Electric Field and Potential Calculation in 10, 15 and 20 kV Water Infested Power Cables

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***Abstract*— Power cables are used in the transmission network in cities and for overseas power transmission. The polyethylene cables used for medium voltage were vulnerable to breakdown due to water treeing. Water treeing significantly reduces the electric breakdown strength of the insulation. The presence of water tree results in the reduction of their dielectric strength. Here the finite element simulation technique is used to evaluate the electric field inside the 10 kV 15 kV and 20 kV power cables. A model that illustrates the water-dielectric interface within the cable insulation system is proposed. The link between the local field concentration in the vicinity of water void and the possibility of insulation failure, which can be developed to a complete breakdown is discussed.**

***Index Terms* – Electrical insulation, finite element, power cables, water absorption.**

I. INTRODUCTION

THE vital role of transmitting electric power between different areas in the power transmission network are performed by power cables. Ordinarily overhead lines are used for this task, but circumstantially power cables are the preferred choice of transmission component. For example, power cables are less sensitive to weather and environmental conditions and therefore more reliable than overhead lines. Power cables are eco-friendly and are less space devouring than overhead lines.

The presence of water inside the insulation material of the cables shortens the life of high voltage cables. This simply explains the fact that, after some years of introducing polyethylene cables (PE), electric breakdown due to ‘‘water trees’’ appeared [1,2].

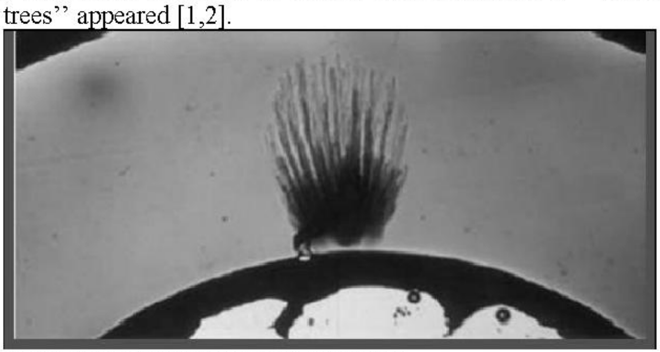

Fig. 1. Damaged insulation-water tree formation.

In this present work the aim is to create models of medium voltage power cables infested with water and to use these models to investigate the risk of water treeing. These models comprise regions of insulation material and water particles with elliptical geometric structure. The field computation program COMSOL Multiphysics 3.3a has been used for the modeling. The cables being modeled are 10 kV, 15 kV and 20 kV medium voltage power cables with Polyethylene insulator. The field enhancement as a function of sharpness of water particles is determined. The potential and field strength values throughout the insulation are calculated for cable under wet and dry conditions. The results for all the three power cables are used to demonstrate the mechanisms responsible for tree initiation and growth, which could be developed to cause breakdown inside the cable insulation.

II. MODELLING AND SIMULATION

A. FE Software

A 2D field computer software [3] is being used in the present study. This software provides automatic mesh generation for solving electrostatic and electromagnetic problems by a differential operator FE method. The computational properties of the Comsol Multiphysics software enable to plot the field and potential values at any boundary.

B. System Constellation

In order to study the electric field characteristics in cable insulation, the Comsol Multiphysics FE computer software is used to build a two-dimensional model for the cables under study as the investigated field lines are perpendicular to equipotential lines and directed from conductor to the outer sheath of the cable, a section made across the cable can illustrate the circumference and sharp edges of the ellipsoids aligned along these field lines.

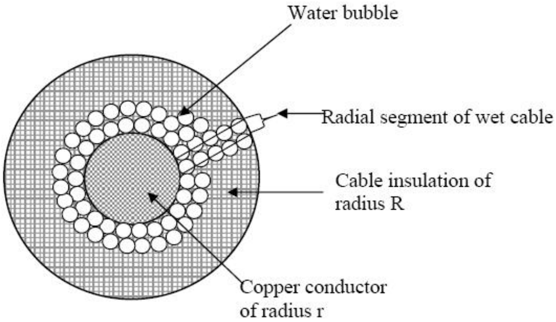

Fig. 2. Simplified proposed model of water content in the power cable

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TABLE I
CABLE CONFIGURATION

Rated Voltage (kV)	Conductor radius **r** (mm)	Insulation thickness I_t (mm)
10	2.8209	3.4
15	3.3378	4.5
20	3.7847	5.5

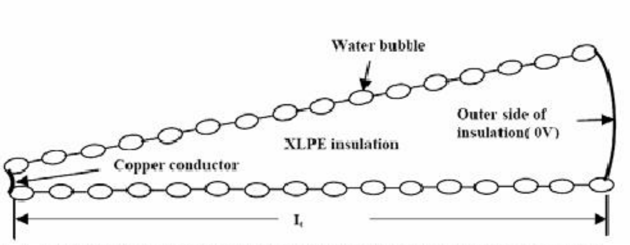

Fig. 3. Cable section containing water bubbles in symmetrical constellation.

