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A Model of Streamer Discharges in Insulating Liquid and Computer Simulation

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Abstract: Liquid insulations are widely used in high voltage equipments such as transformers. Under high electric stress and the presence of impurities or defects streamer discharges may take place in the liquid insulation. This study reports the experimental results on the characteristics of Partial Discharges (PD) silicone oil under sinusoidal and triangular voltages and a proposal for equivalent circuit for explaining the characteristics. Electrode used in the experiment was steel needle-plane arrangement with needle tip radius of curvature of 3 μm. Discharges occurred in the sample were detected with an RC detector. The experimental results shown that the PD inception voltage in silicone oil increased with viscosity. Negative PD pulses appeared at applied voltage of slightly higher than the inception voltage. At higher voltage PD took place at both positive and negative half cycles where the negative PD pulse number was higher but with smaller magnitude. This shown that initiation of negative PD from needle tip was easier to happen compared to those of positive PD from the oil side. PD in silicone oil took place around the peak of the applied voltage under both sinusoidal and triangular applied voltage which indicated that PD occurrence in silicone oil was strongly dependent on the instantaneous applied voltage. The magnitude of the PD also reflected the waveform of the applied voltage. Based on the experimental results equivalent circuits for PD in silicone oil is proposed. In order to obtain more deeply understanding of the streamer discharges in insulating liquid, a computer simulation was done by utilizing the proposed equivalent circuit. The simulation results were compared to discharge patterns obtained from the experiment. The results indicated that simulated discharge patterns were strongly similar to those obtained from experiment. This shown the validity of the proposed equivalent circuit.

Key words: Streamer, discharge, liquid, equivalent circuit, computer simulation

INTRODUCTION

Insulation is an important part of a high voltage equipment. Due to high electric stress and the existence of defects, partial discharges may take place in the insulation. Partial discharges may appear in solid as well as in liquid insulation in the form of streamer discharges (Forster, 1993; Watson *et al*., 1998). The appearance of discharges in insulation of high voltage apparatus related with defect or aging of the insulation and may indicate an aging leading to the failure of the apparatus (Pompili *et al*., 2000; Yan, 2003).

Recognizing the partial discharge patterns and their pulse sequences will be very useful for the diagnostics of the high voltage apparatuses (Bozzo *et al*., 1998; Park *et al*., 2006; Chen *et al*., 2008).

The understanding of the discharge is very important to know the condition of the insulation. The interpretation of the partial discharges and their correlation with the physical processes behind are also very important (Van Brunt, 1994; Suwarno *et al*., 1996). In order to obtain more deeply understanding of streamer discharges, it is important to investigate the characteristics, derive a model and to simulate the streamer discharges.

In this study, experimental results on the partial discharges silicone oil under sinusoidal, triangular and rectangular voltages are presented. The measurement of the PD was done using a pC-based PD measurement system. The PD data was presented in the form of ϕ-q-n pattern where f is the phase angle of PD occurrence, q the PD magnitude and n is the PD pulse number. The analysis of PD magnitude and occurrence in phase angle of applied voltage was done. The PD pulse-sequence analysis of several consecutive cycles was done to know the physical processes behind the appearance of the PD. Based on the experimental results, equivalent circuits are proposed.

MATERIALS AND METHODS

Samples used in this experiment were silicone oil the viscosity of 100 cSt. Partial discharges were generated in the samples by applying a high voltage on the needle electrode in a needle-plane electrode system. The needle electrode (Ogura jewellery) was made from steel with length of 5 cm and diameter of 1 mm. The curvature of the needle tip is 30° and the tip radius is 3 µm. The electric field at the tip of the needle electrode is determined by the Eq. 1 (Mason, 1955):

$$E_m = \frac{2V}{r\ln\left(\frac{4d}{r}\right)} \qquad (1)$$

The applied voltage was either sinusoidal, triangular or rectangular. The high voltage was applied to the needle electrode and the PD pulses were measured using a pC-based PD measurement system.

Characteristics of streamer discharges in silicone oil: Experiment under sinusoidal applied voltage, PD inception voltage was obtained as 6.7 kV. According to Eq. 1, this voltage corresponds to an electric field a the tip of needle electrode of 7.4 MV m^{-1}. This value is in good agreement with typical electric field for initiation of streamer in dielectric liquid as reported by Lewis (1998), which is several MV/m. Figure 1a shows PD pulses took place in 14 consecutive cycles and ϕ-q-n pattern under applied voltage of 8 kV. Figure 1a shows that PD pulses appear at around peak of applied voltage both positive and negative half cycles.

