusses partial discharge (PD) in palm oil under sinusoidal voltages and the comparison with mineral oil. PD was generated using a needle-plane electrode configuration which is enable enhancing electric field at the needle tip. PD pulses were detected using RC detector and they were measured using a Computer-based partial discharge measurement system. The results showed that PD activities in both oils are similar. The PD was initiated at the negative polarity of applied voltage. The discharges took place in both polarity's of applied voltage with PD number was higher at negative one. Several discharges phenomena showed the presence of space charge which changed electric field and governed PD activities besides the main field introduced by voltage application.

Keywords: *palm oil, insulating liquid, partial discharge, PD pattern, space charge.*

1. Introduction

Due to the high electric field strength, low dielectric losses and good long term performance, petroleum based mineral insulating liquids are still the most widely used insulating liquid until now [1]. As the mineral oil are derived from non-renewable source, it is proved to have low rate of biodegradability and low flash point, many researcher are now searching for the alternative liquids to replace mineral oils as insulating liquids in high voltage apparatus.

One of the alternative liquid is palm oil. Investigation on electrical, physical and chemical properties of palm oil shows that this palm oil possesses good properties to be used as substitutes of mineral oils for high voltage equipment. Table 1 shows the electrical, physical and chemical properties of palm oil and mineral oil and the corresponding value from ASTM D6871 standard as standard specification of natural (vegetable oils) ester to be used in electrical apparatus [2].

Identification of abnormal condition e.g. partial discharge in palm oil becomes urgent to be analyzed when the palm oil will be implemented in high voltage apparatus in the future. Partial discharge patterns recognition and interpretation have been proven very useful for the diagnostics of insulating condition of the high voltage apparatus. PD takes place when the local electric field exceeds the threshold value and produces a partial breakdown of the surrounding

insulating material. [3]. For experimental purpose, it needs to generate the high electric field locally to produce partial discharge, and it is achieved by utilizing a needle-plane electrode configuration which yields the highest electric field among other electrode arrangements. For comparison, the electric field (E) produced by the needle-plane and the needle-needle configurations are given in figure 1a and figure 1b, respectively. It can be seen from the figure 1a and figure 1b that for the same applied voltage (V) and electrode gap (d), the maximum electric field (E_{max}) resulted by the needle-plane configuration is higher than that of the needle-needle configuration. The relation between applied voltage and the electric field of any electrodes configuration is expressed by equation (1) [4]. As the applied voltage is equal for both configurations, areas under curve E(x) in figure 1a and figure 1b must also be equal. Due to the strong non-uniform nature of electric field under the needle-plane configuration, its E_{max} must be higher than that of the needle-needle configuration.

$$V = \int_0^d E(x)dx \qquad (1)$$

Where V is the applied voltage, E(x) is the electric field at distance x from the needle electrode, and d is the electrode gap.
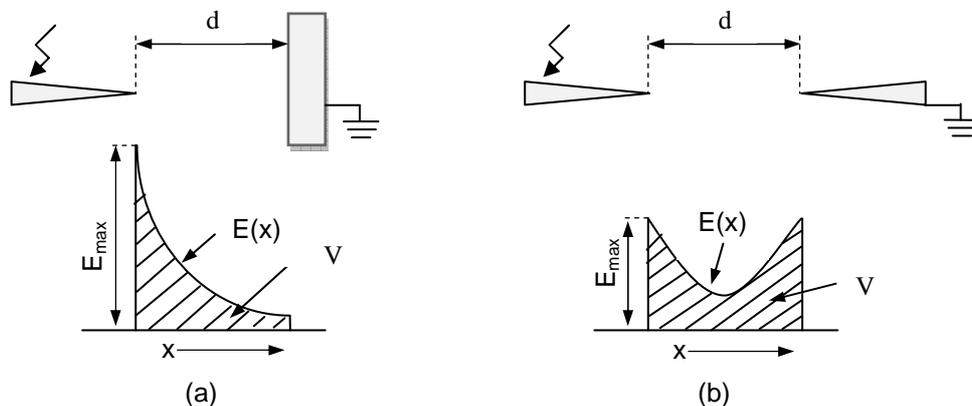

Figure 1 Maximum electric field (E_{max}) under the same applied voltage and electrode gap; (a) Needle-plane configuration, and (b) Needle-needle configuration.

