Model and Computer Simulation of Partial Discharge Patterns in Natural Liquid Insulation for High Voltage Application

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Abstract**—**Electric power is widely used worldwide due to its superior characteristics. The superior characteristics such as easy for generating, transmitting and distributing as well as utilizing the electric power caused the demand of the electric power increased steadily. For transmitting a large amount of electric energy a power system is needed. The high efficiency of the system is obtained by applying high voltage system. In a high voltage system several key equipments such as transformers, insulators, generators play important roles. High voltage transformers is a key equipment and widely used in electric power systems. To withstand high electric field, insulation is most important part. In general a high voltage transformer has solid insulation in the form of paper and liquid insulation in the form of oil. Oil insulation is important component in the transformers. During operating condition, the oil serves as electrical insulation to separate between life parts and with ground and acts as coolant in transformers. For normal operation, the integrity of the oil insulation is important factor of the transformer. In particular condition an excessive electric field may occur and partial discharges may occur in the oil insulation which may degrade the performance of the insulation. The occurrence of the partial discharge (PD) is also an indication of insulation abnormality. There are 3 kinds of oil insulations. They are mineral, synthetic and natural oils. Mineral oils is widely used since long time ago. However, due to the availability of the oil and environmental effects of the mineral oil, the natural oil is being popular. The oil is organic bases and has a high bio-degradability. This paper reports the measurement, modeling and simulation of partial discharges in natural oil. The oil used was BIOTEMP. The partial discharges were generated using needle-plane electrode system under sinusoidal voltage. The needle plane electrode is able to simulate a very high electric field. Partial discharge measurement was conducted using phase-resolved measurement system which able to measure the PD magnitude (q), phase of PD occurrence (φ)as well as PD number (n). The task was done using a digital oscilloscope combined with a personal computer. The analysis of the PD data was conducted by utilizing φ-q-n and φ-n pattern. The experimental results showed that PD took place at around the peak of the applied voltage. Phase-resolved analysis indicated that PD magnitude as well as PD occurrence were strongly dependent on the instantaneous applied voltage. Based on the experimental results, a PD model in natural oil was proposed based on the Whitehead PD equivalent circuit. The model was used to simulate PD in the oil. The simulation was able to generate φ-q-n and φ-n patterns similar to those obtained from the measurement.

Keywords**—** computer simulation, phase-resolved, partial discharges, model, transformer oil.

I. Introduction

The huge amount of electric energy is currently being used in the world. For effective and efficient transmission, high voltage was chosen to transmit the electric energy from generating station to the consumers. High voltage equipments play important role in an electric power system[1]. In order to keep the equipments in good operating condition, it is necessary to maintain the insulation in the equipments. It is well known that there are 3 kinds of insulation materials. They are solid, liquid and gas insulating materials. Composites between two or more insulating materials are also often being used. Liquid insulations are widely used in high voltage equipments such as transformers and capacitors. In particular condition and due to high electric stress and the existence of defects, partial discharges may take place in the liquid insulation [2-4]. The appearance of partial discharges in the insulation may degrade the insulation condition.

Condition based maintenance (CBM) is widely used for maintaining high equipments in an electric power system[5-6]. The key success of the maintenance strategy is the quality of the condition monitoring of the key equipments. In order to know the condition of the insulation and to interpret the aging process it is important to understand the partial discharges and their correlation with the physical processes behind[7-11]. Modelling and computer simulation of partial discharges in liquid insulation are very useful to deeply understand the phenomena. This paper presents the experimental results on the partial discharges in liquid insulation using a PC based PD measurement system. The sample used was natural oil BIOTEMP[12-14]. The discharges in the oil were generated using a needle-plane electrode system which produced a very non-uniform electric field. The electric field distribution around the needle electrode was calculated and visualized using a finite element method by utilizing Flex PDE. 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. Based on the discharge characteristics, an electric equivalent circuits was proposed. By using the proposed model a computer simulation was done and presented. The obtained PD patterns were compared to those obtained from experiment.