Therefore, the investigation of field development at the ellipse sides and the determination of its enhancement at the sharp ends of the ellipsoids are achieved by inspecting the field distribution on the plane of cable section. The lateral component of electric field around the ellipsoid surface, which penetrates the cable depth has less value than that at the horizontal ellipsoid edges. The cable configurations used in the three case studies are tabulated in Table I shown above [4]. Each cable comprises of an inner Copper conductor and outer insulation of polyethylene which has a permittivity of 2.3.

It has been reported that the amount of water, which can be absorbed by cable insulation, varies in the range 2-6% of the total insulation volume [5], 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 [6]. It is taken here 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, these numbers have been ciphered to be as shown in Table II.

To assuage computation of electric field distribution, it is arrogated that the water bubbles are distributed radially along the lines emanating from the conductor surface to the outer surface of insulation, as demonstrated in Fig. 2. If it is arrogated that the elongation of water void to form an ellipse does not alter its area, the number of water voids per radial line can be ciphered as indicated in Table II. These numbers also satisfy the condition that bubbles adjacent to cable conductor and subsequent bubbles in the insulation will not overlap. Fig. 3 depicts how these bubbles are arranged to form sections of cable insulation restricted between pairs of rows of water voids. On the other hand, the electrostatic field analysis is simplified using this symmetrical model in which the total number of nodes and the triangular elements generated by the FE model are depicted in Table III above.

TABLE II
WATER VOIDS CONFIGURATION

Rated voltage(kV)	Water voids	voids/radial line
10	98376	16
15	160928	27
20	230021	38

TABLE III
FINITE ELEMENT LOG

Rated Voltage (kV)	Nodes generated	Elements generated
10	100	4537
15	158	6410
20	230	6802

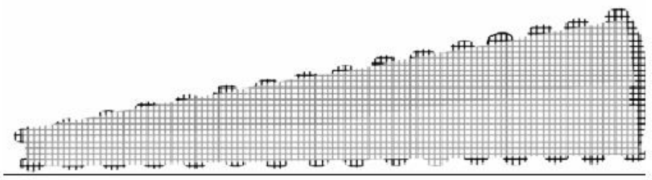

Fig. 4. Computational segment for FE simulation purposed.

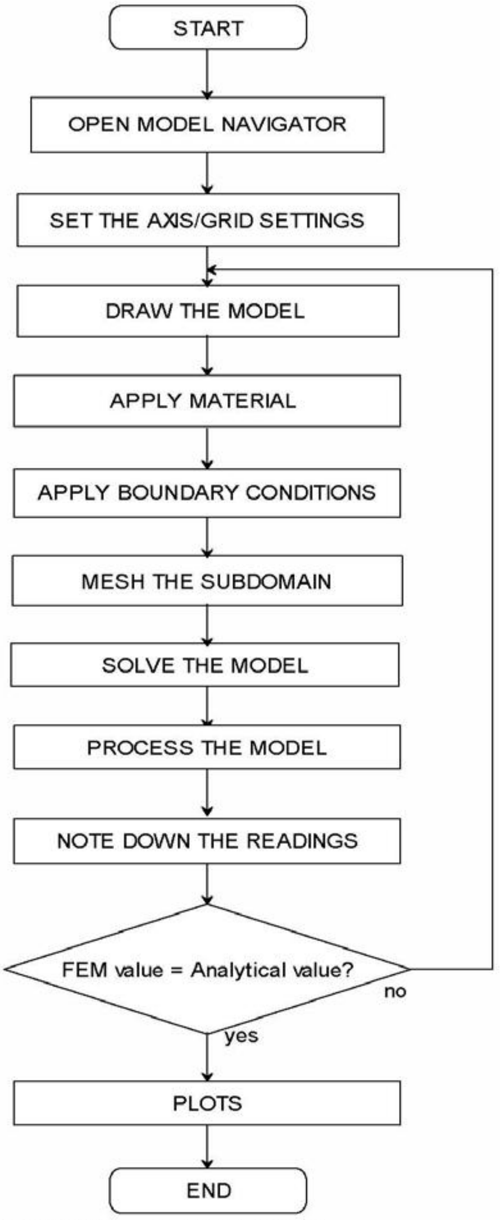

Fig. 5. Sailing the model through FE software.

