Electric and Thermal Properties of Wet Cable 10kV and 15kV

K. Rajagopala*, K.P Vittal, Lunavath Hemsingh
Department of Electrical and Electronics Engg, NITK Surathkal, Mangalore, Karnataka, India
*corresponding author, e-mail: krbhat1964@yahoo.co.in, vittal_nitk@yahoo.com and lhmsr@gmail.com

Abstract
The increased temperature of the cable insulation with rising load currents, are known to accelerate the formation of water and electric trees in cables which ultimately lead to cables failure. There are several factors which will determine the thermal and electrical behaviour of a given wet cable installation. These include the assumed ampacity, the cable construction and circumstances of installation, the thermal properties of the surrounding soil and the electrical properties. The work presented in this paper involves the use of COMSOL multiphysics finite element software to develop an integrated electrical, thermal model with 5 micro meter and 2.5 micro meter water bubble radius. 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, potential and temperature distribution inside the 10 kV and 15 kV power cables. A model that illustrates the water-dielectric interface within the cable insulation system is proposed.

Keywords: FEM, COMSOL, electric field, temperature

Copyright © 2012 Universitas Ahmad Dahlan. All rights reserved.

1. Introduction
Underground construction could be a reasonable alternative to overhead in urban areas where an overhead line cannot be installed with appropriate clearance, at any cost. In suburban areas, aesthetic issues, weather-related outages, some environmental concerns, and the high cost of some ROWs could make an underground option more attractive. Underground transmission construction is most often used in urban areas. However, underground construction may be disruptive to street traffic and individuals because of the extensive excavation necessary. These construction limitations often increase the cost of the project. The trenching for the construction of underground lines causes greater soil disturbance than overhead lines. Overhead line construction disturbs the soil mostly at the site of each transmission pole. The presence of water within the insulation materials can only lead to forming water trees if a sufficient electric field exists. Therefore, many works have indicated that the initiation of water tree depends on the magnitude of electric trees and water availability [2].

In the present work, a model for medium voltage power cable is described based on the FE technique. This model comprises regions of insulation material and water particles with elliptical geometric structure for field and thermal model. 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 condition. The thermal model comprises temperature distribution throughout the cable structure. The significance of the simulation techniques in comparison with the actual experimental methods is highlighted. Finally, the results are used to demonstrate the mechanisms responsible for tree initiation and growth, which could be developed to cause breakdown inside the cable insulation. [1-2].

2. Research method
2.1 Comsol Multiphysics Software
Two-dimensional COMSOL MULTIPHYSICS software was used in the present study. This software provides automatic mesh generation for solving electrostatic, electromagnetic and Heat transfer problems by a differential operator FE method. The computational properties of the COMSOL are enabled.
i. field and potential values at any boundary to be plotted,
ii. the display of equipotential and field lines in meshed regions.

Detailed description of FE formulation principles and procedures can be found in the user manual of such a package is available in paper [3]. In our case two modules are used those are electrostatic and heat transfer module because electrostatic module consist of electric field and potential models and heat transfer module consist of temperature distribution in a cable.

2.2 System Configuration

In order to study the electric field, potential and temperature distribution 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 [4].

![Table 1. Cable Parameters](image)

<table>
<thead>
<tr>
<th>Voltage(kV)</th>
<th>Conductor radius(mm)</th>
<th>Insulation thickness(mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>2.8209</td>
<td>3.4</td>
</tr>
<tr>
<td>15</td>
<td>3.3378</td>
<td>4.5</td>
</tr>
</tbody>
</table>

![Figure 1. Proposed model of water content in the single phase power cable](image)

![Figure 2. Proposed model of water content in the three phase power cable](image)
Table 2. Cable Specifications

<table>
<thead>
<tr>
<th>Insulation</th>
<th>Relative permittivity $\varepsilon_r$</th>
<th>Thermal conductivity(k)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Impregnated Paper</td>
<td>3.6</td>
<td>0.05</td>
</tr>
<tr>
<td>water</td>
<td>80</td>
<td>0.12</td>
</tr>
</tbody>
</table>

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 two case studies are tabulated in Table I shown above [4]. Each cable comprises of an inner Copper conductor and outer insulation of paper which has a permittivity of 3.6. 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 3%. The Radius of the spherical water droplet varies in the range of 0.1 to 5 $\mu$m [6]. It is taken here to be 5 $\mu$m and 2.5 $\mu$m.

