ISSN 1827-6660
Vol. 6 N. 1
January – February 2011

International Review of
Electrical Engineering
(IREE)

PART **B**

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Praise Worthy Prize

International Review of Electrical Engineering (IREE)

The *International Review of Electrical Engineering (IREE)* is a publication of the **Praise Worthy Prize S.r.l.**.
The Review is published bimonthly, appearing on the last day of February, April, June, August, October, December.

Published and Printed in Italy by **Praise Worthy Prize S.r.l.**, Naples, February 28, 2011.

Praise Worthy Prize

International Review of Electrical Engineering (I.R.E.E.), Vol. 6, N. 1
January-February 2011

Partial Discharge Characteristics Over Different Levels of Humidity and Plasma Exposures in a PMMA Bounded Void

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Abstract – *The issue of high voltage equipment tropicalization is critical particularly when high voltage equipment designed for temperate application are imported to areas in the tropics. It raises the question whether the insulation used in these equipments can performance under the impact of high relative humidity level and the intense midst noon sun rays. This paper presents the study of dielectric material performance under the impact of relative humidity and plasma exposures to simulate the material aging in service by studying the discharge characteristics of PMMA which was used as the basis of study. The discharge characteristics in cylindrical void bounded by dielectric of polymethylmethacrylate (PMMA) which were exposed to different levels of relative humidity (RH) and plasmas intensity were investigated. The insulation material under test was subjected to AC excitation. The partial discharge (PD) signatures produced were measured with the aid of a CIGRE Method II (CM II) electrode system. It was found that when the void cavity was humidified from 33 % up to 98 %(extreme level), the PD inception voltage decreased about 15 %. For negative AC cycles, the following discharges occur with larger number of pulses, however, with small number of magnitudes. PD seems easily to occur with larger number of pulses as the surface of specimen was degraded by plasma (especially under humid environment).So it is recommended that high voltage equipments imported from temperate countries must performance in the tropics adverse environmental conditions.*

***Keywords**: PD Characteristics, Relative Humidity, Surface Resistance, Plasma*

I. Introduction

Partial discharge phenomenon is supposedly to be one of the most significant modes of degradation in the electrical insulation systems.

It can be associated with important information about the category of degradation. There are several factors render significant influences on PD characteristics that provide a basis for the determination of the parametric degradation initiator: pressure, contaminant, humidity, dimension and the contents of a void, also the surface roughness of a void.

Numerous studies had been conducted into understanding the effect of each factor to the PD characteristics [1]-[10]. Despite all that accomplishment, still some of these factors yet to be understood. The one that attracts the attention of researchers is especially the deleterious effects of humidity and surface roughness of a void on the PD characteristics.

In order to examine the polymer application as electrical insulators, it is very important to perform the simulation of accelerated aging treatment (by humidity control cell and plasma exposure for the specific period) substituted for the process of long-term humidity stress environment and degradation in actual application on polymer insulators.

The objectives of this present work, among others are to find an explanation for PD characteristics change with respect to relative humidity in the void space. The assumption takes into account of the charge intensity could significantly contribute errors in the interpretation of the PD measurement result(due to the effect of humidity). Another objective is to find an explanation for the single influence of void surface roughness on the PD characteristics.

II. Experimental Procedures

II.1. Specimens

The CM II electrode system used is shown in Fig. 1 [11], [12]. This method is based on standard and widely used for PD study in a single void. The electrodes were made of stainless steel bearing ball spherical metal-piece attached to a copper pipe and covered with the epoxy resin (CY221 + HY2967). The sample was a 1 mm thick PMMA plate.

Polyimide spacer of 125 μm thick was sandwiched between two PMMA plates in order to form a gap where discharges could take place. To control RH, two slits of 10 μm in width were constructed in the spacer.