So far, PD measurement in insulation liquid has been able to distinguish the initiation and development of streamer where the PD takes place. Measurements which were performed by utilizing needle-plane electrode configuration, with DC or impulse applied voltage, have disclosed that the PD or streamer at negative polarity was initiated by electron injected from needle electrode into the liquids at a lower applied voltage level. For positive polarity, initial electrons come from the bulk insulating liquid, which under high electric field were directed toward the needle electrode [5, 6]. With this evidence, Pompili et. al. [7], assumed that negative PD inception voltage was lower than the positive one, and it was also valid for PD measurement under AC applied voltage. However, no experimental evidence was shown to support their assumption.

This paper experimentally confirmed the true of that assumption. Phase of applied voltage where PD pulses took place was analyzed for several applied voltage level to obtain the polarity where the PD pulses were initiated. PD data was then presented in the form of ф-q-n and ф-n patterns, where ф is applied voltage phase of PD occurrence, q is PD magnitude and n is number of PD pulse. These kind of presentations were intended to assess dependency of PD pulses magnitude and PD number on instantaneous value of applied voltage. In addition, PD pulses representation in the form of ф-q-n and ф-n patterns can be used to distinguish PD source in liquid-filled electrical equipment such as transformer. In liquid insulation PD pulses usually concentrated around the peak of applied voltage wave, both positive and negative

polarity's. PD in air (corona) is indicated by PD pulses concentrated around the peak of applied voltage wave at only negative polarity, whereas, PD pulses in solid insulation usually take place at the zero point of applied voltage wave [3], [8].

Table 1 Some properties of palm oil, mineral oil and corresponding value of ASTM D6871 standard (standard specification of natural (vegetable oils) ester to be used in electrical apparatus) [1]

Properties	Palm Oil	Mineral Oil*[9]	ASTM D6871
Breakdown voltage, kV	≥ 57	30	≥ 35
Dissipation factor, (%), 25 ^{o}C	0.03	0.05	≤ 0.2
Relative permittivity	3.1	2.2	3.2
Viscosity, cSt, 40 ^{o}C	21.02	11	≤ 50
Viscosity, cSt, 100 ^{o}C	3.22	-	≤ 15
Acid number, mg KOH/g sample	0.074	0.015	≤ 0.06
Water content, ppm	60	30	≤ 200

*Typical value

2. Experimental Setup

The applied voltage used in the experiment was AC type. Its value was undergo changing with time according to the equation: $v(t) = V_m Sin\omega t$, where $v(t)$ is instantaneous value of applied voltage, V_m is Maximum value of applied voltage, ω is angular frequency and t is time. The applied voltage level is the rms value of applied voltage which is equal to $V_m/\sqrt{2}$.

Partial discharges were generated in sample oil by applying a high voltage on the needle electrode in a needle-plane electrode configuration of 20 mm separation gap (Figure 2). The needle electrode was made from steel of 0.01 mm tip radius. With this geometrical shape the sufficient high electric field can be easily obtained to generate discharges at the needle tip. The electric field at the tip of the needle electrode is estimated by using equation (2) [10].

$$E = \frac{2V}{rln\left(\frac{4d}{r}\right)}$$ (2)

Where E is the electric field, V is the applied voltage, r is the curvature radius of the needle electrode, and d is the electrode gap.
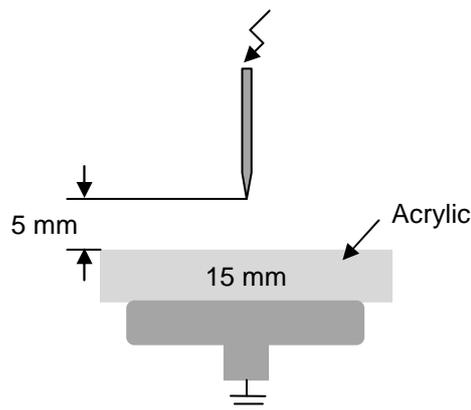

Figure 2 Needle-plane electrodes configuration

Two terminals at the top of chamber were used to enter the oil sample into the chamber and for vacuuming process, and the other one at the bottom of chamber was used to disposethe oil after measurement.

