International Journal of the Physical Sciences Vol. 7(1), pp. 132 - 138, 2 January, 2012
Available online at http://www.academicjournals.org/IJPS
DOI: 10.5897/IJPS11.917
ISSN 1992-1950 ©2012 Academic Journals

Full Length Research Paper

Investigation of electrical treeing in cable grade crosslinked polyethylene (XLPE) insulations

M. I. Qureshi*, N. H. Malik and A. A. Al-Arainy

College of Engineering, King Saud University, Riyadh, Saudi Arabia.

Accepted 5 December, 2011

Using PC-based on-line monitoring system, extensive measurements were performed in insulation blocks cut from the crosslinked polyethylene (XLPE) insulation of 36, 69 and 132 kV rated cables produced in Saudi Arabia. A needle-plane electrode system was used with a needle radius of 10 μm. The role of 'applied voltage step-time duration' and associated time resolved initiation and growth of different types of tree structures were evaluated. Results show that a step of 3 kV/10 min duration provides good comparison to evaluate service aged and new XLPE insulation of different voltage ratings. Velocity of propagation of electrical trees is fast at initiation, but declines exponentially to a constant rate within 20 s of its initiation. Fractal analysis of such trees was also carried out using different types of technical grade XLPE insulations. This paper presents discussion on these results and sheds light on the electrical treeing phenomenon.

Key words: Electrical treeing, crosslinked polyethylene (XLPE) insulation, on-line monitoring, bush-type tree, branch-type tree, new and aged cable insulation, fractal analysis.

INTRODUCTION

The high voltage crosslinked polyethylene (XLPE) insulated polymeric cables play an important role in the transmission and distribution of electric power in bulk to load centers. The long term dielectric integrity of this type of insulation is influenced by the material used and the design parameters adopted. Electrical treeing is particularly important for high voltage cables. The degradation process in XLPE due to electrical treeing occurs in two district phases, that is, inception phase, where a microvoid is formed at or in the vicinity of region of high electric stress, followed by a growth phase, in which an array of filamentry channels is formed in the insulation matrix as a result of partial discharge (PD) activity. Initiation of electrical treeing requires a minimum electrical stress and a certain characteristic time, known as incubation period, after AC voltage application. During the incubation period, charge carriers move back and forth repeatedly between the electrodes and the stressed dielectric, and this repeated charge transfer is believed to be mainly responsible for the treeing initiation. Treeing inception is characterized by the incubation time, which is the time required for generating an observable tree (usually about 10 μm in length). This time is strongly dependent on electrical field strength and is inversely proportional to the frequency under AC stress. After a tree is initiated, detectable partial discharges will occur, which can result in tree growth and the ultimate breakdown of the dielectric.

The high electrical stress necessary for tree generation occurs, generally, due to defects formed during production, installation as well as during its operation. Experimental studies on electrical treeing behavior of XLPE have led to different theoretical aspects of treeing initiation mechanisms as discussed (Du et al., 2011; Gulski et al., 2008; Ling et al., 2008; Malik et al., 2005; Osawa et al., 1997; Zhou et al., 2010). The growth of trees depends upon voltage magnitude, type of applied voltage and test geometry, frequency, space charges, material morphology temperature, additives and crosslinking and other factors (Chapman, 2001; Chen and Tham, 2009; Dodd et al., 2003; Du et al., 2011; Dissado and Fothergill, 1992; Fothergill et al., 1994; Kim, 2001; Samee et al., 2009; Shimizu and Laurent, 1998). After initiation, the tree growth proceeds by a series of sporadic bursts of activity.

*Corresponding author. E-mail: mqureshi1@KSU.EDU.SA.

