Aging Diagnosis of Insulation Systems by PD Measurements

Extraction of Partial Discharge Features in Electrical Treeing

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ABSTRACT

The charge height values associated with PD measured during electrical tree inception and growth are processed according to the Weibull distribution. Test arrangements, based on the needle-plane electrode system, consider specimens having either a cavity at the tip or an intimate contact with insulation. It is shown that the Weibull-function parameters have close relation to discharges occurring in cavity and tree channels, and that an indication of inception of electrical trees can be obtained.

1. INTRODUCTION

THE results presented in [1] suggest that the technique there proposed, based on inference of the PDHD (partial discharge height distribution), can provide indications on the mechanisms associated with PD activity. In particular, features relevant to tree growth in insulating systems have been hypothesized.

It has been shown that the Weibull distribution of pulse charge amplitude fits data obtained from measurements performed on insulation specimens with artificial cavities and insulators [1, 2], which confirms other observations reported in the literature, and relevant to various types of insulating systems [3–7]. Besides the significant correlation between the Weibull distribution parameters, particularly the shape parameter β, and the aging and breakdown times [1], the use of the Weibull function for PDHD treatment may allow inference of the PD sources to be pursued [8], which can contribute to further improve diagnostic reliability. This is not the only way to reach the goal of PD identification because other techniques use PD patterns [9, 10], or PD pulse shapes [11–14], but it seems to be quite interesting for some properties, such as the invariance with respect to PD location [3].

Putting together the aspects of PD recognition and insulation diagnosis, and considering that the aging process of an insulating system has, in general an electrical tree as the final stage, the interest in work aimed at the investigation of the correlation between PDHD features and tree growth is apparent. Indeed, some preliminary results of research on this topic have been presented [6, 15, 16].

The purpose of this paper is to provide a contribution on stochastic analysis of PD, showing how the Weibull function can be used to infer electrical tree inception and growth features. Tree growth is promoted in polymeric specimens by needle-plane electrodes, supplied at constant ac voltage. Two configurations, with either a void at the tip of the needle or with the needle in intimate contact with the insulation, are considered. Tests are made on XLPE (cross-linked polyethylene) and EVA (ethylene-vinylacetate copolymer) specimens.

2. STATISTICAL TOOLS

The basic statistical instrument for PD data processing is simply the 2-parameter Weibull function, which is applied to the distribution of pulse charge height q. The algorithms for the estimation of scale and shape parameters, α and β, the quality-of-fit test, *i.e.* the CVM (Cramer-von Mises) test, are described in [1]. Here, only the expression of the Weibull distribution is recalled

$$F(q;\alpha,\beta) = 1 - \exp\left[-\left(\frac{q}{\alpha}\right)^{\beta}\right] \quad (1)$$

where α and β are scale and shape parameters ($\alpha \geqslant 0$, $\beta \geqslant 0$)

The relationships between standard average quantities commonly employed for PD analysis, that is, the mean number of discharges per cycle, mean integrated charge height and mean value of charge height transferred by each pulse [17, 18], and the Weibull function parameters are shown in [4].

In addition to the treatment by the Weibull function, PDHD values were also processed to calculate the high order moments (*i.e.*, second, third and fourth) and the related indexes (*i.e.*, variance, skewness and kurtosis) of their stochastic distribution [6, 9, 10].

Another option offered by the Weibull function is that it allows to build mixed models, which can account for nonlinear behavior of charge-height data in Weibull graphs [1]. In particular, a five-parameter Weibull distribution can fit PDHD in the presence of two sub-populations of charge-height values, as may occur when two different sources of PD are simultaneously active [1, 3, 4, 8]. Its expression, already given in [1], is

$$f(q) = pf_1(q) + (1-p)f_2(q) \tag{2}$$

where $f_1(q)$ and $f_2(q)$ are the probability density functions of the two sub-populations representative of two different sources of PD or from two different mechanisms. The expressions of $f_1(q)$ and $f_2(q)$ can be obtained by differentiation of Equation (1) [1]. The additive model of Equation (1) is characterized by 5 parameters, that is, α_1 and β_1 describing the first sub-population, corresponding to lower-amplitude PD, α_2 and β_2 identifying the second phenomenon which superimposes on the first one, with probability $0 < p < 1$.