II. Experimental setup

A. Sample and electrode system

The sample used in the experiment was natural transformer oil. The partial discharges in the oil were generated using a needle-plane electrode in open air with separation of 4 mm. The steel needle was made by Ogura with tip radius of 3 µm and curvature angle of 30°. This electrode arrangement was chosen to simulate a protrusion which is a very common found as electric field enhancement site in a high voltage insulation system. The electrode arrangement is shown in figure 1. The maximum electric field E_{max} at the needle tip can be estimated using an analytic solution expressed as [15]

$$E_{\max} = \frac{2V}{r \times \ln\left(\frac{4D}{r}\right)} \quad (1)$$

where V is the applied voltage, r is the radius of needle tip (3 µm) while D is the electrode separation.

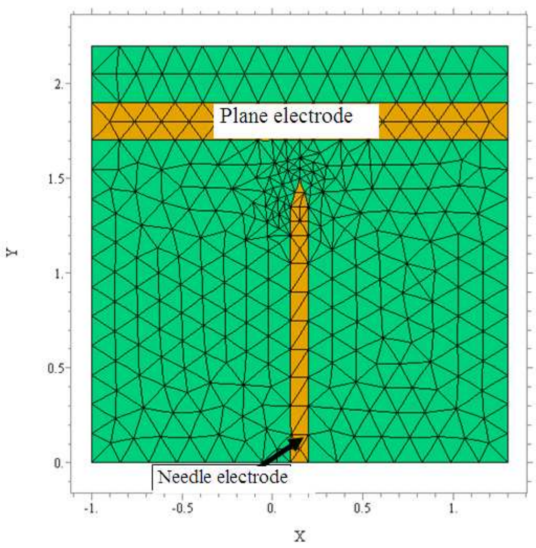
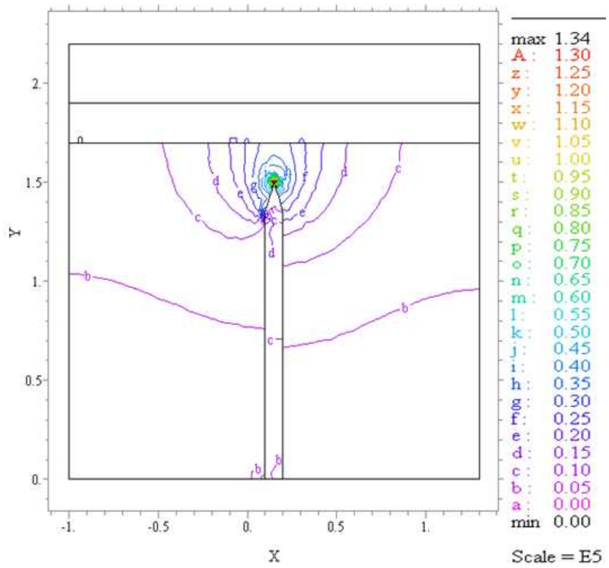


Figure 1. Plane - Electrode arrangement and finite element mesh

When high AC voltage was applied to the needle electrode, a very high electric field was developed at around the needle tip. By using a finite element method the electric field distribution around the needle tip was calculated as shown in figure 2(a). It is clearly seen that a very high electric field was generated at needle tip. At this place the electrons injection may take place and partial discharges were initiated. The equipotential lines are shown in figure 2(b).
Sinusoidal high voltage was applied to the needle electrode. Partial discharges were generated around the needle tip.



