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Role of Applied Voltage Waveforms on Partial Discharge Patterns of Electrical Treeing in Low Density Polyethylene

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Abstract: High voltage apparatuses play an important role in transmitting a huge amount of electrical energy. In order to keep the apparatuses in normal condition, the insulation system should be maintained. Solid as well liquid insulating materials are widely used in high voltage apparatuses. During operation of the apparatuses, the insulation may experience ageing. Appearance of electrical discharges in high voltage apparatuses with reasonable magnitude and frequency can be interpreted as abnormal condition. In order to know the origin of the discharges it is necessary to investigate the characteristics of the discharge. This study reports the experimental results on the characteristics of Partial Discharges (PD) in Low Density Polyethylene (LDPE) under sinusoidal, triangular and rectangular voltages. Electrode used in the experiment was steel needle-plane arrangement with tip radius of curvature of 3 μm. This sharp needle allow to produce a very high electric field of several MV m^{-1} at the needle tip. The PD in LDPE was generated around the tip of needle electrode when an electrical tree appeared. The PD pulses were measured using a personal computer-based measurement system. Discharges occurred in the sample were detected with an RC detector with a lower cut off frequency of 250 kHz. The output of the detector was measured by PD analyzer and digitized. Using the measuring system the discharge magnitude, frequency as well as the phase of discharge occurrence in the applied voltage cycles is measured and the digital data are stored in the PC. The analysis was focused on the ϕ-q-n pattern and the time sequence between consecutive pulses. Here, ϕ is the phase angle of PD occurrence, q is the PD magnitude and n is the number of PD pulses. The experimental results showed that the applied voltage greatly affected the PD in the LDPE. Under sinusoidal applied voltage, the PD pulses due to electrical tree in LDPE distributed around the zero cross. The occurrence is strongly related to the time derivative of the applied voltage. This was clarified under triangular applied voltage where PD pulses distributed almost uniformly as can bee seen in PD pulse sequences. ϕ-q-n pattern under rectangular applied voltage made more clearly where PD pulses only took place around the zero cross where the value of dv/dv was high. The PD magnitude of the electrical tree reflected the instantaneous applied voltage. This was clarified under triangular applied voltage where triangular patterns were obtained. The experimental results under rectangular voltage strongly supported the findings under sinusoidal and triangular applied voltage. Based on the experimental results equivalent circuits for electrical treeing PD in LDPE is proposed.

Key words: LDPE, electrical treeing, PD, sinusoidal voltage, triangular voltage, rectangular voltage

INTRODUCTION

Since long time ago, high voltage has been used in transmitting a huge amount of electric energy. In an electric power system, high voltage equipments are necessary. Insulation plays an important role in a high voltage apparatuses to withstand the working the electric stressed during operation. During operation, partial discharges may take place in solid insulation in the form of tree-like pattern consisting many fine trunks and branches which is called electrical treeing (Hozumi *et al*., 1988; Guastavino and Cerutti, 2003; Vogelsang *et al*., 2005). 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 (Wolter *et al*., 1978; Champion *et al*., 2001). 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. Discrimination of the discharge sources is an important step in order to properly deciding the necessary action to keep the apparatuses to be in the normal condition. 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*., 2003; Yan and Dong, 2005; Gulski *et al*., 2005). In this study, experimental results on the partial discharges due to electrical treeing in Low Density Polyethylene (LDPE) under sinusoidal, triangular and rectangular voltages. 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 circuit for electrical treeing PD is proposed.

MATERIALS AND METHODS

Experiment

Sample and electrode system: Samples used in this experiment was Low Density Polyethylene (LDPE) with density of 0.92 g cm^{-3}. Partial discharges were generated in the sample 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°C and the tip radius is 3 µm. The electric field at the tip of the needle electrode is determined by the following equation (Pulfrey, 1972).

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

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.

Measurement system: PC based measurement system was used to measure the PD took place during the experiment. Discharges occurred in the sample were detected with an RC detector with R of 2 kΩ and C of 330 pF with a lower cut off frequency of 250 kHz. The output of the detector was measured by PD analyzer and digitized. Using the measuring system the discharge magnitude, frequency as well as the phase of discharge occurrence in the applied voltage cycles is measured and the digital data are storage in the PC.

