ORIGINAL PAPER

ANALYSIS OF ELECTRIC FIELD AND POTENTIAL DISTRIBUTION OF EXPERIMENTAL SETUP FOR INITIATING AND GROWING VENTED TYPE WATER TREES USING FINITE ELEMENT METHOD

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Abstract. *Water treeing phenomenon has an important and effective role in the service life of polymeric insulators used in the transmission and distribution of electricity. Water trees can be described as permanently localized degradations or damages that can occur in the presence of electric field and humidity. XLPE is widely used as a polymeric insulator material in medium and high voltage cable applications. An experimental setup was prepared to initiate and grow water trees artificially in a laboratory environment and the tests were performed in accordance with the actual values. The electrical and dielectric values of the test material were used for a detailed analysis with high accuracy. The magnitude of the electric field, which was defined by varying the distance between the water needles formed in the XLPE material and the aluminium plate electrode, has been analyzed for various conditions. After laboratory experiments, electric field and potential distribution were simulated and analyzed by FEM (Finite Element Method) using FEMM (Finite Element Method Magnetics) software package. Experiments revealed clearly, that even small changes in the shape of water needle can dramatically affect the electric field and hence the lifetime of the insulator. By using FEMM, both of these parameters (electric field and potential distribution) can be calculated rapidly with high accuracy. HVDC power cables play a significant role in electric power transmission, hence by using the previously described experimental setup, electric field and potential distribution were simulated and analyzed under DC voltage.*

Keywords: *vented water treeing; XLPE; electric field and potential distribution; finite element method (FEM); finite element method magnetics (FEMM).*

1. INTRODUCTION

Polymeric insulators have an active and important place in transmission and distribution of electricity. In this context, the significance of the aging phenomena that occur in the insulation materials used in the medium and high voltage cables and also the importance of the development of the insulation materials have emerged [1-3]. Crosslinked polyethylene (XLPE) has an important and influential role as a polymeric insulator material in medium and high voltage cable applications since it has good physical, chemical and electrical properties. XLPE insulated cables are widely used for electrical transmission and

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distribution networks [1, 4-10]. Although XLPE material is a good electrical insulator material, aging is inevitable after a certain period of time. Water trees are permanent and localized damages that play a dominant and important role in the aging and hence the service life of polymeric insulators. These damages are hydrophilic in character [11-15].

Electric field magnitude is one of the factors that strongly affect the initiation and growth of water trees. Electric field magnitude is known to increase the number and length of trees [11,15]. The applied voltage level, the distance between the electrodes, the voltage waveform, the needle curvature radius are the factors that are mentioned under this study as they affect the electric field magnitude.

Kim et al. have investigated the electric field distribution in water treed XLPE cable insulation using the FEM [16]. Kim et al. have performed a numerical analysis on water treeing using FEM and Taguchi method. Kim et al. have stated that the electric field distribution inside the water tree plays an active and important role in the initiation and growth of water trees [17]. Khouildi et al. have analyzed the electric field distribution and the potential distribution in the cavities inside XLPE insulation [18].

There are many factors that affect the water treeing and electric field is one of these factors. It is known that water treeing is initiated and grown under AC voltage. However some studies have reported water trees grown also under DC voltage [12, 19]. An experimental setup is already proposed which allows to initiate and grow vented type water trees under AC voltage. This study allowed to simulate and analyze electric field and potential distribution by using this experimental setup under DC voltage.

2. WATER TREE PHENOMENON, EXPERIMENTAL SETUP AND FEM

2.1. VENTED WATER TREEING

Water trees can be described as permanently localized degradations or damages that can occur in the presence of electric field and humidity. Electric field, polymer morphology, frequency, mechanical pressure, temperature, ionic content, relative humidity, additives, contaminants, and treeing retardants etc. are factors affecting the initiation and growth of the water treeing [5, 11, 12, 15, 20-23].

In general, there are 2 types of water trees, vented type of water trees and bow-tie type water trees. Vented tree initiates in the insulator boundaries mostly in the direction of the electric stress and grow towards the other side of the insulator [11, 12]. The image of vented water tree is shown in Fig. 1.

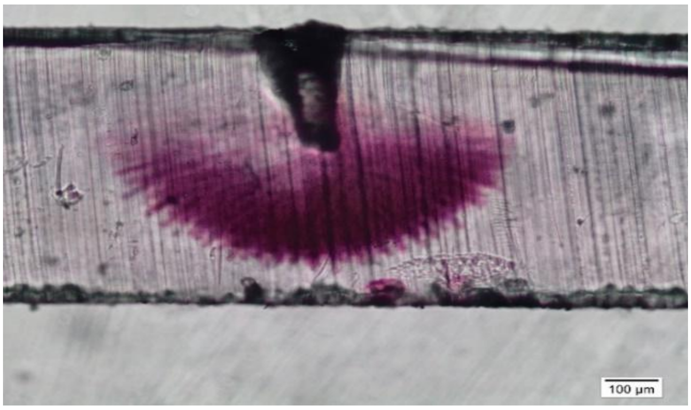

Figure 1. Vented water tree.

