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Analysis of Electric Field and Potential Distribution in a Water Infested Graded Cable Insulation

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Abstract

The presence of water trees in polyethylene and cross linked polyethylene (XLPE) insulated cables was detected in the early seventies, in USA and Japan. The water treeing is generally considered as one of the most important causes of breakdown failures in power cables with polymeric insulation. There are several factors that influence the initiation and growth of water trees in the polymeric insulated power cables, such as the nature of the polymer, voltage magnitude and frequency. The cable modeling comprises of three regions of different insulating material namely impregnated paper, polyester, polyethylene and water particles with elliptical geometric structure. This paper presents the modeling of 10kV medium voltage, capacitive graded power cable under dry and wet conditions. The electric potential and field strength at several positions are computed using the field computation program COMSOL Multiphysics 3.3a. The results of simulation is plotted and analysed.

Keywords: power cable, finite element analysis, electric potential, electric field.

Introduction
The discovering of degradation of polyethylene by the combined action of water and electric stress was published by Miyashita and presented at the electrical insulation conference in Boston in 1969 [1]. A water tree is a diffuse water bubble clustered structure in a dielectric insulating material with an appearance resembling a bush. The presence of water trees reduces the electric breakdown stress level of an insulating material. The water trees in XLPE showed failures after 5 years of service experience

[2, 3]. This calls for understanding their behavior more clearly. It is known that Polyethylenes $(CH_2-CH_2)_n$ are very long macro molecules. The mechanical properties of different polyethylene are mainly determined by the density of these materials. The Polymers whether cross linked or not essentially semi-crystalline, which means that it is the partly crystalline and partly amorphous. The XLPE behaves like a rubber-like substance [4]. Owing to its non-polarity, Polyethylene (PE) surfaces are hydrophobic until oxidized, therefore some water in the PE cannot be excluded during it deployment. The XLPE at a temperature of 20^0 C absorbs < 100 ppm of water. The amount of water absorbed depends strongly on the cable temperature. The water trees are diffuse structures in polymeric insulating materials resembling a bush or a fan. It grows in many different kinds of the polymers under the action of water vapor and an electric field.

The water tree weakens the insulation and causes cable failures. There are two types of water trees they are "bow-tie tree" and the "vented tree". This distinction is based on the location where these trees start growing. The Vented trees are initiated at the insulating surfaces, and bow-tie trees are initiated in the insulation volume. In particular the vented trees are dangerous under service aging conditions than bow-tie trees. The water tree contains water. If this water is evaporated by heating, it is known that the tree will absorb water again if the insulation is exposed to water or water vapor afterwards. The Vented trees and the related path grow in the direction of electric field lines. Under certain circumstances the water tree can initiate an electrical tree when there are over voltages. The vented tree path is a poor insulating material. The breakdown stress level is lower than that of the surrounding material. Water trees are the dendritic paths formed in polyethylene (PE) and cross linked polyethylene (XLPE) power cable insulation associated with electric stress and water immersion. This phenomenon has been found especially in distribution XLPE cables [5]. The characteristics of water trees, the effect of aging parameters on water tree growth and the posibble mechanisms of growth are considered, emphasising vented tree devolopment in poly ethylene insulating materials [6]. The paper describes a new selective detection method for water trees devolopment in consideration of electro physical concept of the water treeing phenomenon [7]. Recently several diagnostic methods of measurement of permittivity and dielectric loss have been developed for non destructive testing of water tree degraded XLPE cables [8]. The loss current through non penetrated water treed polyethylene increases with exposure time at 1000 V, 500 Hz [9]. In this paper a HV dielectric spectroscopy system has been devoloped for diagnostics of water tree deteriorated extruded medium voltage cables [10]. It is well recognised that the electric field distribution is a dominant factor in the initiation of degradation process in the insulation system [11]. This paper describes a pragmatic method to access the resistance of medium voltage polymeric cable insulation to water treeing [12]. Because of the probable incidence of water tree phenomena air cavity and also humidity in electric insulators, increase in electric field happens locally and lead to breakdown in insulator[13]. Electric power utilities and industrial units in Saudi Arabia and other gulf countries extensively using XLPE cables produced in the Arabian Gulf region [14].