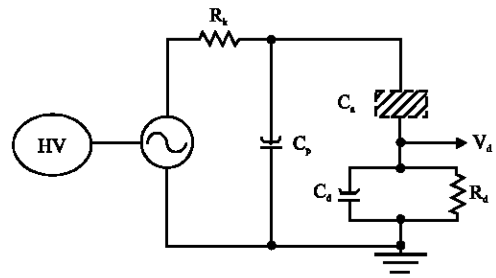

Fig. 1: Schematic diagram of experiment

The sample-measurement arrangement is shown in Fig. 1 high voltage is applied to the sample. Partial discharges take place in the sample are detected using PD detector consisting of a capacitance C_d and resistor R_d.

The output voltage is integration of PD pulse (i.e., the PD charge) as expressed by

$$V_d(t) = \frac{1}{C_d}\int_0^t i(t)\,dt \quad (2)$$

Here:

R_k = Current limiting series resistance (50 kΩ)
C_p = Test capacitance (100 pF)
C_a = Capacitance of sample
C_d = Detecting capacitance (1000 pF)
R_d = Detecting resistance (1 kΩ)
V_d = Output voltage (Volt)

The value of output voltage V_d can be expressed by:

$$V_d(t) = K\exp(-\alpha t) \quad (3)$$

Where,

$$K = \frac{q}{C_d + \frac{C_p C_a}{C_p + C_a}} x \frac{C_p}{C_p + C_a} \quad (4)$$

$$\frac{1}{\alpha} = \left(C_d + \frac{C_p C_a}{C_p + C_a}\right) R_d$$

In this case $C_p \ll C_a$ and $C_d \gg C_a$, therefore:

$$K \approx \frac{q}{C_d} \quad (5)$$

$$\frac{1}{\alpha} = C_d R_d$$

Thus, equation can be simplified as:

$$V_d(t) = \frac{q}{C_d}\exp\left(-\frac{t}{R_d C_d}\right) \quad (6)$$

or:

$$q = V_d . C_d \quad (7)$$

This latest equation indicates that the PD charge is proportional to the output voltage V_d. Each volt measured by the measurement system used in this experiment correlated with PD charge of 285 pC. The PD parameters measured were PD magnitude and its phase angle. In each measurement PD pulses took place in several consecutive cycles were measured. The data can be presented in a ϕ-q-n pattern or PD pulse sequences.

RESULTS AND DISCUSSION

PD due to electrical treeing in LDPE under sinusoidal applied voltage

Electrical treeing and PD during initial stage: Figure 2a shows the picture of electrical treeing after 4 min voltage application of 8 kV AC. At the initial state, electrical treeing initiated from the tip of needle electrode where the electric field was very high. The length of treeing after 4 min is about 150 µm. During this state the treeing grew rapidly and the tree length changed from several tens to several hundreds of µm.

Figure 2b shows typical PD pulse trains took place in 20 consecutive cycles during the tree initiation. Horizontal axis is phase and vertical axis is PD charge magnitude. Each train represented a PD pulse. It was very interesting that there were PD pulses took place in several consecutive cycles in alternate manner (positive and negative) then ceased for several consecutive cycles and then re-appeared again. There was 1 PD pulse in each half cycle for both positive and negative. This phenomena similar with PD behavior in artificially simulated tree channels with diameter of 10 µm (Suwarno *et al*., 1997; Kaneiwa *et al*., 2001). The PD charge was about 5 pC.

Figure 2c shows the typical ϕ-q-n PD pattern of tree initiation. Horizontal axis is phase angle and vertical axis is PD charge magnitude. Each point represents a PD pulse. The ϕ-q-n pattern was constructed from PD pulses took place in 200 consecutive cycles.

Electrical treeing and PD during propagation stage: Figure 3a shows the picture of electrical treeing taken 20 min after application of 8 kV sinusoidal voltage. The tree length increased to >500 µm and several branches developed from the trunks originated from the area of the tip of needle electrode.

