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Modelling Water Treeing in XLPE Insulation using Electric Field Concepts

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A methodology to model water treeing in XLPE insulation by using electric field, elastic deformation due to pressure build up inside void and probability concepts has been developed. Tree patterns have been numerically simulated considering point-plane electrode geometry in XLPE insulation. The strategy of modelling is verified by comparing fractal dimensions of simulated and experimentally generated tree patterns. The current study revealed, that presence of void filled with moisture is less harmful to presence of a metallic particle of same dimension and also the growth of bow tie tree terminates after it develops to a finite size. Depending upon the type of defects such as semi conducting particle or void filled with air etc, that is present in the insulation, further structure of the prebreakdown channel resembled electrical tree.

1.0 INTRODUCTION

High voltage power cable these days invariably employs cross linked polyethylene (XLPE) insulation as it possesses excellent electrical and thermal properties. However, the XLPE exhibits hygroscopic nature and poor resistance to partial discharges. Even with highly sophisticated extrusion process, voids of varied size and number density gets included in the insulation. It is trivial that voids could be either filled with air or moisture of varied content. In the presence of protrusion tip near the vicinity of these voids, high electric field emanating from the tip influences these voids. Invariably the highly stressed (electrically) region leads to partial discharges resulting in localized breakdown more familiarly known as treeing. Among these voids, there is every reason to believe that tree initiation would be first from the void filled with air, as the electric field inside such type would be higher than that in the void filled with moisture.

Since the discovery of water trees in underground cables, although much research work has been carried out still complete understanding of water tree mechanism is yet to be achieved. Extensive research is still being carried-out, world over, to study various aspects of the water treeing phenomenon in XLPE insulation employing different approaches. Mathematical modelling of electrical treeing is one among them.

2.0 WATER TREE MECHANISM

Partial discharges initiating from highly stressed region, is considered to build up pressure inside any void which is in the close vicinity of highly stressed region. The pressure inside the void builds up with some periodicity and when exceeds the mechanical strength (elastic property) of the material, there is local surface tearing or wearing of the insulating material and with repeated tearing, insulation sees wearing in its volume. This process is bound to encompass other voids which are present in the neighbourhood of the teared region. Extending the concept of induced pressure on these newly appended voids the tearing or the wearing of insulation continues and leaves behind a structure which very much resembles a bow or a bush. This mech-

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anism for water tree growth has been checked by carrying out digital simulation studies.

3.0 DIGITAL MODELLING

XLPE material, having the same point-plane electrode geometry as considered for experiments[1], has been modelled by employing 2D FEM package (ANSYS 5.3). Then the modelled regions were discretized using automesh scheme available in FEM package which generates non-uniform triangular/quadrilateral elements. The potentials and local field at each node are computed from the Laplace equation with appropriate boundary conditions. The boundary conditions applied for the needle plane geometry are i) test voltage of 16 kV (determined from experiments), at the nodes that lie at the interface of insulation and needle and ii) ground potential at the nodes on the edge of the insulation opposite to the needle. The material property i.e. permittivity (as applicable to electrostatic problems) is given as 2.35 (as measured) for XLPE. FEM elements obtained for the selected point plane geometry are presented in Figure 1. The equipotential lines are shown in Figure 2.

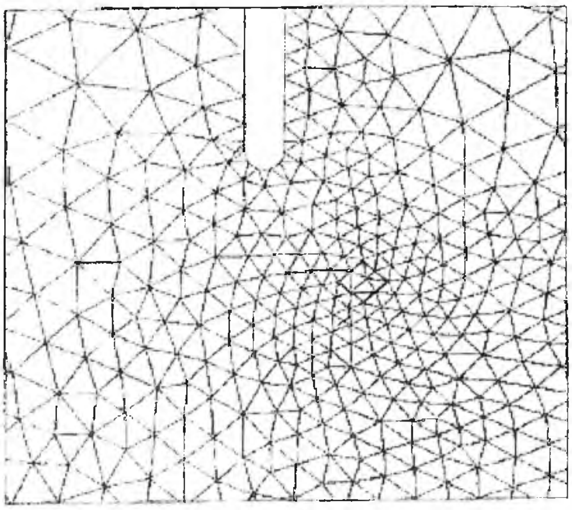

FIG. 1. FEM ELEMENTS IN A SELECTED PORTION OF POINT PLANE GEOMETRY

Various defects like, metallic particles, semiconducting material, voids filled with moisture and air voids in XLPE insulation along with the point plane geometry was also considered for the study as they are generally present in XLPE insulated cable. The influence of these additional defects on tree growth.was studied for defect size ranging from 30–50 μm. These defects were modelled by assigning suitable material property.

