Modeling the Effect of a Water Tree inside Tape Shield and Concentric Neutral Cables

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Abstract:
COMSOL Multiphysics® software is used to model a water tree in two common types of cables, tape shield and concentric neutral. COMSOL allows for the effect on electric field intensity and electric potential due to the water tree to be better understood and for the observation of the increase in the electric field at the tip of the water tree, which is what causes the continuing dielectric breakdown. Also, COMSOL is used to calculate the resistance and capacitance of a section of cable with a water tree as it grows across the insulation. This paper proposes to use COMSOL to show the effect of the water tree on the electric field and electric potential and determine the values of the lumped parameters of the water tree for two common types of cables, tape shield and concentric neutral.

Keywords: Underground cable, Water tree.

1. Introduction

A water tree is a phenomenon that forms in the insulation of underground cables and is one of the main reasons for cable failures [1]. A water tree grows from some imperfection in the insulation shield interface, which causes the electric field to increase. This increase causes the insulation to break down and form microfractures. These microfractures fill with moisture and increase the electric field, thus continuing dielectric breakdown of the insulation. It is difficult to understand or show the increase in the electric field. Water treeing is simulated in a tape shield and concentric neutral cable using COMSOL Multiphysics in order to understand the increase in electric field and to determine the value of the lumped components of the water tree. COMSOL is beneficial for cable simulation because the effect on the electric field and electric potential inside the cable insulation can be observed due to a water tree. It also allows for the changing of the electric field and electric potential to be observed as the water tree crosses the insulation. With this knowledge, we can observe the high electric field caused by the sharp tip of the water tree that causes dielectric break down and the water tree to continually grow.

2. Water Tree Properties

There are several properties of the water trees that need to be defined before one can be modeled in COMSOL for simulation. First is the shape of the water treed region. This is important because the shape will determine how the electric field surrounding the water treed region will be affected. Also, the shape must match the shape of water trees that are growing from the outside of the cable toward the conductor, since these are the most dangerous water trees to cables due to the fact that they have an endless amount of moisture to grow. The second property of water trees that needs to be defined is the electrical conductivity of the water treed region. Since there is ingress of water, which has a higher conductivity than XLPE, the value of the conductivity in the region will vary. Finally, the relative permittivity of the water treed region will vary in a way that is similar to the electrical conductivity. Once these properties are known, a water tree can then be modeled in COMSOL.

2.1 Single Spheroid Model

In 2012 Z. Wang from University of California looked at a single ellipsoid in the middle of the dielectric insulation [2]. This was done in order to see the effect on the electric field and electric potential in the insulation due to a single ellipsoid with different electrical properties. This simulation is repeated in order to better understand the effect of water trees. A spheroid with an aspect ratio of 2.5 and length 10 μm is placed in an insulation material with a constant electric field of 2 MV/m. The spheroid's electrical conductivity is set to 5×10^{-2} S/m [2] and the insulation's electrical conductivity is set to 1×10^{-15} S/m, the electrical conductivity of XLPE. The spheroid's relative permittivity is set to 5 [2] and the insulation's relative permittivity is set to 2.3, the relative permittivity of XLPE. The results from the COMSOL simulation are presented in Figure 1.

These results show that the single droplet with the specified electrical properties is similar to a conductor in an insulation material. This is because of the increase of the electrical conductivity from the water located in the spheroid. Also, the electric field, shown here as read arrows, is perpendicular at the surface of the spheroid, which is the same as a conductor dielectric interface. Furthermore, the electric field increases at the tips of the spheroid and decreases around the straight edges. This is consistent with the way that the water trees grow from the sharp points and discontinuities and not from the smooth surfaces. Since the ellipsoid acts as a conductor, the electric field inside the ellipsoid is very small compared to the electric field in the insulating material. Because of this, the electric potential does not change inside the spheroid due to the nonexistent electric field. From this simulation it can be concluded that the increase in conductivity alters the electric field around the water tree and the shape of the water tree amplifies the electric field at its tip.