In our work we have considered capacitive graded cable with smaller thickness of composite dielectric to have uniform electrostatics stress.

Modeling cable with water trees and field analysis

The process of achieving uniform electrostatic stress in the dielectric of cables is known as grading of cables. The electrostatic stress in a single core cable has a maximum value (g_{max}) at the conductor surface and goes on decreasing as we move towards the sheath. The maximum voltage that can be safely applied to a cable depends upon g_{max}, , which is electrostatic stress at the conductor surface. For safe working of a cable having homogenous dielectric, the strength of dielectric must be more than g_{max}.

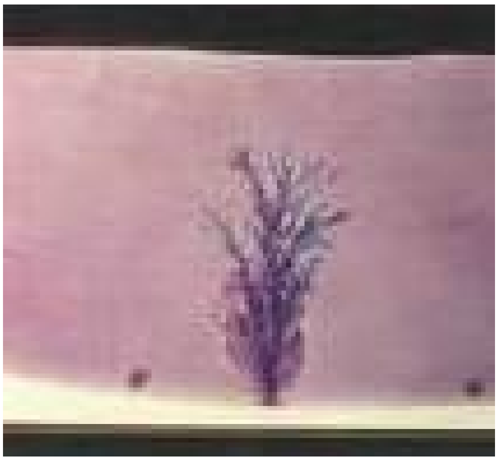

Figure 1: Water tree in cable insulation- initial stage

If a dielectric of high strength is used for a cable, it is useful only near the conductor, where stress is maximum. But as we move away from the conductor, the electrostatic stress decreases, so the dielectric will be unnecessarily over strong.

The unequal stress distribution in a cable is undesirable for two reasons. Firstly, insulation of greater thickness is required which increases the cable size. Secondly, it may lead to the breakdown of insulation. In order to overcome above disadvantages, it is necessary to have a uniform stress distribution in cables. This can be achieved by distributing the stress in such a way that its value is increased in the outer layers of dielectric. This is known as grading of cables [15]. Grading is done in underground cables by two ways. They are capacitive grading and intersheath grading. Capacitive grading makes stress uniform in insulation and uses composite dielectric such a way that it reduces the overall thickness of insulation.

Capacitance grading

The process of achieving uniformity in the dielectric stress by using layers of different dielectrics is known as *capacitive grading.*

In a capacitive grading, the homogenous dielectric is replaced by a composite dielectric. The composite dielectric consists of various layers of different dielectrics in such a manner that relative permittivity ε_r of any layer is inversely proportional to its distance from the centre. Under such conditions, the value of potential gradient at any point in the dielectric is constant and is independent of its distance from the centre. In other words, the dielectric stress in the cable is same everywhere and the grading is ideal one. In practice, two or three dielectrics are used in the decreasing order of permittivity; the dielectric of highest permittivity is used near the core.

There are three dielectrics of radius r_1, r_2, R and the relative permittivity ε_1, ε_2 and ε_3. If the permittivity are such that $\varepsilon_1 > \varepsilon_2 > \varepsilon_3$ and the dielectrics are worked at the same maximum stress, then

$$\frac{1}{\varepsilon_1 r} = \frac{1}{\varepsilon_2 r_1} = \frac{1}{\varepsilon_3 r_2}$$

$$\varepsilon_1 r = \varepsilon_2 r_1 = \varepsilon_3 r_2 \qquad (1)$$

or

$$V_1 = \frac{q}{2\pi\varepsilon_0 \varepsilon_1}\log_e \frac{r_1}{r} = g_{\max} r \log_e \frac{r_1}{r}\left[\text{as } \frac{q}{2\pi\ \varepsilon_0 \varepsilon_1} = g_{\max} r\right] \qquad (2)$$

