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Partial Discharge Patterns in Conducting and Non-Conducting Electrical Trees

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Abstract—**Previous observations on electrical tree growth in epoxy resins has shown that different types of tree growth structure, electrically conducting and non-conducting, can occur dependent on the state, glassy or flexible, of the epoxy resin. In this current study, the partial discharge characteristics were characterized experimentally at a temperature of 20°C within two different epoxy resins systems having glass transition temperatures of 0°C and 50°C. The partial discharge activity (determined from apparent charge measurements) was characterized in terms of ϕ~q~n patterns using statistical tools. The aim was to compare the apparent charge measurements obtained from conducting and non-conducting electrical tree structures with computer simulations of the partial discharge activity in both conducting and non-conducting electrical trees. The results show that there is a significant relationship between the local extent of the partial discharge phenomena, as determined by the conductivity of the tree channels, and the apparent charge, as shown by the experimental and simulated partial discharge patterns. The implications of this work for partial discharge detection as well as for condition monitoring in real insulating systems are discussed.**

Keywords - electrical tree, partial discharge, epoxy resin, detection sensitivity

I. INTRODUCTION

Electrical treeing is of interest as one of the causes of insulation failure in HV cable insulation, electrical machines, switchgear and transformer bushings. Electrical trees propagate as a result of partial discharges (PD) occurring within the tree structure. PD patterns were suggested as a valuable tool in the diagnostic of electrical insulation systems [1] and different techniques were proposed for PD classification [2]. However in order to create reliable monitoring system based on PD pattern recognition it is necessary to improve our understanding on the physical processes governing the PD activity and the way PD patterns evolve with material degradation. Deterministic models of electrical tree growth have been quite successful in producing branched structures and have provided an insight into the physical processes governing electrical tree inception and propagation [3]. A deterministic approach was adopted in [4] for modelling partial discharges in electrical trees and the model was successful in reproducing the spatial extent of the partial discharge activity and the PD apparent charge magnitudes. However, the model was not investigated further to determine whether such deterministic models can reproduce the statistical characteristics of the PD patterns observed in the experiments.

Experimental observations of electrical treeing under 50 Hz alternating applied electric fields in epoxy and polyethylene insulation materials have demonstrated that that two types of tree could be formed; electrically non-conducting, in which the partial discharges occur within the main branches of the tree structure, or, electrically conducting, in which the partial discharge occur only at the growing tree tips. Electrically conducting trees are known to form in epoxy resins in the glassy state (i.e. at a test temperature below the glass transition temperature of the epoxy) or in polyethylene after a critical time of voltage application. Conversely, electrically non-conducting electrical trees form in an epoxy resin in the flexible state (i.e. at a test temperature above its glass transition temperature) or during the initial stages of tree growth in polyethylene. In the case of polyethylene, the transition from non-conducting to conducting tree structures was found to be due to the formation of graphite residues within the tree structure [5].

The current study aims to characterize the partial discharges occurring within the different types of tree structures, in a flexible and a glassy epoxy resin, in terms of the ϕ~q~n patterns using statistical tools. Recent computer simulations of the partial discharge activity in the two types of tree structure have demonstrated a significant difference in the measured partial discharge amplitudes [6]. In this work we compare the different apparent charge measurements obtained from experiment with simulations of the partial discharge activity in both conducting and non-conducting electrical trees to obtain a better understanding of the relationship between the local extent of the partial discharge phenomena and the recorded partial discharge patterns.

II. PD SIMULATION

Deterministic simulations of the partial discharges within electrically conducting and non-conducting tree structures were based on the techniques described in references [4, 6]. The simulations were based on using spheres of charge to describe the pin electrode and the induced charge at the pin-tip from charge contained within the tree structure. Charge dipoles were added to the tree structure to simulate the occurrence of local electron avalanches. The conditions for a local electron avalanche to occur at a particular time step was that the tree segment potential drop must exceed a value V_{on}, called the inception voltage. Dipoles of charge were added until the potential drop along each tree segment was less than the extinction voltage, V_{off}. Each partial discharge event was