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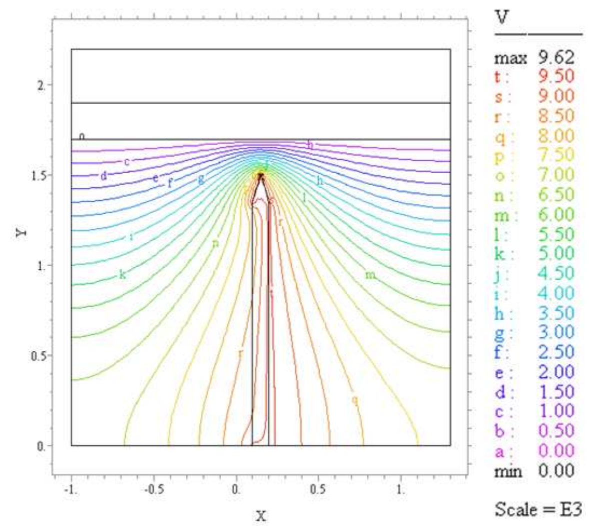


(b)

Figure 2. (a) Electric field distribution (b) equipotential lines

B. Measurement of Partial Discharges

When a high voltage applied to the needle electrode, partial discharges take place. The generated partial discharges were detected with an PD detector with resistance R of 2 kΩ and capacitance C of 330 pF. This detector acts as a high pass filter with a lower cut off frequency of 250 kHz. The detector is a kind of integrator. The output of the detector is a voltage which is proportional to the charge of the partial discharge pulse. The output voltage is measured by a digital oscilloscope and the digital data is transferred to a personal computer for further analysis. The diagram of measurement system is shown in figure 3. The system is able to measure and to show PD pulses in the θ-q-n windows. Here θ is the phase of PD occurrence, q is the magnitude of discharge and n is the PD number.

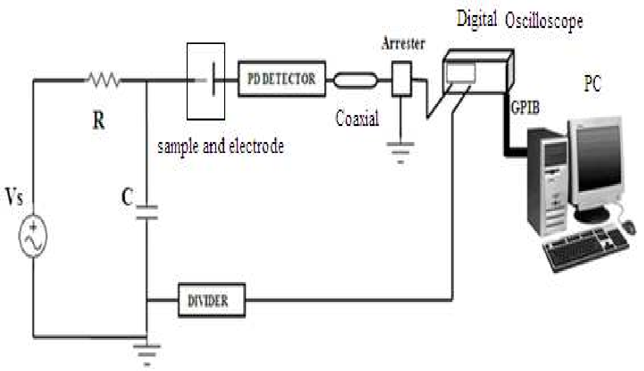


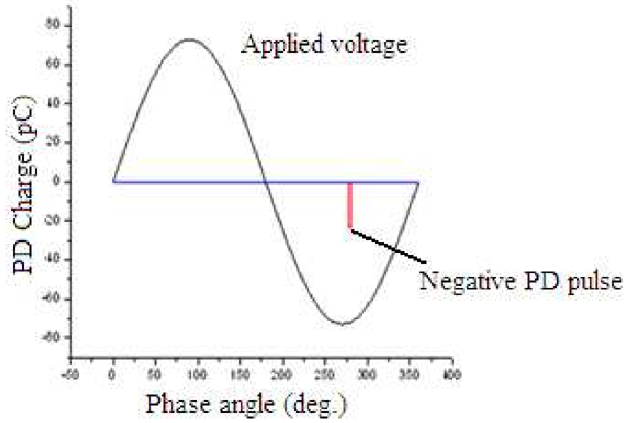
Figure 3: Partial discharge measurement system

Calibration of the measurement system was done by applying a known PD pulses from a PD calibrator at sample and the system was run to measure. The sensitivity of the measurement system was obtained from the pC of the calibrated PD pulses and the measured voltage indicated in the computer. The typical sensitivity of 55 pC/V was used in the experiment. Using the measuring system the discharge magnitude, frequency as well as the phase of discharge occurrence in the applied voltage cycles were determined. The obtained digital data were storage in the PC. Further analysis of the discharges was done by using the PC.

III. EXPERIMENTAL RESULTS

Partial discharges are represented by several parameters. Firstly, the PD inception voltage (Vi) in [kV]. PD inception voltage is the minimum voltage when initial PD starts to occur. In general, negative PD inception voltage is slightly smaller than positive PD. The second paremeter is the PD charge magnitude (in pC). PD current is an impulse. By integrating the impulse current of the PD, the PD charge can be obtained. This process can be achieved using an RC detector which plays as an integrator.