Manuscript received and revised January 2011, accepted February 2011

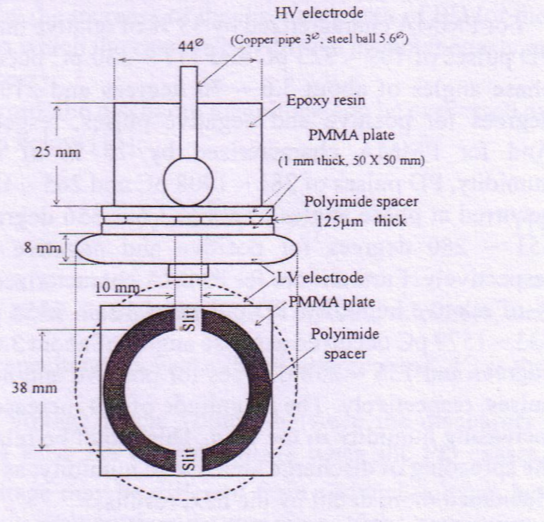


Fig. 1. Configuration of CM II specimen

This specimen was placed in a test cell. The RH of the specimens surrounding air was sprayed with saturated salt solutions: magnesium chloride, sodium chloride, and potassium sulfate, in order to fix relative humidity at 33 %, 75 %, and 98 %, respectively [13].

The specimens were preconditioned continuously for 24 hours to ensure of the RH stabilization prior to the partial discharge measurement.

The specimens for the investigation and measurement were prepared. The 1- mm thick PMMA plate was irradiated plasma (with various periods of 0, 3, 6, 11, 16, and 21 sec) as shown in Fig. 2. The plasma- irradiated-specimen was placed in the CM II electrode system as shown in Fig. 1.

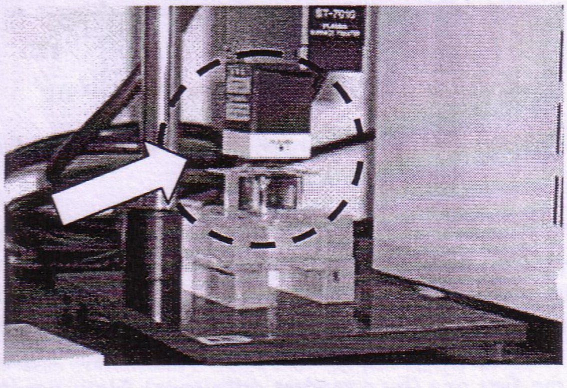


Fig. 2. Plasma exposure procedure

II.2. Partial Discharge Measurement System

The PD measurement system has been established and being used in the previous study [17]. The output of the function generator was amplified by a voltage amplifier that generates a sinusoidal high voltage waveform. Then the AC high voltage was applied to the spherical electrode of the specimen where the lower part was connected to the measurement system. The PD signals were detected via a capacitance-resistance (CR) circuit, by an oscilloscope. Partial discharge data, which were recorded by the oscilloscope, was down loaded to a personal computer for analyzing. The PD inception voltage was measured by applying a linearly varying AC voltage at the rate of 100 V/s to the specimens until discharge occurs.

In order to examine the effect of relative humidity on ϕ-q-n pattern (ϕ is the phase angle, q the PD charge, n the number of PD pulses), PD pulse measurement was carried out using the CM II electrode system under different level of relative humidity. The PD patterns were determined for a consecutive of 100 cycles within one minute after the applied voltage reached 7 kV, 50 Hz under room temperature.

In addition to the evaluation of the effect of humidity and surface roughness on the resistance of void surface, under the same condition, the PD measurements executed in accordance to the standard test method as in ASTM D257. This involved the application of a HVDC across the main and the guard electrodes, and the surface current was measured using a digital pico ampere meter.

III. Experimental Results and Discussion

III.1. Effect of Humidity of Void Space on Partial Discharge Characteristics

In Figure 3 the mean values of PD inception voltage (V_i) was plotted against relative humidity.