Similarly, potential across second layer (V_2) and third layer (V_3) is given by;

$$V_2 = g_{\max} r_1 \log_e \frac{r_2}{r_1} \qquad (3)$$

$$V_3 = g_{\max} r_2 \log_e \frac{R}{r_2} \qquad (4)$$

Total potential difference between core and earthed sheath is

$$V = V_1 + V_2 + V_3$$

$$= g_{\max}\left[r \log_e \frac{r_1}{r} + r_1 \log_e \frac{r_2}{r_1} + r_2 \log_e \frac{R}{r_2}\right] \qquad (5)$$

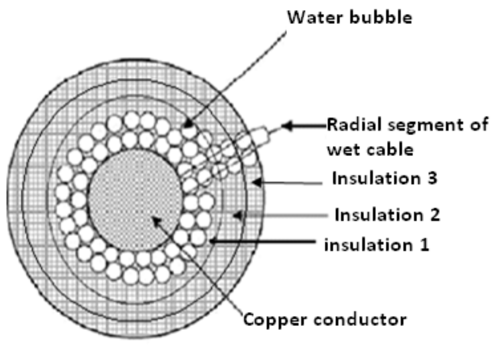

Figure 2: Simplified representation of the proposed model of water content in the cable insulation

After the brief literature survey and explanation of capacitive grading, the next section will be to obtain results and draw the graphs.

The modeling of field distribution of 10 kV power cable is done. In this work we consider medium voltage power cable (10kV). In modeling cable section comprising water bubbles in symmetrical configuration 10 kV. The various plots of electric field and potential variation in dry and wet capacitance graded cable are drawn. Fig 3 shows 16 bubbles on each line.

Field Distribution Modeling of 10kV Power cable

The cable configuration used is a 10kV medium voltage power cable. It comprises of an inner Copper conductor of cross sectional area of 25 mm^2 (2.8209mm radius). For capacitive grading the inner insulation comprises of impregnated paper followed with polyester, having relative permittivity 3.6 and 2.85 respectively. The thickness of each dielectric is 0.74mm and 0.85mm respectively. The outer insulation is polyethylene having relative permittivity of 2.3 and thickness of 1.8056mm.

It has been illustrated in the literature [19] that amount of water, which can be absorbed by cable insulation, varies in the range 2-6% of the total insulation volume, and in the present analysis, the absorption was taken to be 2%. The radius of the spherical water droplet varies in the range of 0.1 to 5μm in literatures [8]. It is taken in present study to be 2.5 μm. Therefore, the total number of water bubbles in the considered cross sectional area can be easily ciphered, and for the present system, this number has been ciphered to be 98376 water bubbles.

To assuage computation of electric field distribution, it is arrogated that the water bubbles are distributed radialy along the lines emanating from the conductor surface to the outer surface of insulation, as demonstrated in figure 3. If it is arrogated that the elongation of water particle to form an ellipse does not alter its area, the number of water bubbles per radial line, Np, can be ciphered.

Concordant to the quoted values of conductor radius and insulation thickness above, the number of water bubbles in each line is 16. This number also satisfies the condition that bubbles adjacent to cable conductor and subsequent bubbles in the insulation will not overlap. Figure 2 depicts how these bubbles are arranged to form sections of cable insulation restricted between pairs of rows of water voids. On the contrary, the electrostatic field analysis is simplified using this symmetrical model, in which the total number triangular elements generated are 3064 and number of boundary elements are 272.

Start COMSOL Multiphysics 3.3 a. Press the multiphysics button in the model navigator dialog box. From the list of application modes choose Electrostatics. Add the generalized electrostatics mode to the model by pressing the add button. The thickness of the sheath is approximately set to zero. Go to the draw menu and chose specify objects and circle. Set the centre position of the circle with the radius of the circle to the radius of the cylinder. Click O.K. Repeat the procedure to create a circle with a radius of the insulation on top of the first circle. Go to the draw menu and choose create composite object. Press shift and select both the circles. Edit the set formula to C_1-C_2 and click O.K. The area where the problem is to be solved is called problem area. On the border of the problem area boundary conditions are defined. In the boundary settings dialog box, select interior boundaries check box. In the generalized electrostatics mode, set the conductivity of the insulation to zero. The mesh should be made as fine as possible since this will improve the accuracy of the system. Since this is a time dependent problem, a time dependent solver must be used. Go to the solver parameters… in the solve menu. The solver parameters dialog box will be opened.