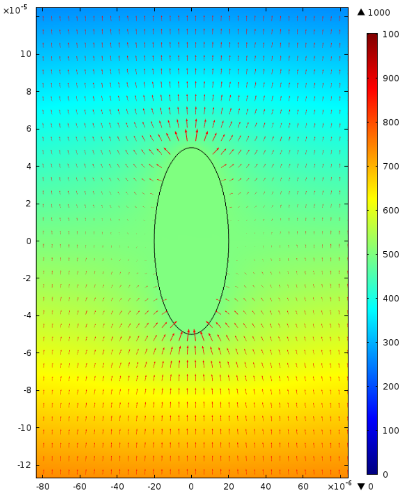

Figure 1: A single droplet of water tree in insulation with constant electric field

2.2 Water Tree Shape

The shape of the water tree model must match the shape of the type of water trees which are growing from the outside of the cable toward the conductor. Because the electric field pulls the moisture from the outside of the cable toward the conductor, the shape of these water trees is long and thin. To match this structure an ellipsoid is chosen to represent the vented water trees as seen in Figure 2. For simulation in COMSOL 10% of each end was removed to match the FEA done by ongoing research by a Clemson University Ph.D. candidate using MATLAB.

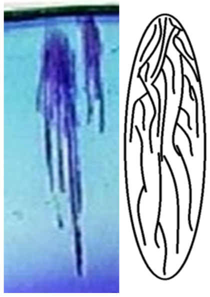

Figure 2: Single water tree and ellipsoid representation

2.3 Electrical Conductivity of Water Trees

The electrical conductivity inside the water tree ellipsoid is not going to be a constant value. This is due to the fact that the water tree is not a water filled ellipsoid in the insulation, but instead, it is a number of micro-cavities filled with water. Therefore, because water has such a higher conductivity than XLPE the conductivity will increase. It was shown in 2001 by T. Toyoda that the conductivity of the water treed region is found to be greater than 10^{10} times the conductivity of healthy XLPE [3]. However, the experiments were performed on square slabs of XLPE and the water trees were grown uniformly in the laboratory. Since field-aged water trees have the shape as seen in Figure 2, the conductivity will vary throughout the entire region due to the varying density of water channels inside the water tree. The edge of the water treed region's conductivity will be the same as the insulation's due to the fact that there is no water channels located in this area. The initiation point of the water tree is the most densely populated with water channels and will have the largest conductivity. Since the goal of this research is to model water trees formed in the field, the maximum conductivity will be 10^{10} times the conductivity of XLPE. Due to the disperse nature of the water tree channels, the conductivity is varied linearly from the initial defect to the healthy insulation. The electrical conductivity can be seen in Figure 3.

2.4 Relative Permittivity of Water Trees

Similar to the electric conductivity, the relative permittivity will not be constant throughout the entire water treed region. It has been shown in 2001 by M. Acedo that the maximum value of the water treed region's relative permittivity is three times the insulations relative permittivity [4]. It was also shown that there is no difference in the electric field if the water treed region's relative permittivity has a decreasing concave (exponential) permittivity, linear permittivity, or convex (logarithmic) permittivity [4]. Therefore, a linear permittivity was used, which is very similar to the electrical conductivity. However the maximum value is three times the relative permittivity of XLPE [4]. The relative permittivity can be seen in Figure 3.

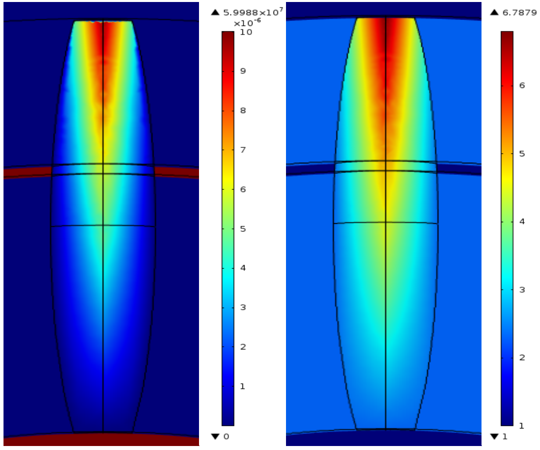

Figure 3: Electrical conductivity and relative permittivty of water tree in COMSOL