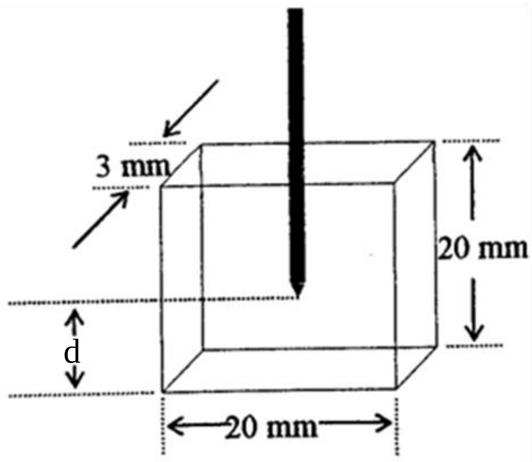

Figure 1. Test sample.

Subsequent to the formation of the first branch, tree growth restarts as two new branches are added to the tip. Thus, the inactive periods can be associated with the initiation of the tip splitting process. Once a number of branches have been formed, it is possible for some to keep growing, while others are inactive; this behavior may continue right up to the runway stage, where the tree continuously grows, leading to a breakdown for branch and bush-type trees. However, in some cases, an extended period of slow growth occurs prior to the runway stage. Consequently, tree branching becomes more frequent and rate of tree growth slows down. Two of the most important factors which influence tree propagation rate are the development of internal gas pressure due to PDs and the shielding effect of adjacent tree branches on the resulting electric field.

The principal objective of this paper is to study the factors governing electrical treeing in XLPE insulation blocks and also to find out the most suitable method of voltage application so that different cable materials can be compared in a short time. This has been achieved using the on-line monitoring of the initiation and growth of electrical trees. The factors examined experimentally include, effect of initial voltage applied, voltage and the time steps used and new and in service aged XLPE insulation materials taken from high voltage cables of different voltage ratings.

EXPERIMENTAL SET-UP AND PROCEDURES

The XLPE cable's insulation was cut first into blocks of 20 $\times$ 20 $\times$ 3 mm. 'Agura' steel needles of 10 μm tip radius were carefully inserted in these blocks at the middle of 20 $\times$ 3 mm side to form point-plane geometry with a specified gap distance (d). The face opposite to the needle was painted with silver conductive paint. Figure 1 illustrates the dimensions of the finally prepared sample.

A test cell was designed and fabricated to accommodate the test sample and the high voltage electrodes. The aim was to facilitate the capture of real time image of the tree at its initiation and during its growth. The cell was filled with silicone oil to avoid discharges on the sample's surface. The optical system consists of a variable intensity light source, a wave guide, a microscope and a digital camera arranged in a vertical format, while the test sample was kept horizontal on a transparent glass platform. This arrangement is as shown in Figure 2. The camera output was fed to computer for image storage, retrieval and analysis. Figure 3 shows the block diagram of the experimental set up.

The high voltage source used was a 30 kV_{rms} PD free transformer. Each experiment was started by applying a voltage ramp of up to 7.22 kV_{rms} which corresponds to a stress of about 184 kV_{rms}/mm at the needle tip. At this stage, the voltage was increased by specified time, that is, fixed voltage increments (ΔV). After each increment, the voltage was kept constant for fixed time duration (Δt).

RESULTS AND DISCUSSION

Bush-tree versus branch-tree

After the completion of incubation period, a small filament appears at the needle tip which leads to further tree growth. Depending upon the applied stress values, the tree can become bush type or branch type. It was found that the branch-type tree initiates at lower stress values as compared to the bush-type tree. Similar character of tree initiation was reported earlier (Malik et al., 2005). However, the incubation time for branch-type tree is longer than that of bush-type tree. The high stress application in the case of bush-type tree causes an increased rate of deterioration of the insulation at the needle tip. Such an increased rate causes a reduction in the incubation time for the formation of the initial tree channel. Figures 4 and 5 show two (branched and bush-type) trees at initiation and during propagation states.

Effect of the voltage step

Tree length is influenced by the stress applied as well as its total duration which depends on ΔV and Δt used. It is reported in literature (Ishibashi et al., 1998; and Malik et al., 2005) and also found in the present experiments that treeing inception stress (E_i) varies in the range of ~250 to ~500 kV/mm. Beside the morphology of the insulation, the mode of the voltage application is perhaps the dominating factor affecting E_i. To examine this aspect, experiments were repeated using several types of XLPE insulations. For each type of insulation, more than three samples were subjected to tests to get an average value.