Figure 3 Test chamber containing the needle-plane electrodes for PD measurement.

An acrylic of 15 mm thickness was put on the plane electrode's surface to prevent breakdown to take places. The electrodes were placed in a sealed chamber (Figure 3), which was filled with approximately 350 ml oil sample. The chamber was vacuumed prior to the experiment to remove bubbles which were formed during the oil filling process. It took time for about an hour for mineral oil to be vacuumed to remove visible bubble within it and about two and half hours for palm oil. The longer vacuuming time for palm oil was due to the fact that its viscosity is higher than that of mineral oil. The space formed above the oil samples was filled with a stable gas, e.g. argon to prevent gases from the air contaminating the oil, due to the lower pressure inside the chamber after vacuuming process. Both oils were used as received, without any further treatment.

PD pulses were detected by an RC detector and they were measured using a Personal Computer-based partial discharge measurement system. Schematic diagram of overall experimental set up is shown in Figure 4. Partial discharge inception voltage was determined by detecting voltage when the discharge pulses take place at the first time. Phase resolved analysis was conducted to know correlation between discharge pulses magnitude and phase angle of applied voltage.
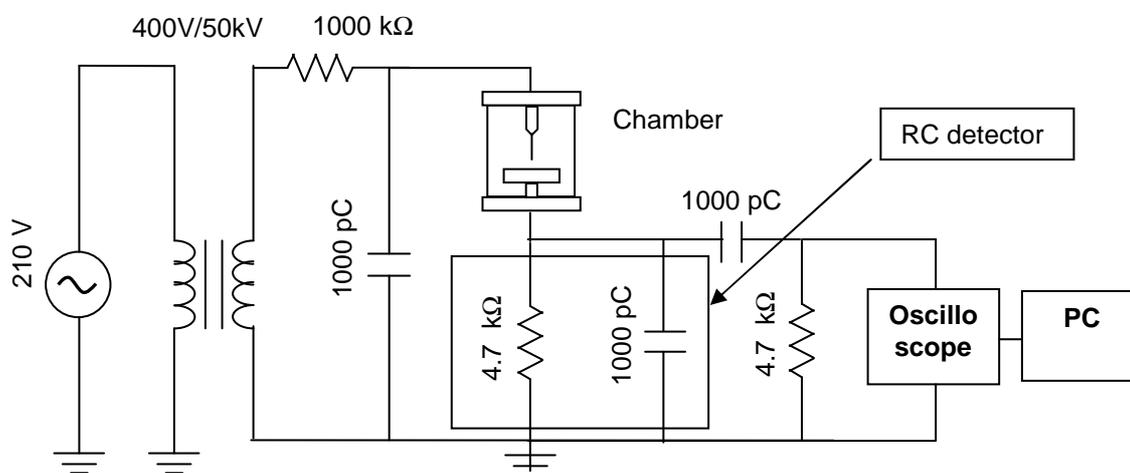

Figure 4 Schematic diagram of experimental set up; RC detector is marked by the box

3. Results and Analysis

Partial discharge inception voltage of palm oil under sinusoidal applied voltage was about 16.2 kV. It is 2.2 kV higher than that of mineral oil. This voltage level was detected by impedance sensing and displayed on oscilloscope.