2.2. EXPERIMENTAL SETUP FOR INITIATING AND GROWING VENTED TYPE WATER TREES

The experimental setup used for initiating and growing vented type water trees is shown in Fig. 2. Aluminum electrodes are connected to high voltage output terminals of transformer, polyamide reservoir is filled with the solution, and samples are taken from polymeric insulators. Test setups used to create water treeing in the laboratory have generally similar structures.

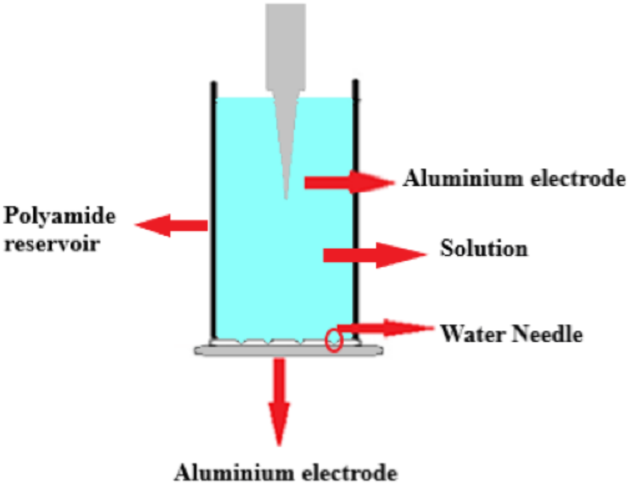

Figure 2. The experimental setup for initiating and growing vented type water trees.

For this study, a previously presented experimental setup designed for AC voltage was used as reference [13, 22]. 2D and 3D drawings of this experimental setup and their appearance in the laboratory environment are shown in Fig. 3. Electrical field and potential distribution for this experimental setup under DC voltage were simulated and analyzed.

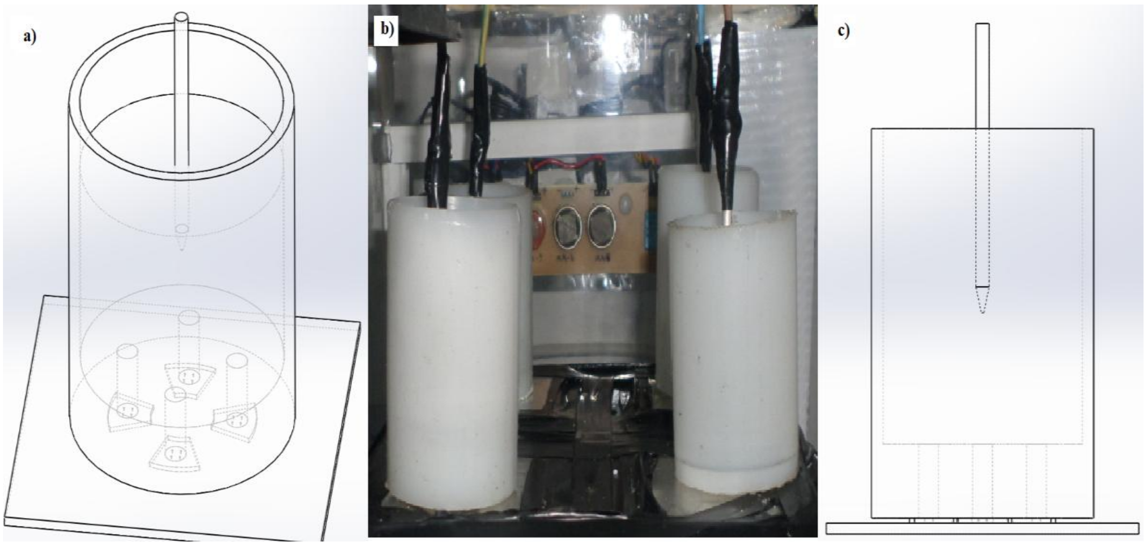

Figure 3. a) 3D CAD drawing; b) Appearance of the experimental setup in laboratory environment; c) 2D CAD drawing.

2.3. FINITE ELEMENT METHOD (FEM)

Finite element method (FEM) is based on the principle of minimization of energy. FEM can be described as a numerical method used to obtain approximate solutions to boundary value problems of physical mathematics. Area to be analysed may be an electric or magnetic field in the Laplace and Poisson type. Laplace equation in the Cartesian coordinate system is given in Eq. (1).

$$\Delta V = \frac{\partial V^2}{\partial x^2} + \frac{\partial V^2}{\partial y^2} + \frac{\partial V^2}{\partial z^2} \tag{1}$$

Total energy in the region can be defined as shown in the Eq. (2). ε_x and ε_y are the dielectric constants depending on the direction of the electric field. z is a constant.

$$W = z \iint \left\{ \frac{1}{2} . \left[\varepsilon_x \left(\frac{\partial V}{\partial x} \right)^2 + \varepsilon_y \left(\frac{\partial V}{\partial y} \right)^2 \right] \right\} . dx . dy \tag{2}$$