3. EXPERIMENTAL PROCEDURES

Specimens of EVA and XLPE, 6 mm thick, were used for the test procedures here summarized. The tree tests were performed by the point-plane electrode system, described in [19], in a laboratory shielded room. Ogura needles with 3 μm tip radius, 60 mm long, 1 mm of diameter were inserted in material slabs (25× 25 × 6 mm^3) by a mold, at 180°C for XLPE and at 95°C for EVA specimens. Specimens were pretreated for 100 h before any test, at 90 and at 70°C respectively. Two different arrangements were realized. One, #1, sees the needle tip in intimate contact with the insulation. The other, #2, was obtained by drawing back the needle after insertion, in order to generate an artificial void at the needle tip [20]. Both arrangements are sketched in Figure 1. Tests were performed at three levels of constant voltage, that is, 9, 10 and 11 kV for XLPE, 5, 6.5 and 12 kV for EVA, at 20°C, placing specimens in a vessel containing silicon oil. Tree Inception was promoted by linearly increasing the voltage, then the test at constant voltage was started. Samples of three specimens were considered for each test. Tree inception and growth were recorded by means of a data acquisition system which collects together, simultaneously, on-line PD measurements and optical observation (with 50× magnification) [21]. A PRPDA (phase resolved partial discharge analysis) system, having a bandwidth from 20 kHz to 2 MHz, was used to measure PD, with an acquisition time of 30 s. This time has significant influence in PDHD inference [22]. It must be reminded, for example, that application of stochastic operators, such as Equation (1), relies upon the assumption of stationarity. PD pulse phase and amplitude values were stored in a 256× 256 matrix, which constitutes the basis for any post-processing. Thus PD patterns (fingerprints, stochastic quantities) were obtained. Such measurements were repeated several times before and after inception of treeing, so that the series of patterns were representative of discharge phenomena occurring in the artificial void of arrangement #2, as well as of tree growth in both #1 and #2.

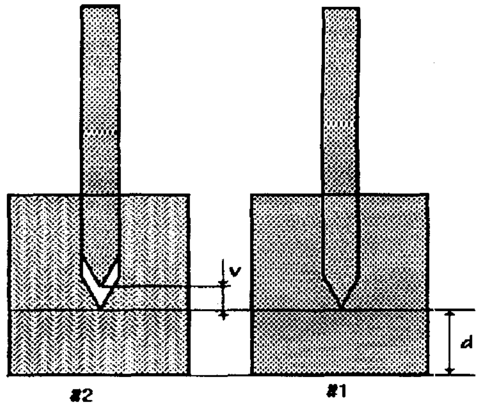

FIGURE 1. Experimental setup for tree inception and growth investigation.

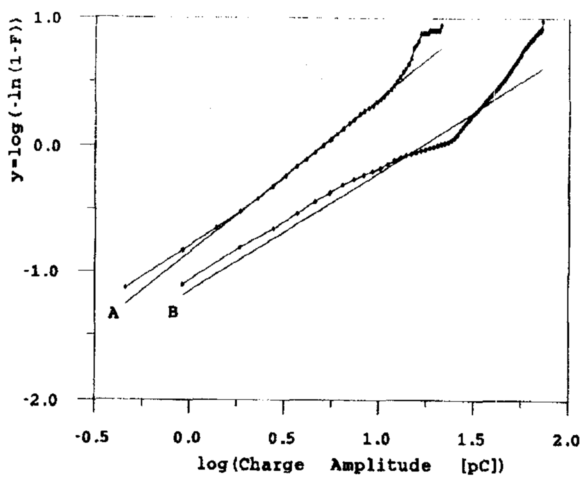

FIGURE 2. Positive PDHD data, fitted by the two-parameter Weibull function, relevant to discharges occurring into #2 (EVA specimen), after 27 (A) and 143 (B) min from the beginning of test 6.5 kV.