Figure 5, Figure 6, and Figure 7 show the partial discharge pulse trains of the first 10 consecutive cycle in palm oil at the applied voltage levels of 18 kV, 25 kV, and 32 kV, respectively. It can be seen that discharges in the palm oil occur in both half cycles of applied voltage. The similar results were observed in silicon oils [8]. However, the results observed in our experiment show a quite distinct from those observed by Suwarno and T. Mizutani [8], where they found the strong dependence of discharge magnitude to instantaneous applied voltage. In our experimental results, as depicted in Figure 5, Figure 6, and Figure 7, charge magnitude seemed to be independent of the instantaneous value of applied voltage.

The magnitude of partial discharge also seemed to be independent of the applied voltage level. No significant change of discharge magnitude was observed when the applied voltage level varied in the range of 18 kV to 25 kV. Once inception voltage exceed, as can be seen from the Figure 5, Figure 6, and Figure 7, there always possibility for discharges of about less than 50 pC to take place. It does not matter, how small the difference between inception voltage and the instantaneous value of applied voltage was. These results confirm the opinion that the development of streamer in liquid insulation, as well as, PD activity was more influenced by local field than the average applied field across the gap [6], [11]. G.J. Fitzpatrick, et. al. [6] showed this experimentally, in one case, chopping applied voltage do not stop the streamer

growth, while in another case, the streamer was stopped even though voltage source was continuously being applied.

Due to the random nature of PD occurrence, the phase at which the first discharge pulses took place show the uncertainty. At 18 kV applied voltage (Figure 4), the discharge pulse firstly occurred at the negative half cycle. When the applied voltage rose to 25 kV (Figure 5), the occurrence of first discharge pulse was observed at positive half cycle. But, when the applied voltage was further increased up to 32 kV (Figure. 7), the first discharge pulse was again observed in negative half cycle. However, for the most cases, the PD pulses occur at the negative cycle of applied voltage, as will be seen later in φ-q-n and q-n presentations.
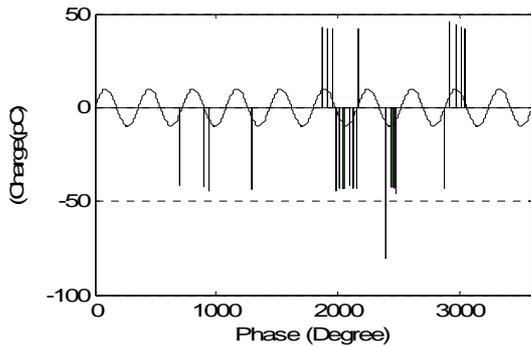

Figure 5 Pulse trains of partial discharge of the first 10 consecutive cycles in palm oil, 18 kV
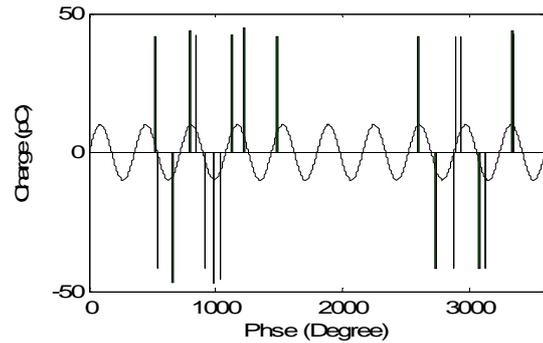

Figure 6 Pulse trains of partial discharge of the first 10 consecutive cycles in palm oil, 25 kV
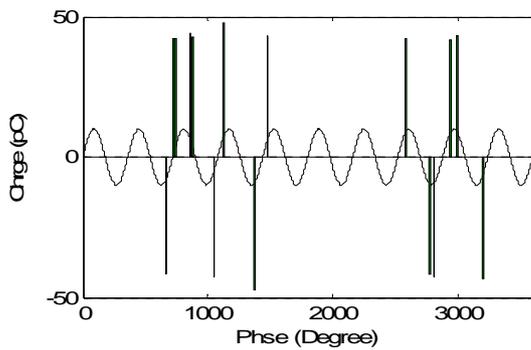