The solution (Eq. 3) provides the Laplace equation, which at the same time minimizes the potential energy in the area.

$$\nabla^2 V = \Delta V = 0 \tag{3}$$

Steps of the solution of any problem by the FEM are given Fig. 4. [24, 25]

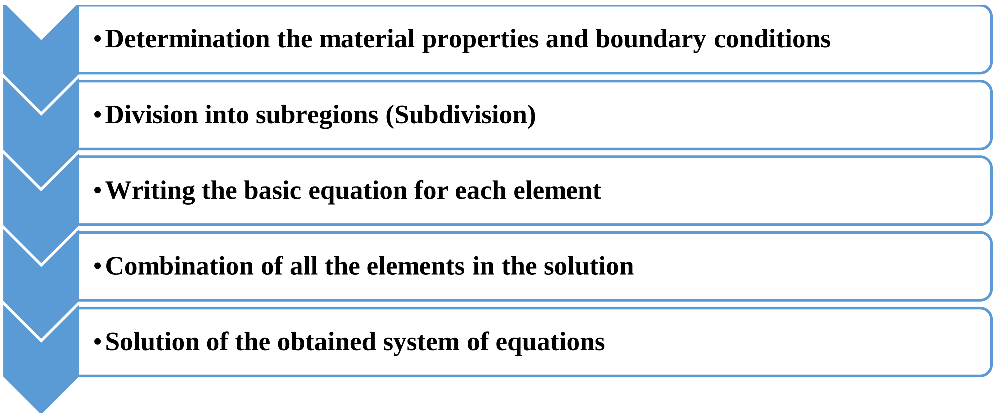

Figure 4. Steps of the solution of any problem by the FEM.

3. RESULTS

An experimental setup was designed and prepared to initiate and grow vented type water trees by Karhan et al. [12]. This experimental setup (Fig. 5) was drawn and imported to FEMM software package.

Water needles are formed with different lengths. The distances between the needles and electrode were selected in micrometre levels (200 µm -750 µm). Thus, it was possible to create electric fields with different and high magnitudes at the tips of water needles. Relative permittivity of polyamide, which is the material of tank, is taken 2.5. Relative permittivity of XLPE, water and air are taken as 2.4, 80.4 and 1 respectively. Mesh was created with 7454 nodes by using FEMM. In this study, the applied voltage is selected as 24 kV.

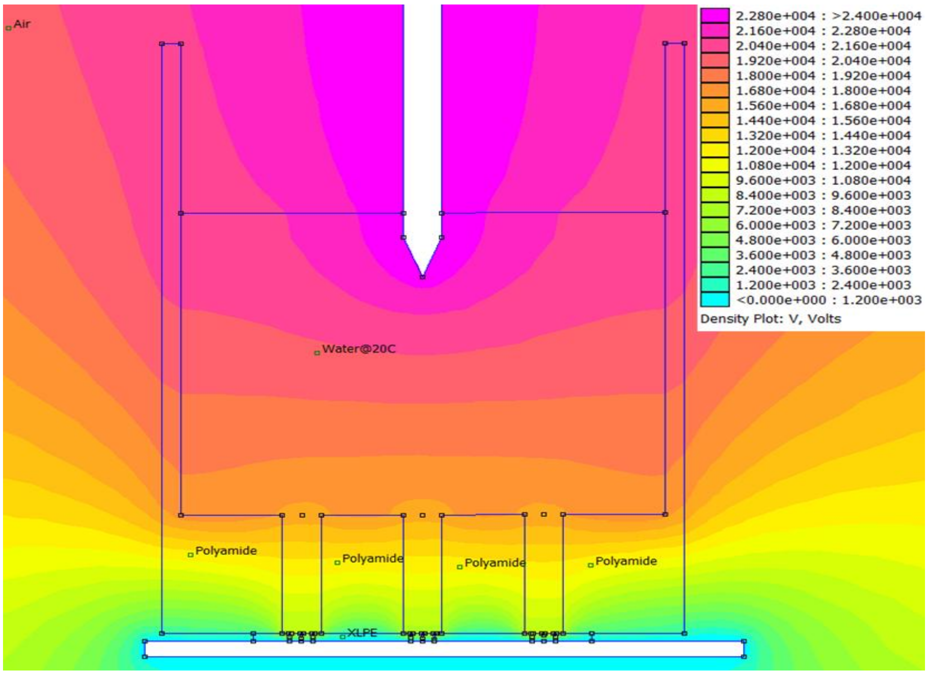

Figure 5. Water treeing experimental setup.

Close-up views of potential distribution of different length water needles are shown in Fig. 6.