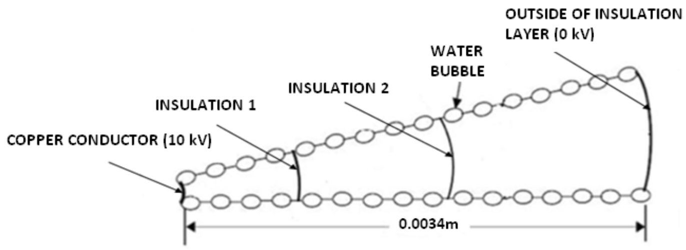

Figure 3: Cable section comprising water bubbles in symmetrical configuration_10kV

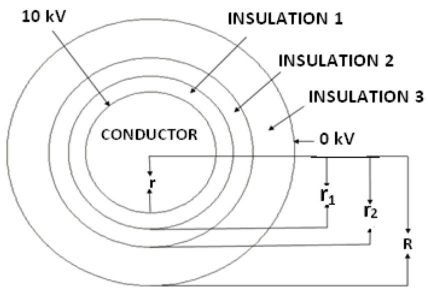

Figure 4: 10kV graded co-axial power cable

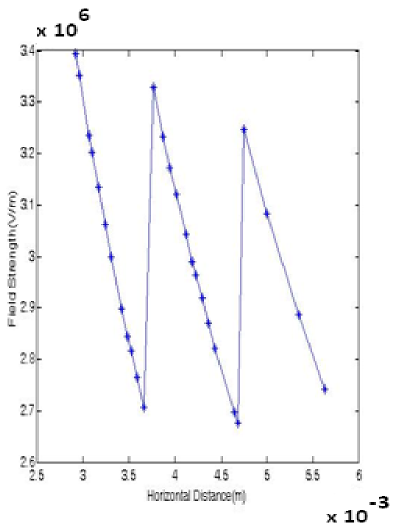

Figure 5: Electric field variation in dry capacitive graded cable for 10kV

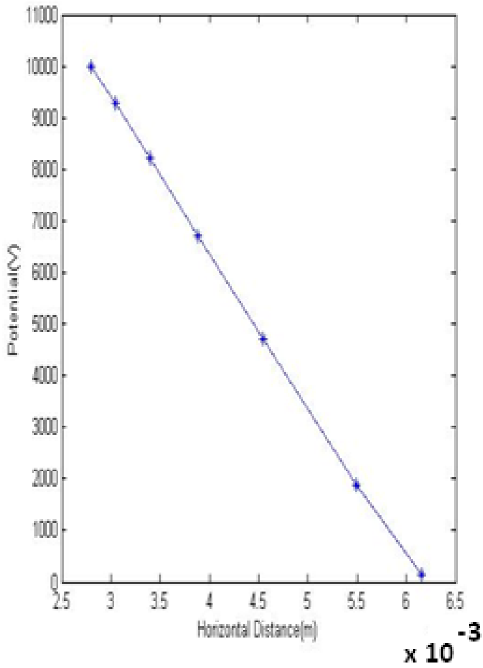

Figure 6: Potential distribution in dry capacitive graded cable for 10kV