Under applied voltage of 8 kV, PD magnitude was distributed from several pC up to about 20 pC. The PD magnitude increases with the applied voltage. Figure 1a and b shows that both positive and negative discharges took place around the peak of applied voltage. Similar results were reported in experimental results in transformer oil with needle tip of 10 µm inserted in oil-impregnated press board (Gao *et al*., 2006). Figure 1a also indicates that the magnitude of positive discharge was higher than negative discharge. The higher the applied voltage the larger the magnitude is. These results indicated that positive discharges took place at higher over voltage than negative one. This asymmetrical behavior reflects the asymmetrical role of electrode system in producing discharge in silicone oil. The magnitude of discharge in both half cycles was proportional to the applied voltage. Therefore, shape of the θ-q-n pattern reflects the shape of the applied voltage around its peak.

Figure 2 shows typical PD pulse sequences for 2 consecutive cycles in silicone oil under sinusoidal voltage of 8 kV. From Fig. 2, it is clearly seen that PD pulses concentrated around the peak of the applied voltage. This indicates that the PD occurrence is dependent on the instantaneous applied voltage. Figure 2 also indicates that the magnitude of the PD pulses reflects the instantaneous applied voltage. The typical PD numbers were 5 and 8 for positive and negative half cycles, respectively. PD pulse sequence as shown in Fig. 2 also shown that the PD magnitude in silicone oil was greatly affected by the

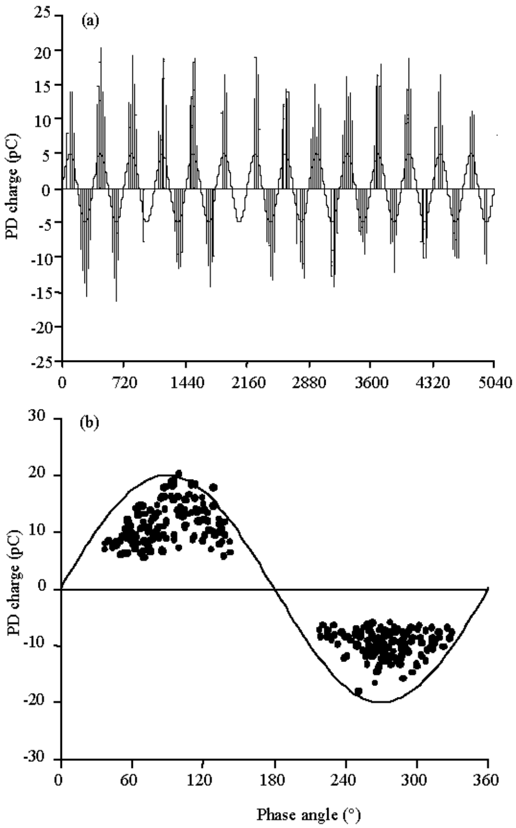

Fig. 1: a) PD pulses in 14 consecutive cycles and b) ϕ-q-n PD patterns of silicone oil at sinusoidal voltages of 8 kV

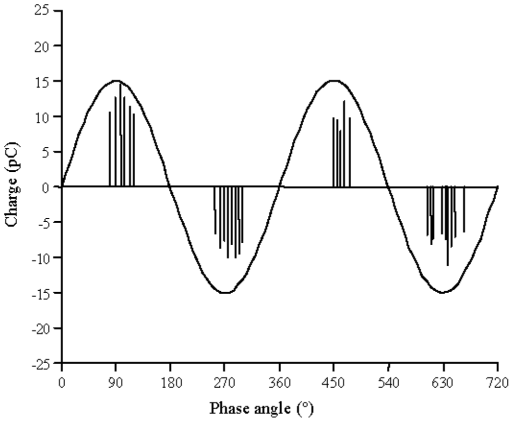

Fig. 2: Typical PD pulse sequences from silicone oil under sinusoidal voltage

instantaneous applied voltage. The patterns similar with those from corona discharges in air (Suwarno and Mizutani, 2006).

Figure 3 shows the typical distribution of PD pulses in phase angle of applied voltage in the form of ϕ-n pattern of streamer discharges in oil under sinusoidal voltage. Figure 3 clearly shows that PD occurrence is strongly dependent on the instantaneous value of the applied voltage. Therefore, the shape of the PD pulse distribution in phase angle fit well with the shape of the applied voltage (i.e., sinusoidal).