4. RESULTS AND DISCUSSION

Figure 2 reports positive PDHD data, fitted by the 2-parameter Weibull function, relevant to discharges occurring into the artificial void of #2 (EVA specimen), 27 and 143 min after the beginning of the test, at 6.5 kV. Likewise, Figure 3 shows data and Weibull plots at different times during tree growth, in a XLPE specimen having arrangement #1, at 11 kV. It can be seen that height of PD pulses relevant to 27 min in #2 and to electrical tree growing in #1 fit well the 2-parameter Weibull function. On the contrary, significant deviation from this function is detected in specimen #2 after 68 min. Before any comment on these data, it must be pointed out that different results can be obtained for a given material by changing the applied voltage. In general, it has been shown that the quality of fitting the 2-parameter Weibull function improves for high test voltages. PD occurring in a cavity, indeed, tend to quite flat charge-height probability density functions for low voltage values, while either increasing voltage, or waiting for some time, gives rise to good agreement with (1) [2]. These considerations, moreover, are affected by PD polarity: positive discharges often tend to fit better to (1), even at low test voltage, than the negative ones [16]. As regards tree growth, it will be shown later that charge-height distribution fits (1) better when the shape of trees tends to be bush-like structure.

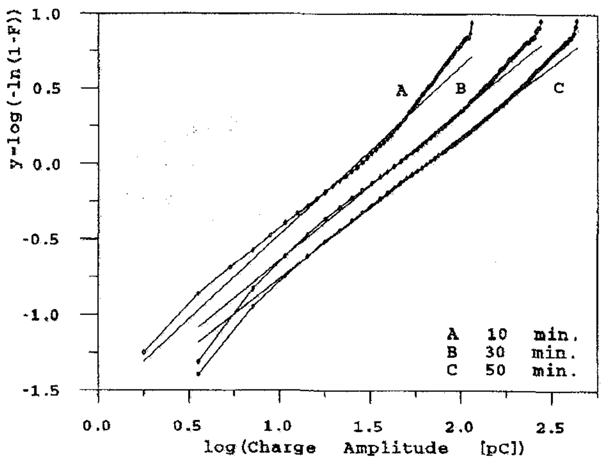

FIGURE 3. Positive PDHD data, fitted by the two-parameter Weibull function, after 10 min (A), 30 min (B) and 50 min (C) of tree growth in #1 (XLPE specimen) 11 kV.

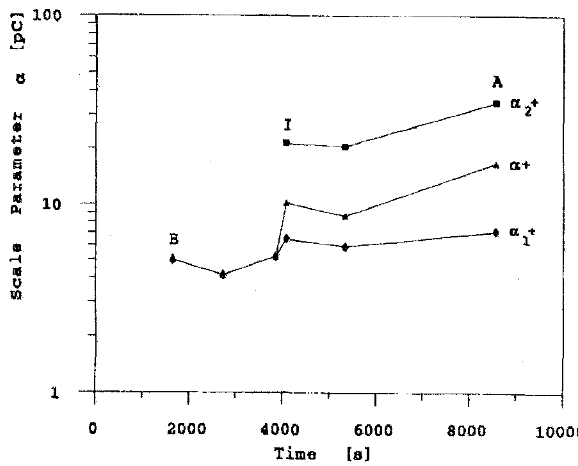

FIGURE 4. Time behavior of α, α_1, α_2 for a test at 6.5 kV performed on specimen #2 of EVA. Times B and A mean before and after tree inception. The inception time (optically established) is indicated by I. Positive discharges.