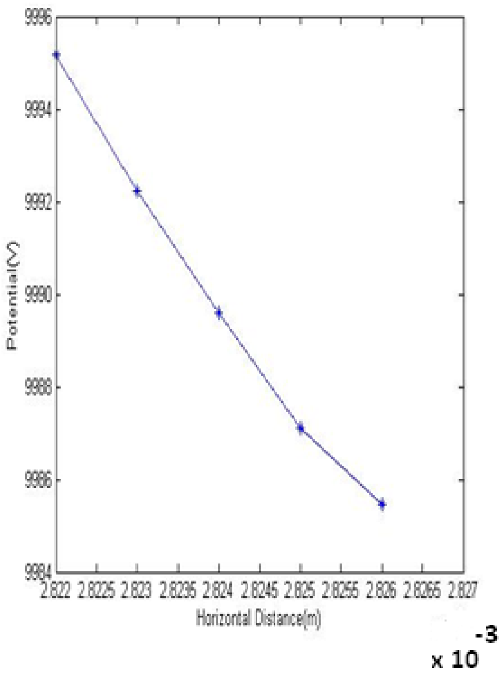

Figure 7: Potential distribution inside the water bubble for Capacitive graded cable 10kV

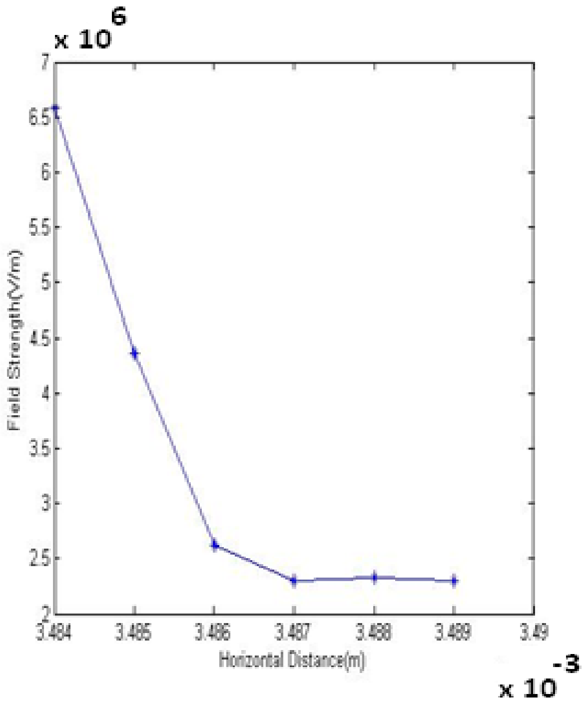

Figure 8: Field Strength on the curved surface water bubble for Capacitive graded cable 10kV

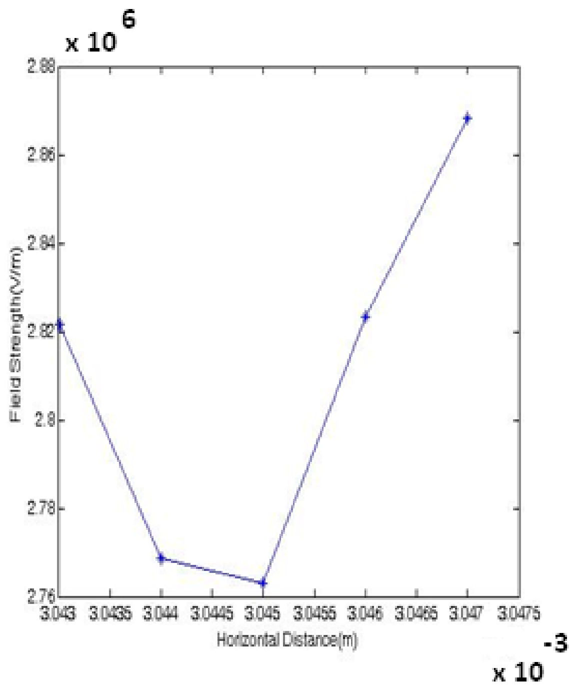

Figure 9: Electric Field inside the water bubble for Capacitive graded cable 10kV