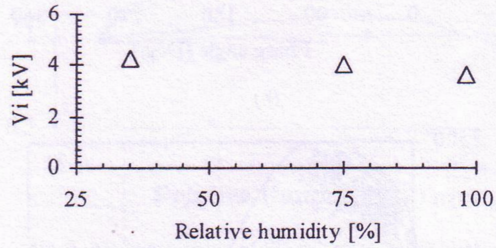
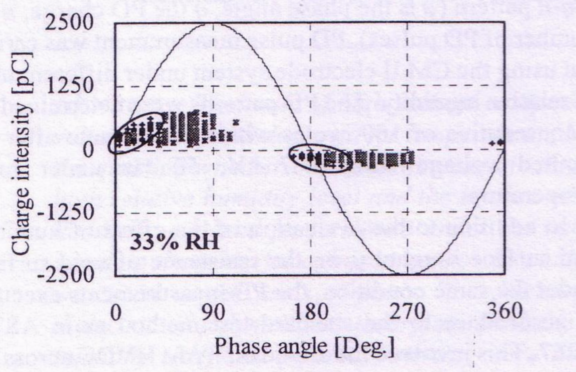


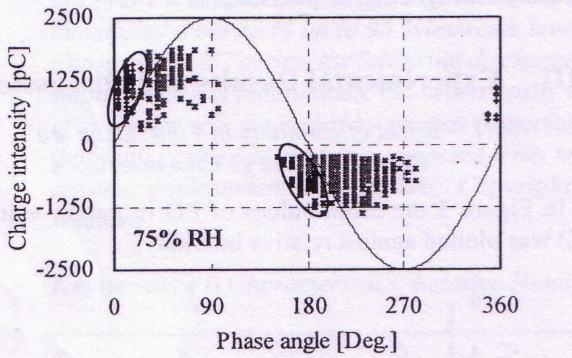
Fig. 3. PD Inception Voltage

The PD inception voltages at 33 %, 75 %, and 98 % of RH were 4.2, 4.0, and 3.6 kVrms, respectively. The PD inception voltage of the void depends on many factors such as the geometry and spacing between electrodes and the type and homogeneity of the insulation and type of contamination on the surface of insulation and the ambient condition [4]. It was shown through the experimental exercises that the PD inception voltages reduced about 15 % with an increased in relative humidity from 33 % to 98 %. This might be caused by the easier release of initial electron at the surface of insulation when the void space was moisturized by humid condition.

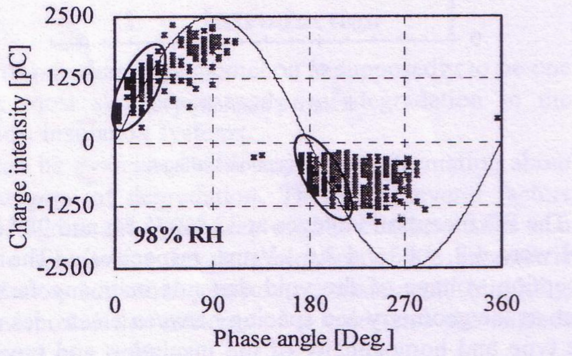
Figures 4 show a typical result of the temporal change in PD ϕ-q-n pattern for various levels of humidity where a 7 kV, 50 Hz was applied for a consecutive of 100 cycles within a minute's period. The PD representation-cluster as shown in Figure 4(a) to Figure 4(c) consisting of the first discharge (oblique scatter) on the positive rising side of the positive half cycle and the subsequent discharge (horizontal scatter) on the negative falling side of the negative half cycle. The PD pulses of positive half cycles are plotted against degrees of phase angle (between 300 ~ 120), while the negative half cycle, between 120 to 300 degrees of the phase angle.



(a)



(b)



(c)

Figs. 4. Characteristic and distribution of PD over different level of RH (a) 33% (b) 75% and (c) 98%

Interestingly, Mizutani et al has divided these dots into two parts; namely "ear" and "body" of a rabbit-like pattern [15]. The "ear", being an oblique scatter, was correlated to the first discharge in the positive half cycle, and the "body", being a horizontal scatter, was correlated to small discharges following the positive half cycle discharges. However, as exemplified by above results, the shapes of ϕ-q-n pattern for both dry and humid conditions were "turtle-like", they were similar to the pattern in void [7], [15].