The impact of cable insulation on the field distribution is dependent on the shape of water bubbles. Being in a non-uniform field, the spherical water particles are subjected to some elongation and therefore, they are considered to have elliptical shape [6]. Transition from spherical water particles with circular cross sectional area to the elliptical particles with a cross sectional area as given in equation 1 was performed without changing the cross sectional areas of the water particles. It is worth noting here that, the ellipticity of the water bubbles is strongly related to the applied electric field, whereas altering the bubble's area did not have a significant influence on the field strength. For simulation purposes and from symmetry point of view, it is sufficient to take the computation segment as shown in Fig. 4. Fig. 5 shows a flow chart for sailing the model through FE software.

$$\text{Area of ellipse} = \pi ab \qquad (1)$$

where a is length of major axis; b is length of minor axis

III. RESULTS

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. However, when the water particles are included within the insulation area, the field and equipotential lines show more divergence compared with the dry case. This non-uniform distribution of field and equipotential lines becomes more noticeable at the dielectric-water interface as the permittivity of the water is significantly greater than the dielectric. Fig. 6 depicts the field and potential lines arranged perpendicular to each other with refraction at the dielectric-water interface.

In this study investigation is done in the field distribution initially with a pure and dry insulation system. The field strength at the surface of the conductor is calculated as shown in Fig. 7, 8 and 9 for respective voltage ratings of the cables. It is in good agreement with analytical calculations of electric fields in such geometry.

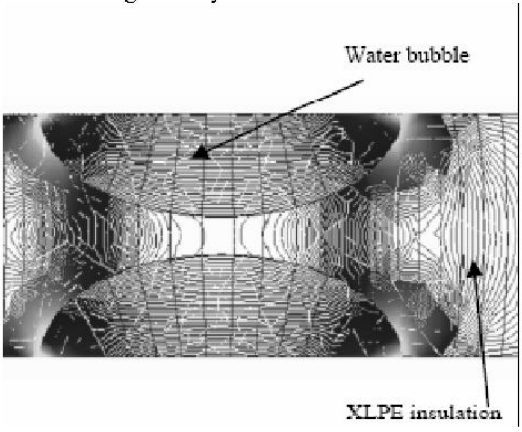

Fig. 6. Electric potential and field lines plot.

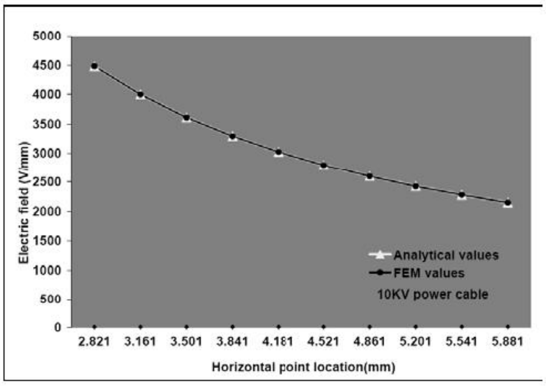

Fig. 7. Electric field variation in dry cable insulation.

When the water voids are sneaked in the cable insulation, the electric field at the tips of elliptically shaped water particles will be much higher. With a relative permittivity of water $\varepsilon_w = 80$ [6,7,8] compared with the cable insulation permittivity ($\varepsilon_{ins} = 2.3$) it is expected to find that the field is heavily distorted in the vicinity of water bubble.