The equation for the water tree's electrical conductivity and relative permittivity are shown in equation 1 and 2 below, respectively.

$$\varepsilon = \frac{(3\varepsilon_{XLPE} - \varepsilon_{XLPE})}{wt_L} \times [y - (Jacket_r - wt_L)] \times \left(1 - \frac{\sqrt{x^2 + z^2}}{\frac{wt_w}{2}}\right) + \varepsilon_{XLPE} \tag{1}$$

$$\sigma = \frac{(1^{10}\sigma_{XLPE} - \sigma_{XLPE})}{wt_L} \times [y - (Jacket_r - wt_L)] \times \left(1 - \frac{\sqrt{x^2+z^2}}{\frac{wt_w}{2}}\right) + \sigma_{XLPE} \tag{2}$$

Where:

- $\varepsilon_{XLPE} = 2.3$
- $\sigma_{XLPE} = 1 \times 10^{-15}$
- $wt_L = Length\ of\ water\ tree$
- $Jacket_r = radius\ of\ the\ cable\ jacket$
- $wt_w = width\ of\ the\ water\ tree$

The equations were formed with a linear decrease from the initial start of the water tree to the tip in the y-axis direction and with a linear decrease from the value of permittivity in at the center of the water tree to the edge of the water tree in the x-axis and z-axis direction. The water tree ellipsoid had an aspect ratio of 5, which makes it thinner than the water droplet performed earlier. Because of this it matches the thinner water trees that have been observed in field aged cables.

3. Water Tree Model in Cables

There are two types of cables that the water tree will be modeled with: a tape shield cable and a concentric neutral cable. The reason these two cables were chosen is because future research will involve implementing water trees into a distribution feeder in Myrtle Beach, South Carolina, which contains these two types of cables. These two types of cables are both manufactured by Prysmian. The tape shield cable is 750 kcmil, with XLPE insulation, a copper tape shield, and a stranded aluminum conductor. The concentric neutral cable is a 1/0 AWG, three phase cable, with XLPE insulation, six copper concentric neutral wires and a stranded aluminum conductor. The type of cables was given by a utility company in South Carolina and their parameters are taken off of Prysmian data sheets. The COMSOL models of the two cables are presented in Figure 4.

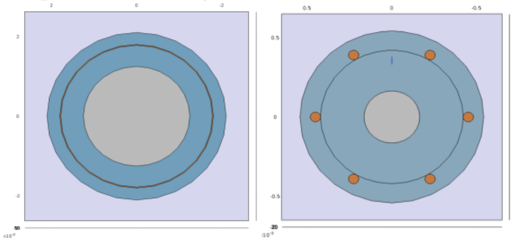

Figure 4: 750 kcmil tape shield cable and 1/0 AWG concentric neutral cable

The method for modeling the tape shield cable and concentric neutral cable in COMSOL is done through the Magnetic and Electric Fields physics branch and the Electric Circuit physics branch. The cables must be surrounded by an air medium in order to perform the simulation. This allows the magnetic field to pass outside the cable for proper calculation of magnetic and electric field. The terminals of the cables were connected to a circuit, which allows for a current to be injected into the cable and to place a voltage between the conductor and shield or neutral wires. Therefore, the electric field will then flow through the insulation. This would allow for the observation of the effect of the water tree on the electric field, as well as give the ability to see the amplification of the electric field at the water tree's tip.

A simple electrical circuit was formed with a 20 kV AC source with a 50 kΩ resistor. It was connected to a 150 kΩ load resistor through the cable being simulated, tape shield or concentric neutral. This circuit was formed to make the voltage across the cable 15 kV. The color scale for the electric potential for the following figures is shown in Figure 5. The next section will consists of the results from COMSOL for the tape shield cable and explain the images produced. Then the results for the concentric neutral cable will precede that section.

3.1 Tape Shield Cable Results

For the next couple of figures, the surface plot is the electric potential of the conductor, insulation and ground and, the red arrow plot is the electric field in the insulation. Figure 5 shows the color scale of the electric potential for the tape shielded cables.