Figure 4 shows typical ϕ-q-n PD patterns in silicone oil under triangular voltage of 6 kV (a) and 8 kV (b). The patterns are composed from discharge pulses took place in 100 cycles. From the Fig. 4, it is seen that discharge in silicone oil took place concentrated at around phase angle of 90 and 270°C. This indicates that the PD occurrence mainly determined by the magnitude of voltage applied to the discharge site, which is proportional to the voltage applied to the electrode.

The positive PD magnitude was slightly higher than negative. The PD number also increased with the applied voltage. The discharges were observed in both sides around 90 and 270°C phase angle under voltage rise and fall (i.e., time derivative of applied voltage dv/dt is positive in the left side and negative in the right side). This indicates that discharge occurrence independent on the dv/dt of the applied voltage. The fact revealed that the instantaneous applied voltage played important role in the PD occurrence. The discharge magnitude reflected the magnitude of the applied voltage (i.e., triangular voltage). This results clarified the measurement results when sinusoidal voltage was applied.

Figure 4a and b also indicate that streamer discharge magnitude is strongly dependent on the applied voltage. The maximum discharge magnitude is about 80 pC for 6 kV and about 125 pC for applied voltage of 8 kV.

Figure 5 shows typical PD pulses took place in 2 consecutive cycles in silicone oil under triangular applied voltage of 8 kV. Similar to those indicated in ϕ-q-n patterns, the PD pulses were concentrated around the peak of the triangular voltage in both positive and negative half cycles. The results supported the explanation of PD patterns obtained under sinusoidal voltage.

Figure 6 shows the typical distribution of PD pulses in phase angle of applied voltage in the form of ϕ-n pattern of streamer discharges in oil under triangular voltage. The pattern is triangular, which is much similar with the applied voltage. As indicated by the Fig. 6, the tip of the triangular almost coincide with the peak of applied voltage at both positive and negative half cycles. These results supported the conclusion that the discharge probability is strongly dependent on the instantaneous value of the applied voltage. In general, the negative PD pulse number is slightly larger than those pf positive PD.

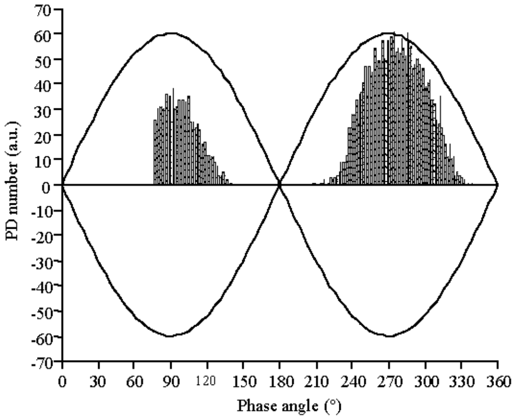

Fig. 3: Typical ϕ-n pattern of streamer discharges in oil under sinusoidal voltage

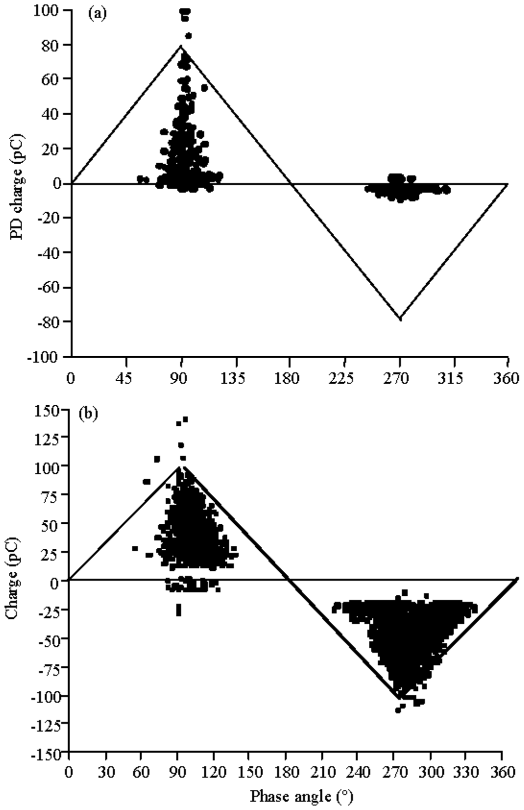

Fig. 4: ϕ-q-n patterns of PD in silicone oil under triangular applied voltage of a) 6 kV and b) 8 kV