The third parameter is the phase angle of PD occurrence (in degree). During the application of AC voltage, the instantaneous voltage varies with time. PD pulse may occur at particular phase angle. The determinant factor affecting the PD occurrence may change with the insulation condition. The last parameters is the PD number or PD frequency in a specific time or phase angle window. .



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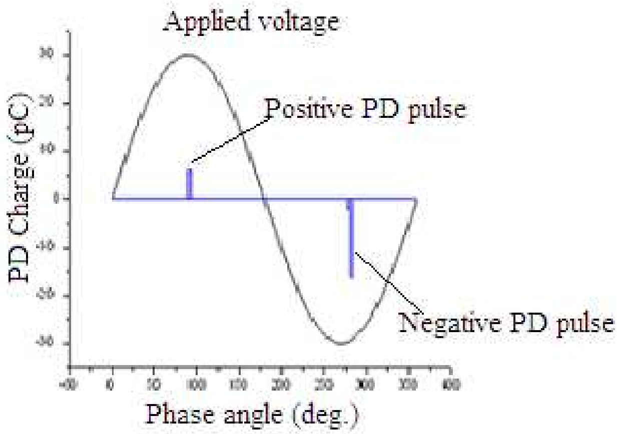


(b)

Figure 4: Typical PD pulse at applied voltage of (a) 6.8 kV and (b) 7 kV

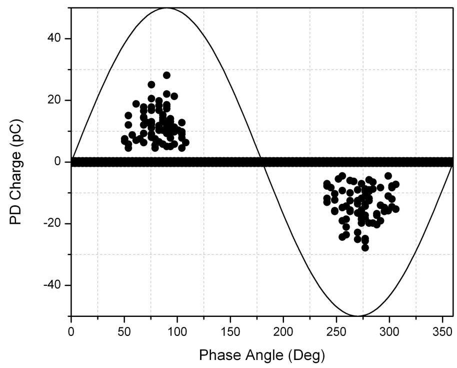
Figure 4 shows partial discharge at initial stage during discharge inception. Figure 4(a) indicated that initial PD pulse was negative which was observed at inception voltage of 6.8 kV. The PD pulse occurred at around the peak of negative half cycle. Under this voltage level no positive PD was observed. The results showed that negative PD occurred more easily than positive one. In the case of negative PD, the polarity of the needle tip was negative. Electron was injected from needle electrode tip due to very high electric field (i.e. field assisted electron injection) and initiated the occurrence of the PD.

Figure 4(b) shows PD pulses at applied voltage of 7 kV which was slightly higher than PD inception voltage. As indicated by the figure, both negative and positive PD pulses were observed. This fact revealed that negative PD pulses in liquid insulation occurred more easily than positive. The phenomenon can be explained as follows. For negative discharges the initial electrons originated from the metal needle tip as field assisted injected electrons while for positive discharges the initial electrons came from the liquid insulation. The electron injection from the metal needle electrode appeared more easily and thus the negative discharges appeared first before positive discharges.

Figure 5 shows ϕ-q-n patterns under applied voltage of 7 kV (a), 8 kV(b) and 8.5 kV (c). The horizontal axis is the phase angle where PD pulses occurred while vertical axis is the PD charge magnitude in PC. Each point represents a PD pulse and the position indicates the PD magnitude and phase angle where the PD takes place. The pattern is composed from discharge pulses took place in 100 cycles. From the figure it is seen that discharge in liquid insulation took place concentrated at around phase angle of 90^o for positive PD and around phase angle of 270^o for negative PD 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. All figures in figure 5 show that PD pulses appear at around peak of applied voltage both positive and negative half cycles. This is different from corona discharges where PD pulses usually only observed at negative half cycles. PD magnitude was distributed from several pC up to about 30 pC for applied voltage of 7 kV, up to 40 pC for applied voltage of 8 kV and up to about 45 pC for applied voltage of 8.5 kV. The PD magnitude increases with the applied voltage.