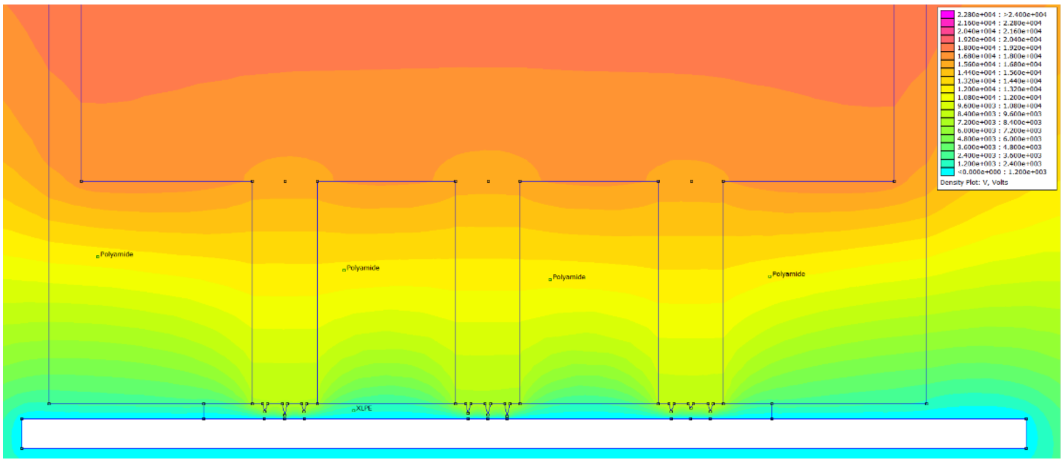

Figure 6. Potential distribution of different length water needles around.

Electric field distribution of different length water needles is shown in Fig. 7. Electric fields with high magnitudes at the tips of water needles can be seen clearly.

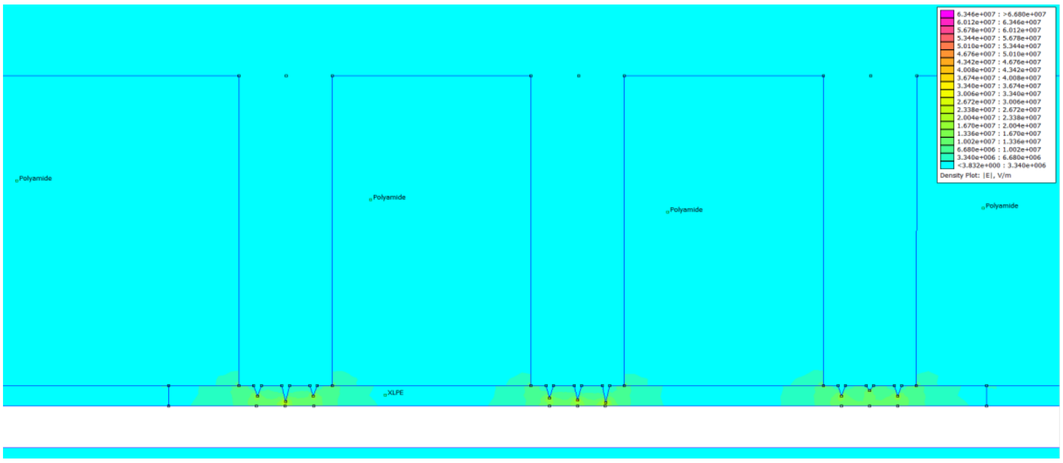

Figure 7. Electric field distribution of different length water needles around.

Figs. 8-10 are the left, middle, and right parts of the experimental setup respectively. Close-up views of electric field distribution of different length water needles around are shown in Figs. 8-10. Distances between the water needle and the aluminium electrode are 500 µm, 250 µm and 500 µm respectively (Fig. 8).

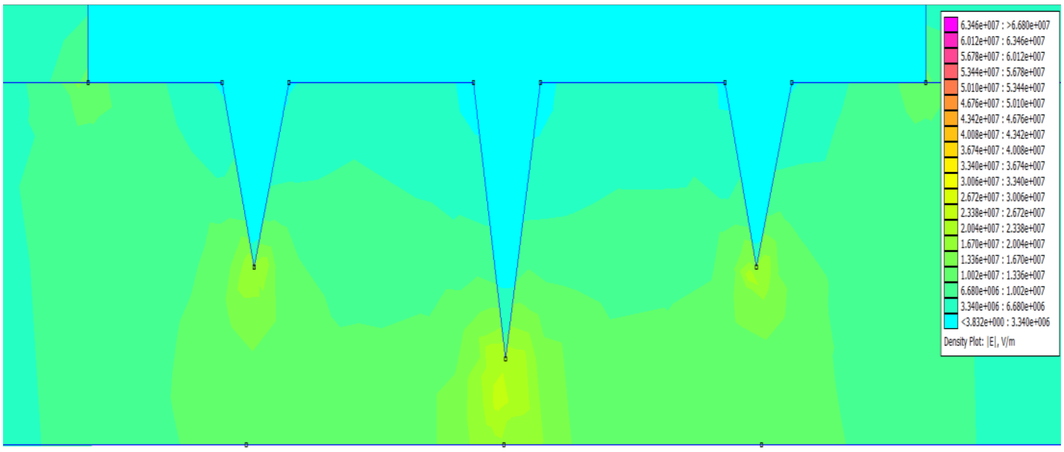

Figure 8. Close-up views of electric field distribution (left part)

Distances between the water needle and the aluminium electrode are 400 µm, 300 µm and 200 µm respectively (Fig. 9).