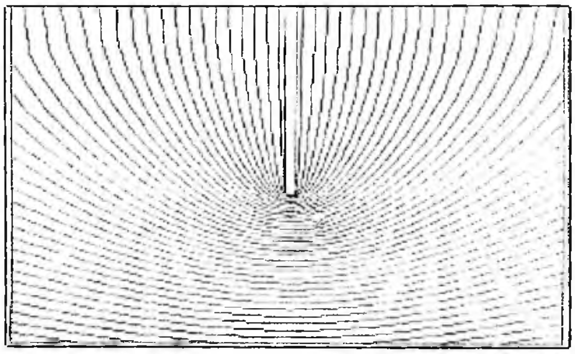

FIG. 2. EQUIPOTNTIAL LINES

3.1 Tree Propagation Strategy

In order to model the tree growth the following assumptions are made;

1. When the electric field at the needle tip exceeds the threshold field of the insulating material, localized breakdown occurs leading to cleavage/micro fracture in the insulation which is nothing but a tree branch.
2. The localized breakdown of XLPE during treeing follows 2 parameter Weibull distribution. The threshold field is assumed to be equivalent to 63.2th percentile of critical field, where critical field is assumed to be x% of maximum electric field (E_{max}).
3. Especially in the neighbourhood of a void filled with moisture water tree formation takes place if the local electrical stress exceeds 10 kV/mm [2].

Based on the above assumptions, the following strategy for tree propagation was formulated. At each node, local stress is computed and compared with the threshold stress (i.e. critical stress as defined in the 2nd assumption) for the nodes away from the void otherwise compared with stress_w = 10 kV/mm (i.e. critical stress) for the nodes in the neighbourhood of the void. If the local stress exceeds the threshold stress/stress_w, probability of tree growth is assigned as 1 to that node. Otherwise probability of tree growth to that node is assigned 0. The elastic deformation level (EDL)[3] was computed from the local electric field at each nodal point and if EDL is less than 0.6, probability of growth was assigned to be 1 otherwise 0. Elastic deformation level less than 0.6 implies that the elastic bond has become weaker and hence insulation is giving way for tearing or opening up. Therefore, a node may be connected to more than one node (tree tip) during propagation as more than one node can have probability associated with it as 1. This connectivity forms tree channel. At all the extended tips of the tree channel, boundary values are reassigned. After each growth, FEM is used with the new boundary conditions to obtain the electric field distribution. This growth strategy is repeated till one of the branches of the tree reaches the ground electrode. A flow chart depicting the propagation strategy is presented in Figure 3. The same tree propagation strategy was followed for the growth of tree in the presence of defects like metallic particles, semiconducting material and air voids in XLPE insulation along with the point plane geometry. A typical bow tie tree generated by above described simulation procedure is shown in Figure 4.

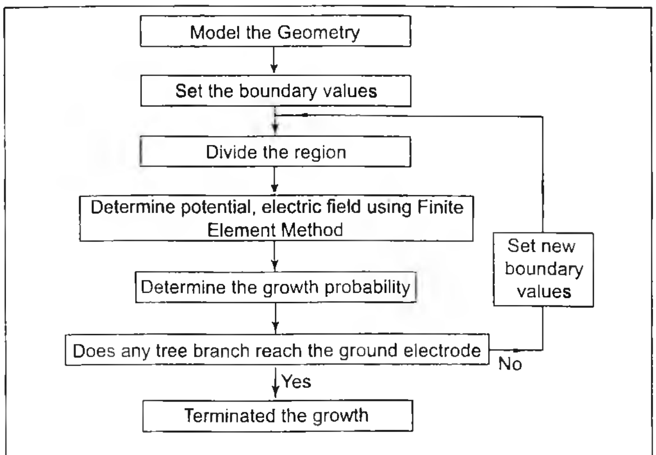

FIG. 3. FLOW CHART OF TREE PROPAGATION

3.2 Inclusion of Randomness Feature

Eventhough identically processed specimens are subjected to the same voltage stress, with other environmental conditions remaining the same, tree initiation time and time to propagate and bridge the gap (between high voltage and ground potential) differ to a large extent among specimens. This large variation is attributed to the stochastic behaviour of the material when subjected to various stresses. The modelling aspect of randomness feature has been discussed at length in reference[1]. The results are summarized in the following table along with the maximum and minimum tree growth in case of presence of defect void filled with moisture. The fractal dimension[4,5] computed for experimentally and digitally simulated bow-tie tree is 1.68 and 1.71 respectively.