Figure 6 shows the typical ϕ-n patterns of partial discharges in natural insulating oil under sinusoidal voltage of 7 kV, 8 kV and 8.5 kV corresponding with ϕ-q-n patterns shown in figure 4. The horizontal axis is phase angle in degree and the vertical axis is the partial discharge number in arbitrary unit. The figure 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).

Partial discharge pulses were observed in both polarity and concentrated around 90^o for positive PD and around 270^o phase angle for negative PD. This is a clear indication of the existence of voltage threshold for partial discharge occurrence. The results also indicated that partial discharge probability strongly dependent on the instantaneous applied voltage and not time derivative dv/dt of the applied voltage as observed for partial discharges in solid [16]. The fact revealed that the instantaneous applied voltage played important role in the PD occurrence in liquid insulating material. The positive PD magnitude was slightly higher than negative. The PD number also increased with the applied voltage.



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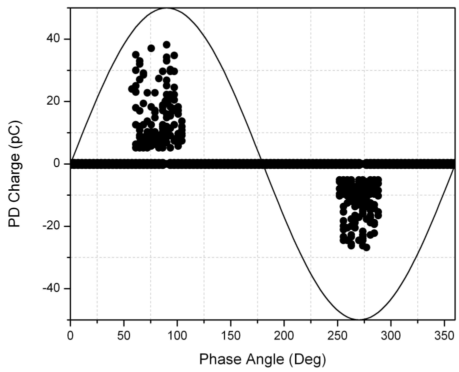

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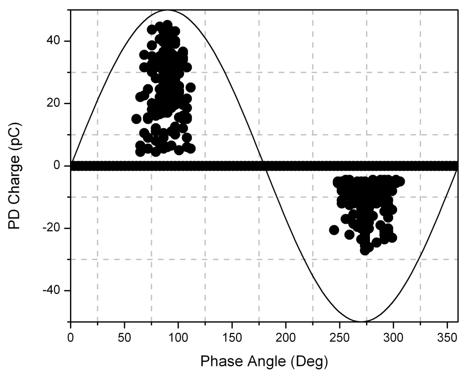

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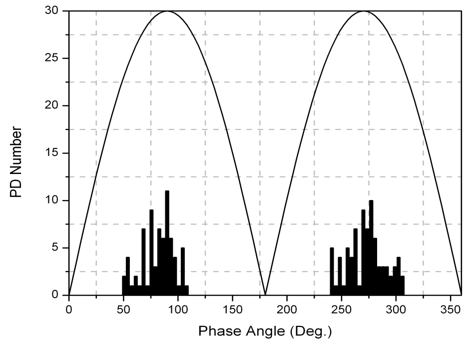
Fig. 5 Typical ϕ-q-n patterns under applied voltage of (a) 7 kV (b) 8 kV and (c) 8.5 kV



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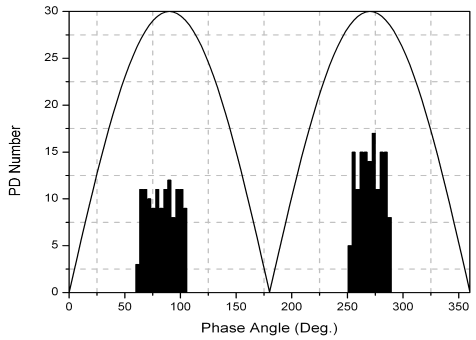

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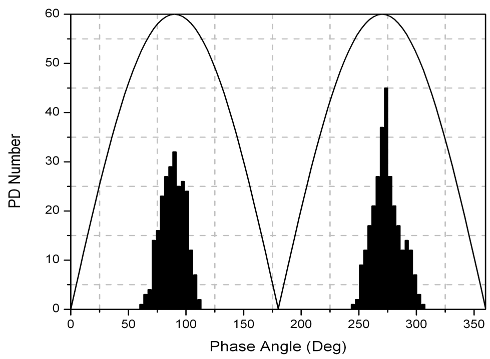