To investigate the influence of the electric field distribution on the wet insulation of the cable, it was necessary to concentrate on one elliptical shape of water particles. The magnitude of the electric field was calculated for a number of points located in the symmetrical section. Fig. 10, 11 and 12 illustrate Potential distribution along the radial line connecting a number of water voids for 10 kV, 15 kV and 20 kV cables. Fig. 13, 14 and 15 illustrates the values of electric field at the tips of the radially lined water voids computed along the line connecting the water bubbles for respective voltage ratings of the cable. The field strength at the vicinity of the water particles is greatly intensified compared with that at the same location when the water particles are absent. With slight shift away from the sharp edge of the water particles, the field starts to decrease dramatically, and its variation from that in pure insulation becomes insignificant. The electric field strength around the circumference of the first elliptically shaped water void are depicted in Fig. 16, 17 and 18 for respective voltage

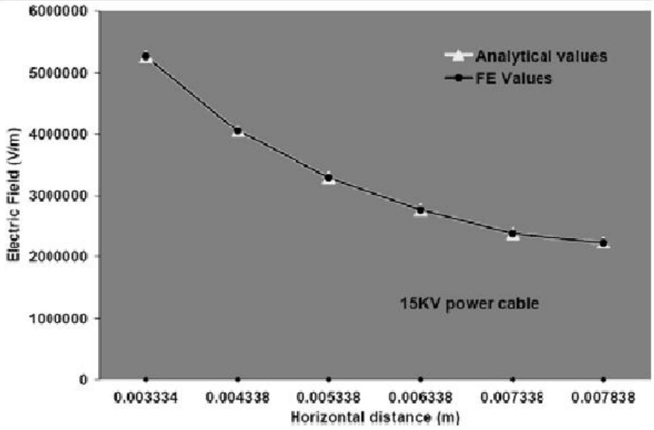

Fig. 8. Electric field variation in dry cable insulation.

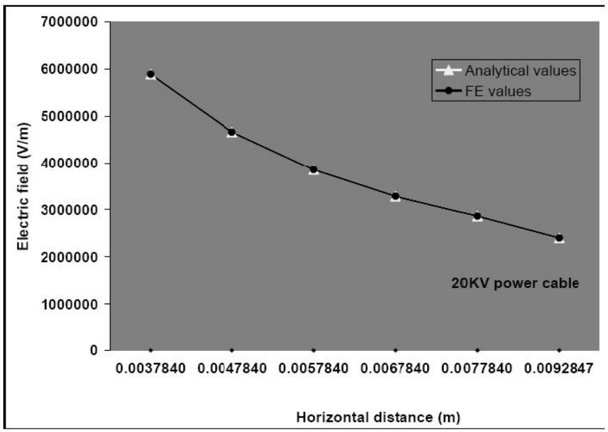

Fig. 9. Electric field variation in dry cable insulation.

ratings of the cables. The lowest value of this field corresponds to the middle point of the curved side at the vertex of this curvature. It is reasonable for the field to have the lowest value at this location, since it is the farthest point from the sharp ends of the elliptically shaped water particle. Regarding the field strength inside the water bubble, it is expected to be of a very low value, since the permittivity of the water is much higher (33 times) than the surrounding insulation. However, the degree in the slope of potential inside the water particles is slightly lower than in the enclosing insulation media. Fig. 19, 20, 21 and 22, 23, 24 clearly illustrate these findings for respective voltage ratings of the cables, where the graphs represent the change of the field and potential along the horizontal line of the major axis of the elliptically shaped water particle. Due to the symmetrical arrangement of the computation segment, the same values of potential and electric field were obtained on the corresponding points of the adjacent string of water particles.

IV. GENERAL DISCUSSION

A fundamental and vital role in the long term performance and reliability of cables is performed by the dielectric strength of insulating materials. Ordinarily, high voltage insulation is subjected to a wide range of problem that seriously threatens the service life of the cables. In the presence of an ac-applied field, water treeing occurs which may lead to the formation of electrical treeing and consequently breakdown of

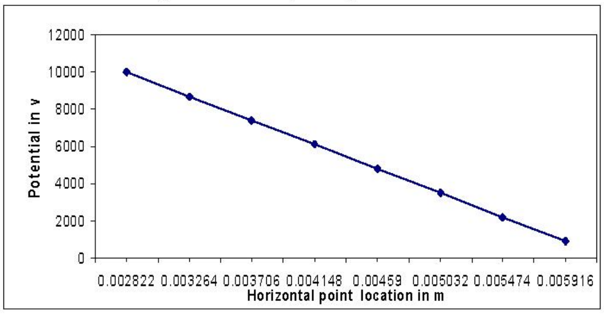

Fig. 10. Potential distribution along the radial line connecting a number of water voids (10 kV).