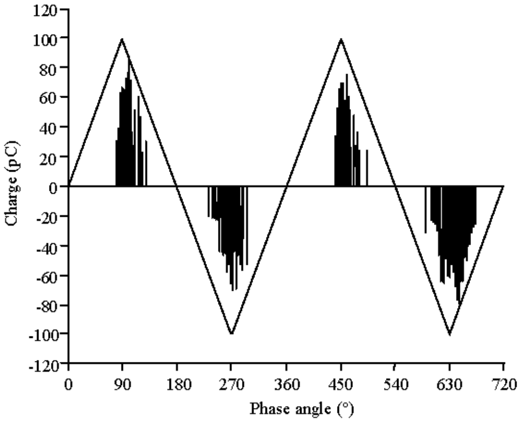

Fig. 5: Typical PD pulse sequences of silicone oil under triangular applied voltage

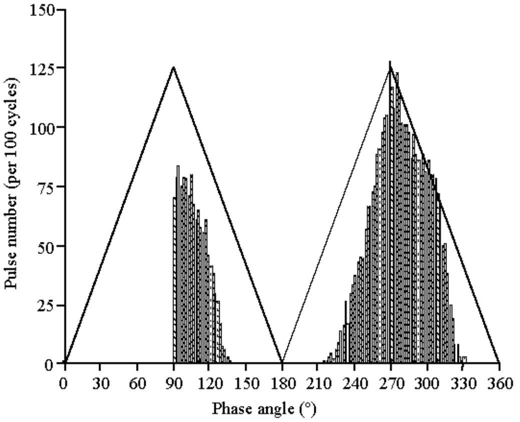

Fig. 6: Typical ϕ-n pattern of streamer discharges in oil under triangular voltage

Equivalent circuit of discharge in silicone oil: The phase-resolved measurement results and analysis on PD in silicone oil it is clear that the PD magnitude as well as the PD occurrence are dependent on the instantaneous applied voltage. The positive PD probability is slightly smaller than negative PD. Based on the characteristics, equivalent circuit for streamer discharge is proposed as shown in Fig. 7.

Insulating liquid is represented as capacitances. The streamer is represented by capacitance C_g in parallel with a spark gap. C_b represented capacitance of the sound part of the insulation, while the rest of the sample is represented by Dan C_m.

If the applied voltage is V (t) the voltage applied to the streamer before any discharge take place is:

$$V_g(t)=\frac{C_b}{C_g+C_b}\times V(t) \tag{2}$$

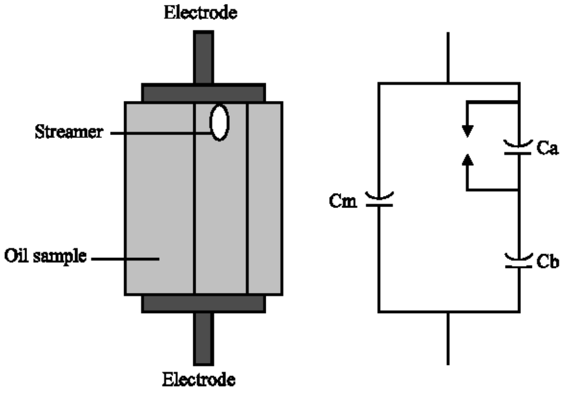

Fig. 7: Equivalent circuit of streamer in silicone oil

Therefore, the magnitude for the first discharge can be expressed as:

$$Q = C_g\,(kV\,(t) - V_r) \tag{3}$$

Since from the experimental results, it was found that q reflected the value of V (t) this indicated that the residual voltage after the discharge V_r is much smaller than kV (t). The small residual voltage resulting in a small phase shift of PD occurrence. Therefore, the PD pulses concentrated around the peak of the applied voltage.

Computer simulation of streamer discharges: Based on the equivalent circuit, computer simulation of streamer discharges was done. This simulation consists of two subprograms embedded in one. The subprograms are:

- Generating partial discharges pulses
- Visualization of PD patterns and their pulses sequence, including ϕ-q-n graph, ϕ-q graph for five consecutive cycle and p-n graph

Beside the information about PD patterns and their pulse sequence, the result of this simulation is statistical data printing that consist of every pulses generated. To run this simulation, 5 inputs are needed. The five inputs are number of applied cycles, applied voltage, positive inception voltage, negative inception voltage and file name to record the result. The difference of positive inception voltage and negative inception voltage should not >0.5 kV. The applied voltage in this simulation is sinusoidal voltage. The flow chart of the simulation is shown in Fig. 8.