(c)

Fig. 6 Typical ϕ-n patterns under applied voltage of (a) 7 kV (b) 8 kV and (c) 8.5 kV

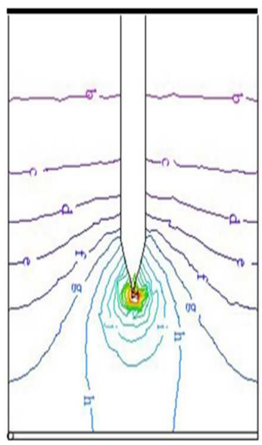
IV. MODEL AND COMPUTER SIMULATION OF PARTIAL DISCHARGES

For deeper understanding of partial discharges, modeling and simulation are very useful. This method was applied for several cases of partial discharges such as for gas insulated switchgears or electrical treeing discharges in solid insulation[17-19].

The results of phase-resolved measurement of partial discharges and analysis on PD in the BIOTEMP oil showed that the PD magnitude as well as the PD occurrence were dependent on the instantaneous applied voltage. The positive PD probability was slightly smaller than negative PD. The numerical values for the negative and positive inception voltage were 6.8 kV and 7 kV respectively. From the results several properties of partial discharges in natural insulating oils can be summarized as:

a. There is a threshold voltage which no discharge may occur if the applied voltage less than the threshold value. The threshold voltage is found for both negative as well as positive half cycles . The value of the threshold voltage dependent on the polarity. Negative partial discharges threshold is slightly smaller than positive partial discharges
b. The partial discharge probability to occur proportional to the instantaneous applied voltage. This property implies that the partial discharge pulses mainly occur at phase angles around the peak of applied voltage.
c. The partial discharge magnitude (charge) in pC is proportional to the instantaneous applied voltage. This property implies that the partial discharge pulse with maximum magnitude occur at around the pek of the applied voltage.

Based on the partial discharge properties, equivalent circuit is used to explain the partial discharges in natural liquid insulating material.



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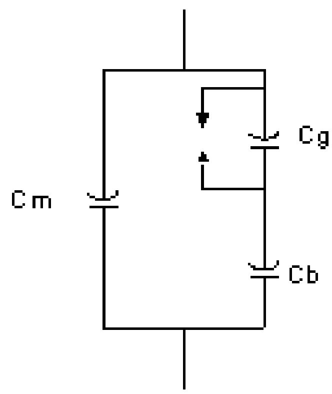


(b)

Fig. 7 (a) Electrode system and (b) Whitehead equivalent circuit of partial discharge

Figure 7 shows the electrode system of natural oil discharges and electric field distribution (a) and Whitehead electrical equivalent circuit (b)[20]. The Whitehead electrical equivalent circuit was originally proposed for partial discharges in polyethylene. However, the partial discharges in natural liquid insulating materials indicates that the Whitehead equivalent circuit is fit well to be used for explaining the partial discharges. Therefore, in this paper the equivalent circuit is used to explain the partial discharges occurred at the tip of needle electrode. Based on the circuit of 4(b) simulation of the PD in natural oil was conducted. Insulating liquid is represented as capacitances. The discharge is represented by capacitance C_g in parallel with a spark gap. The charge in the capacitance dependent on the value of capacitance and the applied voltage across the capacitance. This charge strongly relates with the partial discharge magnitude. C_b represents the capacitance of the sound part of the natural oil insulation while the rest of the sample is represented by a capacitance C_m.

For external applied voltage of *V(t)* , the voltage applied to the PD capacitance before any discharge take place is expressed by

$$V_g(t) = \frac{C_b}{C_g + C_b} \, x \, V(t) \qquad (2)$$

If a partial discharge take place, then the voltage on the discharge site collapse to a very low value of residual voltage V_r. The magnitude for the first discharge will be proportional to the PD capacitance and the different between PD voltage and residual voltage. The PD magnitude can be expressed as

$$Q = C_g \; k \,(V(t) - Vr)) \qquad (3)$$

where V_r is residual voltage after a discharge occurs.