Figure 5: Electric potential scale for following figures

First, however, a healthy cable is simulated in order to see the voltage potential through the insulation and the electric field lines from the conductor to the tape shield. This is displayed in Figure 6.

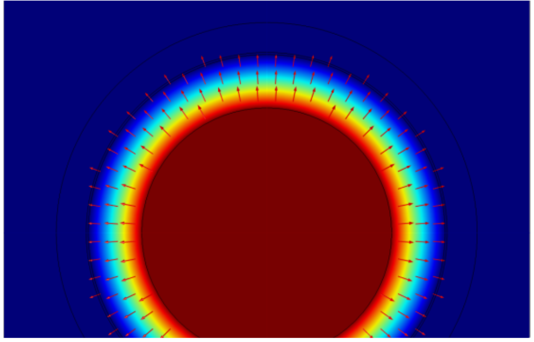

Figure 6: Tape shield cable with no water tree

Figure 6 shows that the conductor is at the maximum potential at about 15 kV and the electric potential reduces constantly until it reaches the grounded tape shield. Outside of the grounded tape shield, the voltage is nearly zero. This is due to the fact that the electric field is being contained by the tape shield, since the tape shield is acting as a Faraday cage and keeping all the electric field inside the cable. Next, a water tree is added to the cable where it is 50% across the width of the insulation. This value was chosen because smaller than this does not have as much effect on the electrical field. It is shown in Figure 7.

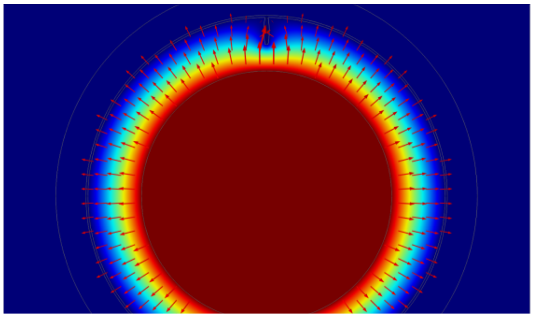

Figure 7: Tape shield cable with water tree crossing 50% of the insulation

With the water tree inserted into the cable, it can be seen that the electric field surrounding the water tree is beginning to bend toward the water tree. Since the water tree is small, it is not amplifying the electric field yet, so therefore the growth of the water tree will be slow. Also, since the water tree is grounded by the tape shield, the electric potential will be almost zero inside the water tree due to its increased conductivity. Next, the water tree is grown to 70% across distance between the cable and conductor and is shown in Figure 8.

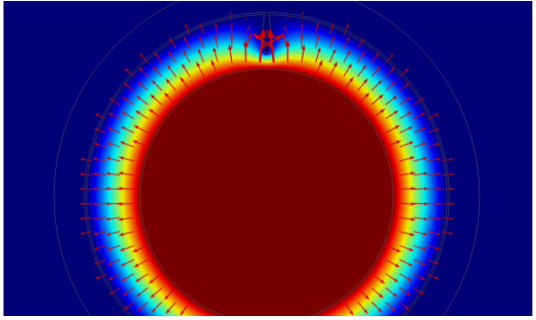

Figure 8: Water tree at 70% across tape shield insulation

Notice the water tree is now causing the electric field to increase. It is not a dramatic increase, but it is still more than the electric field at other locations. Also, the electric potential inside the insulation is becoming distorted due to the water tree and the reduction of the electric field around the sides of the water tree. Now that the electric field is increasing at the tip of the water tree, the insulation will start to break down more quickly and the speed of the growth of the water tree will increase due to the higher electric field. Next, the water tree has grown to 90% across the difference of the cable and the conductor, and is shown in Figure 9.