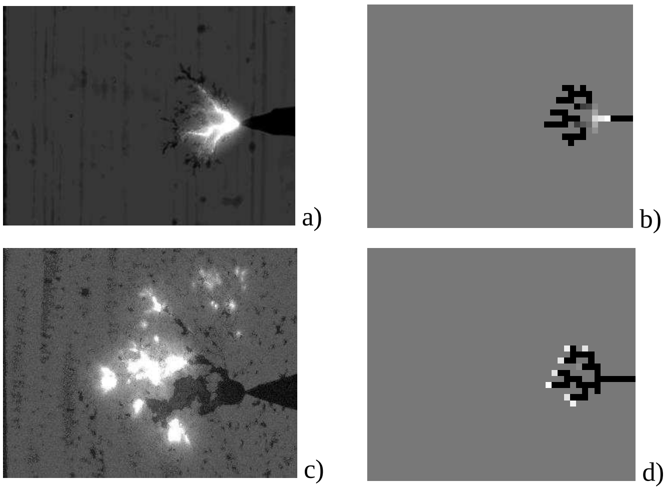

Fig. 1: Composite images showing different tree structures and light emission from the tree structure in the case of non-conducting tree a) experiment, b) simulation and conducting tree c) experiment, d) simulation.

therefore the sum of one or more local electron avalanches occurring within the tree structure at a particular time step. The apparent charge was calculated from the change in the calculated induced charge on the pin electrode following each discharge event. The charge representing the pin potential was assumed sinusoidal with a frequency of 50 Hz. Tree channel conductivity was simulated by calculating the charge flow along each tree segment in proportion to the segment potential difference. Thus the conduction of charge along tree segments was considered Ohmic.

III. EXPERIMENTAL

Pin-plane samples were used to conduct all treeing experiments with pin-plane distance approximately 2mm. The samples were cast from bisphenol-A epoxy resins Araldite CY1301 and Araldite CY1311, the latter being a modified version of the former with added plasticizer and having a glass transition temperature of 0°C. The glass transition temperature of Araldite CY1301 is about 55°C. Both resins were cured with hardener HY1300GB in a ratio resin to hardener 3:1 by mass. The epoxy samples were left to cure for two days in a mould. Afterwards, they were post-cured for an hour in a vacuum oven at 100°C and slowly cooled down to room temperature. All samples were stored in sealed containers under controlled temperature and humidity conditions.

The treeing experiments were performed at room temperature, therefore Araldite CY1311 samples were in the flexible state and Araldite CY1301 samples were in the glassy state. Samples were tested in a Faraday cage to exclude external electromagnetic interference. The pin-plane electrode geometry samples were contained within a glass cell filled with silicone fluid to eliminate discharges occurring along the surface of the sample during the tests. A HV transformer rated at 20 kV rms provided the 50 Hz applied voltage, which was connected to the pin electrode. The brass base-plate of the glass cell formed the plane electrode, which was connected to earth potential. Test voltages between 10 kV rms and 13.5 kV rms were used. The apparent charge was measured using a RCL resonant circuit connected in series with a high voltage discharge free coupling capacitor. Simulations of non-conducting electrical trees, as grown in the flexible resin, were found to have typical partial discharge (PD) apparent magnitudes in the range 1 pC to 10 nC [6]. In this case, PD magnitudes were detected experimentally using a resonant RLC circuit of frequency 200 kHz and amplitudes recorded by a digital storage oscilloscope (DSO). The minimum sensitivity of this measurement system was 1.5pC. The data acquisition interval was 1s with 10s time delay between the consecutive acquisitions. In the case of conducting trees, simulations show typical PD apparent charge magnitudes less than 10 pC and typically of the order of 50 fC. Hence, for the glassy resin samples, a RCL resonant circuit having a significantly higher resonant frequency of 10MHz and a sensitivity of 10 fC was used in the experiments. The short duration of the partial discharge voltage pulses from the detector presents a serious problem for the accurate measurement of their amplitudes using data acquisition based on sampling. A threshold detector and a set of four counters were therefore used instead of the DSO. The threshold detector was tuned to register all PD pulses above a certain apparent charge level. The threshold levels were 0.01, 0.1, 0.3, 1, 3 and 10 pC. The acquisition period was 20s at each level and during this interval, the partial discharges were counted. Further details of the threshold detector and PD counter can be found in reference [7].