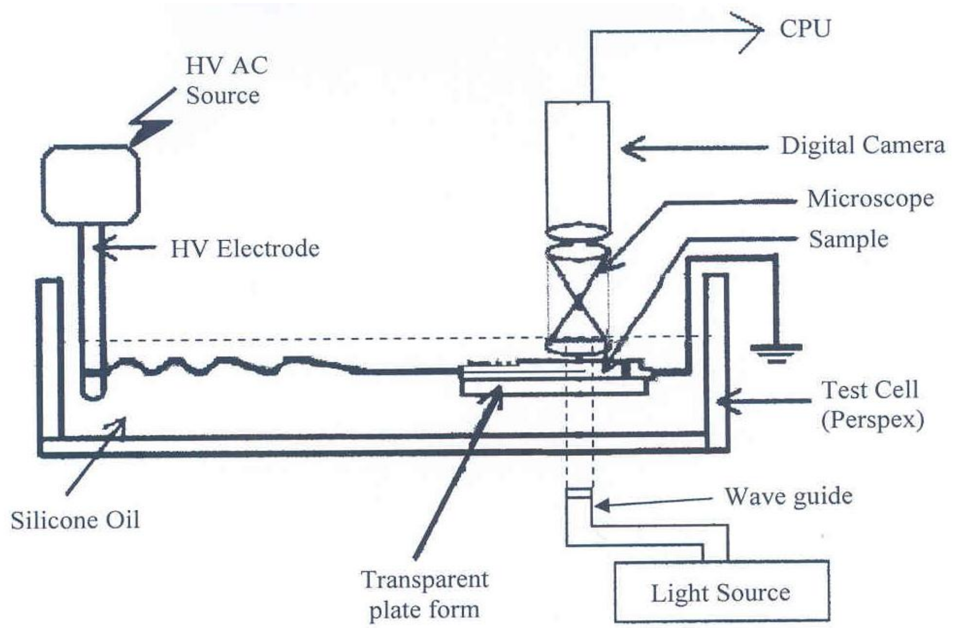

Figure 2. Arrangement of specimen in test cell and optical imaging system.

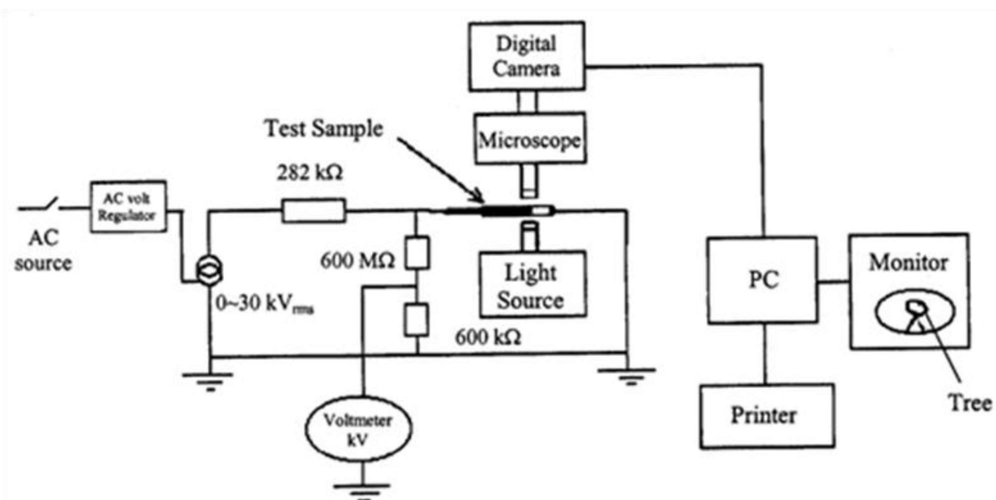

Figure 3. Block diagram of experimental set-up for real time acquisition of electrical treeing characteristics.