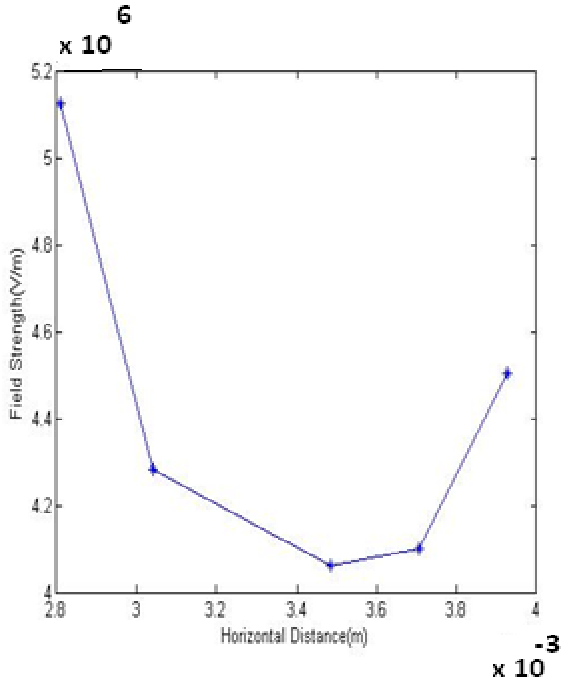

Figure 10: Field at the tip of the water bubble for Capacitive graded cable 10kV

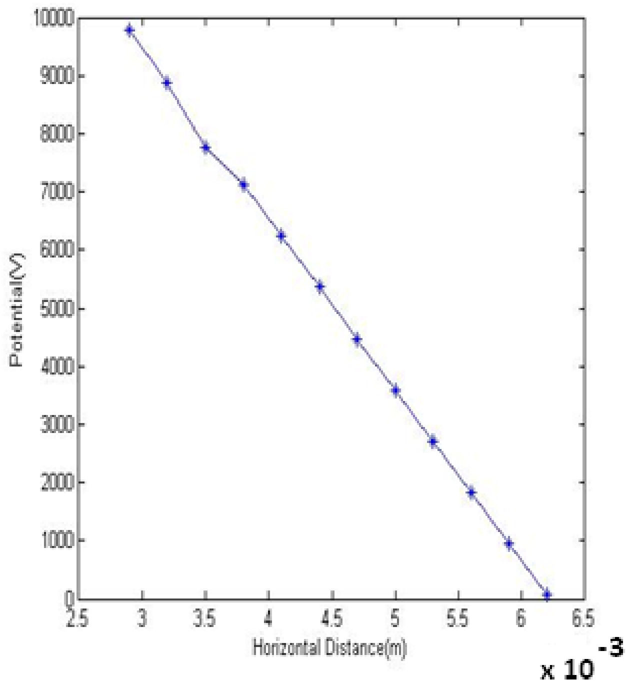

Figure 11: Potential distribution on the radial line for Capacitive graded cable 10kV

Table 1: Modeling data for capacitive grading for 10 kV cable

CABLE RATING	10 kV
Radius of conductor (r) m	0.0028209
Radius of power cable (R) m	0.0062209
Radius of the first insulation(r_1)m	0.0035632
Radius of the second insulation (r_2)m	0.0044153
Inner insulation thickness1 (r_1-r) m	0.00074
Inner insulation thickness2 (r_2-r_1) m	0.00085
Outer insulation thickness (R- r_2) m	0.0018056
Major axis of water particle a m	0.0000025
Minor axis of water particle b m	0.00000125
Inter-water particle space I_{wp} m	0.0002213
Total water bubbles present N_{wp}	98376
Water particles per radial line N_p	16