Figure 2 points out that significant deviation from (1) occur with test time. We can argue that the reason for such a behavior is the appearance of a second population of discharges, likely associated with electrical trees, having amplitudes larger than those occurring in the artificial void. This hypothesis was confirmed by optical observation, which allowed inception of tree to be singled out: after 68 min from the beginning of the test, the presence of an electrical tree was clearly detectable. Resorting to model (2), which can be more properly used to treat this case, the two sub-populations of charge-height data can be separated,

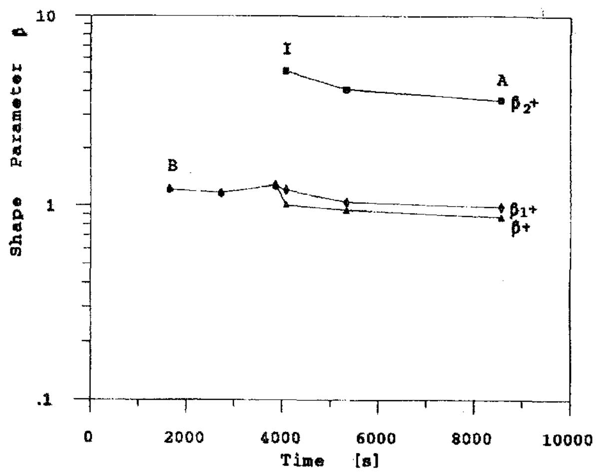

FIGURE 5. Time behavior of β, β_1, β_2 for a test at 6.5 kV performed on specimen #2 of EVA. Times B, I and A are the same as in Figure 4. Positive discharges.

and the parameters of each sub-population, *i.e.* α_1, β_1 and α_2, β_2, can be estimated. This way, the behavior of these parameters with test time can be plotted, resulting in Figures 4 and 5.

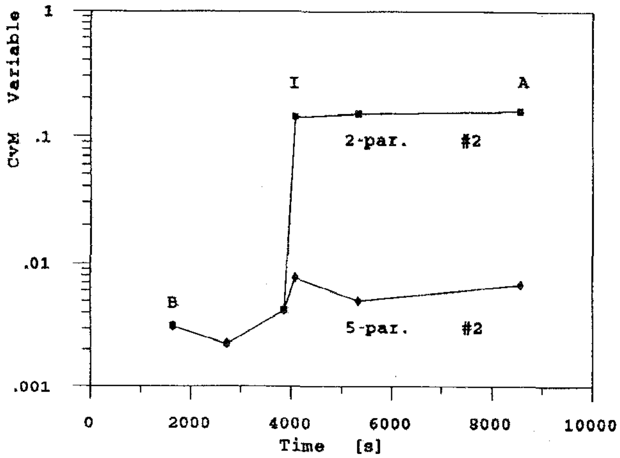

FIGURE 6. Time behavior of the Cramer-von Mises variable, applied to both the two-parameter and the five-parameter Weibull function, for a test at 6.5 kV performed on specimen #2 of EVA. Times B, I and A are the same as in Figure 4. Positive discharges.

The significant feature singled out by these Figures is that there is a steep variation of both scale and shape parameters at the inception of electrical tree (optically established). Before inception α, α_1 and α_2 coincide (the same holds for β, β_1, β_2), since data are processed according to (1). After inception, the CVM variable value calculated on the basis of the 2-parameter Weibull function largely exceeds that obtained from the 5-parameter function (see Figure 6), hence the test supports use of Equation (2). The larger the value of the variable, in fact, the worst the quality of fitting. α_2 and β_2 can be thus estimated, and associated to the appearance of a second sub-population. It is noteworthy that the values of α_2 and β_2 differ considerably from those obtained before inception. Moreover, as electrical tree grows, α_2 increases and β_2 slightly decreases, while α_1 and β_1 do not remarkably differ.

Therefore, an interesting output derives from Weibull processing of PDHD; the tree inception can be detected clearly referring to three diagnostic quantities, *i.e.*, α, β and the CVM variable. This can help in investigation of tree inception in simple insulation systems, even when non-transparent materials are used. Of course, such an intriguing result should not be always expected, since it comes out only when the height of discharges occurring in the cavity and in tree channels are not fully overlapped. However, several tests performed changing size of artificial cavity and voltage have shown that if PD acquisition system sensitivity is high enough, the above-discussed behavior turns out frequently, at most with some delay of the appearance of the second sub-population. In general, before failure, when tree PD activity largely exceeds that occurring in the cavity, data tends to fit again a 2-parameter distribution (Equation (1)). A comparison of this approach with that using PD patterns, [23, 24], has shown that even PD patterns are often able to infer inception of tree [20], but they do not provide objective quantities. On the contrary, α, β and CVM variables can be used in diagnosis, even in conjunction with complex operators such as expert systems or neural networks [25].