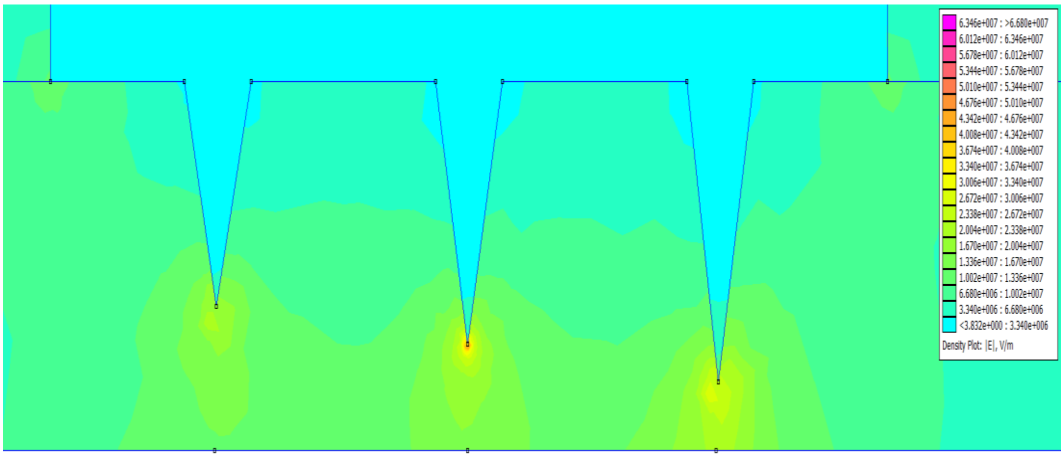

Figure 9. Close-up views of electric field distribution (middle part).

Distances between the water needle and the aluminium electrode are 500 µm, 750 µm and 500 µm respectively (Fig. 10).

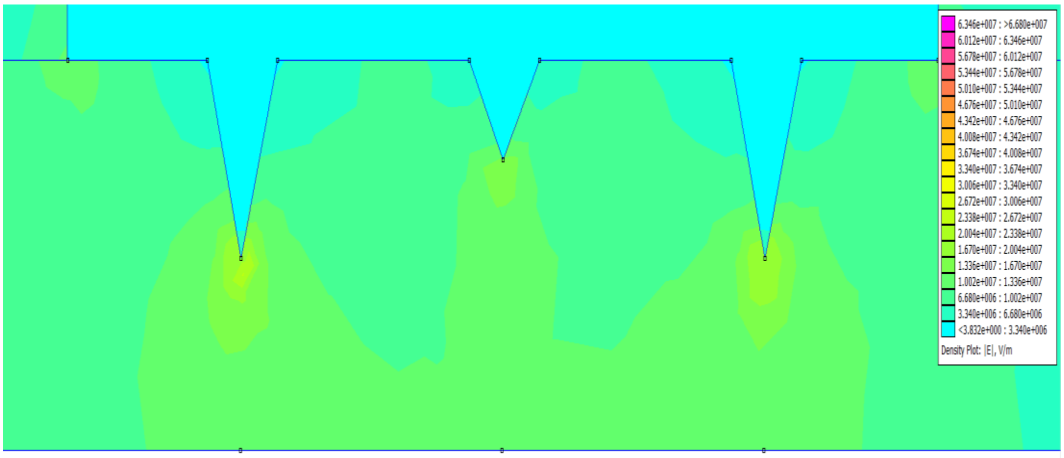

Figure 10. Close-up views of electric field distribution (right part).

The gap to be analysed between the rod aluminium electrode and the tip of water needle is shown in Fig. 11. Distance between the tip of the selected water needle and the aluminium plate electrode is selected as 300 µm (Figs. 11-13).

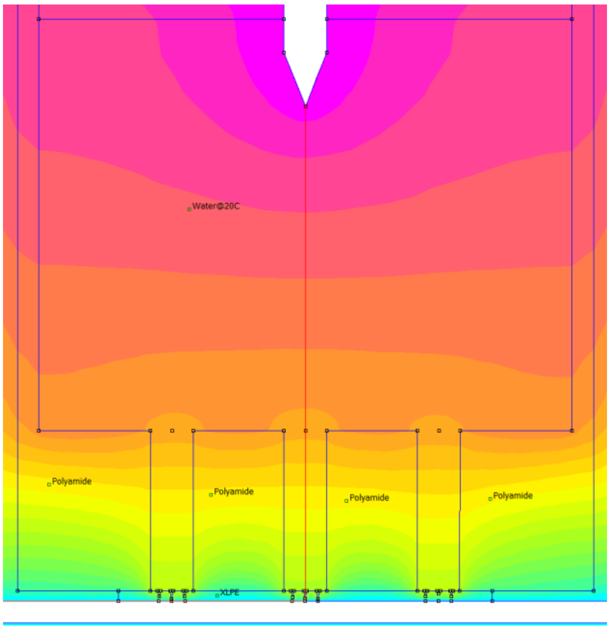

Figure 11. The gap to be analyzed between the electrode and the tip of water needle.