The 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 Figure 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 3. These numbers also satisfy the condition that bubbles adjacent to cable conductor and subsequent bubbles in the insulation will not overlap. Figure 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.

Table 3. Water Void Configuration

<table>
<thead>
<tr>
<th>Voltage(kV)</th>
<th>Bubble Radius($\mu$m)</th>
<th>Water Voids</th>
<th>Voids/radial line</th>
<th>Elements generated</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>5 $\mu$m</td>
<td>36891</td>
<td>6</td>
<td>3020</td>
</tr>
<tr>
<td></td>
<td>2.5 $\mu$m</td>
<td>147562</td>
<td>25</td>
<td>3523</td>
</tr>
<tr>
<td>15</td>
<td>5 $\mu$m</td>
<td>59804</td>
<td>10</td>
<td>5623</td>
</tr>
<tr>
<td></td>
<td>2.5 $\mu$m</td>
<td>241393</td>
<td>40</td>
<td>5292</td>
</tr>
</tbody>
</table>

To facilitate computation of electric field distribution, it is assumed that the water bubbles are distributed radially along the lines emanating from the conductor surface to the outer surface of insulation, as demonstrated in Figure 2. If it is assumed that the elongation of water particle to form an ellipse does not alter its area, the number of water bubbles per radial line, $N_p$, can be calculated from equation 1. Equation 2 gives the area of ellipse, which is assumed to be equivalent to a circular area of water bubble.
\[ N_p = \frac{0.5DM(r^2 - r_f^2)}{r_{wp}^2} \]  \hspace{1cm} (1)

\[ \Lambda_{\text{ell}} = \pi ab \]  \hspace{1cm} (2)

Where \( R \) is the outer Radius of the cable; \( r \) is the Radius of the conductor; \( M \) is the percentage of absorbed water; \( r_{wp} \) the Radius of the water particle; \( a \) and \( b \) are the major and minor axes of the elliptical shaped water particle. The parameter \( D \) is reported as a proportional value, relating that part of the circle restricted between two adjacent radial lines to the whole circle. According to the quoted values of conductor Radius and insulation thickness above, the number of water bubbles in each line is varied. This number also satisfies the condition that bubbles adjacent to cable conductor and subsequent bubbles in the insulation will not overlap.

![Elliptical shape of water bubble](image1)

Figure 4. Elliptical shape of water bubble

![Geometrical parameters of elliptically shaped water bubbles](image2)

Figure 5. Geometrical parameters of elliptically shaped water bubbles

The difference in the dimensions of the water bubbles and the surrounding dielectric, containing these bubbles, is significant. This mismatch in dimensions actually leads to some inconvenience in the illustration of the studied model and in the selection of the accurate subdivisions during meshing process of various regions of the model. The Figure 4 shows all water bubbles along with the radial line and individual elliptical water bubble shape consisting of minor and major axis.

![Meshing size variation according to the region size and shape](image3)

Figure 6. Meshing size variation according to the region size and shape.

Figure 6 shows different degrees of meshing size for adjacent regions of the present model. Also, it is extremely difficult to clearly show the field changes at all region boundaries as one plot in a complete representation. Therefore, the only way to illustrate these results is to focus on each boundary separately and then combine all boundaries using a suitable scale.

### 2.3 Boundary conditions:

The PDE is solved subject to the following boundary conditions:

\[ \text{Outer layer of cable} : \quad V = 0 \]  \hspace{1cm} (3)
Conductors \( V(t) = V_0 \cos(\omega t + \frac{2\pi n t}{3}) \) \hspace{1cm} (4)

Where \( n = 0, 1, 2 \) on the 2 dimensional domain represented by the cable cross section (Figure 3). \( V_0 \) is set at 10.15kV, \( \varepsilon_r \) is taken as 3.6 for the insulation.

The differential equation which is used to calculate the temperature in state thermal field is defined as equation [7]

\[-\nabla(K\nabla T) = Q + h(T_{ext} - T)\] \hspace{1cm} (5)

The boundary condition for the most outside interface is set to a certain temperature which is equivalent to the ambient temperature.

\[-\nabla(KT) = h(T_{ext} - T)\] \hspace{1cm} (6)

Likewise, the temperature in both materials at the border points must be the same [8]. For temperature distribution in a cable the ampacity of cable is required. The ampacity of cable which depends upon the temperature and losses.