The investigation of growth of electrical treeing can be carried out more accurately by a test assembly as #1 (Figure 1). The data reported in the following are relevant to XLPE, but similar results were achieved with EVA (at the above-mentioned test voltage values).

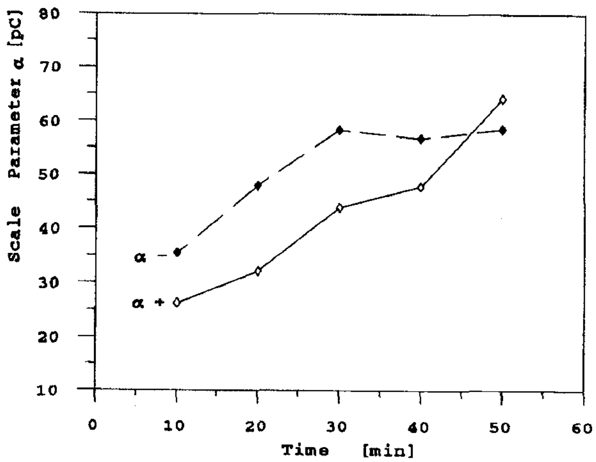

FIGURE 7. Time behavior of α for both positive and negative discharges, obtained from a test performed at 11 kV, the same providing the Weibull plots of Figure 3 (XLPE specimen, arrangement #1).

Figures 7, 8 and 9 show the time behavior of α, β and CVM variable, for both positive and negative discharges, obtained from a test performed at 11 kV, the same providing the Weibull plots of Figure 3. Here, only the 2-parameter Weibull function has been used, since the CVM variable did not indicate any need to resort to the 5-parameter model (Figure 9). Thus, tree growth is associated to PD activity which can fit well model (1). As in the previous case (#2, tree growth, Figures 4, 5), the scale parameter value α increases with time, while β slightly decreases.

The tree shape relevant to growth time of 50 min is displayed in Figure 10. As can be seen, tree shape is clearly bush-like. Optical observations, associated to PD measurements, seem to indicate that the decrease of β with time is associated to increasing activity of streamers departing from tree bush. Considering that the shape parameter of the Weibull

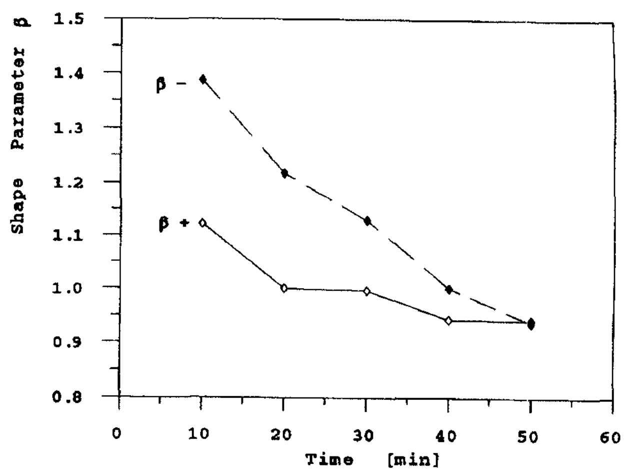

FIGURE 8. Time behavior of β for both positive and negative discharges, relevant to the test conditions of Figure 7.