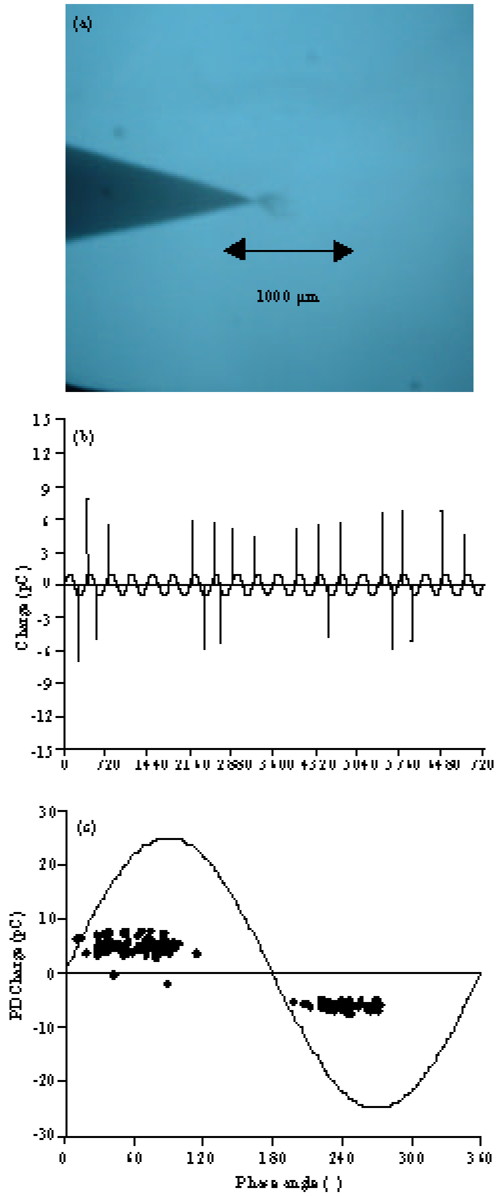

Fig. 2: Treeing picture (a), PD pulses (b) and f-q-n pattern (c) during tree initiation (4 min)

Figure 3b shows typical PD pulse trains took place in 20 consecutive cycles during the tree propagation. The figure clearly indicated that PD pulses took place in all cycles both for positive and negative. In each half cycle >1 PD pulses appeared. The PD magnitude varied from <5 pC to about 20 pC. The significant increase in PD number and magnitude was due to the increase of the tree branches and their length.

Figure 3c shows the typical ϕ-q-n PD pattern of tree during tree propagation. Horizontal axis is phase angle and vertical axis is PD charge magnitude. Each point

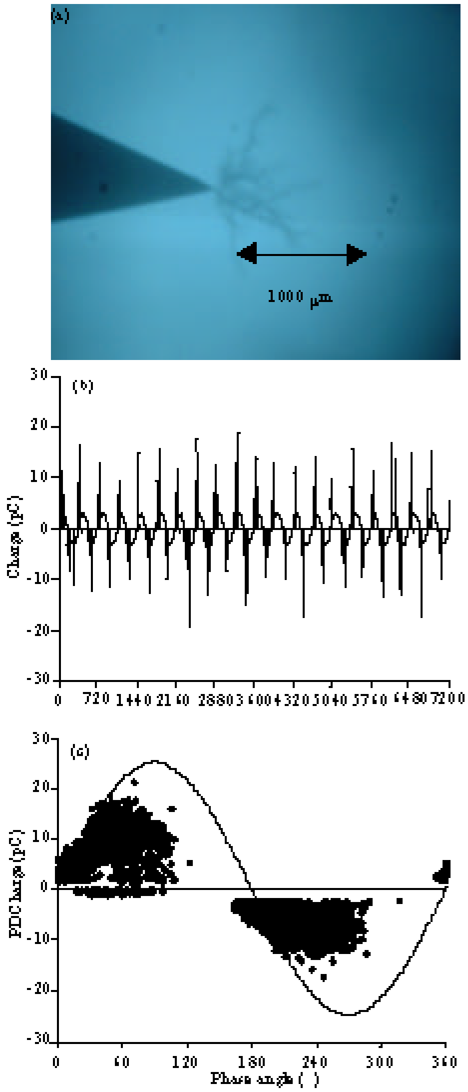

Fig. 3: Treeing picture (a), PD pulses (b) and f-q-n pattern (c) during tree propagation (tree like tree) at 20 min after 8 kV sinusoidal voltage application