For PMMA characterized by 33 % of relative humidity, PD pulses of 109 ~ 723 pC and 117 ~ 330 pC occurred at phase angles of about 3.6 ~ 76 degrees and 216 ~ 238 degrees for positive and negative pulses, respectively. And for PMMA characterized by 75 % of relative humidity, PD pulses of 281 ~ 1908 pC and 265 ~ 1385 pC occurred at phase angles of about 3.6 ~ 356 degrees and 151 ~ 280 degrees for positive and negative pulses, respectively. Furthermore for PMMA characterized by 98 % of relative humidity, PD pulses of 301 ~ 2354 pC and 233 ~ 1579 pC occurred at phase angles of about 3.6 ~ 356 degrees and 136 ~ 288 degrees for positive and negative pulses, respectively. The magnitude of PD increased with increasing humidity in the void. This might be relating to the spreading of discharge area due to humidity, as will be elucidated more detail by the next results.

The change of average PD magnitude (Q average) due to increasing of RH during a minute after 7 kV voltage applications was shown in Fig. 5.

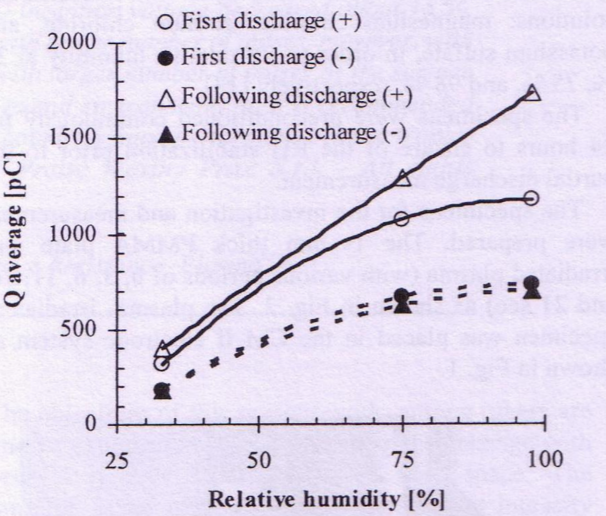


Fig. 5. The average magnitude of the first and following discharges over different level of humidity

The increased of relative humidity is followed by the increased of the first and following discharge magnitudes during positive and negative cycles of PD pulses. For positive cycle of PD pulses, under dry condition of 33 % RH, the magnitude of following discharges was higher than the first one (by a modest difference). However, as the humidity increased, the magnitude of the following discharges will become much higher than the first one (by greatly difference). Such a great difference was not occurred during a negative cycle of PD. For the negative cycle of PD pulses, under the dry condition, the first discharge was a slightly higher in magnitude than the following one (by a little difference). This difference stays unchanged even though the RH was increased up to 98 %.

Unlike the case of a void with a narrow diameter [16], there was a great increase of PD magnitude was observed in a large void in the PD aging process. This suggested that the increase of PD magnitude in a large void might be caused by the increase of the discharge area of PD (or the region to which the carriers can diffuse instantaneously in PD process).

In a void, the discharge magnitude can be expressed as equation below [13]:

$$Q = \frac{\varepsilon S}{d}\left(V_s - V_c\right) \quad (1)$$

where S is the discharge area, d is the void thickness, and $\frac{\varepsilon S}{d}$ is capacitance between the discharge areas, V_s is the average voltage in the volume between the discharges' area and V_c is the critical voltage when the PD ceases. This voltage may be different from residual voltage, but we simply assume they are the same. If the permittivity relative ε and void thickness d are fixed, the discharge magnitude value is depending on the discharge area S and (V_s-V_c) or ΔV.

On the other result, the surface resistivity of void changes due to the increase of relative humidity as shown in Figure 6.