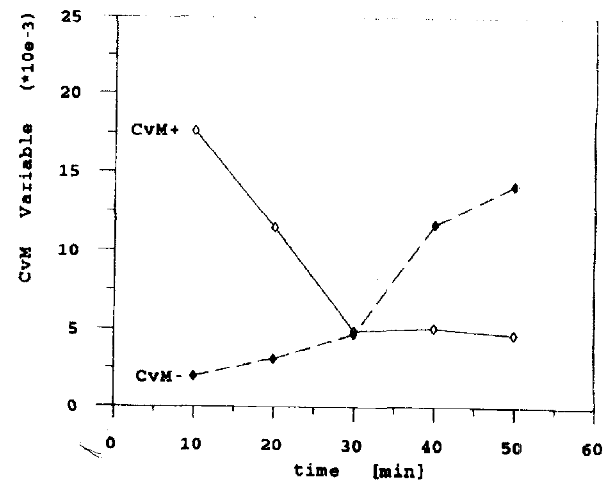

FIGURE 9. Time behavior of Cramer-von Mises variable, applied to Equation (1), for both positive and negative discharges, relevant to the test conditions of Figure 7.

function could be associated to the fractal dimension of tree, [5, 26], we may argue that slight changes of the fractal dimension of tree, which tend to increase dispersion of PDHD, determine small modifications of the shape parameter.

The tests at lower voltage levels generally provided some deviation from the above picture. Both α and β tend to show non-monotone behavior, with slightly-lower values than at HV. The CVM variable becomes larger, thus indicating that fitting to the 2-parameter Weibull function worsen. As an example, Figures 11 to 13 report the time behavior of α, β and CVM, for both positive and negative discharges, for tree a growing at 10 kV.

Again, optical observations indicated explanations for this behavior. It was noted, in fact, that significant changes of tree shape began to occur at 10 kV (on XLPE). One of the three tested specimens, in fact, (Figures 11 to 13) showed clear transition from bush to branch structure. At 9 kV, all specimens produced branched trees. The other two specimens at 10 kV showed behavior of α, β and CVM variable similar to that detected at 11 kV. Thus, 10 kV can be considered a transition voltage, and, indeed,

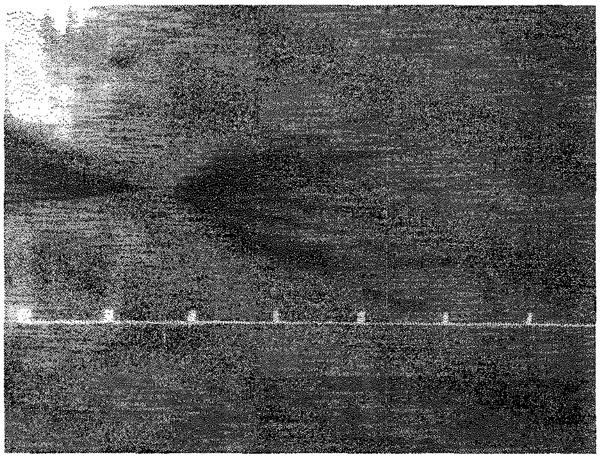

FIGURE 10. Tree shape relevant to growth time of 50 min, corresponding to a Weibull plot of Figure 3. Test conditions of Figure 7. x-scale 0.3 mm/div. The needle and the plane are on the left and the right side of the picture respectively.

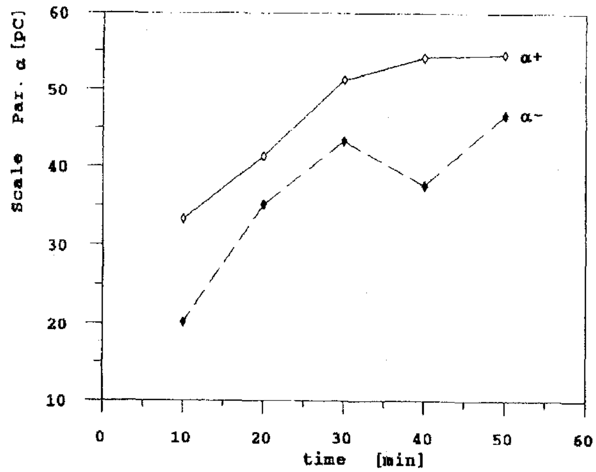

FIGURE 11. Time behavior of α, for positive and negative discharges, obtained from tests performed at 10 kV (XLPE specimen, arrangement #1).

