Electrical treeing in XLPE insulation in frequency range between 20 and 500 Hz

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Abstract Electrical tree is one of the main reasons for long term degradation of polymeric materials used in high voltage ac applications. In this paper we report an investigation of electrical tree growth characteristics in XLPE samples from a commercial XLPE power cable. Electrical treeing has been grown over a frequency range from 20 Hz to 500 Hz and images were taken using CCD camera without interrupting the application of voltage. The fractal dimension of electric tree is obtained using a simple box-counting technique. Contrary to our expectation it has been found that the fractal dimension prior to the breakdown shows no significant change when frequency of the applied voltage increases. Instead, the frequency accelerates tree growth rate and reduces the time to breakdown. A new approach for investigating the frequency effect on trees has been devised. Besides looking into the fractal analysis of tree as a whole, regions of growth are being sectioned to reveal differences in terms of growth rate, accumulated damage and fractal dimension.

Key Words: electrical tree, fractal dimension, box-counting, variable frequency, growth rate, accumulated damage, partial discharge

INTRODUCTION

Nowadays, XLPE cables are widely chosen for power distribution and transmission lines up to 500 kV owing to its excellent electrical, mechanical and thermal characteristics. Similar to any other insulating materials, its electrical properties deteriorate over the time when it is subjected to electrical stress. Electrical tree is one of the main reasons for long-term degradation of polymeric materials used in high voltage ac applications. Consequently, there have been continuous efforts in last two decades to characterize electrical treeing in XLPE.

Electrical trees in solid insulation were firstly reported by Mason [1]. One of the detailed studies on electrical tree was carried out by Ieda and Nawata [2]. Few aspects were examined and the experimental results concluded that tree extension was induced by internal gas discharge in existing tree channel. The gas discharge was pulsive, lasting less than 0.1μs and the electric potential of a needle electrode was transferred to the tip of an existing tree channel through the conductive plasma of a gas discharge. It was also suggested that frequency only accelerates the growth process by increasing the number of gas discharges but not the nature of each discharge while the magnitude of local electric field at the tip of discharge columns was determined by the applied voltage. Noto and Yoshimura [3] examined polyethylene under various frequencies under ac electrical stress. It was found tree does not follow a linear growth relationship with the frequency. Under various applied voltages, tree exhibits different growth characteristics with various frequencies. The process of tree initiation decreased with increasing voltage and frequency and was assumed to be due to the increase in local electric field at the tip of the discharge column. Densley [4] studied the effects of frequency, voltage, temperature and mechanical stress on the time-to-breakdown (TTB) of XLPE cable insulation subjected to highly divergent field. It was found that trees grow in different shapes and colours at various frequencies and voltages. Tree shape changes at higher frequency which in turn reduces the TTB. TTB are also reduced significantly at higher temperatures and mechanical stress. The measurement of PD also suggested the role of space charges were dominant in determining TTB and the shape of the tree. A comprehensive review of the developments made in the understanding of tree mechanisms was attempted by Dissado [5].

The concept of fractal dimension was firstly introduced to describe the geometrical characteristics of gas discharges by Niemeyer et al [6]. A simple two-dimensional stochastic model producing structures similar to those observed in experimental studies of branching gas discharges was established. Barclay et al [7] later constructed a two-dimensional stochastic model of electrical treeing using fractal analysis and statistical method. It was found that trees with low fractal dimension, D are the most dangerous while trees with high fractal dimension cause more damages to the insulation. Factors which reduce the fractal dimension increases the risk to the system. These include a crossover from bush-type to branch-type trees with higher voltage [4]. Smaller pin-plane spacing was also found to increase the branch density of trees formed

[4], indicating that fractal dimension is determined by the local electric field, which will depend on both the applied voltage and the pin-plane spacing. Cooper and Steven [8] studied the relationship between the fractal dimension of trees in a XLPE resin and its bulk properties for various degrees of cross-linking. It was observed that the post-curing temperature of the resin influences the treeing behavior and the fractal dimension increases with increasing post-curing temperature and degree of cross-linking. Maruyama et al [9] revealed that a higher fractal dimension was resulted from a higher gel content. In the same study, the relation between the tree length and the fractal dimension was also made. It was observed that trees changes from branch-type to dense bush-type with increasing applied voltage and the fractal dimension increases with a stressing voltage of approximately 16 kV, after which it tends to saturate regardless of the increase in tree length. Fuji et al [10] examined the effect of the polarity of applied dc voltage on tree patterns obtained in polymethylmethacrylate samples. The studies pointed out that the fractal dimensions obtained at the two polarities differs and the fractal behavior depends on the local field or the space charge. A better understanding of fractal analysis and dimension applied on tree with various methods, both experimental and computational was done by Kudo [11]. The work estimated the fractal dimension of tree using methods such as box-counting, fractal measure relations, correlation function, distribution function and power spectrum. It was found that there is a difference in fractal dimensions obtained by the different methods and is unclear of the best method for estimating tree patterns. 3-D fractal analysis of real electrical trees had also been developed.