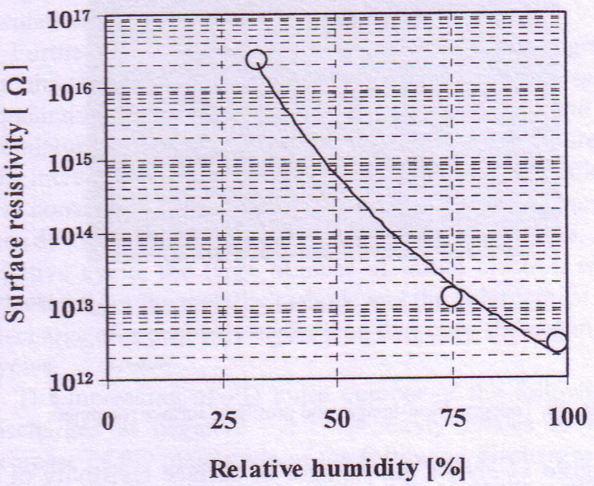


Fig. 6. Surface resistivity as a function of RH

The surface resistivity of the specimen was within the range of 10^{16} Ohm/cm^2 when in dry condition of 33 % RH and was remarkably decreased to the range of 10^{13} and 10^{12} Ohm/cm^2 (decreased about three of four orders of magnitude) after exposure to humid condition of 75 % and 98 %. The surface resistivity of the void becomes lower (or higher surface conductivity) with increasing of relative humidity. This would have a relation with the enhancement of mobility of charge carriers on the void surface when the void is humidified.

According to Figure 3, PD inception voltage decreased by 15 % with the increase of relative humidity from 33 % to 98 %. However, the discharge magnitude increased by about three times when relative humidity changed from 33 % to 98 % (Fig. 5). It means that the increasing of the discharge magnitude at the humid condition in void between insulating-insulating surfaces was strongly affected by the spreading in discharge area S which probably due to the increase of surface conductivity of the void.

Fig. 5 also shows the increasing of PD magnitude of the first and following discharges at positive cycle are higher than those at negative cycle. This phenomenon probably relates to the electrification process on the cathode surface (or insulation surface in the side of cathode). At positive cycle, the large number of initial electron was released from insulation surface in the side of a metallic cathode and the enlargement process of discharge area probably easier than that upon the negative cycles.

Moreover, the average number of PD pulses per cycle for 33 %, 75 %, and 98 % of relative humidity was shown in Fig. 7.

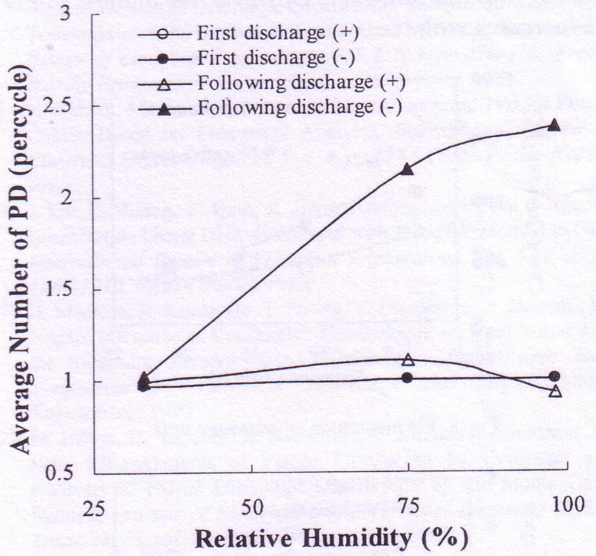


Fig. 7. Average number of PD pulses per cycle over various humidity levels

The increased of humidity was not followed by the increased of the average number of first discharge pulses both in positive and negative cycles. They were relatively stable at 1 pulse per cycle. By increasing humidity, the number of following discharges pulses increased mainly at negative cycle. It was possible when the PD inception voltage occurred at lower voltage and the following discharges would be easy to be triggered, as the void space had been activated by the first discharge in a half cycle. The increasing of the PD pulse number of the following discharges at negative cycle probably relates to the decrease of PD magnitude of the following discharge at negative cycle (as shown in Fig. 5). This was possible when the small discharges occurred with the large number of pulses. The increase of following discharges pulse number at the negative cycle with increasing humidity can, in principle, be due to an increase in carrier density or in the mobility rate of the carriers.