Table 1 summarizes the variation of different parameters related to electrical treeing in several new and aged (36 kV, XLPE cable) samples tested. Here, T_i is the incubation time and V_i is the inception voltage for treeing inception. E_i corresponds to the Laplacian inception stress at the needle tip. Bush type trees appear when subjected under E_i values $\geq$ 400 kV_{rms}/mm, whereas the branch (filamentary)-type trees emerge at E_i $\leq$ 300 kV_{rms}/mm, while branched-bush tree structures appear in a stress range of 330 to 390 kV_{rms}/mm. These values apply equally to aged as well as new 36 kV cable insulations, and are almost the same as that found for 69 and 132 kV rated cable insulations.

Comparison of different insulations

Figure 6 compares the tree length as a function of time for five types of XLPE cable insulation tested. The value of gap spacing is ~5 mm, while the application of stress

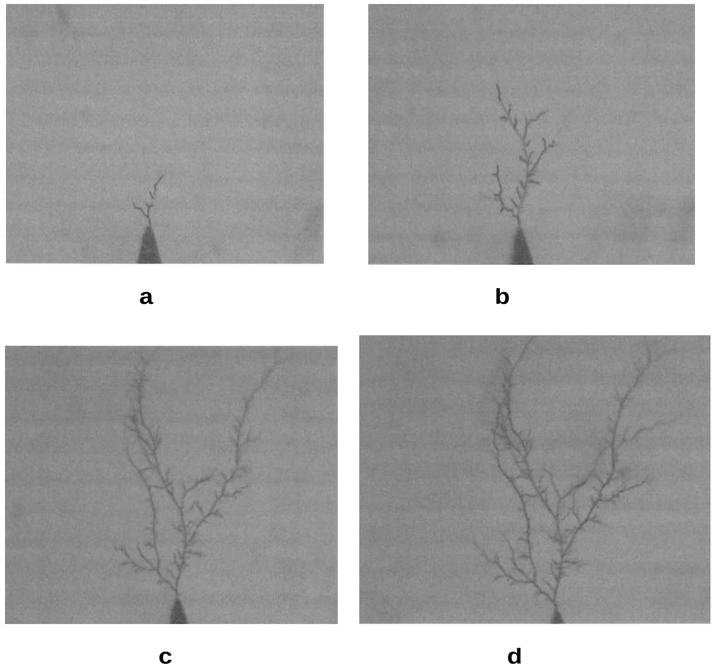

Figure 4. Branch type electrical tree growth: (a) L_m = 60 μm, t = 2 s; (b) L_m = 500 μm, t = 7 s; (c) L_m = 670 μm, t = 15 s; and (d) L_m = 780 μm, t = 25 s. Applied voltage = 12 kV. L_m = Maximum axial tree length.