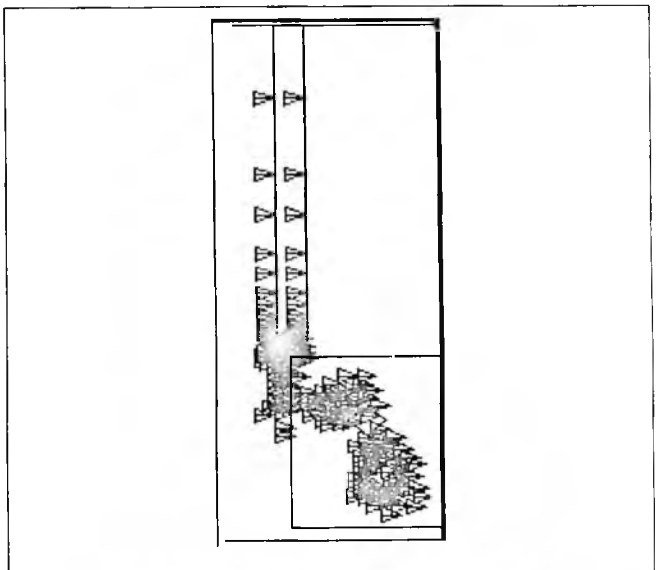

FIG. 4. TYPICAL BOW-TIE TREE FROM VOID

TABLE 1

VARIATION OF TREE GROWTH IN THE PRESENCE OF DIFFERENT DEFECT

Type of defect	Min. growth (μm)	Max. growth (μm)
Metallic particle	100	210
Semiconducting particle	78.5	181.2
Void (air)	58.0	158
Void (moisture)	14.5	29.0

4.0 DISCUSSION

The statistical nature of treeing phenomenon in XLPE has been observed from trees grown in identical samples during experiments carried out under identical conditions. A significant change in tree structure was seen. In order to incorporate this feature of statistical behaviour during simulation, it was assumed that electrical breakdown (local) of XLPE follow Weibull distribution for tree growth. Fractal dimension for experimentally grown tree and simulated tree compare well. This verifies that the assumptions made and the strategy employed for tree simulation are satisfactory.

More branching has been observed in the presence of metallic defect. It is apparent that the spread at the needle tip and around the defect is more. Of the defects considered, maximum and minimum spread was observed for metallic particle and void filled with moisture respectively.

Electrical stress alone is sufficient enough to cause latent damage to the insulation in the form of bow-tie tree in the neighbourhood of the void filled with moisture. The shape and size of the tree growth depends on the shape and size of the void and its location with respect to protrusion.

Simulations of tree growth with defects of size less than 50 μm, showed insignificant change in the tree structure. It appears, therefore, that defects of size 50 μm and above are critical.

From Table 1, it is clear that in the presence of metallic particle (size 50 μm), spread in the tree can vary from a minimum of 100 μm to a maximum of 210 μm. Other results revealed that with an increase in size of the defect the spread in the tree also increased.

Tree growth in the vicinity of the void filled with moisture is a local phenomenon. It grows only to certain definite dimension. Once the growth encompasses all the micro voids in the neighbourhood of that void which is near the defect protrusion the growth terminates.

The current study revealed, that presence of void filled with moisture is less harmful to presence of a metallic particle of same dimension and also the growth of bow tie tree terminates after it develops to a finite size. Depending upon the type of defects such as semi conducting particle or void filled with air etc, that is present in the insulation, further structure of the prebreakdown channel resembled electrical tree.

5.0 CONCLUSIONS

From the results and discussion it could be inferred that the modelling of electrical treeing is satisfactory. The presence of additional impurities enhances the local field and hence spread in the tree growth is slightly more. The harmful effect of metallic particle has also been clearly revealed by the digital simulation study. Among the defects, void, semi-conducting and metallic particle, the last one appears to be more harmful. Also defects of size less than 50 μm have not caused any significant variation in the electric field. Modelling randomness feature appears satisfactory. Electrical stress alone is sufficient enough to cause latent damage to the insulation in the form of bow-tie tree in the neighbourhood of the void filled with moisture. The shape and size of the tree growth depends on the shape and size of the void and its location with respect to protrusion. Defects arranged with respect to its most harmful to least harmful was found to be in the order: metallic particle, semiconducting particle, void filled with air and void filled with moisture. Water tree (Bow-tie tree) alone cannot cause catastrophic failure as the growth ceases after certain extent in either directions. Water tree can cause breakdown only if its prebreakdown channel merges with the prebreakdown channels of electrical tree.

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