During the tree growth experiments, the light emitted, as a result of the PDs occurring within the tree structure, was captured using a Peltier-cooled CCD camera. The exposure times for the light emission images were 10 seconds. The CCD camera was also used to monitor the tree growth structure using back-illumination to capture images of the electrical trees. Superimposing the grey-scale light emission image on top of a red/black image of the tree structure could produce composite images that make clear the position within the tree where the partial discharges are occurring.

IV. RESULTS AND DISCUSSION

A CCD image of a non-conducting electrical tree grown at applied voltage 10kV rms and the corresponding light due to the PD activity is shown in Fig. 1a. The CCD image reveals that partial discharges occur within the main tree channels leading from the pin-tip towards the tree ends. In the case of a conducting tree grown at applied voltage 13.5 kV (Fig. 1c) the conducting tree structure acts as an extension of the pin tip and PD occur only in localized regions at the tree ends. Similar results were reported in [6]. Deterministic simulations of the partial discharge activity are also shown in figure 1 (b) and (d) for comparison with the experimental images. The simulation parameters used are given in Table 1.

TABLE I. VALUES OF THE MODEL PARAMETERS

Parameter	**Non-conducting tree**	**Conducting tree**
V_0 [V]	10 000	10 000
V_{on} [V]	3 500	1 500
V_{off} [V]	1 000	1 000
ε_r	4.8	4.8
R_{seg} [Ω]	1.0×10^{12}	1.0×10^{8}

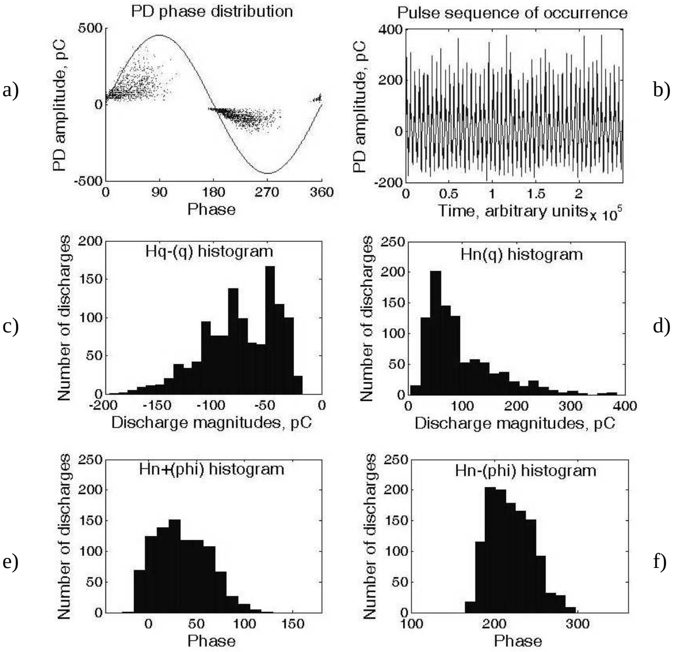

Fig. 2: Typical PD distributions during the growth of non-conducting electrical tree, experimental PD data acquired for 1s, applied voltage 10kV.

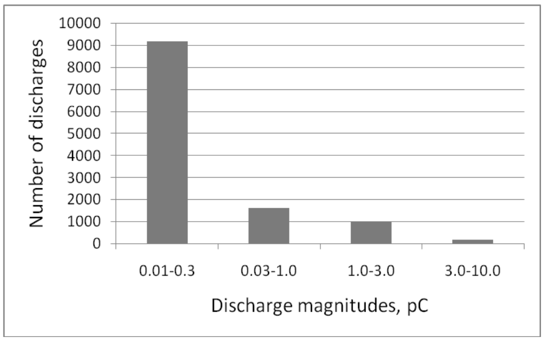

Fig.3: Discharge magnitude histogram obtained during the growth of a conducting electrical tree, applied voltage 13.5kV, corrected for an acquisition of 1 second.