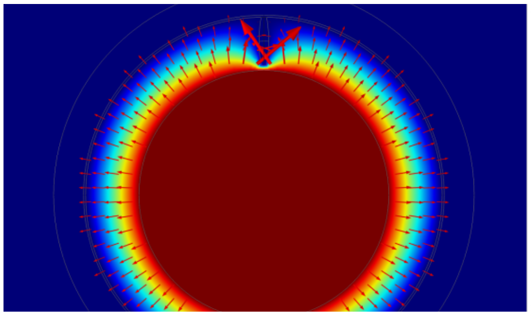

Figure 9: Water tree 90% across the insulation in tape shield cable

With the water tree crossing 90% of the insulation, the amplification of the electric field at the tip is significantly greater than the normal electric field of the cable. This will cause the insulation at the tip to breakdown very fast. Therefore, the water tree will grow with very fast speeds until it reaches the conductor. Even though the water tree is very close to the conductor, there is no drastic change in the voltage, and it remains approximately 15 kV or the rated voltage. Therefore, traditional SCADA units are not capable of determining whether there is a water tree in the cable, since the water tree will cause no deviation of voltage magnitude. Finally, the water tree has grown 100% across the insulation and is touching the conductor as shown in Figure 10.

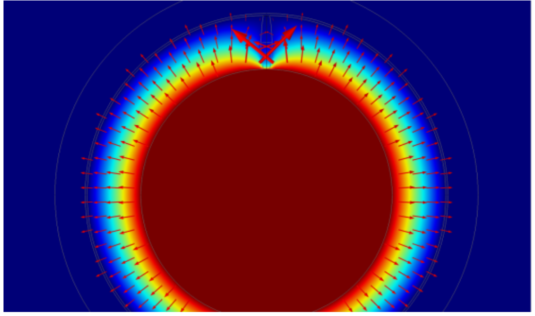

Figure 10: Water tree 100% across the insulation in tape shield cable

Now that the water tree has reached the conductor, the electric field is about the same as it was when the water tree was at 90%. At this point the water tree is going to start increasing the density of channels at the tip of the water tree and store electrons for the growth of electrical trees. Notice that even though the water tree is touching the conductor there is no voltage break down. This phenomenon, that water trees do not cause voltage breakdown, was stated previously in 2012 by William A. Thue in Electrical Power Cable Engineering [1]

3.2 Concentric Neutral Results

The plots of the concentric neutral cable are set up the same as the tape shield cable except that the electric potential across the conductor and neutral wires is 10 kV. This was done to know whether the effects were voltage dependent. Figure 11 shows the color scale of the electric potential for the concentric neutral cable.

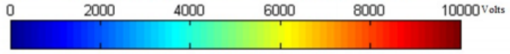

Figure 11: Color scale of electric potential for the concentric neutral cable

Also, with the concentric neutral there are two scenarios for the water tree's location. First is that the water tree is not touching one of the concentric neutrals and the second is that it is touching one of the concentric neutrals.

3.2.1 Ungrounded Water Trees

First a healthy cable is simulated in order to explain the difference between tape shield and concentric neutral cables electric potential and electric field lines. It is shown in Figure 12.

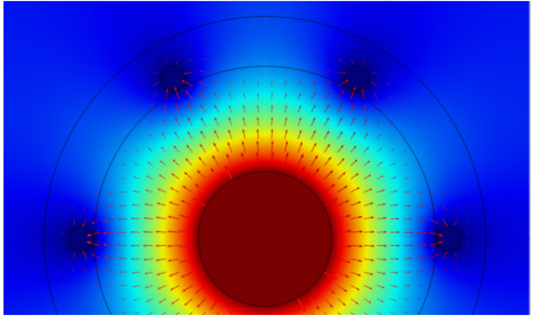

Figure 12: Healthy concentric neutral cable

The electric field lines in the concentric neutral are perpendicular to the conductor but then start angling toward the concentric neutral wires outside of the insulation. The concentric neutral wires still act as a Faraday cage in comparison to the outside of the cable. However, they allow for places in between the neutral wires to have some electric potential. This electric potential can cause different effects with the water tree and that is the reason that there are two scenarios for the location of the water tree. Next, a water tree is placed at 50% growth across the insulation since there is not much effect of the electric field when the water tree is smaller. In the first scenario the water tree is not touching the conductor. It is shown in Figure 13.