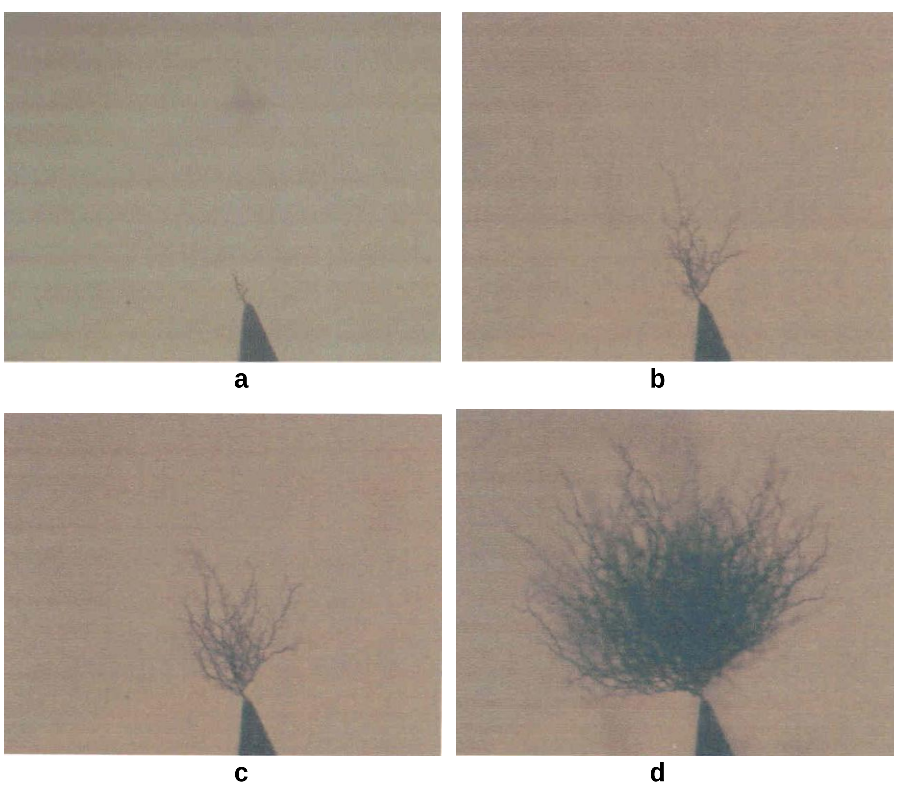

Figure 5. Bush type electrical tree growth: (a) L_m = 18 μm, t = 1.0 s; (b) L_m = 374 μm, t = 12 s; (c) L_m = 415 μm, t = 32 s; and (d) L_m = 747 μm, t = 50 s. Applied voltage = 15 kV, d = 5 mm.

Table 1. Variation of different parameters related to treeing in insulation samples.

Sample No.	D (mm)	T_i (min:s)	$\Delta V/\Delta t$ (kV/min)	V_i (kV)	E_i (kV/mm)	Type of tree
A_1	6	32:00	3/10	16	409	Bush
A_2	6	42:00	1.5/5	19	483	Bush
A_3	4	50:18	1.0/15	11	294	Branch
N_1	5	31:08	3/10	16	411	Bush
N_2	5	23:27	1.5/5	3	336	Branch-Bush
N_3	4	106:50	1.0/15	15	390	Branch-Bush

A = Aged 36 kV cable insulation, N = new 36 kV cable insulation.

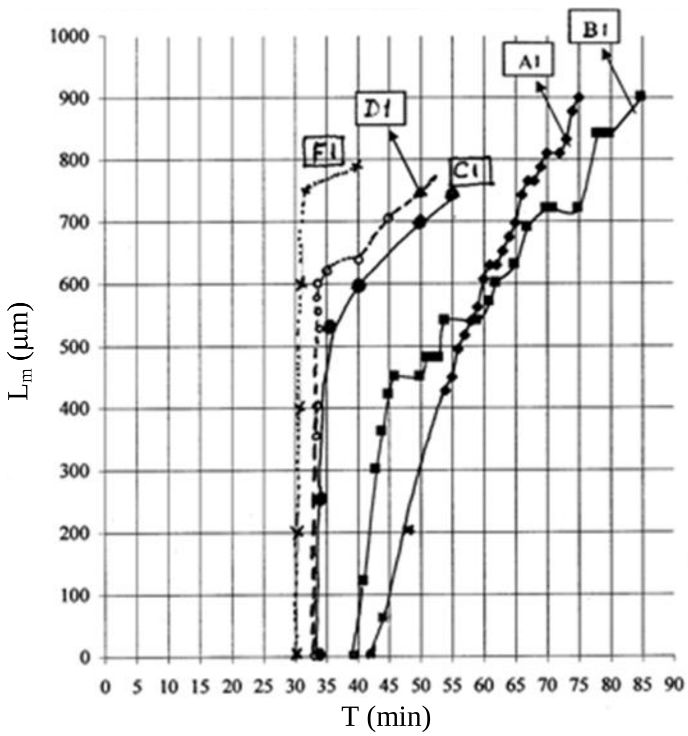

Figure 6. Tree length with time for different types of new XLPE insulation. ΔV = 3 kV, Δt = 10 min, d = 5 mm.