The potential distribution between the rod aluminium electrode and the tip of water needle (along the gap) is shown Fig. 12.

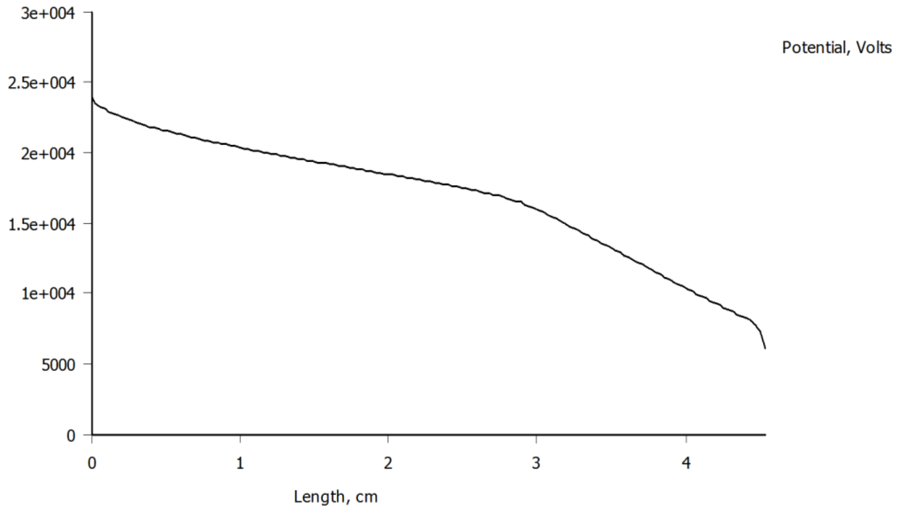

Figure 12. Potential distribution of the gap.

The electric field distribution between the rod aluminium electrode and the tip of water needle (along the gap) is shown Fig. 13.

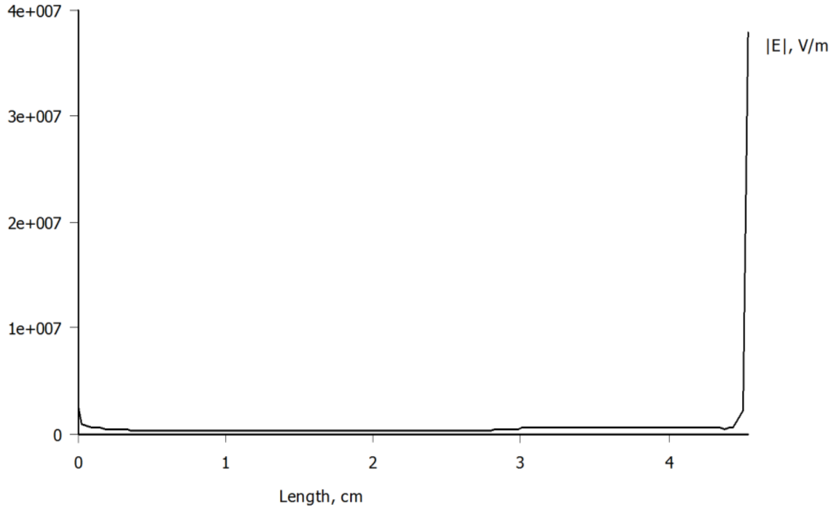

Figure 13. Electric field distribution of the gap.

The gap to be analyzed between the rod aluminium electrode and the tip of water needle is shown in Fig. 14. Distance between the tip of selected water needle and the aluminium plate electrode is 500 μm in Figs. 14-16, respectively.

The potential distribution between the rod aluminium electrode and the tip of water needle (along the gap) is shown Fig. 15. The electric field distribution between the rod aluminium electrode and the tip of water needle (along the gap) is shown Fig. 16.

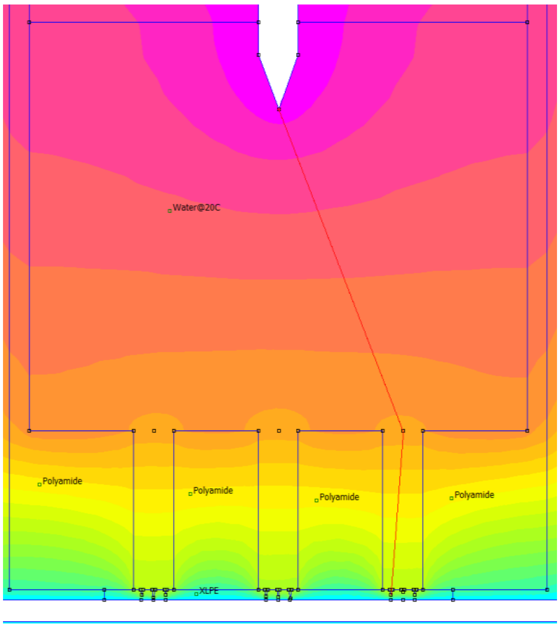

Figure 14. The gap to be analyzed between the electrode and the tip of water needle.