While, at positive cycle of following discharges, the number of pulses somewhat increased with increasing humidity from 33 % up to 75 %. However, it decreased when the humidity reached 98 %. The number of following discharges at positive cycle was smaller than that of at negative cycle. It means that the occurrence probability of positive pulse is smaller than that of a negative cycle. The smaller probability for positive cycle leads to a longer time lag for discharge occurrence, resulting in larger of charge intensity. This result was in agreement with the PD magnitude at positive cycle of following discharges (as shown in Fig. 5).

III.2. *Effect of the Roughness of Void Surface due to Plasma Exposure on PD Characteristics*

In case of PD experiment using the specimen with artificial surface roughness by plasma exposure (as shown in Figures 8 and 9), the PD magnitude decreases with increasing the exposure-time. However, the number of PD pulse increases with it.

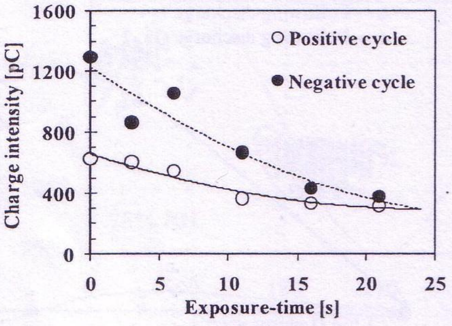


Fig. 8. PD magnitude vs. exposure time

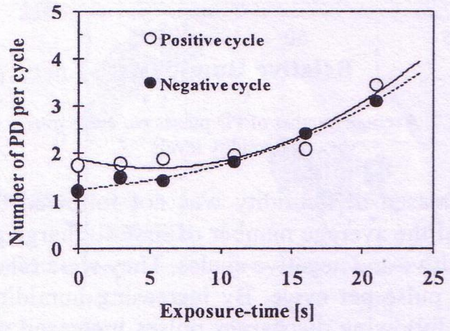


Fig. 9. The PD pulses per cycle vs. exposure time

It is believed that in roughened surface PD tends to occur at many places somewhat apart from the sphere electrode. In case of smooth surface, the PD tends to occur at one place on the specimen surface right under the sphere electrode. It is considered that PD is easily to occur with a higher number of pulses when the surface of a specimen was degraded by plasma. This phenomenon may be due to the change of surface by plasma exposure including an increase of surface roughness and decrease of surface resistivity. After plasma exposure the surface becomes rough, which causes a higher local electric field at the protrusion tips and thus discharges easier to occur.

To ensure this effect, topographical-images and profile of surface roughness can be traced along the center line of the eroded specimen by a laser microscope (Keyence VK-8510) to give erosion profile as shown in Fig. 10. It is recognized that the erosion increase, as aging time increases from 6 to 21 s. In addition, many bumps were seen on the material surface. There is data scatter in short range of position at the edges of micrographs. This is considered to be caused by original surface roughness of the specimens.