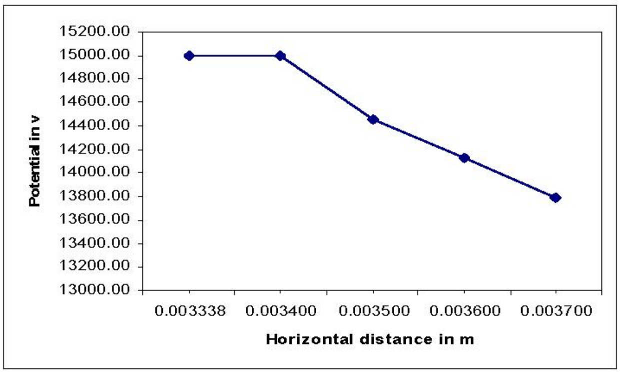

Fig. 11. Potential distribution along the radial line connecting a number of water voids (15 kV).

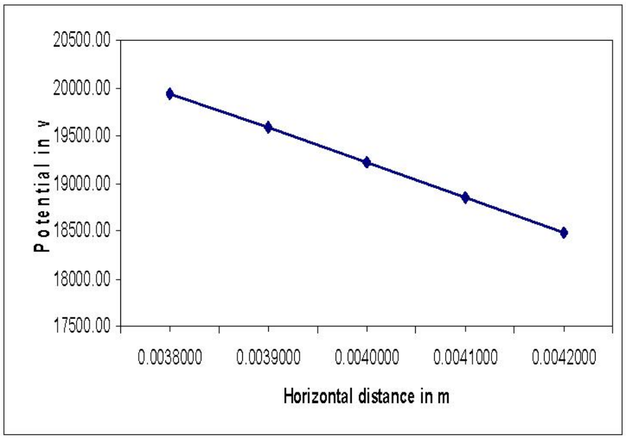

Fig. 12. Potential distribution along the radial line connecting a number of water voids (20 kV).

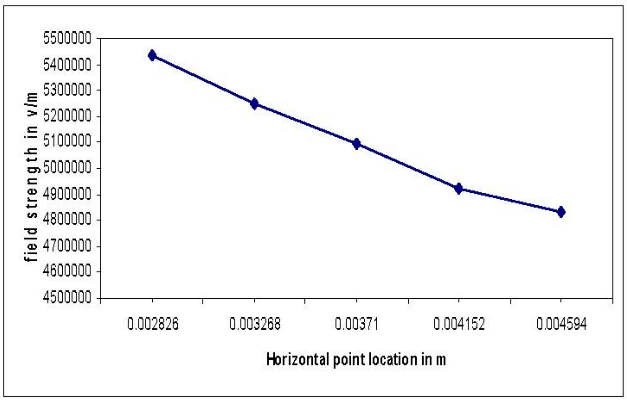

Fig. 13. Field strength at the tips of the radially lined elliptically shaped water voids (10 kV).

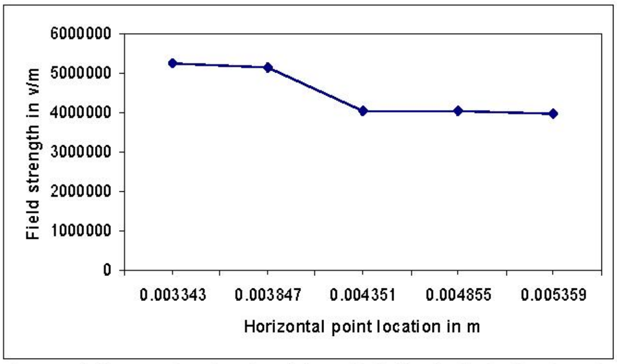

Fig. 14. Field strength at the tips of the radially lined elliptically shaped water voids (15 kV).

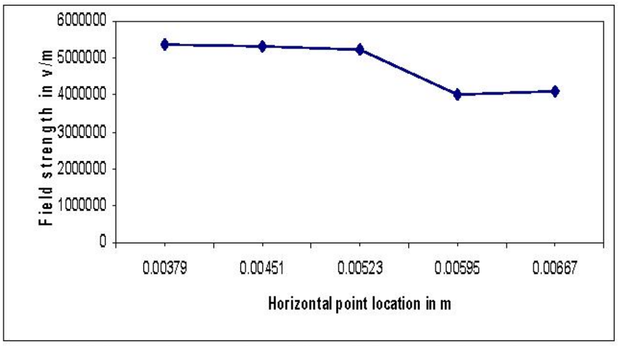

Fig 15. Field strength at the tips of the radially lined elliptically shaped water voids (20 kV).