![Flow chart for COMSOL multiphysics for obtaining solution](image)

Figure 7. Flow chart for COMSOL multiphysics for obtaining solution
3. Results and Discussion

When the insulation system is free of water, 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.

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 \(\varepsilon = 80\) [6] compared with the cable insulation permittivity \((\varepsilon_r = 3.6)\) 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. There are several factors which will determine the thermal behaviour of a given cable installation. These include the assumed ampacity, the cable construction and circumstances of installation, the thermal properties of the surrounding soil and the ambient temperature. The principal heat source in the problem is the Joule heat dissipated in the conductor(s). The transfer of this heat to the surroundings is governed by the geometry and material properties of the conductor, insulation, screening, sheathing and trench fill materials as well as the ambient conditions are shown in Figure 8. The thermal and electrical systems are coupled via the temperature dependence of the resistivity’s of the conductor and sheath materials [7].

![Figure 8. Temperature distribution in wet cable for 10kV water bubble radius5μm.](image)

In the normal operation of a cable, the heat loss, if any, is disregarded. However, the thermal instability, being a consequence of mismatch between steady state heat developed and dissipated, appears to be sensitive to omission of heat input function. The complexity arising out of the inclusion of this additional term is, admittedly, considerable. However, in order to be able to compute the temperature distribution to a higher degree of accuracy, it becomes necessary to take into account the heat input function despite mathematical complexity [10].
General discussion

The Electric field and thermal properties of wet cable is plotted here for two cases they are:

i. 10 kV operating voltage, 5 and 2.5 micro meter Radius of water bubble.
ii. 15 kV operating voltage, 5 and 2.5 micro meter Radius of water bubble.

The plots are plotted for each case considering

i. Electric field, potential and temperature distribution along the radial line connecting number of water bubbles.
ii. Electric field, potential and temperature distribution along the water bubble curve.
iii. Electric field, potential and temperature distribution along the tip of water bubble.
iv. Electric field, potential and temperature distribution inside the water bubble.

3.1. Electric field, potential and temperature distribution from conductor surface to water bubble

Figure 9, 10, 11 and 12 illustrates the values of electric field from conductor surface to outer sheath of radially lined water voids computed along the line connecting the water bubbles for 10 and 15 kV voltage ratings for case i. By observing these plots the field is maximum at conductor surface and then decreases towards the water bubble and the graphs are plotted with respect to horizontal distance from conductor to the sheath. Because the electric field varies with respect to distance i.e. electric field is inversely proportional to the distance squared [11].

3.1.1. Radius 5μm, 10kV and 15kV

![Electric field distribution for 10kV](image)

Figure 9. Electric field distribution along the radial line connecting number of water bubbles 10kV

![Electric field distribution for 15kV](image)

Figure 10. Electric field distribution along the radial line connecting number of water bubbles 15kV

3.1.2. Radius 2.5μm, 10kV and 15kV

![Electric field distribution for 10kV](image)

Figure 11. Electric field distribution along the radial line connecting number of water bubbles 10kV

![Electric field distribution for 15kV](image)

Figure 12. Electric field distribution along the radial line connecting number of water bubbles 15kV
Figure 13, 14 ,15 and 16 illustrates the values of electric potential from conductor surface to the radially lined water voids computed along the line connecting the water bubbles for 10 and 15kV voltage ratings for case i. By observing these plots the potential is maximum at conductor surface and then decreases towards the first water bubble and the graphs are plotted with respect to horizontal distance from conductor to the sheath. Because the electric field and electric potential are correlated each other in terms of Horizontal distance.

3.1.3. Radius 5μm, 10kV and 15kV

![Figure 13. Potential distribution along the radial line connecting number of water bubbles 10kV](image1)

![Figure 14. Potential distribution along the radial line connecting number of water bubbles 15kV](image2)

3.1.4. Radius 2.5μm, 10kV and 15kV

![Figure 15. Potential distribution along the radial line connecting number of water bubbles 10kV](image3)

![Figure 16. Potential distribution along the radial line connecting number of water bubbles 15kV](image4)

3.1.5. Radius 5μm, 10kV and 15kV

![Figure 17: Temperature distribution along the radial line connecting number of water bubbles 10kV](image5)

![Figure 18: Temperature distribution along the radial line connecting number of water bubbles 15kV](image6)
The temperature distribution from conductor surface to the radial line connecting water bubble is illustrated in Figure 17, 18, 19 and 20. The temperature at the vicinity of the water particles is greatly intensified compared with that at the same location when the water particles are absent. The maximum boundary condition of temperature at conductor surface is 363 K and outer sheath temperature is 293 K.

