Statistical Analysis of Electrical Breakdown in a Micro Gap Using Weibull Distribution and Discussion on its Processes in High Voltage

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In this study, an experimental model is made on the basis of the Whitehead abc model and the properties of partial discharge (PD) breakdown in the micro gap are investigated. The quite unique properties of the PD breakdown in the micro gap are obtained: The voltage dependence of time to the PD breakdown and spread of residual negative charge distributions in the micro gap become discontinuous at a certain voltage amplitude. The discontinuousness in the PD breakdown properties is found to be due to the difference in surface discharge patterns in the micro gap: Polbüschel-type at lower voltage and Gleitbüschel-type at higher voltage. This paper aims at discussing the PD breakdown process at higher voltage. Time to the PD breakdown in the micro gap is analyzed using the Weibull probability distribution. The result suggests that the PD breakdown processes are classified into two different types: fatigue-failure-type and early/random-failure-type. Assuming that the PD breakdown of fatigue-failure-type is a thermally activated degradation process of Arrhenius type, the activation energy is calculated. The value is in good accord with activation energy required for polymer bond scission caused by interaction with oxygen and ozone. The result suggests that the PD breakdown of fatigue-failure-type is caused by oxidative degradation. On the other hand, residual negative charges in the micro gap play an important role in the PD breakdown process of early/random-failure-type. In view of previous studies, it is possible that the PD breakdown process of early/random-failure-type is governed by the existing probability of structural defects where a great deal of the negative charges accumulates.

Keywords : discontinuous PD characteristic, Weibull distribution, surface discharge pattern, fatigue failure type, early/random failure type

1. Introduction

It is well known that abrupt defects in insulating materials for a high voltage apparatus- such as voids, cracks, and gas-filled space at dielectric-conductor or dielectric-dielectric interfaces- lead to the occurrence of PD and act as starting points of the PD degradation. The PD degradation advances not only with accumulation of the PD products and material erosion on the inner surface of the gas-filled defect but also with the change in the situation of the PD generation; it eventually brings about an electrical breakdown. Even if such a gas-filled defect does not exist in insulating materials, PD degradation can initiate due to the existence of unavoidably field-enhancing defects. Consequently, the PD degradation promotes reduction in lifetimes of insulating materials in a high voltage apparatus. Therefore, it is very important to investigate the properties of PD degradation or PD breakdowns. However, the details remain still unsolved, because the PD phenomena involve complicated physical and chemical reaction.

Recently, the properties of the PD degradation or the PD breakdown have been investigated using a CIGRE method II electrode system. This electrode system is made up of a micro gap surrounded by polymeric insulators, a polymeric film as an insulating layer, and a sphere-plane electrode system. Consequently, it is difficult to investigate the properties of the PD degradation or the PD breakdown for each structural part separately. However, if the properties of the PD degradation or the PD breakdown for each structural part are grasped, the results will

throw light on these mechanisms. From this point of view, the author has made an improved Whitehead abc model as shown in Fig. 1 and has discussed a relationship between time variations in PD generations and PD degradation of cavity walls⁽¹⁾. As a result, the PD became non-pulsive as soon as $\tan \delta$ of the improved Whitehead abc model increased drastically. After the non-pulsive PD occurrence, part of the cavity wall was carbonized by PD. However, such carbonization of the cavity wall was not observed immediately before the non-pulsive PD occurrence. The results suggested that this phenomenon is caused by forming a conductive channel on the cavity wall. Furthermore, the total discharge energy required for the occurrence of the non-pulsive PD is almost constant regardless of applied voltage. However, the PD degradation or the PD breakdown of the insulating layer part exposed to PD has not been yet investigated.