The partial discharges occurring within the different types of tree structures can be characterized in terms of ϕ~q~n patterns using statistical tools [8]. A typical PD data set acquired during the growth of a non-conducting tree can be analysed in terms of pulse count distribution Hn(ϕ) and pulse magnitude distribution Hn(q). The pulse count distribution represents the number of the pulses observed in each phase window as a function of the phase angle of the applied voltage and the pulse magnitude distribution represents the number of pulses within the same PD amplitude window. Two distributions of each kind are obtained for each polarity of the PD pulses – positive and negative. A typical snapshot of the experimental PD distributions during the tree growth of a non-conducting electrical tree of length ~0.5 mm is shown in Fig. 2. The partial discharge phase distribution obtained over one second is shown in Fig. 2a. Each partial discharge event is shown as a dot on the graph. The sequence of partial discharge amplitudes is plotted in Fig.2b showing how the discharge magnitudes evolve over the one second time interval. The partial discharge amplitude distributions for the negative and positive discharges are shown in Fig.2c and 2d respectively. The corresponding partial discharge phase histograms are shown in Fig. 2e and 2f for the positive and negative partial discharges respectively. Because some of the positive discharges appear at phase angles between 330° and 360°, i.e. during the negative half-cycle of the applied voltage, it was necessary to subtract 360° from the corresponding angles so that a continuous Hn$^+(\phi)$ distribution was obtained. These discharges appear at negative phase angles in the Hn$^+(\phi)$ histogram in Fig. 2e and the consecutive figures shown in this paper depicting the pulse count distribution Hn$^+(\phi)$. The common features between all statistical distributions investigated in the case of non-conducting electrical trees are that the amplitude distributions are skewed and with kurtosis equal or greater than 3. The other significant feature of the distributions depicted in Fig. 2 is the asymmetry between the positive and negative PD amplitude and phase distributions. In the case of a tree of length ~0.5 mm the partial discharge amplitude distributions extended to –200 pC for the negative discharges and 400pC for the positive discharges.

In the case of electrically conducting trees, the data acquired from the threshold detector allowed only pulse magnitude distribution Hn(q) to be constructed for PDs. In this case, it was not possible to discriminate between positive and negative PD pulses. The histogram shown in Fig.3 represents total number of PDs as a function of discharge magnitude. Although the shape of the distribution is similar to the shape of distributions in Fig. 2c and 2d, it is noteworthy to emphasize that the partial discharge rates are significantly higher while the magnitudes of the measured discharges are approximately 2-3 orders of magnitude smaller.

The deterministic simulation model of PDs in electrical trees proposed in [4, 6] was used to simulate the PD activity in conducting and non-conducting electrical trees and to obtain the corresponding PD apparent charge magnitudes. The PDs were simulated over 50 cycles of the applied sinusoidal voltage, so that the results of the simulation can be directly compared to the experimental data. The model parameters as in [6] are: applied voltage V_0, discharge inception potential V_{on}, discharge extinction potential V_{off}, relative permittivity of the resin ε_r, and tree segment resistance R_{seg}. The values of the parameters used to simulate the PD activity in the case of conducting and non-conducting tree are given in Table 1. The model allowed two aspects of the PD activity to be simulated, namely the location at which discharges take place and the PD magnitude of the discharges as a function of the phase of the applied voltage, i.e. phase resolved PD data. The simulated light emissions have already been shown in Fig, 1b (non-conducting tree) and Fig.1d (conducting tree). The spatial extent of the simulated light emission closely resembles the experimental data in that for the electrically non-conducting tree, the partial discharges occur within the main body of the tree while for conducting trees, the partial discharges occur at the tree tips owing to the higher segment resistance of these tree segments.

The phase resolved PD patterns of the simulated partial discharge data are shown in Fig. 4 and Fig. 5 for the non-conducting and conducting trees respectively. For both types of tree, the simulated partial discharge magnitude distributions