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

Based on the equivalent circuit, computer simulation of partial discharges in natural insulating liquid was done. This simulation consists of two subprograms. The sub programs are (a) generating partial discharges pulses and (b) visualization of PD patterns including ϕ-q-n graph and ϕ-q graph. To run this simulation, 5 inputs are needed. The five inputs are number of applied voltage cycles, magnitude applied voltage (kV), positive inception voltage (kV), negative inception voltage (kV), and file name to record the simulation results. The difference of positive inception voltage and negative inception voltage should not higher than 0.5 kV (experimental result was about 0.2 kV).

Based on experimental results, there are two prerequisites in generating PD pulse in the simulation:

- applied voltage should higher than positive inception voltage,
- 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.

To simulate the stochastic behavior of PD, the availability of early electron is determined by random number. The random number will be multiplied with the difference between applied voltage and inception voltage resulting a determinant factor of early electron appearance value. This value reflects the probability of partial discharge to occur and is expressed by the following equation.

$$P = (V_{ext} - V_i).Rand. \qquad (4)$$

where V_i is the inception voltage and *Rand* is 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 satisfied or not.

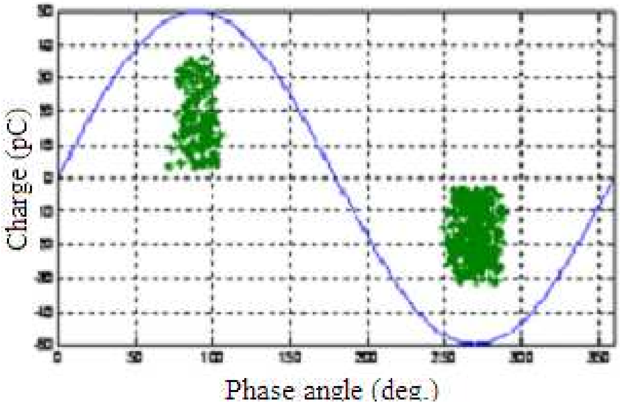
Positive threshold was used to generate PD in positive half cycle while negative threshold was used to generate PD in negative half cycle. For half positive cycle, if determinant factor was higher than positive threshold, early electron was exhibit and released a PD. In half negative cycles, the determinant factor should be below the negative threshold in order to exhibit early electron that produced PD pulses.

From the simulation, a large number of partial discharge data can be obtained. The simulated partial discharge data may be represented in various patterns such as phase-charge-frequency (ϕ-q-n pattern) and phase-frequency (ϕ-n pattern).

V. Simulation Results and Discussion

Figure 8 shows typical simulated ϕ-q-n pattern under applied voltage of (a) 8 kV and (b) 8.5 kV. Each point represents a PD pulse. The vertical position indicated the PD magnitude in pC and the horizontal position indicated the phase angle in degree where the PD pulse occurred. It is seen that PD pulses concentrated around the peak of applied voltage at both negative and positive cycles. This was caused by the fact that PD probability proportional to the instantaneous of the applied voltage and therefore the highest probability took place around the peak of the applied voltage.

Similar behavior was observed for PD magnitude. The PD magnitude as well as the range of phase angle where PD pulses took place increased from applied voltage of 8 kV to 8.5 kV. The PD patterns are similar to those obtained from the experiment under same applied voltage as shown in figure 5(b) and 5(c).