Despite these efforts, a full understanding has not yet achieved due to complexity and various factors that may affect tree initiation and growth. In this paper we intend to investigate the influence of frequency on fractal dimension of electrical trees in XLPE under a fixed applied voltage. Methods for investigating the frequency effect on trees have been devised. Besides looking into the fractal analysis of tree as a whole, regions of growth are being sectioned to bring the study further.

EXPERIMENTAL

Sample and Experimental Setup

Semiconducting layer and conductor of a commercial XLPE cable, having an insulation thickness of 15mm, were removed, leaving only the insulation. Each cable specimen measuring 5mm in lengths was then cut. The steel needle with a tip radius of 5µm was inserted gradually into the specimen to give a tip to earth-plane electrode separation of 2mm± 0.2mm at elevated temperature of between 120-140 °C. The sample was then annealed for approximately 5 minutes to minimize any mechanical stress build up around the pin-plane region before it was cooled down to room temperature. All samples were inspected for the presence of mechanical stress around the pin tip region under polarized light. The samples with the presence of mechanical stress were discarded. Detailed information of preparing samples can be found in our earlier research [12].

The needle-plane specimen was kept in silicone oil cell to control their temperature and to prevent external discharges or flashover. They were subjected to continuous 7kV rms ac electrical stress over a range of frequencies. An average of six samples were tested at each frequency with test frequencies at 20, 50, 100, 300 and 500 Hz. Prior to monitoring the growth of tree, all samples were pre-initiated using a 2kHz, 7kV AC voltage until a small (50-80µm) tree has formed at the tip. Densley [4] considered that once tree has initiated, it would have little or no effect on the subsequent growth of tree. Therefore, the pre-initiation will have limited effect on the result. A CCD camera (JVC TK1380) which is of sufficient sensitivity to measure the spatial distribution of tree channel was then used to monitor electrical treeing optically during stressing. The skeletal structure of the tree will be monitored by back lighting the sample with a projection lamp.

Images of evolving tree structures were captured periodically until the tree spanned approximately 90% of the pin-plane spacing. At this point, the test was terminated to protect both the external circuitry and the tree from damage in the event of a breakdown. The optical bench microscope was adjusted to a standard magnification level during all stages of tree growth so as to minimize errors due to the influence of magnification. The captured image was processed on the KS400 system (Carl Zeiss Vision). After that, the fractal dimension was computed with box-counting method.

CALCULATION OF FRACTAL DIMENSION

Image Acquisition and Segmentation

A high quality original image is an essential condition for accurate data analysis. The digitised image can be presented as binary, skeletonized or border-only image depending on the fractal dimension method used. It must also allow a clear distinction between the tree and the background, either by greyscale or by colours; to allow a simple thresholding operation. Thresholding provides an easy and convenient way to perform simple segmentation, an operation transforming digitised image into binary image required for data extraction; on the basis of the different intensities or colours in the foreground and background regions of an image. In the simplest implementation, the output is a binary image representing the segmentation. By looking at the image intensity histogram, the appropriate segmentation technique can be determined.

Image Analysis and Measurement of Fractal Dimensions

For automatic image analysis, the software-based imaging system KS400 was used. KS400 allows the development of application-specific macros which enables one to include all necessary functions in a single given application, i.e. image acquisition, calibration, processing, measurement and data output.

Box Counting Method

To estimate the box-counting fractal dimension, D_b, the Euclidean space containing the tree is divided into a grid of boxes of size ε, with the initial box size being 1.3 times of the tree. Box size ε is then made progressively smaller and the corresponding number of boxes, N, covering any part of the tree is counted. The sequence of box sizes for grids is usually reduced by a factor of half from one grid to the next. The count depends on box size ε and D_b according to Eqn. (1),

$$N(\varepsilon) \propto \varepsilon^{D_b} \qquad (1)$$

Thus, for fractal structure a double-logarithmic plot yields a straight line whose gradient corresponds to D_b,

$$\log N(\varepsilon) = D_b \log(\varepsilon) + c \qquad (2)$$

where c is a constant.