Fig. 1. Configuration of an improved Whitehead abc model

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In mechanical engineering, it is proposed that statistical analysis with a Weibull probability distribution is effective to investigate mechanical deterioration or failure of materials, such as crack initiation of metals and craze appearance of polymeric materials ⁽²⁾⁽³⁾. This analysis is based on the following hypothesis: the statistical scatter in time required for mechanical deterioration and lifetimes of materials is regarded as the nature of the phenomenon itself, rather than the measurement errors ⁽³⁾. Accordingly, shape parameters deduced from the time Weibull probability distribution, which are the indexes of statistical scatters in the time required for mechanical deterioration, have a close relation to mechanical deterioration mechanisms. Recently, a statistical analysis using the time Weibull probability distribution has been applied to investigation on electrical degradation mechanisms of dielectric materials ⁽⁴⁾.

In this study, for the purpose of investigating PD breakdown characteristics of an insulating layer exposed to PD in gas-filled gaps, an electrode system which comprises a micro gap without cavity walls (free-air-filled space) and a polymeric film is employed as an artificial void in the Whitehead abc model; here, the artificial void is simply called a micro gap. A relationship between time to a PD breakdown in the micro gap and applied voltage is investigated. In addition, influence of residual charges in the micro gap on the PD breakdown is examined by using dust figure technique. This paper describes the PD breakdown properties in the micro gap. Furthermore, the PD breakdown processes at higher voltage are discussed on the basis of these results and the values of shape parameters in the Weibull probability distribution of the time to the PD breakdown in the micro gap.

2. Experimental Model and Procedure

2.1 Experimental Model The configuration of a micro gap is illustrated in Fig.2. Polypropylene (PP) films with 40 μm thick were prepared as a test sample. The PP film (40 $\times$ 40 mm) was placed on a grounded plane electrode in a sphere-plane electrode system (sphere electrode: ϕ 12.5mm, disc-plane electrode: ϕ 40mm). The distance between the sphere electrode and the upper surface of the PP film was adjusted to be 500 μm using a micrometer connected to the grounded plane electrode. To control temperature of the PP film using a temperature controller, a thermocouple was attached to an inner surface of a glass case with epoxy resin.

The experimental model is shown in Fig. 3. A 100 pF capacitor was connected in series to the micro gap. Moreover, a 3400 pF

Fig. 2. Configuration of a micro gap

capacitor was connected across the combination of the 100 pF capacitor and the micro gap. These capacitors are identical with those in the previous studies. The reason is that in the case of these

Fig. 3. Equivalent circuit of an experimental model

Fig. 4. Experimental apparatus

(a) In absence of PD breakdown

(b) In the case of non PP film

Fig. 5. Voltage waveforms across a micro gap

capacitors, the wave front of a PD pulse detected by a PD detector did not oscillate.

2.2 Experimental Procedure The schematic diagram of experimental apparatus is illustrated in Fig. 4. Before application of ac voltage, the micro gap shown in Fig. 2 was heated and temperatures of the inner surface of the glass case and the PP film surface were measured with two thermocouples; on the bases of the correlation between these two temperatures, the temperature of PP film surface was controlled using a heater and a temperature controller. Constant ac voltage of 60 Hz was applied to the experimental model. In absence of electrical breakdown of the PP film (PD breakdown), the voltage waveform across the micro gap is observed on an oscilloscope, as depicted in Fig. 5 (a). However, PD is generated between the electrodes at time that the PD breakdown occurs and as such, the voltage waveforms are the same as those across an idealized cavity in a Whitehead's equivalent circuit: the voltage waveform across the micro gap is observed as depicted in Fig. 5 (b). Therefore, the change in this voltage waveform was utilized as a sign of the PD breakdown and time to the PD breakdown was measured. At the same time, in order to grasp time variations in the PD generation, the maximum charge magnitude of PD in the micro gap was continuously measured using a PD detector until the PD breakdown occurred. However, the maximum charge magnitude of PD was almost constant regardless of application time under application of constant ac voltage. After the PD breakdown, a residual charge distribution on the upper surface of the PP film in the micro gap was observed with dust figure technique. These measurements were carried out at a film temperature of 20 °C and the micro gap was cooled down to room temperature (15 °C) after the measurements.