was controlled by a ($\Delta V/\Delta t$) step of 3 kV/10 min in all cases. It is clear that 132 kV cable insulation performs better than 69 and 36 kV cable insulations, both in the sense of incubation period, tree length as well as the tree inception voltage. Here,

A_i = 132 kV, XLPE insulation from manufacturer A.
B_i = 132 kV, XLPE insulation from manufacturer B.
C_i = 69 kV, XLPE insulation from manufacturer A.
D_i = XLPE, 2 h cured, from local pallet manufacturer.
F_i = 36 kV, XLPE insulation from manufacturer A.

where i = sample number from same insulation.

Figure 7 illustrates tree growth rate versus time for six insulation samples. It is clear that initially, the tree propagates with a relatively larger rate which retards with the passage of time as the tree traverses toward the opposite electrode. For the investigated XLPE insulations, after a time lapse of about 20 s, the tree growth rate becomes slow and attains almost a constant value. It further shows that, in the first 20 s after initiation, the tree growth rate is field dependent, while after this time period, it becomes space charge limited and almost constant which verifies the self limiting growth behavior of electrical trees (Dissado and Fothergill, 1992).

Fractal behavior of electrical trees

The electrical trees are highly branched structures, which

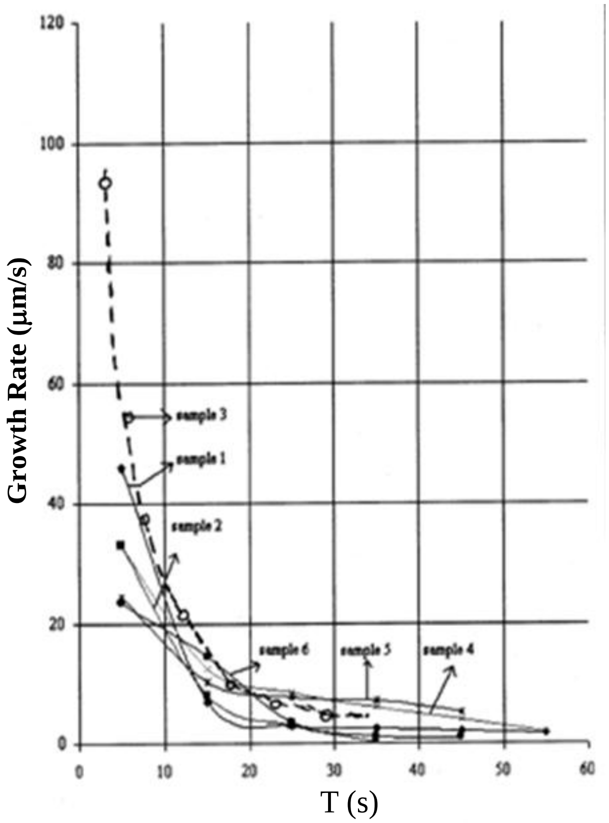

Figure 7. Average tree growth rate in 6 samples of type # D insulation during the first minute after treeing initiation.