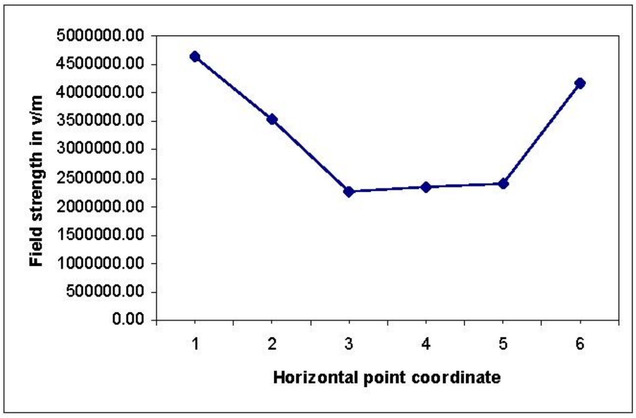

Fig. 16. Field Strength distribution on the curved surface of the elliptical shaped water void (10 kV).

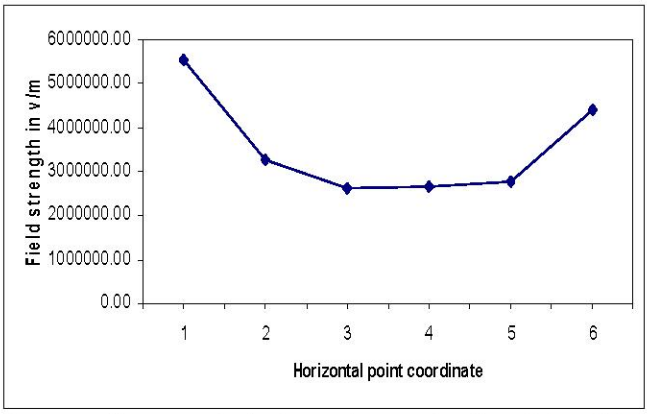

Fig. 17. Field Strength distribution on the curved surface of the elliptical shaped water void (15 kV).

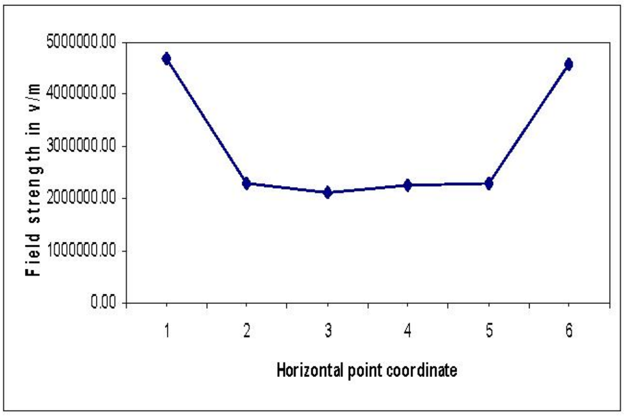

Fig. 18. Field Strength distribution on the curved surface of the elliptical shaped water void (20 kV).

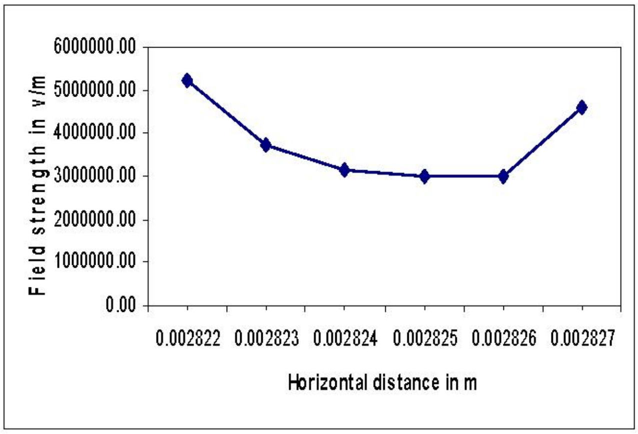

Fig. 19. Field distribution inside the elliptically shaped water particle (10 kV).

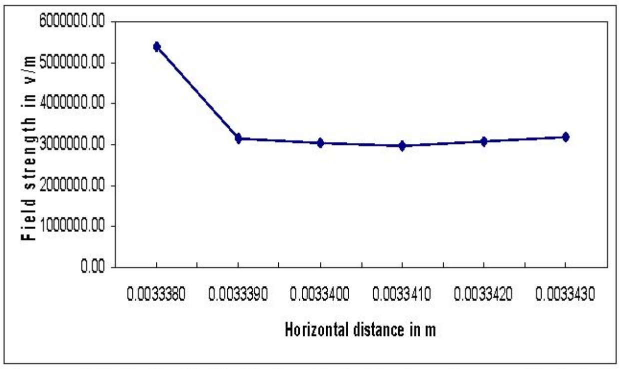

Fig. 20. Field distribution inside the elliptically shaped water void (15 kV).