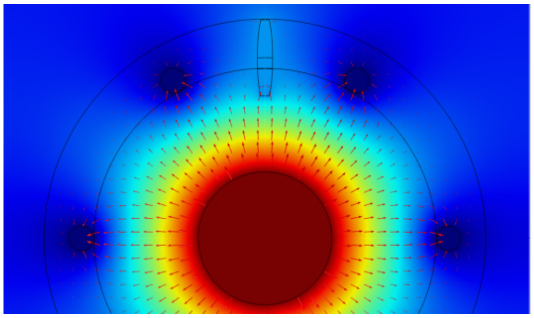

Figure 13: Water tree 50% across insulation for concentric neutral cable not grounded

The water tree in the concentric neutral cable that is unground is very different than the water tree in the tape shield cable. In a concentric neutral cable at 50% you can see that the electric field lines are starting to angle toward the water tree. However, the more interesting aspect of this water tree is the electric potential inside the water tree. Now that the water tree is ungrounded, and because of the fact that it acts as a conductor, the electric field is very small inside the water tree. Therefore, its electric potential becomes the same as the highest electric potential in the water tree. This will be seen more in the next plot when the water tree has grown to 70% across the insulation, as located in Figure 14.

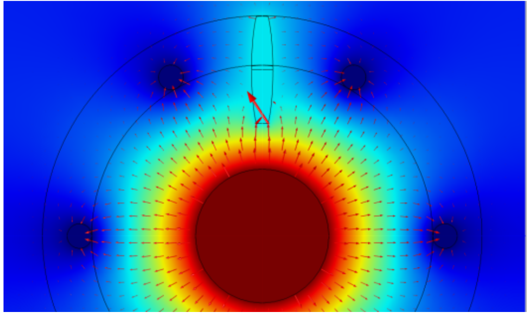

Figure 14: Water tree 70% across insulation in concentric neutral ungrounded

Once the water tree has grown 70% across the insulation, the effect on the electric field has started to increase. At the tip of the water tree the electric field is increased in comparison with the nominal electric field. The electric field in the concentric neutral cable is increased by the water tree a lot more than the tape shield cable due to the fact that the water tree at 70% is much larger in the concentric neutral. This is because the conductor of the tape shield proportionally is much bigger; thereby the amount that the water tree can grow reduces. However, it also means that water trees will grow faster in the concentric neutral cables. Now that the water tree is bigger, the electric potential inside the water tree has increased and it is causing the electric potential outside the cable to be non-zero. This is dangerous and for three-phase cables can affect the other phase cables mutual or self-inductance or capacitance. Next, the water tree will be shown at 90% across the insulation in Figure 15.

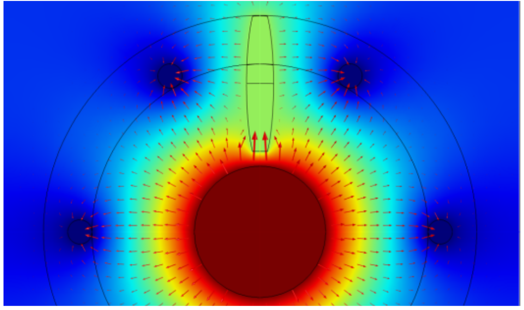

Figure 15: Water tree 90% across insulation in concentric neutral ungrounded

The water tree has now reach 90% across the insulation and is about to touch the conductor. Just like in the tape shield, there is no voltage difference that is able to be detected by SCADA. Also, like in the tape shield, the electric field has increased at the tip. However, now the water tree is at a high potential and is acting as a conductor, and there is now electric field flowing from the water tree to the neutral wires, causing an electric potential between the two. Furthermore, there is electric field flowing out of the cable and it is not a small amount of electric field, either. This can start to affect the surrounding cables and their characteristic properties, such as self or mutual capacitance or inductance. Finally, the water tree has grown across the entire insulation and is touching the conductor as seen in Figure 16.

