# PARTIAL DISCHARGE-INDUCED AGING OF CAST EPOXIES AND RELATED NONSTATIONARY BEHAVIOR OF THE DISCHARGE STATISTICS

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## INTRODUCTION

Investigations have been under way in a number of laboratories to relate the observed statistical characteristics of partial discharge (PD) to properties of the site at which the discharge occurs [1,2]. There is an expectation that the statistical characteristics of PD can provide information needed for insulation defect site identification [3,4]. The success of PD identification schemes depends in part on finding sufficiently complete defect site descriptions that will allow assignment of unique, meaningful PD signatures to these sites. Special difficulties are encountered in cases where PD-induced aging occurs, i.e., there are physical and chemical changes at the discharge site that in turn cause modifications in the statistical characteristics of the PD. Evidence of PD-induced changes in the surface resistivity of epoxy materials with concomitant changes in PD characteristics have been reported by Hudon and coworkers [5]. The present work provides additional evidence for PD-induced changes in epoxy surface resistivity and relates these changes to observed nonstationary behavior in the statistical characteristics of the PD with the aid of a previously described Monte-Carlo simulator [6,7].

## MEASUREMENTS

The experimental results were obtained for an alternating voltage of variable frequency applied to a point-dielectric gap configuration described previously [7,8]. Partial discharge was generated under conditions where a conical stainless-steel "point" electrode with a radius-of-curvature at the tip of about 0.05 mm <u>touched</u> the flat surface of a rectangular 4 × 8 cm sheet of 1 mm thick epoxy attached to a grounded metal surface in air. Two types of cast epoxy (with and without $Al_2O_3$ "filler") supplied by the Electrotechnical Institute in Warsaw[1] were used in this investigation. The applied sinusoidal voltage was always 3.0 kV rms at a frequency between 50 and 400 Hz.

[1] The identification of commercial materials and their sources is made to describe the experiment adequately. This neither implies recommendation by the National Institute of Standards and Technology, nor that the material is the best available.

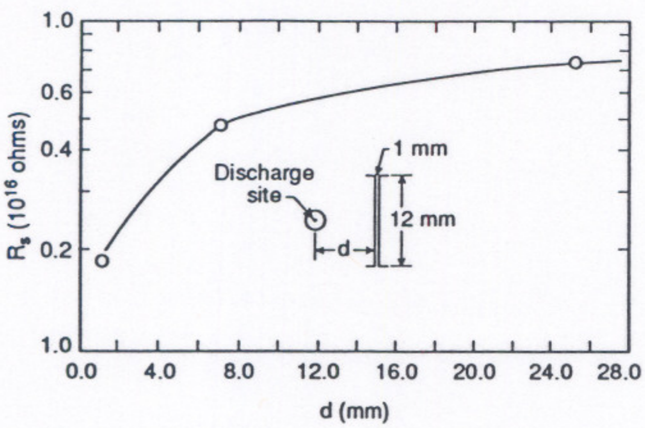


**Figure 1.** Measured surface resistance of epoxy with filler as a function of distance from the discharge site. These results apply to the case used to obtain the data in Fig. 2.

During continuous application of the voltage, various conditional and unconditional PD pulse-height, pulse-phase, and integrated-charge distributions were measured with a stochastic analyzer [8]. Results are reported here for the unconditional phase-of-occurrence distributions for the first negative PD pulse, $p_o(\phi_1^-)$ and for the integrated-charge distributions, $p_o(Q^+)$ and $p_o(Q^-)$, where $Q^+$ and $Q^-$ are respectively the sums of charges, $q_i^\pm$, in pC of all positive or negative PD pulses in one cycle of the applied voltage, i.e.,

$$Q^\pm = \sum_i q_i^\pm. \tag{1}$$

After exposure to PD, surface resistivities of the epoxy were measured in the region where the discharge had occurred. These measurements were made by recording the current produced when a dc voltage was applied to movable parallel conductors separated by a distance of 1.0 mm as shown in Fig. 1. The resistances were measured as a function of the distance *d* from the center of the discharge site.

## EXPERIMENTAL RESULTS

Measured integrated-charge distributions $p_o(Q^+)$ and $p_o(Q^-)$ are shown in Figs. 2 and 3 for epoxy with and without filler respectively. Indicated in each figure are the times after application of the voltage at which the measurements were made. The time required to measure each distribution was about 4 minutes. Also indicated in Fig. 2 are the mean numbers of positive and negative PD pulses that occurred per cycle during the time of measurement. The data in Fig. 2 were obtained at a frequency of 50 Hz, whereas the data in Fig. 3 were obtained at 400 Hz. The distributions shown in both figures have been arbitrarily normalized to their maximum values. Figure 4 shows