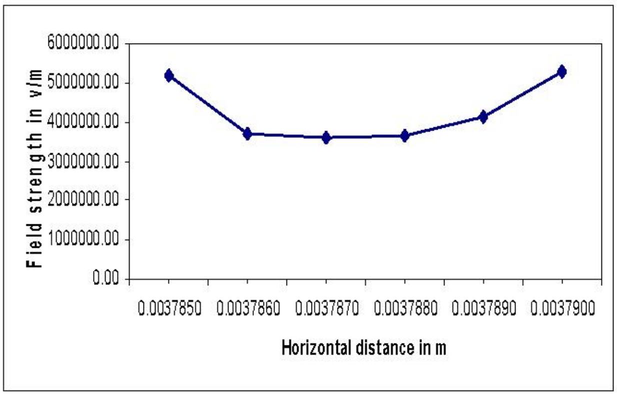

Fig. 21. Field distribution inside the elliptically shaped water void (20 kV).

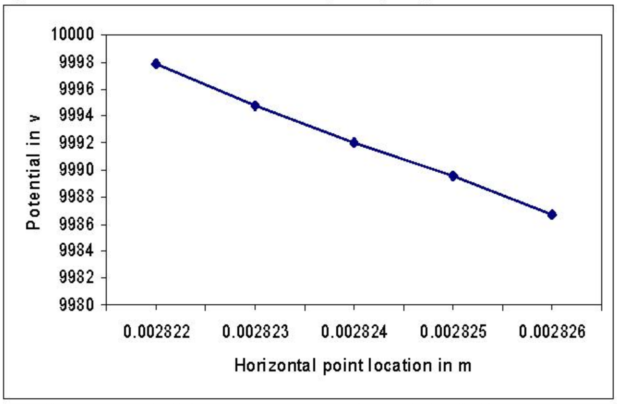

Fig. 22. Potential distribution inside the water particle (10 kV).

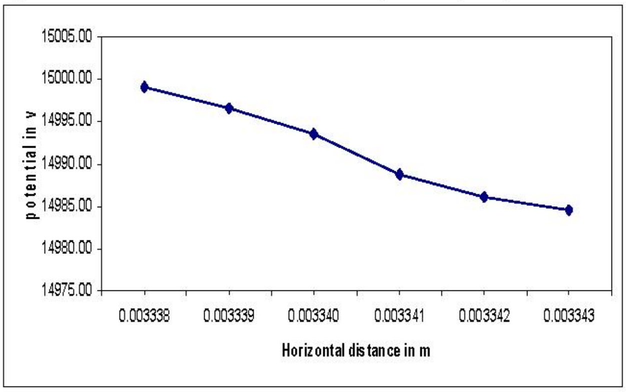

Fig. 23. Potential distribution inside the elliptically shaped water void (15 kV).

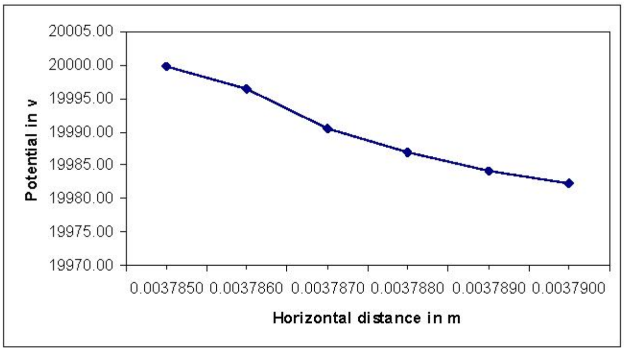

Fig. 24. Potential distribution inside the elliptically shaped water void (20 kV).

insulation. The concept of threshold for insulator materials [9, 10], is applied here. In this case limiting values of electric field must be reached in insulation to trigger microscopic damage to incept treeing process