This method is drudgery if done manually considering the time and effort required to obtain the fractal dimension. But the merit is simplicity, allowing one to estimate the fractal dimension intuitively. The box-counting method was chosen in this study.

Data Processing

The fractal dimension, D, may vary depending how it is obtained from the double-logarithmic plot. In such a plot, D is related to the slope of the line, the number of data points being related to the number of measuring steps. The actual data points generally do not lie on a straight line, thus showing limited self-similarity or scale invariance which is a characteristic of nature object. Measured fractal dimensions can only be compared if this influence is excluded either by specifying a lower and upper limit for the linear regression or by introducing other criteria, such as defining a level of confidence in the R-squared value. It is an indicator from 0 (worst) to 1 (best) that reveals how closely the estimated values for the trend line correspond to the actual data. By applying the limits, certain data points will be selectively rejected as long as the linear regression of the remaining data improved the R-squared value.

EXPERIMENTAL RESULTS

Growth Rate and Accumulated Damage

Two methods were used to analyse tree growth from a sequence of images captured periodically as tree grew from the tip to the earth-plane electrode. In the first method, arc of radii from an origin at the tip is drawn and the maximum tree extent from the tip is measured. The differences in tree length and time between photographs are used to compute a growth rate:

$$Growth \quad rate \quad (mm/\min) = \frac{Max.Extent2 \quad - \quad Max.Extent1}{Time2 \quad - \quad Time1}$$

The other method is a measure of the effective accumulated damages done which is computed using KS400 after a series of image processing were made on the captured images. The area is estimated by extracting the total number of pixels covering the tree. Each pixel is approximately to have an area of 4.255µm x 4.255µm. The two methods can effectively describe the spatial and temporal development of tree growth.

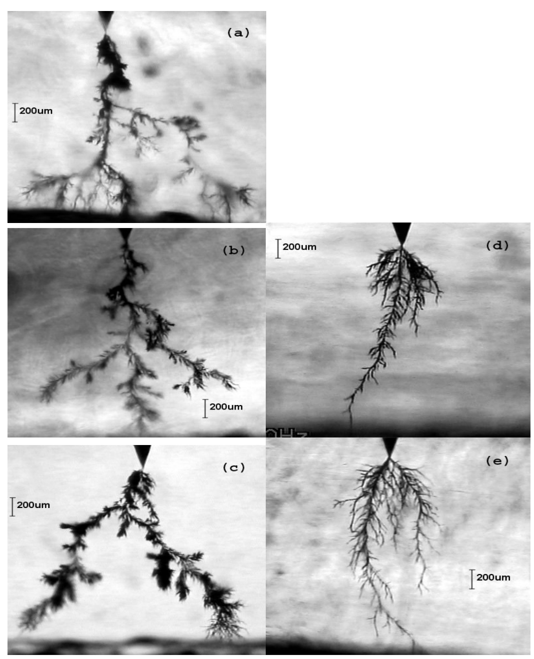

Figure 1 Captured photographs of tree growth for the XLPE cable samples prior to breakdown (a) 20Hz, (b) 50Hz, (c) 100Hz, (d) 300Hz and (e) 500Hz

Images of the trees for various frequencies taken prior to breakdown are shown in Figure 1. They were stressed continuously at 7 kV rms and images were captured during tree growth and each image was separated analysed to estimate the various parameters such as growth rate and accumulated damage. Scattering did exist within six samples tested for each frequency and data are only presented from reproducible trees. The selected results from 20 Hz, 50 Hz and 500 Hz are reported here to limit the length of the paper as the results from 100 Hz and 300 Hz are similar to those from 50 Hz and 300 Hz, respectively.

Figure 2 illustrates the growth rate and accumulated damage versus the pin-plane distance at 20 Hz.

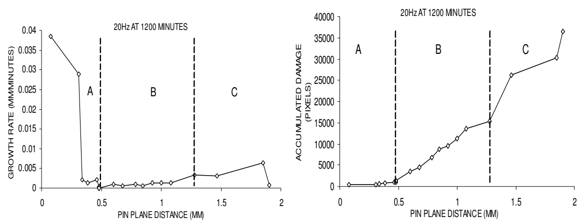

Figure 2 Accumulated damage and growth rate as a function of pin-plane distance showing the three regions A, B and C of tree growth.