In generating PD pulses, there are two prerequisite for each half cycle. Prerequisites for positive half cycle are:

- Applied voltage should higher than positive inception voltage

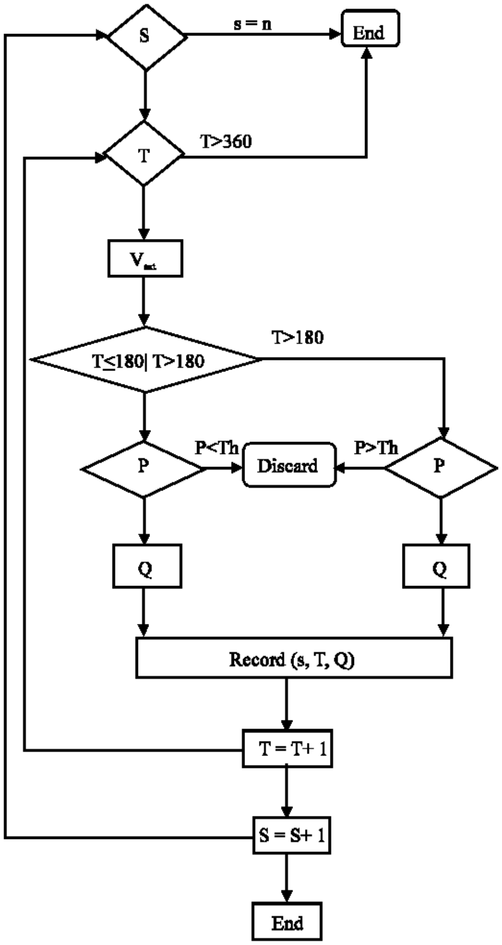

Fig. 8: Flow chart for generating PD pulses

- Determinant factor representing appearance of early electron should higher than positive threshold

The prerequisites for negative half cycle are:

- Applied voltage should lower than negative inception voltage
- Probability representing appearance of early electron should lower than maximum allowed probability

The determinant factor of early electron appearance is determined by random number that represent stochastic occasion regarding the appearance of early electron. The random number will be multiplied with the difference between applied voltage and inception voltage resulting determinant factor of early electron appearance value:

$$P = (V_{ext} - V_i) \times Rand$$

Where:

V_i = Inception voltage

Rand = Random number

The number of P will be compared with positive/ negative threshold of early electron appearance. This determinant factor also indicates, whether 2 prerequisites for generating PD pulses are qualified or not.

Positive/negative threshold of early electron appearance (T_h) is a threshold that determines whether there is early electron or not. Positive threshold is used in positive half cycle and negative threshold is used in negative one. For half positive cycle, if determinant factor is higher than positive threshold, early electron is exhibit and conduct PD phenomena. In half negative cycles, the determinant factor should below negative threshold in order to exhibit early electron that conducts PD.

Positive/negative threshold of early electron appearance depends on inception voltage and applied voltage. The higher inception voltage result the higher positive threshold and the smaller negative threshold of early electron appearance. So that early electron voltage that trigger PD will getting hard to appear in an increasing inception voltage. Nevertheless, increasing applied voltage will also decrease positive threshold and increase negative threshold of early electron appearance. So that the discharge will be easier to occur in higher applied voltage rather than lower one.

RESULTS AND DISCUSSION

Insulating liquid, take for example, have positive inception voltage equal to 6 kV and negative inception voltage equal to -5.8 kV. Applied voltages in this simulation are 8 and 10 kV. The simulated PD patterns are shown in Fig. 9 and 10.

From ϕ-q-n graph in Fig. 9 and 10, it is shown that PD pulses concentrated on the peak of applied voltage at both negative and positive cycles. These indicate that instantaneous applied voltage strongly affected PD occurrence, the discharges amplitude also strongly reflects applied voltage (6). The PD patterns are similar to those obtained from the experiment.

From Fig. 9 and 10 also, PD characteristics distributed symmetrically because influenced by bubble symmetry patterns characteristics. PD magnitude may vary randomly during simulation because the influence of applied voltage and size of the bubbles.