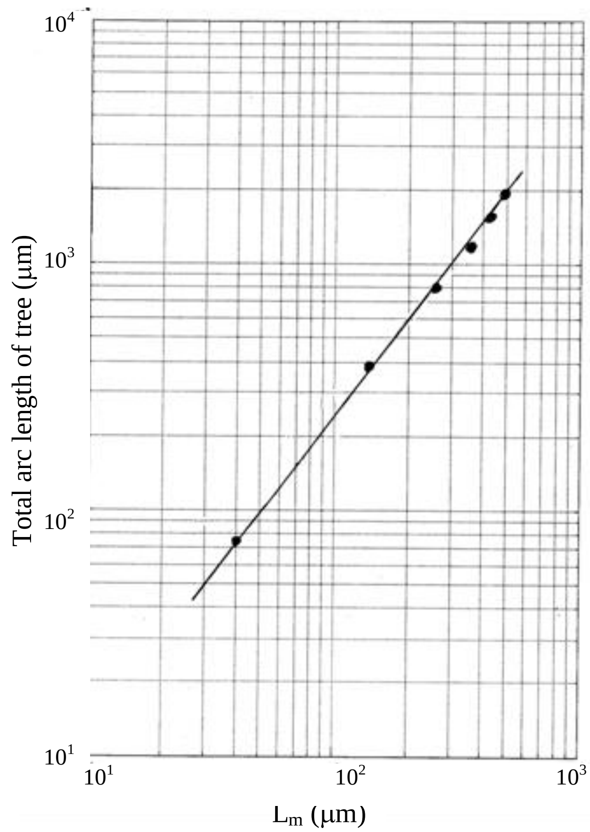

Figure 8. The variation of total arc length of branch elements with the maximum axial length of branch-type tree for two samples.

are often considered as fractal objects. The degree to which such objects fill the space is characterized by a fractal dimension, which provides a measure of the branch density of the tree. This parameter is therefore important in relation to the length of the tree and to the volume of material damage that has occurred. Models have been proposed in the literature (David, 1995; Dissado and Fothergill, 1992) which suggest that the arc length of each branch (Si) summed over all branches within axial length (L) is related as:

$$S_t = (\Sigma\ Si) \propto L^{df} \qquad (1)$$

where (d_f) is the fractal dimension.

Tree growth in polyethylene under power frequency voltage has been found to show the fractal dimension as d_f = (1.6 – 1.7) for branch-type trees, while it is (2.4 – 2.6) for bush-type trees (Dissado and Fothergill, 1992). In some binary-mixtures of polyethylene, values of d_f = 1.3 have also been reported for Branch type trees, whereas in case of bush-type trees d_f was found to exceed 2.0 (Dodd et al., 2003).

The tree parameters for several samples of insulation tested here were evaluated for determining d_f. For this purpose, 2-D patterns of the branch-type electrical trees were subjected to the fractal analysis. Figure 8, for instance, illustrates the variation of total arc length of tree branches as a function of axial growth length (L_m) for two samples. The data fits well on the log-log plot. The slope of the curve gives d_f = 1.18. Similarly, it was found that relation between L_m and the total number of alternating pulses of applied voltage fit well on log-log plot (not shown here). From such a plot, the reciprocal of the slope of the curve (= d_f) is equal to 1.2 and is almost the same as obtained with ΣS_t versus L_m. The value of d_f is therefore confirmed by two different ways, but is less than the value (1.6 – 1.7) reported in literature for polyethylene (Dissado and Fothergill, 1992). XLPE is a more complex matrix than polyethylene (PE). Moreover, its melting point is ~ 106°C as compared to 70 °C for PE. The fractal effect of the Maxwell's forces due to the applied field is more severe on PE than XLPE. Perhaps this is the reason that the branch density in PE is higher than that in XLPE insulation.

Conclusions

The following conclusions can be drawn from this study.

1. Using 10 μm defect size, stress of around (280 to 510) kV_{rms}/mm is required to initiate tree in ≤ 1 h in XLPE insulation blocks investigated in this work.
2. The values of voltage step ΔV and time step Δt at each voltage level control the type of tree. If ΔV is kept small and Δt large, then branch-type trees are initiated. However, if ΔV is increased and Δt is decreased, bush-type tree results.
3. During the initial 1 min after a tree's inception, the tree growth rate decreases in an almost exponential manner and approaches to a constant value.
4. Electrical trees are fractal objects and the fractal dimension (d_f) is determined for several types of insulations. It shows that d_f can be a useful tool for comparison of different types of insulations.

ACKNOWLEDGEMENT

The support provided by the Research Center, College of Engineering and Deanship of Scientific Research, King Saud University is thankfully acknowledged.