Figure 7 Pulse trains of partial discharge of the first 10 consecutive cycles in palm oil, 32 kV
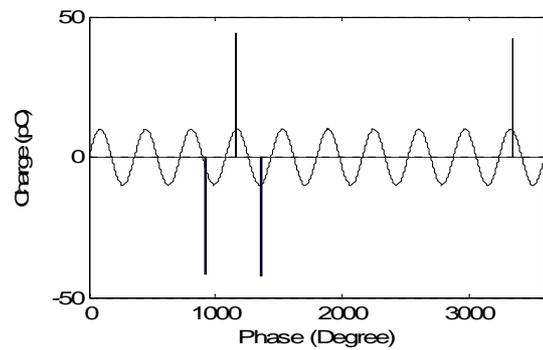

Figure 8 Pulse trains of partial discharge of the first 10 consecutive cycles in mineral oil, 20 kV
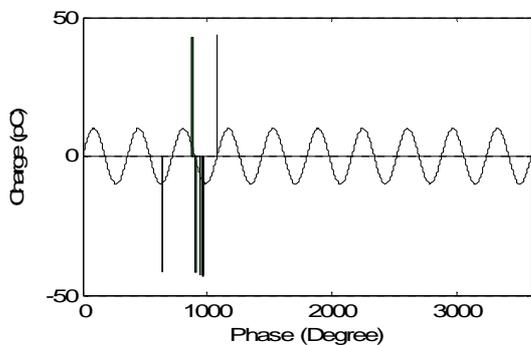

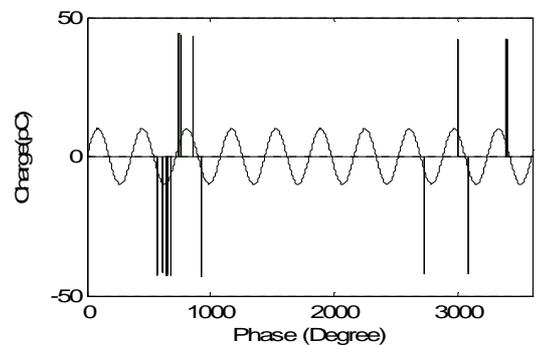Figure 9 Pulse trains of partial discharge of the first 10 consecutive cycles in mineral oil, 25 kV

Figure 10 Pulse trains of partial discharge of the first 10 consecutive cycles in mineral oil, 30 kV

The similar results were observed in mineral oil under the same experimental condition. Figures 8, Figure 9, and Figure 10 show the pulse trains of PD of the first 10 consecutive cycles in mineral oil of 20 kV, 25 kV, and 30 kV applied voltage, respectively. The more consistent results, concerning the phase occurrence of the first PD pulse for each level of applied voltage, was observed at negative half cycle. The figures also show the independency of discharge magnitude to instantaneous applied voltage value, and the level of applied voltage, as well.

In order to reveal the more comprehensive conclusions, the partial discharge pulses, which was occurred in 100 cycles of applied voltage of 32 kV in palm oil, was presented in one cycle. Figure 11 shows the ɸ-q-n and ɸ-n patterns of PD in palm oil occurring in 100 cycles using needle-plane electrode arrangement. It can be observed that discharge pulses occurred in both half cycles of applied voltage, with the higher PD number at negative one (Figure 11b). Unlike the Suwarno and T. Mizutani's experimental results in silicon oil using needle-plane electrode configuration, where PD pulses were concentrated around the peak of applied voltage, both positive and negative cycles [8], in our experimental results as shown in Figure 11, PD pulses spread at the wider area of phase angle, with a phase shift was observed in negative half cycle.