3. PD Breakdown Properties in the Micro Gap

3.1 Voltage Dependence of Time to the PD Breakdown in the Micro Gap Voltage dependence of the time to the PD breakdown in the micro gap is shown in Fig. 6 (—○—). The voltage dependence (V - t characteristics) is realized as linear characteristics which bend at 11 kV and 16 kV. Each of the linear characteristics is expressed as $t \propto V^{-n}$ (t : time to the PD breakdown, V : applied voltage, n : constant number). Moreover, It is quite unique in the V - t characteristics that the time to the PD breakdown at 13 kV is longer than that at 12 kV: the V - t characteristics become discontinuous at a certain voltage amplitude between 12kV and 13kV. For convenience sake, the voltage region where the identical V - t equation is satisfied is called Rgns. I, II, III, and

IV, respectively, as shown in Fig. 4 and the PD breakdown properties are investigated based on this separation.

3.2 Influence of Residual Charges on the Inner Surface of the PP Film on the PD Breakdown In order to investigate the effect of residual charges in the micro gap on the PD breakdown, the charge distributions are observed by dust figure technique with copy-toners which stick to negative charges. Figure 7 shows the typical distribution of negative charges on the inner surface of the PP film in the micro gap for each voltage region. The PD breakdown always occurs at an area where negative charges accumulate. It is likely that the PD breakdown occurs during a positive half cycle of ac applied voltage, because field strength at the air-filled space in the micro gap is enhanced by negative charges on the inner surface. However, the negative charge distributions on the inner surface at $V \leq 12$ kV (Rgns. I and II) are different from those at $V \geq 13$ kV (Rgns. III and IV). At $V \leq 12$ kV, the distribution patterns for Rgn. I are the same as those for Rgn. II and most of the negative charges on the inner surface are distributed circularly just under the sphere electrode. Accordingly, the PD breakdown point also exists just under the sphere electrode.

At $V \geq 13$ kV, negative charge distribution patterns for Rgn. III are different from those for Rgn. IV. For Rgn. III, the negative charges on the inner surface have not only a circular distribution just under the sphere electrode but also a ringed distribution around it. On the other hand, the negative charge distribution for Rgn. IV spread sparsely. In addition to these results, the fact that

Fig. 6. Voltage dependence of time to PD breakdown and the shape parameter in the time Weibull probability distribution

↓ : PD breakdown point

Fig. 7. Typical negative charge distribution

for Rgns. III and IV, the PD breakdown point does not always exist just under the sphere electrode is also observed: at times the PD breakdown occurs at a accumulation area of negative charges away from the point directly beneath the sphere electrode.

A relationship between spread of negative charge distribution and applied voltage is shown in Fig. 8. The negative charge distribution extends according to an increase in applied voltage in Rgns. I, II, and III. However, the spread characteristic in Rgn. IV saturates. This is because the PP film size is smaller than the propagation length of surface discharges in the micro gap. Hence, the negative charge distribution may also extend with applied voltage in Rgn. IV. It is worth noting that this characteristic, as well as the V - t characteristics, becomes discontinuous at the voltage between 12 kV and 13 kV. Therefore, the discontinuousness in these PD breakdown properties may be deeply concerned with surface discharges in the micro gap.

3.3 Difference in Surface Discharge Pattern in the Micro Gap The voltage dependence of time to the PD breakdown and the spread of negative charge distribution is found to be discontinuous at the certain voltage between 12 kV and 13 kV. The discontinuousness in the PD breakdown properties may be attributed to some effect of the surface discharge in the micro gap. In general, it is accepted that surface discharge patterns change from Polbüschel-type to Gleitbüschel-type according to an increase in applied voltage⁽⁵⁾⁻⁽⁷⁾. It has been also reported that in a case of Gleitbüschel-type, a maximum charge magnitude of surface discharges increases drastically with applied voltage⁽⁸⁾.