When applied voltage is higher, chance to enhance energetic discharges is bigger. When energetic discharge occurs, large bubbles will be disrupted. Disruption in large bubbles makes size of bubbles become vary. This phenomena explain that applied voltage strongly influence the size of the bubbles.

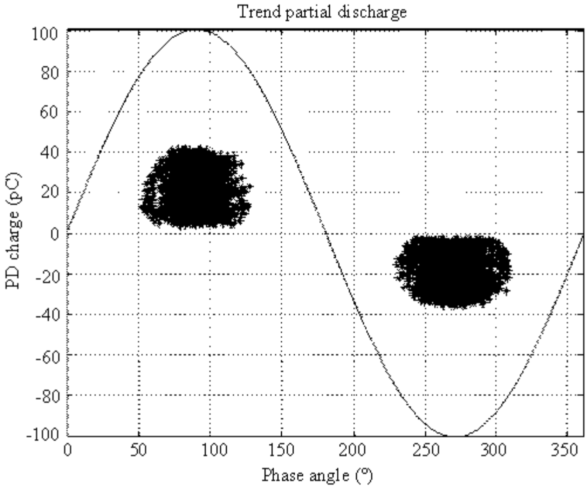

Fig. 9: ϕ-q-n in applied voltage 8 kV

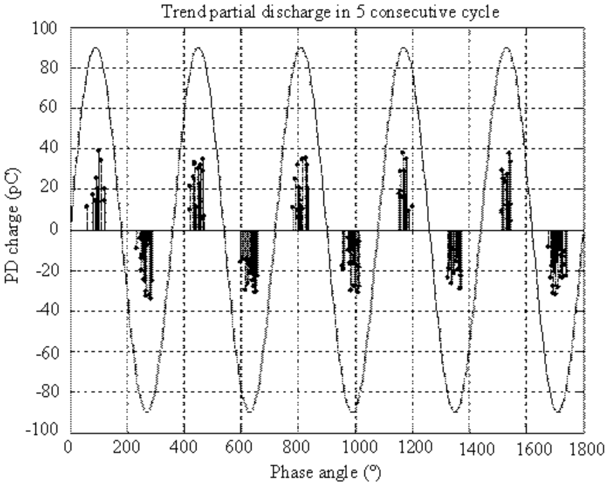

Fig. 11: Pulse trains graph under applied voltage of 8 kV

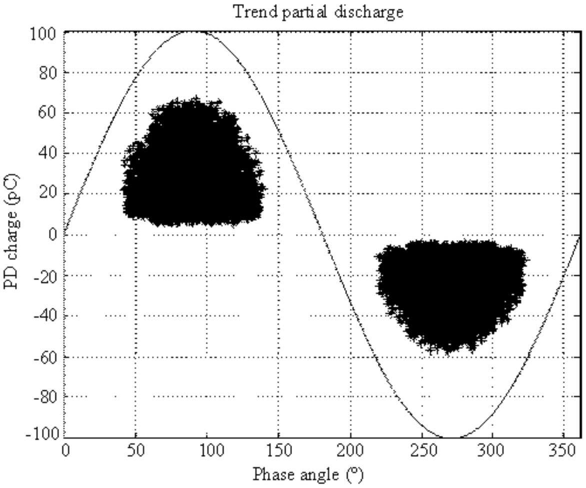

Fig. 10: ϕ-q-n graph in applied voltage 10 kV

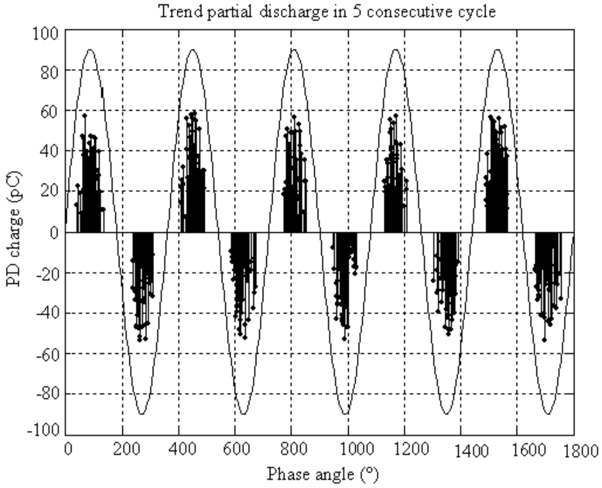

Fig. 12: Pulse trains graph under applied voltage of 10 kV

Figure 11 and 12 show the details about discharge intensity in five consecutive cycles. From Fig. 11 and 12, it is obviously clear that applied voltage strongly influence discharges intensity. Figure 11 and 12 also show that discharges amplitude in positive cycles is higher than negative one. These phenomena can be explained by the difference of inception voltage in positive and negative half cycles. Positive half cycles usually has higher inception voltage rather than negative. It makes positive discharges more energetic rather than negative discharges.