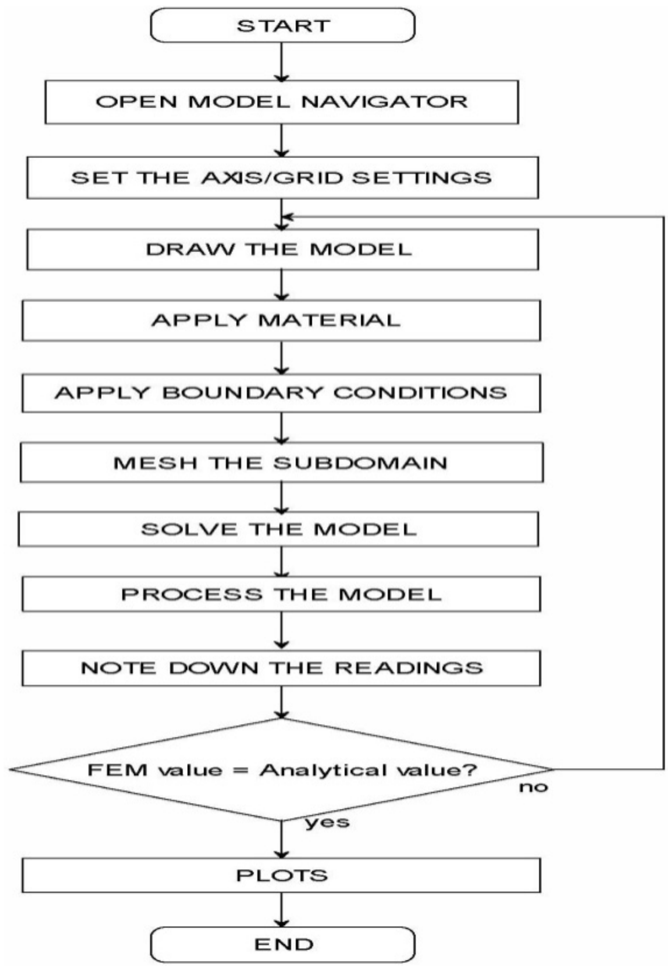

Figure 12: Sailing the model through comsol multiphysics

Simulation Results and General Discussion

Effect of different conditions of water void existence inside cable insulation is simulated in COMSOL Multiphysics 3.3 a. then the presented results are analysed. Fig, 5 shows a variation of electric field with the distance in dry capacitive graded cable for 10 kV. Here electric stress is made uniform in composite dielectric medium. Fig 6 shows potential distribution in dry capacitive graded cable. Here we plot potential (V) versus horizontal distance (m) and it can be shown that potential is inversely proportional to distance. The potential distribution inside the water bubble for capacitive graded is shown in fig 7 at a horizontal distance 2.822 mm potential is 9995V. The potential value reaches 9985 V at a distance 2.826 mm. From the graph it is clear that as we move from one end of the bubble to the other end potential value decreases. Fig 8 shows a plot of field strength on the curved surface water bubble versus horizontal distance in m. When the field strength (V/m) 6.5 kV/mm at a distance 3.484mm and it decreases till 3.487mm after that it becomes steady up to distance 3.489 mm. Fig 9 shows an electric field inside the water bubble for capacitive graded cable. Field strength is $2.82x10^6$ V/m at 3.043 mm and decreases till 3.045 mm is reached after that it increases to $2.87x\ 10^6$ V/m at a distance 3.047 mm. Fig 10 shows a field strength versus horizontal distance at the tip of water bubble. There are 16 water bubbles in a radial line and field strength decreases at the tip of water bubbles. Fig 11 shows a potential distribution on the radial line for capacitive graded cable 10 kV. For an insulation system which is waterless, the potential and field values have been decreasing in unequal steps from the conductor surface to the cable outer sheath. With water the field and equipotential lines show more divergence compared with the dry cases. The electric field at the tip of elliptically shaped water particles will be much higher and field will be heavily distorted in the vicinity of water bubble.

Conclusions

In this work a study of electric field and electric potential distribution in dry and wet cable insulation using Capacitive grading techniques for 10kV, power cables. For this purpose, the modeling procedures are endeavored using two-dimensional Finite Element - based model of the power cables. The modeling and simulation is carried out using Finite Element technique based software COMSOL MULTIPHYSICS. The cable configuration with adequate insulation materials having different permittivity are considered in this model. These models were used to compute the Electric field and potential distribution inside the insulation and the field enhancement at the tips of elliptical water particles. It was ascertained that the field enhancement is strongly subordinated upon the shape and quantity of the absorbed water particles. The potential and electric field were calculated for various cases; along the elliptical major axis between water voids, along the void curvature and inside the void. In this work it is shown that electric field is a function of void shape and number of water cavities inside cable insulation. The electric field is also function of edge curvature. The electric field will be maximum in sharp head of elliptically shaped bubbles.

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