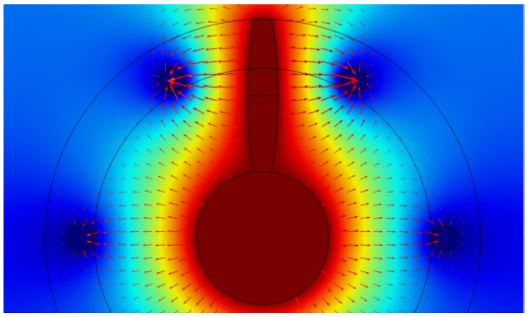

Figure 16: Water tree 100% across insulation in concentric neutral ungrounded

With the water tree finally breaching the insulation, it is touching the conductor. Because it is not grounded anywhere it is at the same potential as the conductor. This situation allows for large amounts of electric field to be flowing between the water tree and the neutral wires surrounding it. It also allows for a lot of electric field to be flowing out of the cable. This situation does not look good. However, since the cables are most likely located in conduit that is an insulating material; there is no connection of the conductor to ground and not allowing for circulating current. Therefore, there will be no heating and more breaking down of the insulation.

3.2.2 Grounded Water Trees

Next a water tree is placed in the cable so that it is touching a neutral wire and it has grown 70% across the insulation as shown in Figure 17.

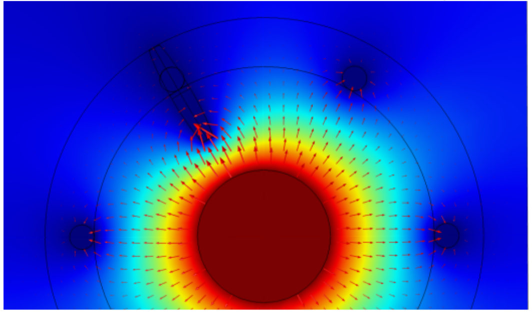

Figure 17: Water tree 70% across insulation in concentric neutral cable grounded

This water tree acts very similar to the tape shield water tree due to the fact that, since it is grounded, the electric potential is zero throughout the entire water tree. This water tree does not affect the electric field that much since it is acting as a neutral wire at this stage. However, the water tree still increases the electric field at its tip and will therefore continue to grow as the insulation breaks down. The water tree also reduces the electric field on the side of the water tree, causing it to reduce the electric potential in that area. Finally, the water tree has grown to 100% across the insulation as shown in Figure 18.

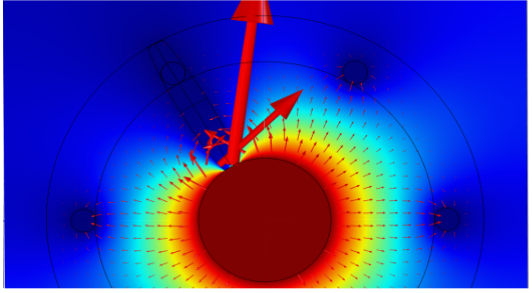

Figure 18: Water tree 100% across insulation in concentric neutral cable grounded

Notice that this water tree has breached the insulation, but the electric potential is still unchanged inside the cable. It is at .986 p.u., which is definitely within operation range. However, the electric field at the tip of the water tree is very large and since the water tree is creating a direct path to the neutral wire and the conductor, current will circulate, which causes the insulation to heat. This heat will provide the required energy for electrical trees to start growing inside the water tree and then lead to voltage breakdown of the cable. Therefore, the water tree that is making a direct path from the neutral wire or tape shield to the conductor is the most dangerous water tree because of the fact that it will cause circulating current which produces heat, and later on, electrical trees.

4. Water Tree Lumped Parameters

The main reason that a water tree was simulated in COMSOL was to determine the resistance and the capacitance of a water tree. It is known that the lumped parameters of a water tree consist of a parallel resistor and capacitor [5,6,3,7]. Some use a model where the healthy insulation is a capacitance and then it is in series with the parallel resistance and capacitance [3]. However, this circuit can be simplified to find the Thevenin equivalent impedance, which will be an impedance with a resistive element and a capacitive element. Therefore, in this research, the water tree will be represented as a parallel capacitance and resistance. In order to calculate this resistance and capacitance, two different simulations were performed in COMSOL that solves for each of the parameters individually.