3.1.6 Radius $2.5 \mu m$, 10kV and 15kV

3.2 Field, potential and temperature distribution along water bubble curve

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 is depicted in Figure 21, 22 and 23 for respective voltage ratings.

3.2.1. Radius $5 \mu m$, 10kV and 15kV

Figure 19: Temperature distribution along the radial line connecting number of water bubbles 10kV

Figure 20. Temperature distribution along the radial line connecting number of water bubbles 15kV

Figure 21. Electric field distribution along the water bubble curve for 10kV

Figure 22. Electric field distribution along the water bubble curve for 15kV
3.2.2. Radius 2.5µm, 10kV

Figure 23. Electric field distribution along the water bubble curve for 10kV

3.2.3 Radius 5µm, 10kV and 15kV

The potential 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 potential starts to decrease dramatically, and its variation from that in pure insulation becomes insignificant. The potential around the circumference of the first elliptically shaped water void is depicted in Fig.24, 25, 26 and 27 for respective voltage ratings.

Figure 24. Electric potential distribution along the water bubble curve for 10kV

Figure 25. Electric potential distribution along the water bubble curve for 15kV

3.2.4 Radius 2.5µm, 10kV and 15kV

Figure 26. Electric potential distribution along the water bubble curve for 10kV

Figure 27. Electric potential distribution along the water bubble curve for 15kV
The temperature distribution along water bubble is illustrated in Figure 28, 29, 30 and 31. The temperature at the conductor surface to the first water bubble is more compared with temperature along water bubble curve i.e variations in temperature is very less. The maximum boundary condition of temperature at conductor surface is 363 K and outer sheath temperature is 293 K so the temperature is in the range of 328K in this case.

3.2.5. Radius 5μm, 10kV and 15kV

![Figure 28. Temperature distribution along water bubble curve for 10kV](image)

![Figure 29. Temperature distribution along water bubble curve for 15kV](image)

3.2.6. Radius 2.5μm, 10kV and 15kV

![Figure 30. Temperature distribution along water bubble curve for 10kV](image)

![Figure 31. Temperature distribution along water bubble curve for 15kV](image)

3.3 Field and potential distribution along tip of water bubble.

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 lowfield 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.

The electric field distribution from conductor surface is higher compared with electric field along the tip of the water bubble. Here for different cases number of water bubbles are varied depends on water bubble radius thus electric field is calculated each end point of every bubble i.e tip of the water bubble. Initially at conductor surface is higher for every water bubble field distributes with gradual change. Thus the change in field and potential is shown in Figure 32, 33, 34, 35 and 36.
3.3.1. Radius $5\mu m$ and $2.5\mu m$, 10kV and 15kV

Figure 32. Electric field distribution along tip of the water bubble curve for 10kV

Figure 33. Electric field distribution along tip of the water bubble curve for 15kV

3.3.2: Radius $2.5\mu m$, 10kV and 15kV

Figure 34. Electric field distribution along tip of the water bubble curve for 10kV $2.5\mu m$

Figure 35. Electric potential distribution along tip of the water bubble curve for 10kV

Figure 36. Electric potential distribution along tip of the water bubble curve for 15kV, $2.5\mu m$
4. Conclusion

In this paper a study of electric field, electric potential and temperature distribution in wet cable insulation for 10 kV and 15 kV power cable are endeavoured using two-dimensional finite element based models of the power cables. These models were used to compute the electric field and temperature distribution inside the insulation and the field enhancement at the tips of elliptical water particles. According to the results, we can see that the temperature in the conductor core of cable is more. This is due to the power losses in the conductor. The temperature decreases when we come to the outer sheath of the cable. It is showed that the highest distribution in the conductor while the cable insulation near grounded showed lower distribution of temperature as according to given boundary condition. It was ascertained that the field enhancement is strongly subordinated upon the shape and absorbed water particles. Eventually, the role of electric field in the power cable and the possible mechanisms of the insulation aging and break down due to water infestations are briefly addressed.

References:

[7]. Peter A Wallace, Donald M Hepburn, Chengke ZHOU, Mohamed Alsharif. Thermal response of a three core belted piless cable under varying load conditions. CIRED 20th International Conference on Electricity Distribution Prague, 2009: 8-11.