The explanations we propose to explain these evidences as follows. The electrode gap we used in our experiment, 5 mm, was longer than one used by Suwarno and T. Mizutani, 4 mm [8]. When the needle electrode was negative, a positive charge left near the electrode. As the electron has much higher velocity than the positive ion's velocity, then the longer gap made possible for the positive ions, formed at the pervious discharge, arrived late at the needle electrode and left at the area near the needle electrode, increased the electric field at the tip which is tend to increase electron multiplication. At some distance from the needle electrode, electrons trapped by gas molecules produced negative space charge, resulted in a lowering electric field and decrease electron multiplication. The negative space charge must be firstly swept out towards the plane electrode before the next discharge took place [12]. As a consequence, there must be a time delay between two consecutive discharges, and it was represented by the phase shift of PD occurrence (Figure 11b).

The use of acrylic in our experimental set up was another difference with the experiment conducted by Suwarno and T. Mizutani [8]. The presence of acrylic in our experimental set up gave rise the time needed by the negative space charge to move through the edge side of the acrylic before penetrate into plane electrode. Figure 12a illustratively shows the electric field change in the electrode gap due to the presence of the negative space charge. The acrylic also prevented a secondary emission process to take place in the side of acrylic and plane electrode. The acrylic we used in the experiment was attached on the surface of plane electrode. Electrons need space to accelerate under influence of electric field before the electrons gain enough kinetic energy to dissociate oil molecules by collision and developing avalanche in gaseous phase to produce secondary process [13], [14], [15].

Electric force works on electron under influence of electric field is expressed by equation (3), with the resulting acceleration as described by equation (4). Electron velocity is increase during acceleration leads to an increase in its kinetic energy based on equation (5). If the kinetic energy of electron was greater than or equal to the dissociation energy of oil molecules it collides, then molecules with lower molecular weight are generated in gaseous phase. Gas molecules, under influence of electric field, may be ionized by photo ionization result in secondary electron which is required to develop the secondary avalanche process [13], [14], [15].

$$F = eE \tag{3}$$

$$a = \frac{F}{m} \tag{4}$$

$$E_k = \frac{1}{2}mv^2 \tag{5}$$

Where F is the electric force, e is the electron charge, E is the electric field, a is the acceleration, m is the mass of electron, Ek is the kinetic energy, and v is the electron velocity.

(a)

(b)

Figure 11 ɸ-q-n and ɸ-n patterns of PD on palm oil under sinusoidal applied voltage, 32 kV

| Needle | Acrylic Plane | Needle | Acrylic Plane |
| (a) | | (b) | |

Figure 12 Illustration of the electric field in electrode gap due to the presence of space charge.
The length of arrows do not represent the magnitude of the electric field;
(a) When the needle is negative, (b) When the needle is positive.
◄ - - is the path of positive ion,
◄ · — is the path of electron, and
◄— Is the electric field line.

When the needle was positive, initial electrons come from the insulating liquid, which under high electric field directed toward the needle electrode and develop avalanche. Positive ions left behind the electrons lead to the formation of a positive space charge and lowering the tip electric field, as well as electron multiplication. The positive space charge simply became an extension of the needle electrode. Therefore, it did not introduce phase shift of PD occurrence, its effect was only reducing the local electric field, and hence, the positive PD magnitude. That's why PD magnitude seemed to be similar at both half cycles of applied voltage. In absence of the space charge, the positive PD magnitude should be higher than the negative one. This conclusion was supported by the experimental result in silicon oil utilizing the needle-plane electrode configuration, where PD magnitude at positive half cycle of applied voltage was higher than at negative half cycle one [16]. Figure 12b illustratively shows the electric field change due to the presence of the positive space charge.

(a)