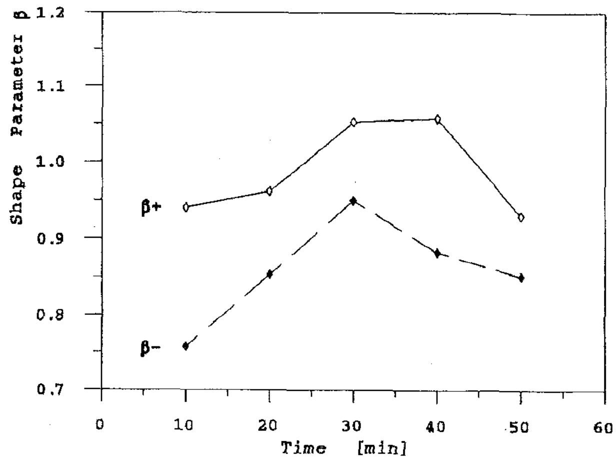

FIGURE 12. Time behavior of β, for positive and negative discharges, obtained from tests performed at 10 kV (XLPE specimen, arrangement #1).

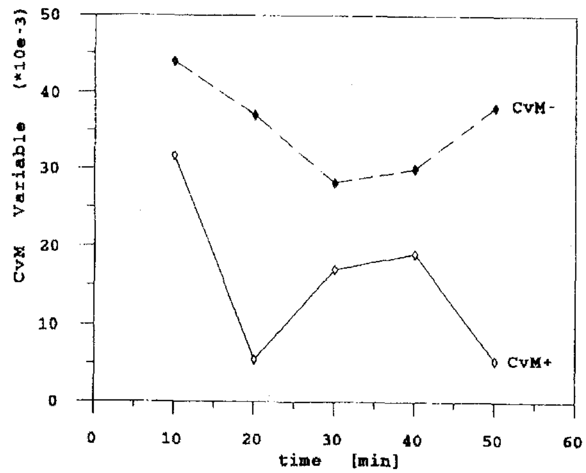

FIGURE 13. Time behavior of Cramer-von Mises variable, applied to Equation (1), for positive and negative discharges, obtained from tests performed at 10 kV (XLPE specimen, arrangement #1).

the breakdown times recorded at this voltage levels were the most scattered among the whole test-voltage set.

On the basis of these observations, it was argued that the time behavior of β is associated to tree-shape changes, and, in particular, to the way of growing of active branches.

Decreasing of test voltage affects remarkably fitting to Equation (1), as it is pointed out by the CVM test (Figure 13) and clearly displayed by Figure 14, where the 2-parameter Weibull plot is reported together with experimental data and the corresponding tree structure (10 kV, same specimen of Figures 11 to 13). As can be seen, the quality of fitting is not as good as at 11 kV, and, on the other hand, tree structure is clearly of branch-type. It was noted that at low voltage (*e.g.* 9 kV), when tree growth is slow and very few branches are simultaneously active (*e.g.* 2 or 3), the number of bends in the line connecting experimental points in Weibull graph was sometimes coincident approximately with the number of branches; this occurs when the active branches provide discharges of amplitude which do not overlap totally.

The change of tree structure also affects the value of, as expected having associated the shape parameter value to the fractal structure of tree. Comparing Figures 14(a) and 10, it can be seen that the fractal dimension of tree considerably changes (decreases from bush to branch), which complies with the values of β displayed in Figure 12, where $0.7 \leqslant \beta \leqslant 1.1$. Moreover, it can be observed that in the case of branch shape the time evolution of α and β varies less than for the bush structure.

It is noteworthy that occurrence of significant deviation from the 2-parameter Weibull function may affect the meaning of β estimates, made according to (1), thus hiding its relationship with physical features.

Concluding, even in the case of tree growth the use of the Weibull function to process PDHD data provides diagnostic indications. These indications are not limited to increase of scale parameter (related to pulse-charge height), which may lead to derive probabilistic life models [5], but also enable inference into tree physics.