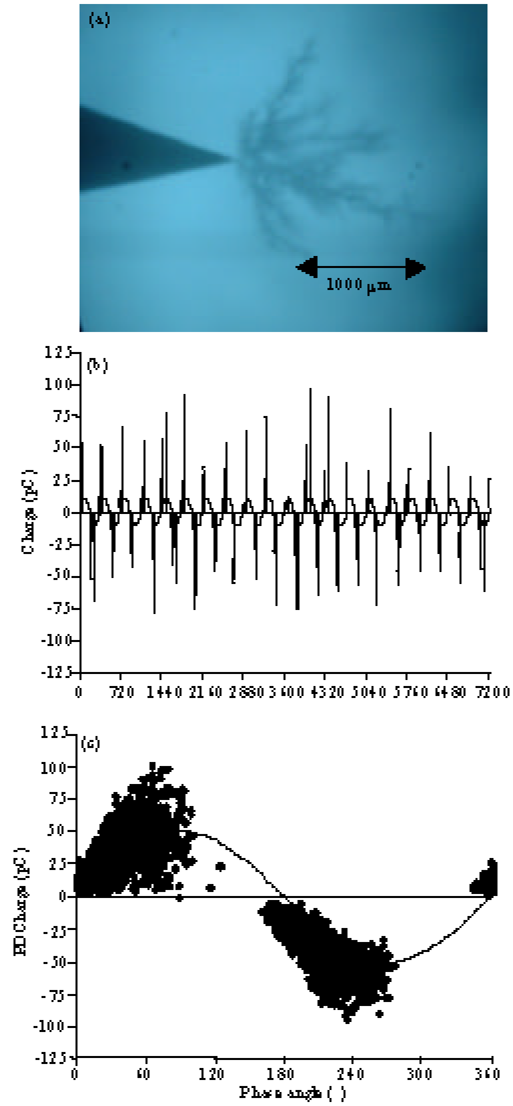

Fig. 4: Treeing picture (a), PD pulses (b) and f-q-n pattern (c) for bush-like tree at 100 min after 8 kV sinusoidal voltage application

represents a PD pulse. The ϕ-q-n pattern was constructed from PD pulses took place in 300 consecutive cycles. The positive PD distributed from -10-105° in phase while, negative PD distributed from 165-290°. The phase angle of PD occurrence was shifted from the peak of the applied voltage but the magnitude reflected the magnitude of the applied voltage. The magnitude of the PD distributed from several pC to about 20 pC. The wide distribution correlated with the length distribution of tree trunks or channels.

Electrical treeing and PD 100 min after voltage application: Figure 4a shows typical picture of bush like tree taken 100 min after application of 8 kV sinusoidal voltage. The tree length increased to about 1400 μm and the tree branches became more densely. Figure 4b showed the PD pulse trains took place in 20 consecutive cycles. PD pulses occurred in both positive and negative half cycles with PD pulse number of >2 in each half cycle. The PD magnitude increased significantly to >80 pC in line with the increase of tree length. Positive PD magnitude was slightly higher than negative one. Figure 4c is typical θ-q-n pattern for bush-like tree. The pattern was constructed from PD pulses took place in 100 consecutive cycles. From Fig. 4c it is shown that the magnitude of positive discharge was slightly higher than negative discharge. This means that positive discharges took place in higher over voltage and the availability of initial electron for positive discharges was more difficult than for negative discharges.

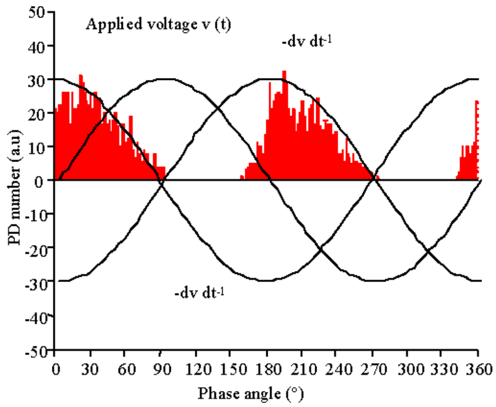

Fig. 5: Typical ϕ-n PD pattern of electrical tree under sinusoidal applied voltage

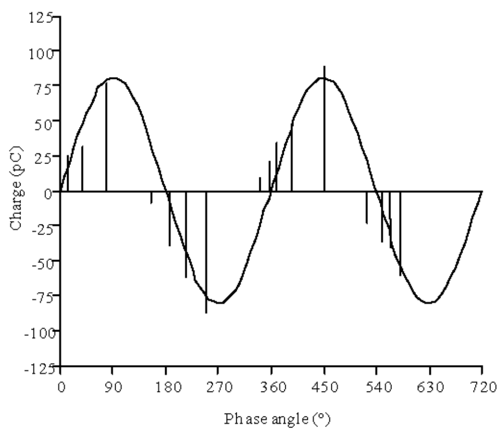

Fig. 6: Typical pulse sequences in 2 consecutive cycles of PD due to electrical treeing in LDPE

The figure also indicates that the magnitude of the discharge increased with instantaneous applied voltage. The discharge took place around the zero cross of the applied voltage and distributed up to the peak. Phase shift was observed in the electrical treeing discharges from the fact that several PD pulses took place at phase angle of several degree before 180° or 360°. This phase shift indicated the influence of space charge on the electrical tree on the discharge process.