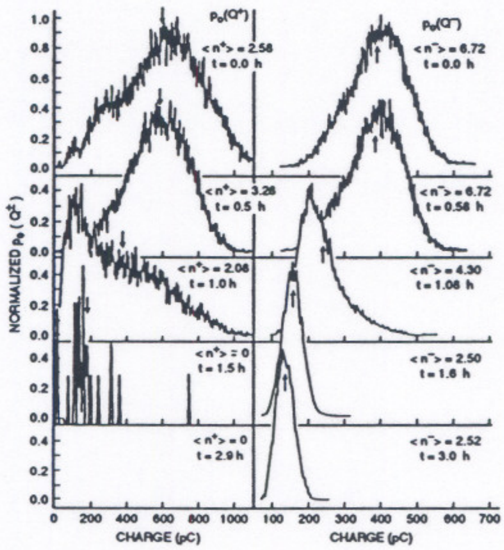


**Figure 2.** Positive and negative integrated-charge distributions measured for epoxy with $Al_2O_3$ filler at the indicated times after the 50-Hz voltage was applied. Also shown are the corresponding mean numbers of positive and negative PD pulses and the mean charge values (vertical arrows).

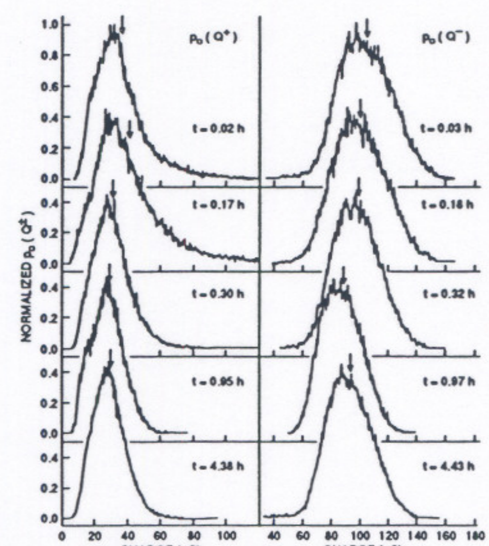


**Figure 3.** Positive and negative integrated-charge distributions measured for epoxy without filler at the indicated times after the 400 Hz voltage was applied. The vertical arrows indicate mean values.

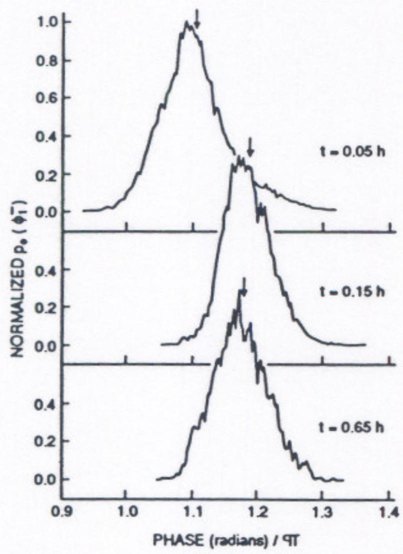


**Figure 4.** Measured phase-of-occurrence distributions of the first negative PD pulse for the indicated times after 400 Hz voltage was applied. The vertical arrows indicate mean values.

examples of normalized phase distributions, $p_o(\phi_1^-)$, of the first negative PD pulse measured at different indicated times for epoxy with filler at a frequency of 400 Hz.

The most significant features about the results shown in Fig. 2 are the abrupt shifts downward of both $p_o(Q^+)$ and $p_o(Q^-)$ after about 1 hour and the complete disappearance of positive PD pulses after about 1.5 hours. The time at which the positive pulses ceased was found to be quite reproducible and nearly inversely proportional to the frequency of the applied voltage. When the positive discharges cease, the mean of $\phi_1^-$ shifts to a higher value closer to the voltage minimum on the negative half-cycle as seen in Fig. 4. It should be noted that, unlike the data in Fig. 2 which were obtained at 50 Hz, the data in Fig. 4 were obtained at 400 Hz, and therefore the positive pulses disappeared in a shorter time of about 0.12 hours.

In the case of the epoxy sample with filler that was used to obtain the data in Fig. 2, a measurement was also made of the surface resistivity near the discharge site after the sample had been exposed to the discharge for 3 hours. The results in Fig. 1 show that the exposure to the discharge resulted in a local decrease of surface resistivity in the vicinity of the discharge consistent with results reported by Hudon and coworkers [5]. The disappearance of positive PD pulses can be related to the decrease in surface resistivity as discussed in the next section. It can be seen from Fig. 3 that in the case of epoxy without filler, the stochastic properties of the PD were much more stationary with time, e.g., there is no disappearance of positive pulses.

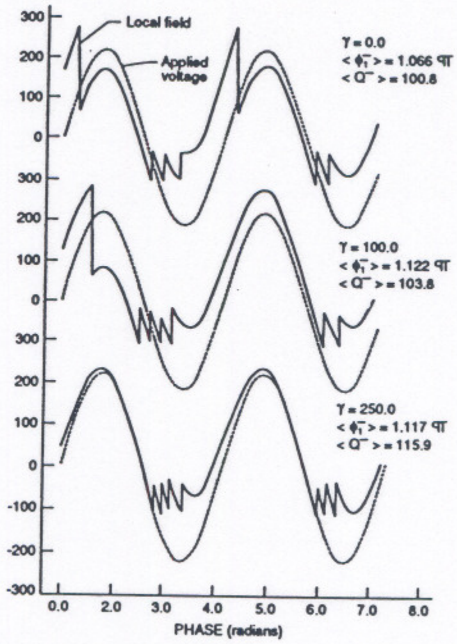


**Figure 5.** Two randomly selected cycles from a Monte-Carlo simulation of PD. Shown are the applied voltage (dashed line) and local field (solid line) at the discharge site. Also indicated are the decay constant, $\gamma$ in units of $s^{-1}$, and the mean values for $\phi_1^-$ and $Q^-$.