The last comment regards the comparison of β values relevant to

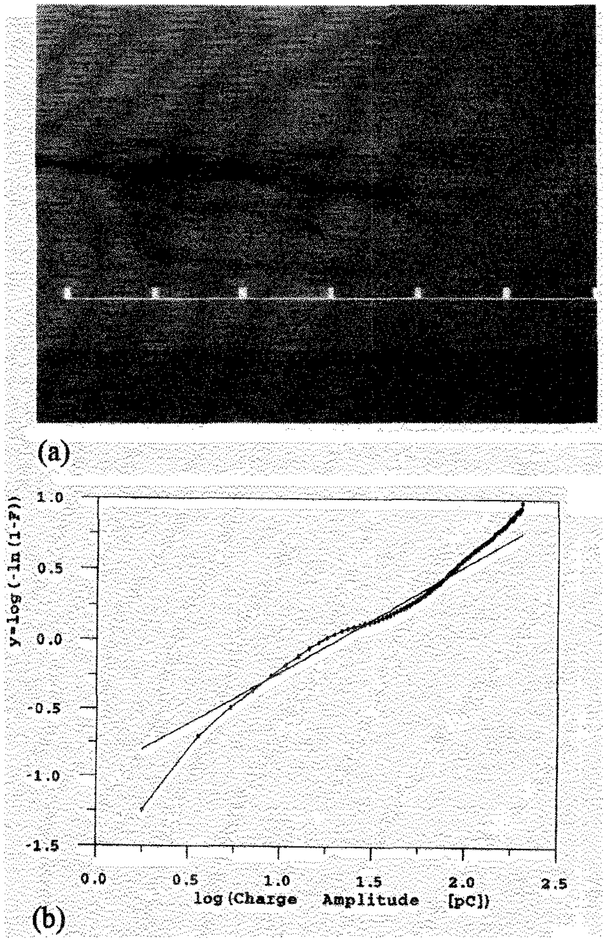

FIGURE 14. Tree shape (A) and corresponding Weibull plot (B) (Equation (1)), positive polarity, relevant to growth time of 10 min, 10 kV, XLPE specimen (the same as in Figures 11 to 13), arrangement #1. x-scale of Figure 14 (A): 0.3 mm/div. The needle and the plane are on the left and the right side of the picture respectively.

tree growth detected by arrangements #1 and #2. As can be seen, looking at Figures 5 and 8, 12, the value of the shape parameter of the sub-population identified with tree growth (*i.e.* β_2) is considerably different from that of β obtained from tree growth tests made by #1, when only the 2-parameter Weibull function is applied. The reason lies in the technique of application of the 5-parameter Weibull function (Equation (2)). When the purpose is diagnosis of the occurrence of a new phenomenon during test time (*e.g.*, inception of treeing), the reference charge amplitude for both sub-populations encompassed by model (2) is unchanged (it coincides with the low level trigger of the adopted instrumentation): this provides the results of Figure 5. If pattern identification is required, the reference for the second sub-population must be turned into its lowest charge height value q_L, which does not generally coincide with that of the first sub-population (this corresponds into the introduction of quantities $(q - q_{L1})$ and $(q - q_{L2})$ in Equation (2), in place of q, for the first and second sub-population, respectively). Applying this procedure, the values of β_2 (Figure 5) are shifted to the range 1 to 1.5, thus very close to those characteristic of tree growth shown in Figures 8 and 12.

5. CONCLUSIONS

THE results here reported give an evidence of the correlation between the parameters of the Weibull function of pulse-charge height and PD activity occurring in cavities and in electrical trees. It has been underlined that this correlations turns into diagnostic tools for tree inception and growth inference, at least in a simple insulation system configurations as that used herein. Moreover, insights into the physics of electrical tree, as regards shape and fractal dimension, can be achieved. This contributes to obtain the amount of information needed for insulation aging and quality inference, which is allowed by the modern instrumentation for PD measurements.

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