REFERENCES

Chapman JV (2001). Morphology and Growth of Electrical Trees in Propylene / Ethylene Copolymer. IEEE Trans. Dielectr. Electr. Insul., 8: 284-292.

Chen G, Tham C (2009). Electrical Treeing Characteristics in XLPE Power Cable Insulation in Frequency Range Between 20 and 500 Hz. IEEE Trans. Dielectr. Electr. Insul., 16(1): 179-188.

David E (1995). Comparison between Experimental Results and Fractal Growth Model for Electrical Treeing in Polyethylene. Proceedings of the 1995 IEEE 5th International Conference on Conduction and Breakdown in Solid Dielectrics, pp. 199-203.

Dissado LA, Fothergill JC (1992). Electrical Degradation and Breakdown in Polymers. Peter Peregrines Ltd. U.K, pp. 117-140.

Dodd SJ, Champion JV, Zhao Y, Vaughan AS, Sutton SJ, Swingler SG, (2003). Influence of Morphology on Electrical Treeing in Polyethylene blends. IEE Proceedings Science, Measurement Technol., 150(2): 58-64.

Du BX, Han T, Gao Y, Zhu XH (2011). Dependence of Electrical Treeing Behavior on Cross-Linking Temperature of XLPE. Annual Report Conference on Electrical Insulation and Dielectric Phenomena (CEIDP), pp. 1-4.

Du BX, Ma ZL, Gao Y, Han T (2011). Effect of Ambient Temperature on Electrical Treeing Characteristics in Silicone Rubber. IEEE Trans. Dielectr. Electr. Insul., 18(2): 401-407.

Fothergill JC, Dissado LA, Sweeney PJJ (1994). A Discharge-Avalanche Theory for the Propagation of Electrical Trees: A physical Basis for Their Voltage Dependence. IEEE Trans. Dielectr. Electr. Insul., 1: 474-486.

Gulski E, Putter H, Smit JJ, (2008). Investigation of Water Treeing – Electrical Treeing Transition in Power Cables. Int. Confer. Condition Monitoring Diagnosis, China, pp. 234-237.

Ishibashi A, Kawai T, Nakagawa S, Muto H, Katakai S, Hirotsu K, Nakatsuka T (1998). A Study of Treeing Phenomena in the Development of Insulation for 500 kV XLPE Cables. IEEE Trans. Electr. Insul., 5: 695-706.

Kim WS (2001). Tree Initiation Characteristics in LDPE with Different Crystallinaties. Proceedings of 6th IEEE Int. Confer. Properties Appl. Dielectr. Mater, China, pp. 542-545.

Ling Liu, Quan Zhou, Ruijin Liao, Kaiyan Ye (2008). The Chaos Characteristics Analysis for Electrical Treeing Propagation in XLPE Power Cables. IEEE Int. Symposium Electr. Insul., pp. 1-6.

Malik NH, Abdullah AA, Al-Arainy AA, Qureshi MI (2005). Factors Influencing Electrical Treeing in XLPE Insulation. European Trans. Electr. Power (ETEP); 16: 205-218.

Osawa K, Urano K, Ehara Y, Kishida H, Ito T (1997). The Influence of Instantaneous Value and dv/dt of Applied Voltage Upon Electrical Treeing Deterioration. IEEE Confer. Electr. Insul. Dielectr. Phenomena (DEIDP), 1: 321-324.

Samee A, Li ZH, Huang ZP (2009). Investigation on Electrical Treeing Characteristics of Thermally Aged XLPE Cable. IEEE 9th Int. Confer. Properties Appl. Dielectr. Mater. (ICPADM), Harbin, China, pp. 437-440.

Shimizu N, Laurent C (1998). Electrical Tree Initiation. Dielectr. Electr. Insul., 5: 651-659.

Zhou T, Ling Liu, Ruijin Liao, Chen G (2010). Study on Propagation Characteristics and Analysis of Partial Discharges for Electrical Treeing in XLPE Power Cables. 10th IEEE Int. Confer. Solid Dielectr. (ICSD) Potsdam, pp. 1-4.