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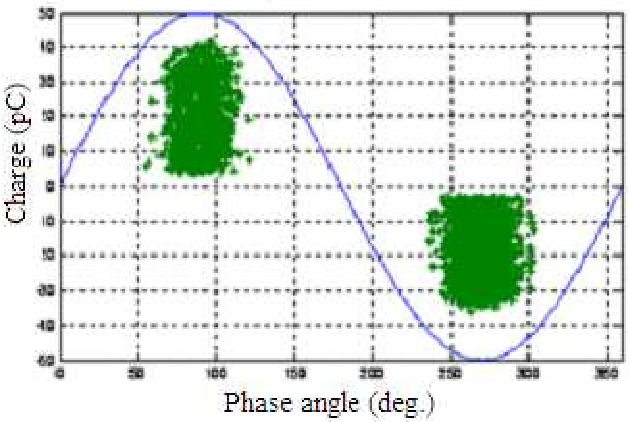
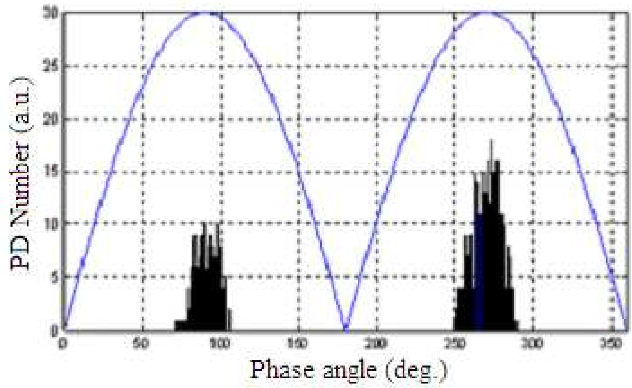


(b)

Fig. 8 Typical ϕ-q-n patterns under applied voltage of (a) 8 kV and (b) 8.5 kV

Figure 9 shows typical ϕ-n patterns for applied voltage of 8 kV and 8.5 kV. The patterns indicated the PD number distribution in phase angle of PD occurrence. The patterns clearly shows that partial discharge pulses concentrated at around the peak of applied voltage both for positive and negative half cycle. The pattern is also reflects the same shape of the applied voltage.



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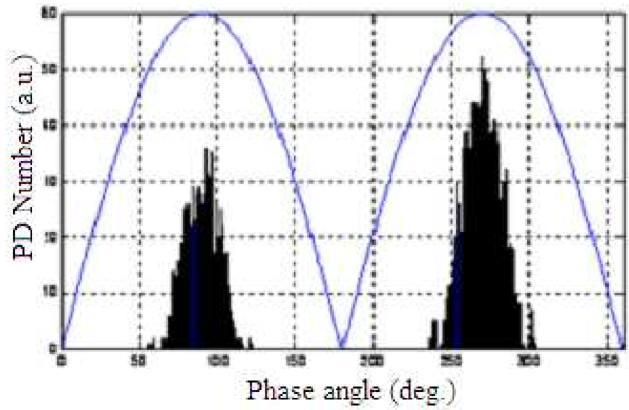

(b)

Figure 9. Typical ϕ-n pattern under sinusoidal voltage obtained from simulation under applied voltage of (a) 8 kV and (b) 8.5 kV

VI. CONCLUSION

We have investigated partial discharges in BIOTEMP natural oil using needle-plane electrode system under sinusoidal applied voltage. Partial discharge measurement was conducted using phase-resolved measurement system which able to measure the PD magnitude (q), phase of PD occurrence (φ) as well as PD number (n). The analysis of the PD data was conducted by utilizing φ-q-n and φ-n pattern. The experimental results showed that PD took place at around the peak of the applied voltage. Phase-resolved analysis indicated that PD magnitude as well as PD occurrence were strongly dependent on the instantaneous applied voltage. Based on the experimental results, a PD model in natural oil was proposed based on the Whitehead PD equivalent circuit. The model was chosen since it able to explain the partial discharge in oil clearly. The model was used to simulate partial discharges in natural liquid insulation under sinusoidal voltage. The simulation was able to generate φ-q-n and φ-n patterns similar to those obtained from the measurement. The results indicated that Whitehead equivalent circuit model is suitable for explaining partial discharges in natural liquid insulating material.

ACKNOWLEDGMENT

The authors express their sincere thank to Directorate of Higher Education, Ministry of National Education of Indonesia for grand in aid for this research.

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