These field values correspond to the threshold for a specific degradation mechanism. Therefore, the threshold for treeing process is not necessary to coincide with that of other degradation processes but it can be strongly related to it. In configuration of non-uniform fields, the maximum electric field is always higher than the average value. The value of this field is influenced by the shape of electrodes, the insulating material and the insulation system configuration. The presence of water particles in the non-uniform field gives rise to the elongation and shaping of these particles in elliptical form due to the polarization effect [11].The degree of deviation of these particles from the spherical shape is expected to be a function of the applied potential. However, the maximum field at the sharp edges of these elliptically shaped water voids is a function of the curvature of these edges. Equivalence between the obtained values of electric field illustrates that the highest electric field is the boundary one, acting in the direction of the major axis of the elliptically shaped water particles. According to the results obtained the electric field distribution in the dry insulation is not sufficient to cause failure for this insulation. This means that the presence of water was the responsible factor for this enhancement in field. If the enhancement of this field persists for a long time the chance of developing an electric tree in the insulation area is increased .For points located far from the curved edges of the elliptically shaped water voids, there is no significant difference in the field magnitude under dry and wet conditions.

However, the regions located in the vicinity of the sharp edges of the water particles, especially those close to the conductor surface and characterized by a high field are suitable points for tree initiation. The growth of such trees means a high field will be originated at the tip of the structural channels of these trees, which can inevitably affect those low-field areas with time. If the water absorption process continues, the number of water particles will increase and consequently the number of high-field regions also increases. With time, more space will be filled with water and the permutation of the generation of water voids increases.

V. CONCLUSIONS

In this analysis, a study of electric field and electric potential distribution in wet cable insulation for 10kV, 15kV and 20kV power cables are endeavored using two-dimensional Finite Element - based model of the power cables. The models were used to compute the field 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. Eventually, the role of the electric field in the power cable and the possible mechanisms of the insulation aging and breakdown due to water infestation are briefly addressed.

VI. REFERENCES

[1] H. Faremo and E. Ilstad, "Dissipation Factor and Water Treeing of WTR-XLPE Cable Insulation", 6th Intern. Conf. Dielectric Materials, Measurements and Applications, Manchester, UK, pp. 306_309, 1992.

[2] A. Eccles, L. A. Dissado, J. C. Fothergill and A. Houlgreave, "Water Tree Inception-Experimental Support for a Mechanical/ Chemical/ Electrical/ Theory", 6th Intern. Conf. Dielectric Materials, Measurements and Applications. Manchester, UK, pp. 294_297, 1992.

[3] Comsol Multiphysics Software package, Version 3.3a, December 2006, COMSOL Group Ltd., Stockholm, Sweden.

[4] E.W.G. Bungay and D. Mc Allister, "Electric Cables Handbook", Oxford University Press, B.S.P. Professional books, U.K, 1994.

[5] R. Neimanis, T. K. Saha and R. Eriksson, "Determination of Moisture Content in Mass Impregnated Cable Insulation Using Low Frequency Dielectric Spectroscopy", IEEE Power Engineering Society Meeting, Seattle, USA, pp, 463_468, 2000.

[6] H.S.B. Elayyan and M.H.Abderrazzaq, "Electric Field computation in wet cable insulation using Finite Element Approach", IEEE Trans.Dielectr. Electr. Insul, Vol. 12, pp 1125-1133,2005.

[7] M. Acedo, F. Frutos. M. Torres and J. C. Filippini. "The Cylindrical Capacitive Model for Water Treeing Degradation in Extruded HV Cables", IEEE 5th Intern. Conf. Conduction and Breakdown in Solid Dielectrics, Leicester. England. pp. 661_666, 1995.

[8] I. Radu, M. Acedo, J. C. Filippini. P. Nortingher and F. Frutos, "The Effect of Water Treeing on the Electric Field Distribution of XLPE", IEEE Trans. Dielectr. Electr. Insul., Vol. 7, pp.860_868, 2000.

[9] G. C. Montanari, "The Electrical Degradation Threshold of Polyethylene Investigated by Space Charge and Conduction Current Measurements" IEEE Trans. Dielectr. Electr. Insul., Vol. 7, pp. 309_315, 2000.

[10] M. D. Noskov, A. S. Malinovski, M. Sack, A. J. Schwab, "Self-Consistent Modeling of Electrical Tree Propagation and PD Activity", IEEE Trans. Dielectr. Electr. Insul., Vol. 7, pp. . 725_733, 2000.

[11] S. Capaccioli, M. Lucchesi, R Casalini, P. A. Rolla and N. Bona, "Effect of Water Inclusions on Charge Transport and Polarization in Porous Media", IEEE Trans. Dielectr. Electr. Insul., VoL 8, pp. 454_460, 2001.