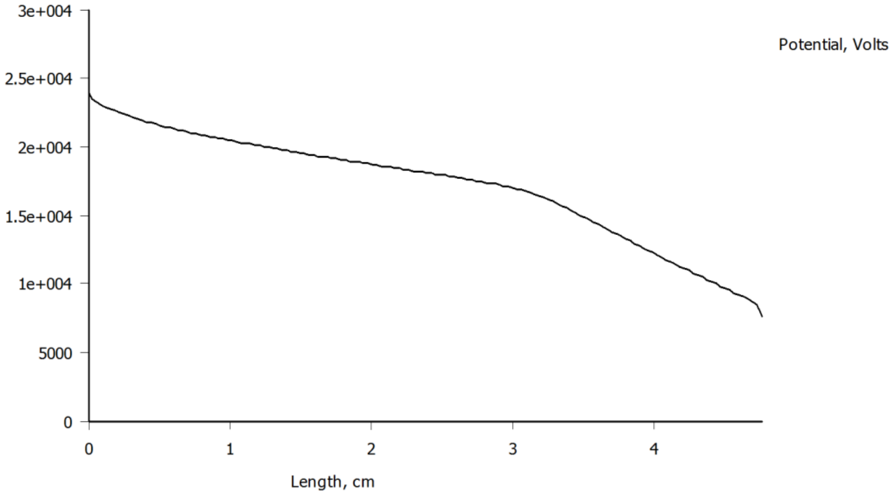

Figure 15. Potential distribution of the gap.

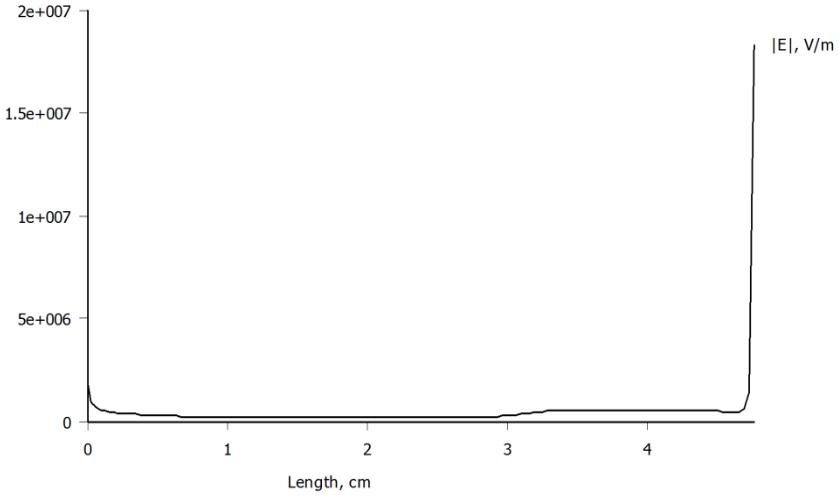

Figure 16. Electric field distribution of the gap.

Distances between the water needle and the aluminium plate electrode (Fig. 17) are selected as 500 µm, 750 µm and 500 µm respectively. The gap to be analyzed (electric field and potential distribution) between two water needles is shown in Fig. 17.

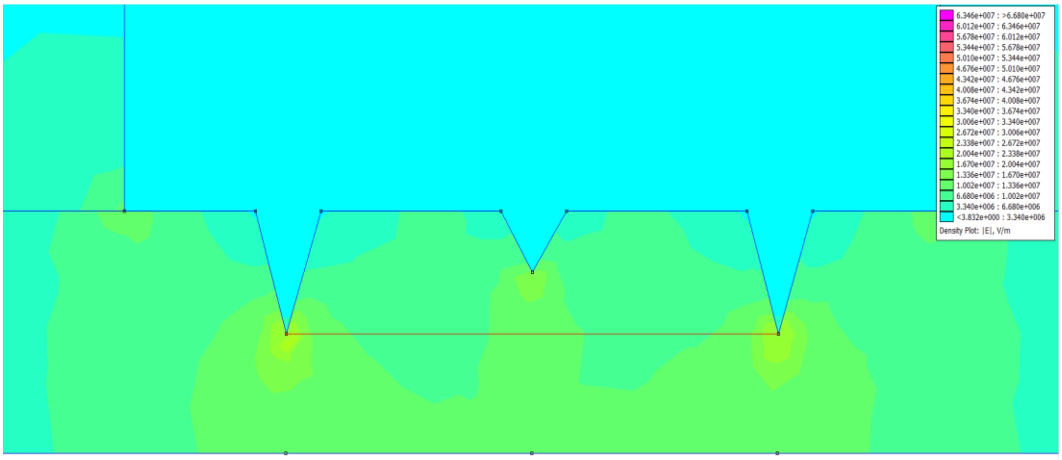

Figure 17. The gap to be analyzed between two water needles.