Figure 5 shows typical ϕ-n PD pattern of electrical tree under sinusoidal applied voltage. The Fig. 5 clearly indicates that PD number strongly correlates with the time derivative of the applied voltage. This means that the time derivative of the applied voltage strongly affects the PD occurrence. Later this phenomena will be clarified by triangular voltage application.

Figure 6 shows pulse sequence of discharges took place in 2 consecutive cycles. From the Fig. 6, it is clearly seen that discharge occurrence (repetition rate) was

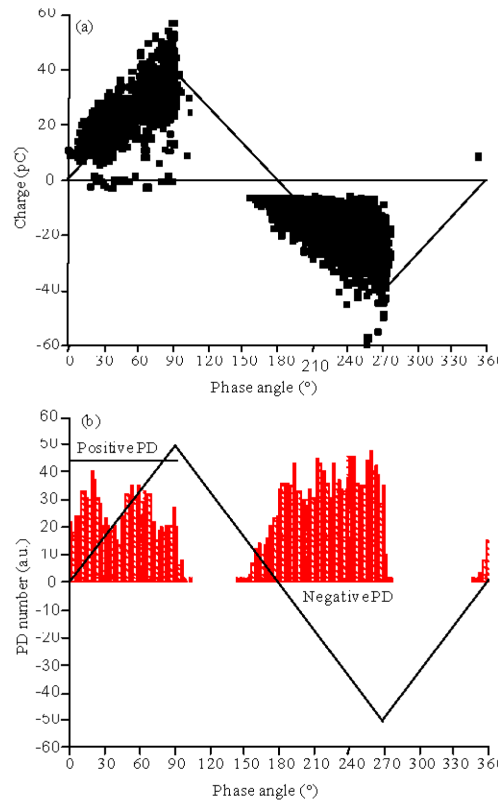

Fig. 7: Typical θ-q-n and θ-n patterns of PD due to electrical treeing in LDPE under triangular applied voltage

higher at around zero cross of applied voltage (high the dv dt^{-1}) than that around peak (small dv dt^{-1}) of the applied voltage. These suggested the important role of the time derivative of applied voltage (dv dt^{-1}) on the occurrence of treeing discharges. The figure also, indicates a trend that PD magnitude increase with the applied voltage.

PD due to electrical treeing in LDPE under triangular applied voltage: Figure 7 shows typical θ-q-n and θ-n patterns of partial discharges due to electrical treeing in LDPE.

From Fig. 7(a) it is seen that he shape of θ-q-n pattern is triangular for both positive and negative half cycles. This PD pattern strongly reflects the waveform of the applied voltage.

The Fig. 7a clearly shows that the magnitude of the discharge increased with instantaneous voltage. The Fig. 7a also, indicates that the magnitude of positive discharge was slightly higher than negative discharge. This means that positive discharges took place in higher over voltage and the availability of initial electron for positive discharge was more difficult than for

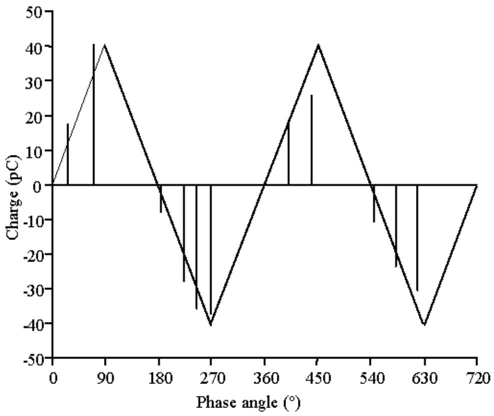

Fig. 8: Pulse sequences in 2 consecutive cycles of PD due to electrical treeing in LDPE under triangular applied voltage

negative discharge. Phase shift of PD was observed under triangular voltage similar to those under sinusoidal voltage which indicated a strong influence of space charge on the PD process.