It can be seen that during the initial growth stage, the tree displayed some rapid growth out to some 300µm from the pin tip in 10 minutes. It exhibited a high growth rate during that period but slowed down as tree extended away from the tip. Branching was concentrated, extending to some 500µm and discernible damages were seen. The growth rate has dropped significantly as growth continued. Slow growth continues to be observed until the tree had advanced past 50% of the pin-plane distance followed by an increase in growth rate. At around 1200µm, growth rate increased further and multiple branches were formed. It can be seen from the increased in accumulated damage. This latter region has often been identified as 'runaway' growth by many authors.

The accumulated damage (number of pixels) versus the tree length across the pin-plane spacing shows a general increase. Together with the growth rate, it suggests that tree actually exhibits three distinct growth regions. In region A, initial rapid filamentary tree growth occurs. Here the rate of damage with distance increases, with multiple branches being formed. Densely branching may also occurs near the pin tip. This is followed by an intermediate region B, in which low growth rate is observed. Finally, a region C occurs (the 'runaway' region), in which a large amount of damage per unit radial extent reflects the large increase in tree branching that occurs. In this region, it is also observed that the growth rate increases as leading branches extend towards the earth plane.

Figure 3 illustrates the growth rate and accumulated damage versus the pin-plane distance at 50 Hz.

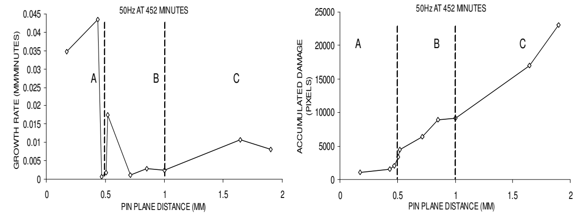

Figure 3 Accumulated damage and growth rate as a function of pin-plane distance showing the three regions A, B and C of tree growth.

Samples stressed continuously with frequency at 50Hz revealed that tree shape remains branch-type without significant changes to its shape. The tree exhibited a very rapid growth, extending up to some 500µm in the first 12 minutes. It can be seen from the high growth rate occurring in this region. After this initial growth, there was a long period of quiescence where there was very little or no significant growth from the leading branches. Accumulated damage versus the distance shows constant tree damage with length. During this period, partial discharge activities were known to be pre-dominant within the side-branches and channels which were lengthened and thickened in size. This observation can be further reinforced from Figure 3 that the tree had stop extending but the number of pixels actually shown an increment in value. Subsequently, tree growth accelerated again after it had spanned past the 50% spacing.

Tree formed near the origin with a rapid growth was observed in the first 5 minutes at 500Hz test as shown in Figure 4. There was a lessening in growth after initial activity with growth rate comparable to those observed at low frequency. Large accumulated damage occurred near the origin followed by one or two leading branches extending outward till breakdown. Tree growth can be spit into two regions with A-C transition occurs at 1400±100µm. In region C, the leading branch takes less than 10 minutes to breakdown, influenced by the high growth rate.

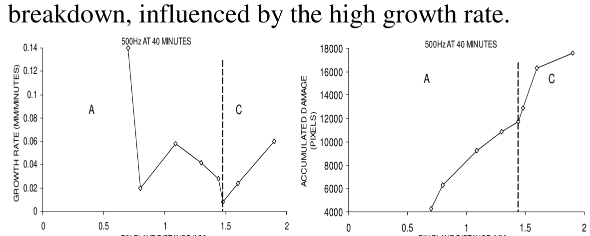

Figure 4 Accumulated damage and growth rate as a function of pin-plane distance showing the two regions A and C of tree growth.

DISCUSSION

Growth Characteristics

While the success of the growth rate and accumulated damage methods may have provided the study of tree growth into regions, the methods are not easily incorporated into other models found in the literature such as the field driven tree growth (FDTG) model [13]. Growth rate computed by taking the maximum radial extent of the tree is found that the leading branch taken as the largest extent may stop growing for some time while other side branches from the origin continue to grow. This method may be ineffective in taking account of growth occurring at other branches with shorter radial extent. Therefore, the accumulated damage method was devised to look into the spatial development of tree more accurately.

From analyses, tree exhibits two or more regions of growth and the fractal dimension in each region is dissimilar. Thus the variation in local field E_L may have the effect of affecting the fractal dimension. It is believed there are some variances in E_L instead of equaling in magnitude in both regions since the fractal dimensions are different, which is thought to be affected by E_L. The difference in growth duration at each region can further reinforce this analysis.