## RESULTS OF MONTE-CARLO SIMULATION

The stochastic properties of PD generated by applying an alternating voltage to a point-dielectric gap can be predicted using a Monte-Carlo computer simulation based on a model similar to that previously described [6,7]. The version of the model used to obtain the results presented here has been modified to allow a decay of PD-deposited negative charge on the dielectric surface by a factor $\exp(-\gamma t)$, where the decay constant $\gamma$, which has units of inverse seconds, increases with increasing local surface conductivity. The present model also allows the probability of extracting an initiatory electron from the negatively charged surface to increase with increasing negative-charge density. By incorporating these features into the model, it is possible to simulate conditions under which positive PD pulses will disappear with increasing surface conductivity as illustrated in Fig. 5. This figure shows two randomly selected cycles of a 50-Hz applied voltage and corresponding local field at the PD site for different assumed values of $\gamma$. In this example, positive PD pulses cease when $\gamma > 150\ s^{-1}$. Also, the mean value for the phase of the first negative pulse, $\langle\phi_1^-\rangle$, increases when the positive PD cease. This trend is consistent with the data in Fig. 4.

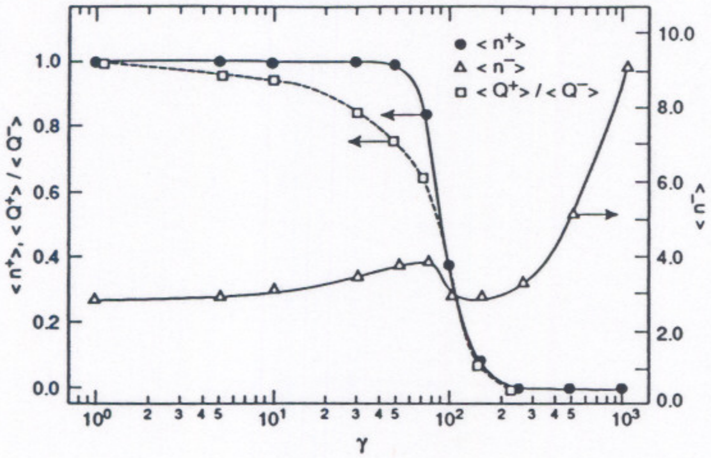


**Figure 6.** Dependencies of the mean numbers of positive and negative PD pulses ($\langle n^+ \rangle$ and $\langle n^- \rangle$) and the ratio of mean absolute charge values $|\langle Q^+ \rangle / \langle Q^- \rangle|$ on the assumed decay constant in the Monte-Carlo simulation.

Shown in Fig. 6 are the mean numbers of positive and negative PD pulses per cycle ($\langle n^+ \rangle$ and $\langle n^- \rangle$) and the ratio of mean values for $Q^+$ and $Q^-$ determined from this simulation as a function of $\gamma$. It is seen that $\langle n^- \rangle$ initially decreases with increasing $\gamma$ in the region where $\langle n^+ \rangle \to 0$, which is consistent with the data for $\langle n^- \rangle$ in Fig. 2. The corresponding drop in measured $\langle Q^- \rangle$ indicated by the vertical arrows in Fig. 2 is associated with the drop in $\langle n^- \rangle$. In the case of the simulation results, however, the drop in $\langle n^- \rangle$ was not great enough to cause a significant change in $\langle Q^- \rangle$. Conditions closer to those observed experimentally can be obtained by varying the model parameters such as surface work functions and applied voltage. It is interesting to note that the drop in $\langle n^+ \rangle$ becomes evident as soon as $\gamma$ assumes a value equal to or greater than that for the frequency of the applied voltage, in this case 50 $s^{-1}$.

Finally, it should be noted that if the surface has a finite conductivity that allows a more rapid decay of negative charge than positive charge, i.e., $\gamma > 0$, then in general, $|\langle Q^- \rangle| > |\langle Q^+ \rangle|$. The fact that this condition appears to be satisfied for the case of epoxy without filler (see Fig. 3) suggests that the surface of this material is initially more conductive than that of the epoxy with filler. There is evidence that the initial charge inbalance ($|\langle Q^+ \rangle| > |\langle Q^- \rangle|$) for the epoxy with filler at times less than 0.6 hours (see Fig. 2) is due mainly to a lack of positive PD pulses in every cycle. The calculation of $\langle Q^+ \rangle$ using the measured distribution $p_o(Q^+)$ will overestimate the true mean of $Q^+$ if positive PD pulses fail to occur in every cycle.

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