Figure 7 (b) shows typical θ-n patterns of PD due to electrical treeing in LDPE under triangular applied voltage. From this Fig. 7b it is seen that PD number strongly correlates with the time derivative of the applied voltage. This clarifies the role of $dv\ dt^{-1}$ on the PD occurrence as indicated in θ-n PD pattern of electrical treeing under sinusoidal voltage. Observing this Fig. 7b, it is obvious that negative PD number is slightly higher than positive one. This is indicated by larger area of negative PD compared to those of positive PD.

Figure 8 shows PD pulse sequences of 2 consecutive cycles for electrical treeing under triangular applied voltage. The Fig. 8 revealed that PD pulse magnitude increased with the instantaneous applied voltage.

PD patterns of electrical treeing under rectangular applied voltage: Figure 9 shows ϕ-q-n and ϕ-n patterns of electrical treeing in LDPE under rectangular applied voltage of 7 kV. Although it was desired to applied the rectangular voltage, actually an ideal rectangular voltage could not be obtained since for real equipment no abrupt change of voltage may take place due to capacitance in the electronic high voltage source. There voltage changed within a short period from positive to negative around 180° of phase angle and from negative to positive around 0° of phase angle.

From Fig. 9a it is clearly seen that PD pulses took place within several degrees after the zero cross of the applied voltage. The shape of PD ϕ-q-n pattern of electrical treeing under rectangular voltage reflects the instantaneous applied voltage. Figure 9b shows the ϕ-n

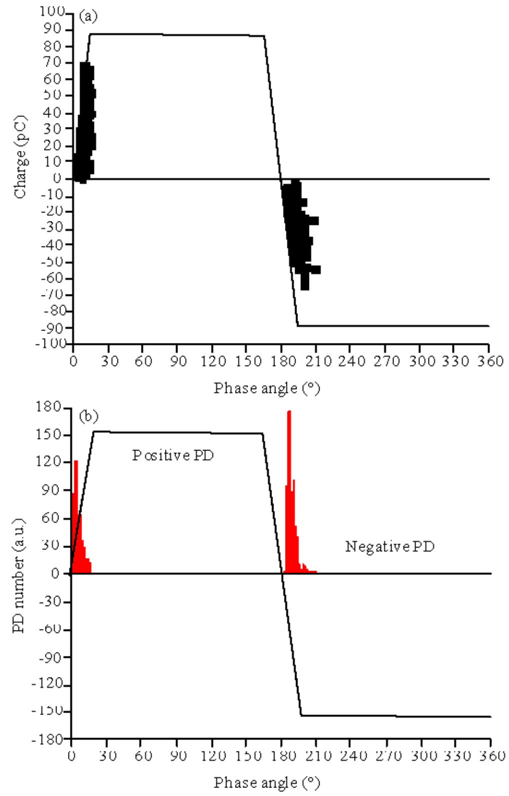

Fig. 9: Typical (a) θ-q-n pattern and (b) θ-n pattern of PD due to electrical treeing in LDPE under rectangular applied voltage

patterns. As shown in the Fig. 9b, PD pulses took place in a narrow phase angle where time derivative of the applied voltage was high (i.e., within the period of the polarity reversal of the applied voltage). Almost no PD pulse was observed flat section of the applied voltage for both positive and negative half cycle. This is because small $dv\ dt^{-1}$ during this period which is not enough to initiate the PD process. The facts strongly supported the conclusion that the magnitude of PD due to electrical treeing is dependent on the instantaneous of the applied voltage v(t) while the PD occurrence (i.e., PD probability to occur) is dependent on the time derivative of the applied voltage $dv\ dt^{-1}$.

CONCLUSION

We have investigated partial discharges due to electrical treeing in low density polyethylene with needle-plane electrode system under sinusoidal, triangular and rectangular applied voltages. Based on the experimental results some conclusions can be drawn as follows: θ-q-n pattern of electrical treeing PD reflects the waveform of the applied voltage; the PD magnitude is strongly dependent on the instantaneous applied voltage; the PD occurrence is dependent on the time derivative of the applied voltage; PD magnitude for a given applied voltage dependent on the length of electrical treeing while the number dependent on the number of tree channels; during the bush-like tree, the small PD ceased indicated that the PD originated from longer tree channel compared from those of tree-like tree.

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