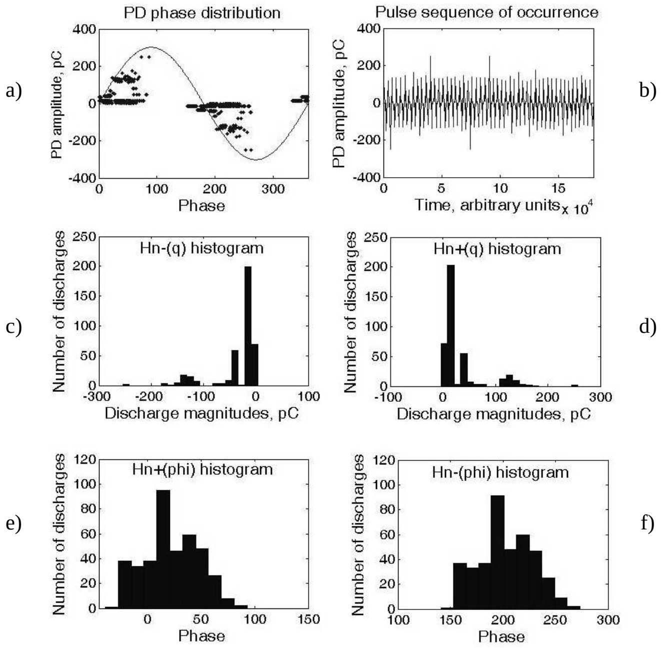

Fig. 4:Typical PD distributions during the growth of non-conducting electrical tree, the PD data was simulated for 1s.

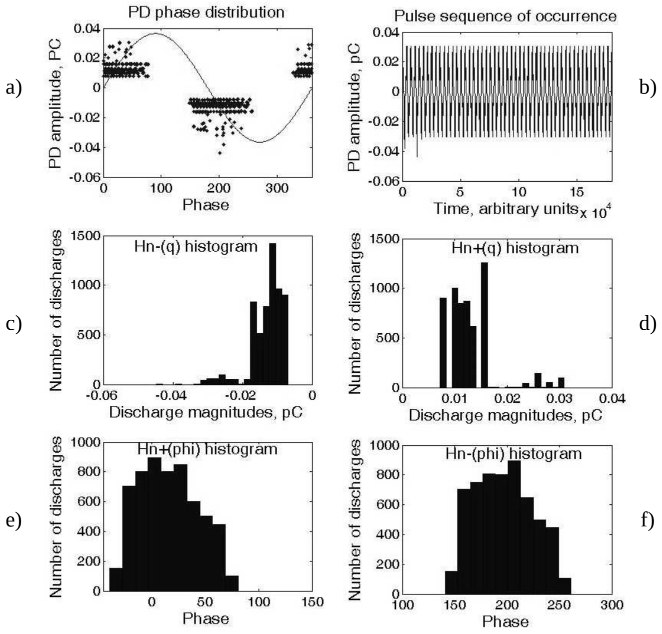

Fig. 5: Typical PD distributions during the growth of conducting electrical tree, the PD data was simulated for 1s.

also appear skewed and comparable to the experimental data. However, there are some subtle differences between the simulated and experimental data. The simulated data for the case of non-conducting trees showed good symmetry between the positive and negative PD distributions, which was not the case in the experimental data. This is due to the simulation parameters being symmetric for both positive and negative discharges, which may not be true for the experimental trees. The simulation model also does not take into account the material properties of the epoxy resin such as charge carrier conduction storage or transport, which may influence the magnitudes of the local electric fields internal to the tree structure in the two half cycles of the applied voltage.

In the case of the conducting trees, the simulated PD magnitudes were about the same order of magnitude as the PD amplitudes observed in the experiment and significantly lower than the amplitudes found for the non-conducting trees. However, by using the threshold detector, it was not possible to examine the asymmetry in the partial discharge distributions in terms of the positive and negative polarities. The much smaller apparent charges found for the conducting electrical trees is due to the much smaller change in induced image charge on the pin electrode following each partial discharge event. The simulated numbers of partial discharge are much greater than in the case of the non-conducting electrical trees as the electrically conducting tree structure acts as an electrical extension of the pin electrode and the tree tips act as independent sites for partial discharge activity. Therefore, the difference in the PD numbers and the apparent charge measured in the two cases (conducting trees and non-conducting trees) can be explained by the differing spatial extents of the PD activity.

V. CONCLUSIONS

Deterministic simulations of the partial discharge activity in electrically conducting and non-conducting electrical tree structures have shown good agreement with experimental data. This comparison demonstrates that for conducting trees, the partial discharge apparent charge amplitudes are two to three orders of magnitude less than that for non-conducting electrical trees and much less than the sensitivity of commercial PD detection instrumentation, ~1 pC. The use of PD monitoring for condition monitoring of HV plant in which the degradation structures are electrically conducting and where measurements were taken in a noisy environment would not be possible.

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