It is also noted that tree exhibits same type of growth characteristic with high initial growth rate follows by a period of quiescence (for tree with two growth regions), then a 'runaway' region. The initial high growth may be attributed by the field enhancement near the pin tip. With tree approaching the earth-plane electrode, field is once again enhanced. Other explanations may be given for this behavior such as image charges intensifying the local field on approaching the plane electrode [14].

Frequency-Dependent Tree Breakdown

Trees shown in Figure 1 (a to c) are often known as 'monkey puzzle' (MP) tree [13]. It is in the last two regions that tree takes on the appearance of a MP tree. This type of structure is an open structure on the macroscopic level with microscopic secondary branching existing along the length of each main tree channel, the branch structure having a hairy spider's leg appearance. It is known to grow with stressing voltage at low voltage [13]. At increasingly higher stressing frequency, MP tree is not featured as branch density dropped. At higher frequency, tree extends faster through fine filamentary branches. This type of behaviour has been reported to occur [3].

Fractal Dimension--- Regions A, B and C

The fractal nature of tree is demonstrated by the consistency of the fractal dimension estimates obtained. Disregarding the very small trees grew initially; value of 1.55 to 1.71 is always obtained for five frequencies tested without a clear trend. It tends to saturate in this range as trees were of branch-type. Thus, there is no significant change to the fractal dimension. This branch-type characteristic has been shown to produce under a stressing voltage of 7 kV [3]. Kudo [11] performed a fractal analysis on the photographs of the branch trees (Figure 9 of [3]), which were stressed at 7 kV, has an estimated fractal dimension of around 1.6. This value coincides closely with data here.

As fractal dimension for different frequencies varies randomly from 1.55 to 1.71, it is difficult to draw any inference. On the other hand, there are different stages during tree growth, it would be interesting to look at the fractal dimension in each region. Images were sectioned into three regions using the approximated transition zone and the fractal dimension of each region was computed using the KS400 system as shown in Table 1.

Table 1 Fractal dimension of tree growth in different regions.

Frequency (Hz)	Region A	Region B	Region C
20	1.79	1.71	1.70
50	1.69	1.71	1.64
100	1.70	1.63	1.66
300	1.68	-	1.59
500	1.66	-	1.54

It can be seen that the value of fractal dimension in region A is always higher than C for all the frequencies. In region C, tree only constitutes of a few leading branches to form the complete breakdown path, resulting in a lower fractal dimension than in region A. At frequency of above 300Hz, fewer branches were formed, leading to a lower fractal dimension than at lower frequency.

Accumulated Damage – Regions A, B and C

The devised accumulated damage method was also applied to the different regions similar to that of fractal analysis and the results are shown in Table 2.

More accumulated damages appear to have been done to region A at higher frequency. This is due to a larger region exhibited from the tests and a higher branching density near the tip. In the same region, the branch density is higher with finer filamentary branches spreading at a wider arc angle from the tip. At lower frequency, thicker branches were densely packed together resulting in a solidly filled structure and the branching is concentrated with only one or two such branches present.

Table 2 Number of pixels accumulated in different growth regions.

Frequency (Hz)	Region A	Region B	Region C
20	3303	11230	23864
50	3625	6930	16925
100	5126	5148	13331
300	11842	-	2073
500	17539	-	1797

In region C, only a few runaway branches leading to breakdown at higher frequency are formed, giving lower damages. Tree growth occurs at all tree tips at low frequency lead to tree structures in these region having a higher branching density than in region B, resulting in higher damages made.

CONCLUSION

Tree growth under the influence of frequency is not able to infer much with fractal dimension due to the similar branch-type structure formed. Instead, it is found to have accelerated the breakdown process with higher frequency leading to a faster breakdown. This could be due to the higher number of partial discharges at higher frequency. Fractal dimension is thus thought to be influenced primarily by the magnitude of stressing voltage as frequently discussed in the literature.

Further analyses were made and by using the devised approaches, tree growth can be sectioned into two or three regions depending on the frequency applied. At low frequency, three regions are present in the growth process while there are only two at higher frequency. The first is region A, where high growth rate is exhibited in which filamentary tree growth occurs at the pin tip. Next is region B in which tree growth is slowed and the fractal dimension is lower than in region A. Lastly in region C, growth rate picks up with an increase in branch density and decrease in accumulated damage as tree extends towards the earth-plane electrode. Again, the fractal dimension is lower than in region A. Therefore, the regions analyses suggest that the time-to-breakdown is primarily influenced by the fractal dimension in region A and the amount of tree damage in region C.

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