The potential distribution between the tips of two water needles (along the gap) is shown in Fig. 18. Potential value takes maximum and minimum values, which depends on the distance to the aluminium plate electrode.

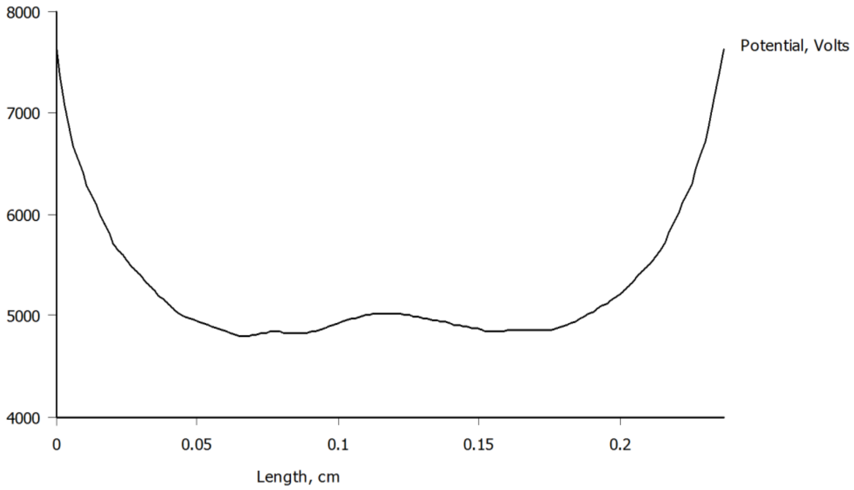

Figure 18. Potential distribution of the gap.

The electric field distribution between the tips of two water needles (along the gap) is shown in Fig. 19. Electric field intensity takes maximum and minimum values, which depends on distance to the aluminium plate electrode.

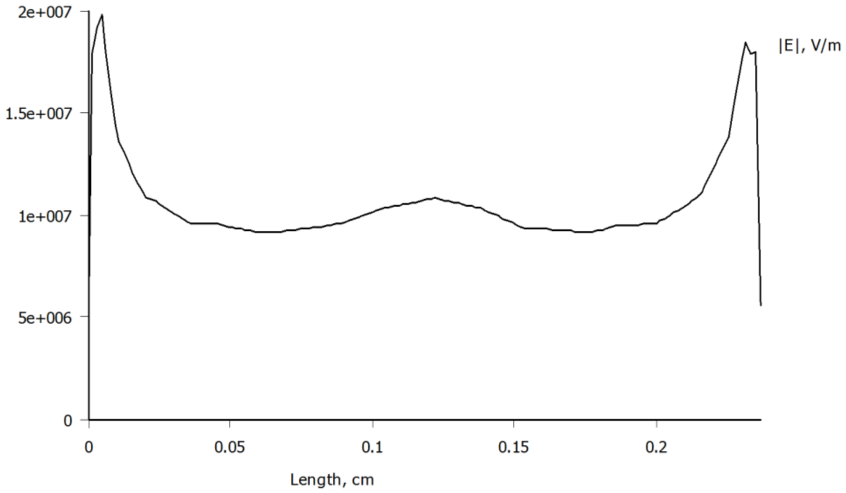

Figure 19. Electric field distribution of the gap.

4. CONCLUSION AND FUTURE SCOPE

In this study, an experimental setup, which is proposed in previous studies to initiate and grow the vented type water trees in the laboratory environment, is used with different solution conductivities. This experimental setup was drawn and imported to FEMM software package. Electric field and potential distribution in the XLPE material used in medium and high voltage cables for different length of water needles were analysed by using finite element method. In order to establish high electric field, the distances between the tips of water needles and the aluminium plate electrodes were set to 200 µm, 250 µm, 300 µm, 400 µm, 500 µm and 750 µm respectively. Electric field magnitude is one of the important factors affecting the water treeing. The potential distribution and electric field distribution between the aluminium rod electrode and the tip of water needle (for distances of 300 µm and 500 µm) are shown. A more distinctive electric field is observed at the tip of water needles, which are close to the aluminium plate electrode.

Previous studies and literature review point out that water treeing is generally initiated and grown under AC voltage, however some studies claimed that water trees are also observed under DC voltage. In this study, the potential distribution and electric field distribution between the aluminium electrode and the tips of water needles were analyzed using by FEM. By using the measured and simulated electrical field values, it is possible to determine the optimum test voltage during water treeing experiments, which eventually enables to prevent prebreakdown of the insulating material. As a result of this study, the experiments can easily be conducted in a controlled manner with higher accuracy. In the future, it is planned that this simulated study will be repeated in the laboratory. In future laboratory experiments, it will be observed how the trees take shape under high DC voltage using this experimental setup.

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