Fig. 8. Spread characteristic of residual charge distribution

Fig. 9. Voltage dependence of maximum charge magnitude of PD

With the aim of investigating the surface discharge patterns in the micro gap, a relationship between the maximum charge magnitude of PD in the micro gap and applied voltage is obtained. The result is shown in Fig. 9. At $V \leq 12$ kV, the maximum charge magnitude of PD in the micro gap increases gradually with applied voltage. However, a drastic increase in the maximum charge magnitude of PD in the micro gap starts when applied voltage exceeds 12 kV. The result shows that the transition from Polbüschel-type to Gleitbüschel-type occurs at certain voltage between 12 kV and 13 kV (≈ 12.3 kV). Therefore, it is apparent that the discontinuous properties of the PD breakdown in the micro gap are caused by the difference in the surface discharge pattern on the inner surface.

4. PD Breakdown Processes in the Micro Gap under Surface Discharge Pattern of Gleitbüschel-Type

In previous section, it is evident that the surface discharge patterns in the micro gap are Polbüschel-type and Gleitbüschel-type at $V \leq 12$ kV (Rgns. I and II) and $V \geq 13$ kV (Rgns. III and IV), respectively. In practical design of insulation for high voltage apparatuses, knowledge of electrical breakdowns and degradation at higher voltage is very useful. Therefore, in this section, the details of the PD breakdown process in the micro gap are discussed when the surface discharge pattern is Gleitbüschel-type.

4.1 Voltage Dependence of Shape Parameters in Time Weibull Probability Distribution It is well-known that analysis of electrical degradation and an electrical breakdown in dielectric materials with a Weibull probability distribution is very effective and the values of shape parameters deduced from the Weibull probability distribution of time such as lifetimes of insulating materials have a close relation to electrical breakdown processes of the materials⁽⁹⁾. The shape parameters are also concerned with exponents of V - t characteristics⁽¹⁰⁾. Therefore, it is possible that the PD breakdown processes in the micro gap change with applied voltage, because the exponent of the V - t characteristic for Rgn. III ($n=10.5$) is different from that for Rgn. IV ($n=22.7$). Here, the time to the PD breakdown in the micro gap is plotted according to the following equation as shown in Fig. 10, which is called a Weibull plot, and the shape parameters are estimated from these distributions.

F(t): Cumulative probability of the PD breakdown

Fig. 10. Weibull probability distribution of time to PD breakdown

Fig. 11. Typical PD degradation in Rgn III

Fig. 13. Typical PD degradation in Rgn IV

Fig. 12. Arrhenius plots of time to PD breakdown

$$F_{(t)} = 1 - \exp \left\{ - \left(\frac{t - \gamma}{\alpha} \right)^m \right\} \dots \dots \dots (1)$$

$F_{(t)}$: Cumulative probability of the PD breakdown

t : time to PD breakdown

m : Shape parameter

γ : Location parameter

α : Scale parameter

The result is also shown in Fig. 6 with the object of clarifying the relationship between the exponent and the shape parameter (-●-). The shape parameters m are grouped into two different categories: $m > 1$ in Rgn. III, and $m \leq 1$ in Rgn. IV. The result suggests that a dominant process of the PD breakdown in the micro gap is fatigue-failure-type and early/random-failure-type in Rgns. III and IV, respectively.

4.2 PD Breakdown of Fatigue-Failure-Type In order to investigate the PD breakdown process of fatigue-failure-type, the surface of the PP films in the micro gap is observed. Figure 11 shows the typical aspects of the PD degradation for Rgn. III. PD degradation products accumulate on the surface and the PD degradation area conforms to the negative charge distribution on the surface. This result shows that surface discharges in the micro gap play an important role in forming the PD degradation area. It is widely accepted that most of PD degradation products in voids, free-air-filled gaps, etc. are oxidation products which create due to PD exposure⁽¹¹⁾. Therefore, it is possible that the PD degradation area consists of oxidation products and the oxidative degradation is dominant in the PD breakdown process of fatigue-failure-type. Furthermore, chemical degradation including oxidative degradation is generally considered to be a thermally activated degradation process of Arrhenius type⁽²⁾. Here, assuming that the PD breakdown process of fatigue-failure-type is a thermally