(b)
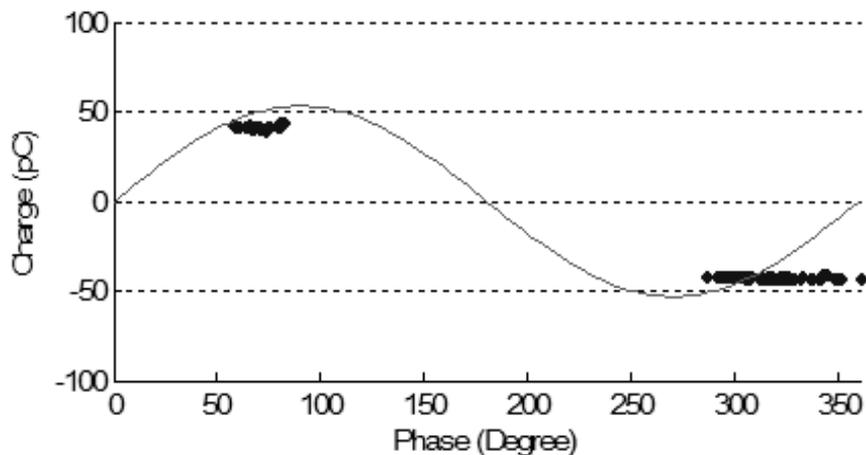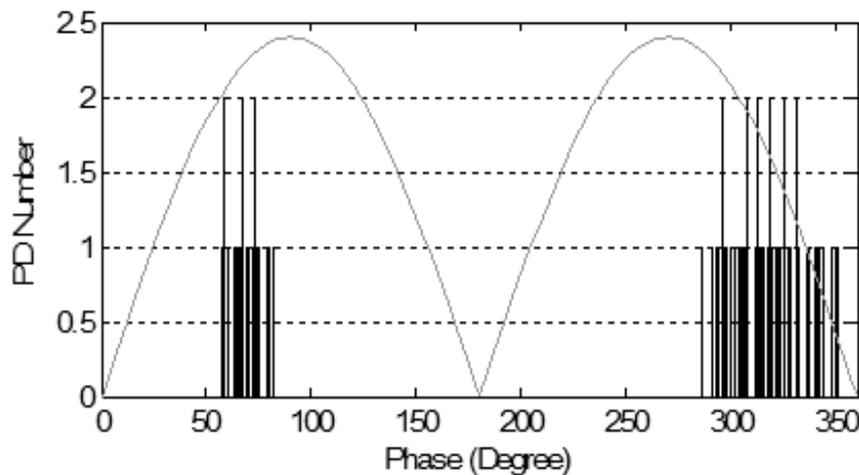
Figure 13 ɸ-q-n and ɸ-n patterns of PD of mineral oil under sinusoidal applied voltage, 30 kV

The similar phenomena were found in mineral oil under the same experimental condition. Figure 13 shows the ɸ-q-n and ɸ-n patterns of PD in mineral oil occurring in 100 cycles using needle-plane electrode arrangement. As can be seen from the Figure 13, a quite distinct from palm oil was observed (Figure 11). In mineral oil, discharges took place at the more

narrow area of phase angle of applied voltage. The phase shift of PD occurrence was also smaller in mineral oil then one in palm oil. This evidence probably caused by the lower viscosity of mineral oil then that of palm oil. As the electron and ion mobility's is inversely proportional to the viscosity [17], then the space charges in the lower viscosity of mineral oil diffused into the electrode faster than one in higher viscosity of palm oil. As a consequence, the space charge formed in mineral oil was smaller than one in palm oil.

4. Conclusions

Discharges in palm oil and mineral oil were investigated under sinusoidal voltage using needle-plane electrode configuration. PD activities in both oils are similar in the following findings: the PD was initiated at the negative polarity of applied voltage, the discharges took place in both half cycles of applied voltage with PD number was higher at negative one, there is independency of PD magnitudes to the instantaneous value of applied voltage, the similarity of PD magnitude at both half cycles of applied voltage, and the presence of phase shift of PD occurrence. The PD phase shifting indicated the presence of space charge that changed electric field in electrode gap. The space charge induced electric field that governs PD activities, besides the main field introduced by voltage application.

PD pattern of palm oil where the PD pulses spread at the wider area of phase angle of applied voltage, with a phase shift was observed in negative half cycle is distinguishable from that of solid insulation which are usually take place at the zero point of applied voltage wave. Therefore, it can be used as diagnostic tool for palm oil-filled electrical apparatus if it could be realized in the future.

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