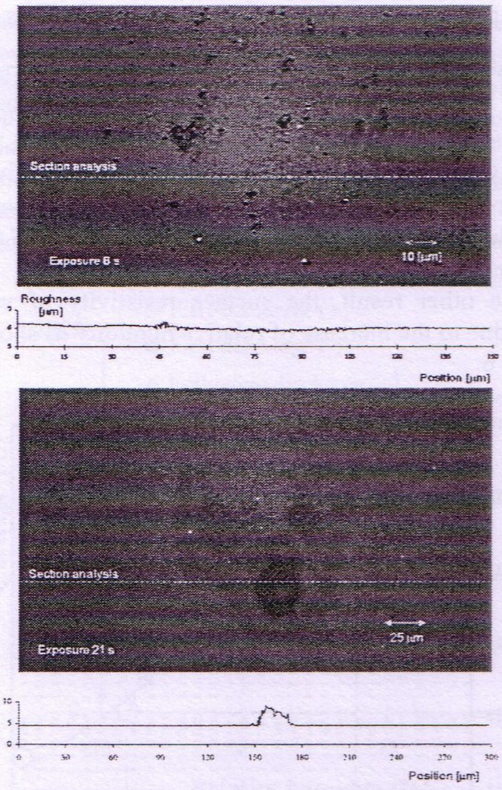


Fig. 10. Topographical-images and profile of surface roughness

Figure 11 shows the changes of surface resistivity of rough and smooth specimens under exposure of humidity. Characteristics of these curves are that surface resistivity showed steeply dependence upon humidity.

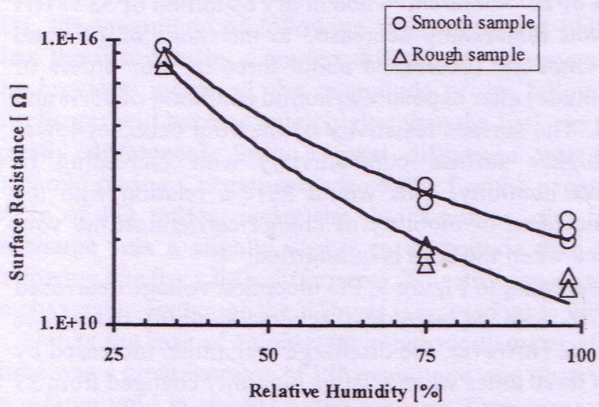


Fig. 11. The surface resistivity changes of smooth and rough surfaces due to humidity

The roughened surface shifts to a lower value of resistivity. It is believed that the shift of roughened surface intensifies local field and increases supply of initial electron.

IV. Conclusion

Partial discharge measurements were carried out in PMMA bounded void with the CM II electrode system by changing the level of humidity in the void space and plasma exposure in the surface of the void. The humid void space and rough specimens imitate the environment aging under tropical climate area and the degraded void surface by PD, respectively. The results were obtained from the experiments are summarized as follows.

The prerequisite for discharge to develop is the availability of a free electron in the void, in the cathode side. The electron initiates an electron avalanche drifting towards the anode side. Given the presence of an initiatory electron it has been found that there exist minimum voltages for the PD inception. PD inception voltage decreased by about 15 % when the surrounding humidity increased from 33 % up to 98 %. It occurred due to the easier release of initial electron from the surface of insulation when the void space was humidified.

Furthermore, the first effect of humidity related aging on the insulation surface is an increase of surface conductivity (or decrease of surface resistivity) and a simultaneous increase in the spreading of discharge area. The increasing of discharge magnitude at humid condition was considered affected by the spreading in the discharge area due to the increase of surface conductivity of void. At positive cycle, the large number of initial electron was released from the metallic cathode and the enlargement of discharge area probably easier than that upon the negative cycles.

The increasing of PD pulse number of the following discharges at negative cycles probably relates to the decrease of PD magnitude of the following discharges at same cycle. The occurrence probability of positive pulse is smaller than that of negative cycle. This would lead to a longer time lag for discharge occurrence, resulting in larger charge density. This will need further study, indeed.

Another result shows that PD is easily to occur with higher number of pulse when the surfaces of specimen were degraded by mean of plasma. This phenomenon may be due to surface conditioning as result of plasma exposure including an increase of surface roughness in combination with the decrease of surface resistivity (especially under humid condition), which causes a local electric field enhancement and intensification at the protrusion tips, thus discharge easier to occur at more than two places.

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Autorizzazione del Tribunale di Napoli n. 31 del 5/04/2006