activated degradation process of Arrhenius type, Arrhenius plots of the time to the PD breakdown are carried out. The result is shown in Fig. 12. The relationship between the time to the PD breakdown and a reciprocal temperature is represented as an exponential function ($t \propto e^{E/KT}$, E : activation energy, K : Boltzman constant, T : temperature). This result suggests that the PD breakdown process of fatigue-failure-type is the thermally activated degradation process of Arrhenius type. Furthermore, the activation energy required for the PD breakdown process of fatigue-failure-type is estimated to be 104.31 kJ/mol. The value is in good accord with activation energy required for polymer bond scission caused by interaction with oxygen and ozone (85 - 125 kJ/mol)⁽²⁾. Therefore, it is probable that oxidative degradation leads to the PD breakdown of fatigue-failure-type.

4.3 PD Breakdown of Early/Random-Failure-Type

Figure 13 shows the typical aspects of the PD degradation for Rgn. IV. Some of PP films deteriorate due to interaction with PD and others do not deteriorate. Furthermore, the PD degradation area does not accord with the negative charge distribution on the surface. Therefore, it seems that oxidative degradation does not play a dominant role in the PD breakdown of early/random-failure-type.

It is apparent in previous section that the PD breakdown always occurs at an area where negative charges accumulate. Furthermore, the negative charges have a sparse distribution in Rgn. IV, as shown in Fig. 7. It is generally accepted that such charged particles are easy to be trapped at structural defects. Consequently the negative charge distribution is deeply concerned with a structural defect distribution. In previous reports, the author has suggested that a degradation process of early/random-failure-type is governed by stochastic factors such as the existing probability of structural defects acting as starting points of the degradation process⁽¹²⁾⁻⁽¹⁵⁾. From these results, it is likely that structural defects at which a great deal of negative charges accumulates play an important role in the PD breakdown of early/random failure type and their existence has statistical randomness; this suggestion is also supported by the fact that not all the breakdown points are just under the sphere electrode. Therefore, it is probable that the PD breakdown of early/random-failure-type becomes dominant at $V \geq 16$ kV (Rgn. IV). However, the further details will be investigated in future.

The author touches on the PD breakdown processes in the micro gap under the surface discharge of Polbüschel-type. As shown in Fig. 6 (-○-), the shape parameters m are grouped into two different categories: $m > 1$ in Rgn. I, and $m \approx 1$ in Rgn. II. Consequently, it is likely that that a dominant process of the PD breakdown in the micro gap is fatigue-failure-type and random-failure-type in Rgns. I and II, respectively. However, the details of each PD breakdown process have not been yet

investigated. Therefore, these processes will be discussed in detail.

5. Conclusion

The PD breakdown properties in the micro gap are investigated using the experimental model which is made on the basis of the Whitehead abc model. Furthermore, the PD breakdown processes in higher voltage range are discussed. The results are summarized as follows.

(1) The PD breakdown properties in the micro gap become discontinuous at the certain voltage between 12 kV and 13 kV. The discontinuousness is probably caused by the transition from Polbüschel-type to Gleitbüschel-type.

(2) The time to the PD breakdown is analyzed with the Weibull probability distribution, especially when the surface discharge pattern is Gleitbüschel-type. The PD breakdown processes are classified into two different types: fatigue-failure-type for $13 \text{ kV} \leq V < 16 \text{ kV}$ (Rgn. III) and early/random-failure-type at $V \geq 16 \text{ kV}$ (Rgn. IV).

(3) The activation energy required for the PD breakdown of fatigue-failure-type is estimated to be 104.31 kJ/mol. Therefore, it is suggested that oxidative degradation leads to the PD breakdown of fatigue-failure-type, because the activation energy is in good accord with activation energy required for polymer bond scission caused by interaction with oxygen and ozone. However, the PD breakdown of early/random-failure-type is probably governed by the existing probability of structural defects at which a great deal of negative charges accumulates but not oxidative degradation.

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