Although, having higher discharges magnitude, amount of positive discharge is lower than negative discharge. It is shown in Fig. 13 and 14, horizontal axis represents phase angle locating PD phenomena and vertical axis represents the amount of discharge pulses. These characteristics are strongly influenced by inception voltage where in positive cycles, the inception voltage is higher than negative half cycle. Because of positive half cycle has higher inception voltage than negative cycle, the discharge in positive half cycle is more difficult to occur rather than in negative half cycle. Factor that inhibiting PD occurrence in positive half cycle is the disruption of large bubbles because of inception voltage is increasing.

The simulation results are similar with experimental results as shown in Fig. 9-11.

The simulated ϕ-n PD patterns as shown in Fig. 13 and 14 are similar to those obtained from the experiment. These indicated the validity of the proposed streamer discharge model.

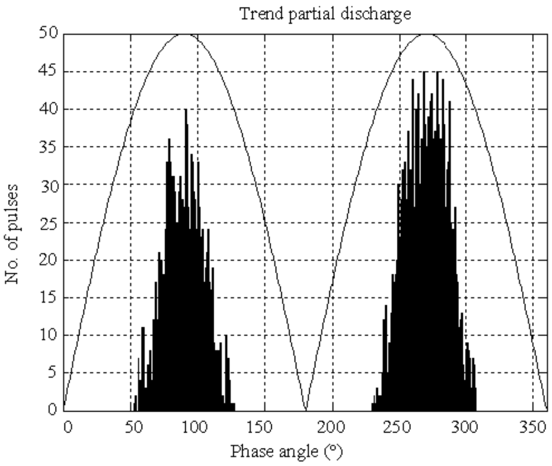

Fig. 13: ϕ-n graph in applied voltage 8 kV

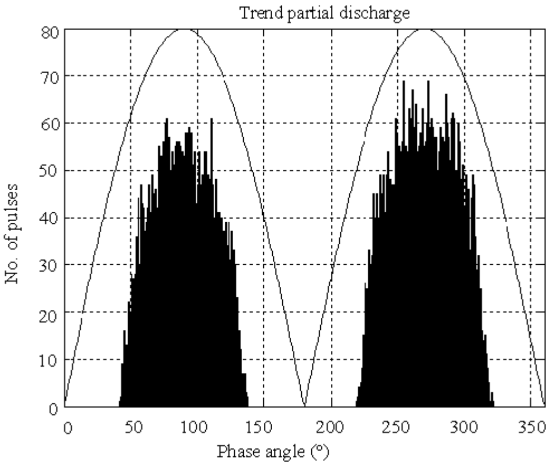

Fig. 14: ϕ-n graph in applied voltage 10 kV

CONCLUSION

Streamer discharges in silicone oil was investigated using point-plane electrode system under sinusoidal as well as triangular applied voltage. The unsymmetrical behavior of PD in positive and negative half cycles, we observed. Negative PD pulses were observed first and big positive PD pulses were observed at higher applied voltage. Under sinusoidal as well as triangular applied voltages in silicone oil, PD pulses took place around the peak of the applied voltage.

Under triangular applied voltage, PD pulses also distributed around the peak.The magnitude as well as discharge occurrences in silicone oil are greatly dependent on the instantaneous applied voltage. The discharge behavior in silicone oil can be explained by an equivalent circuit consisting of a streamer capacitance in parallel with a spark gap and in series with the oil capacitance. In order to verify the validity of the proposed model, computer simulation was done to generate ϕ-q-n, ϕ-n patterns and PD pulse sequences. It was found that simulated patterns are similar to those obtained from experiment. This result indicated the validity of the proposed model.

Nomenclature:

S = Executed cycle
n = Applied cycle
T = Phase angle
V_{ext} = Applied voltage, $V_{ext} = V\sin(T)$
P = Determinant factor of early electron appearance
T_h = Negative/positive threshold of early electron appearance
Q = Discharges magnitude, $Q = (V_{ext} - V_r) \times C_b$
V_r = Residual voltage
C_b = Bubbles capacitance

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