4.1 Capacitance Calculation

The capacitance of the cable is affected by the change in the relative permittivity. The Electrostatics physics branch in COMSOL allows for the capacitance to be calculated because it only focuses on the relative permittivity and not the conductivity. Therefore, both cables were simulated the same way in COMSOL. The conductor was set to a potential of 15 kV and the tape shield or neutral wires were grounded. The percentage of water tree growth was varied from no water tree to a water tree breaching the insulation by a factor of 10% of the insulation thickness. The capacitances were solved with the equation 3:

$$C=\frac{2\pi\varepsilon_r\varepsilon_o L}{\ln\left(\frac{r_2}{r_1}\right)} \qquad (3)$$

Where:

- ε_r is the relative permittivity
- ε_o is the permittivity of free space
- L is the length of the cable
- r_1 is the radius of the conductor
- r_2 is the radius of the insulation

The capacitance as the water tree grows is shown in Figure 19 for the tape shield cable and in Figure 20 for the concentric neutral cable.

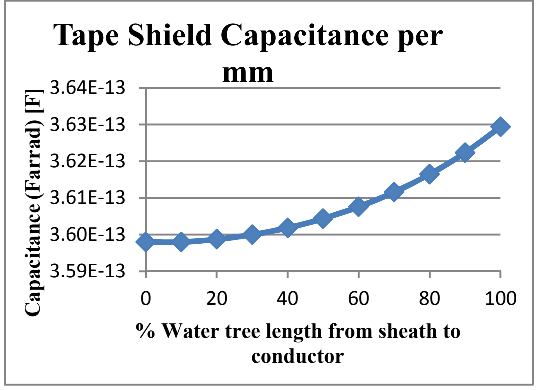

Figure 19: Tape shield capacitance from water tree growth

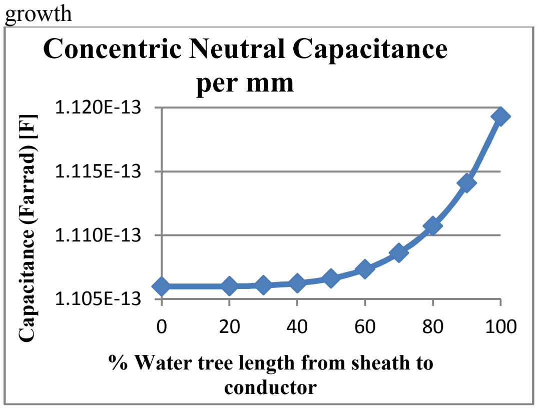

Figure 20: Concentric neutral capacitance for water tree growth

The shape of the curve of the capacitance is an exponential growth curve. What would be expected for the water tree growth is that the capacitance would increase as the water tree got closer because of the fact that the conducting plates are getting closer in that region. However, the magnitude with which the capacitance changes are very small.

4.2 Resistance Calculation

The resistance of a conductor is a factor of the conductivity. The Electric Currents physics branch in COMSOL uses the conductivity to calculate the current flowing in the materials. Therefore, this physics branch was used to calculate the conductance for both types of cables. The same procedure for the simulation was performed. The conductors were set to a potential of 15 kV and the tape shield or concentric neutral wires were grounded. The water tree was varied across the insulation by 10% of the insulation width. The conductance was solved with equation 4:

$$G = \frac{\sigma A}{l} \qquad (4)$$

Where:

- l is the length of the conductor
- A is the cross sectional area of the conductor
- σ is the conductivity

The resistance plots are shown in Figure 21 for tape shield and Figure 22 for concentric neutral.

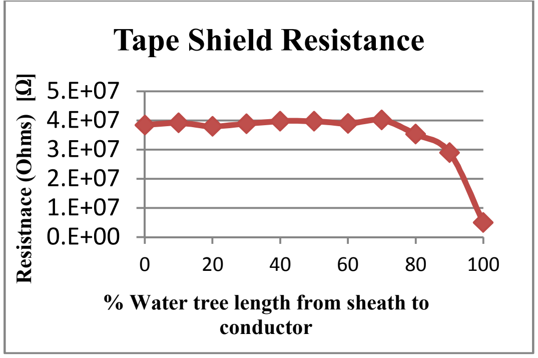

Figure 21: Tape shield resistance due to water tree growth

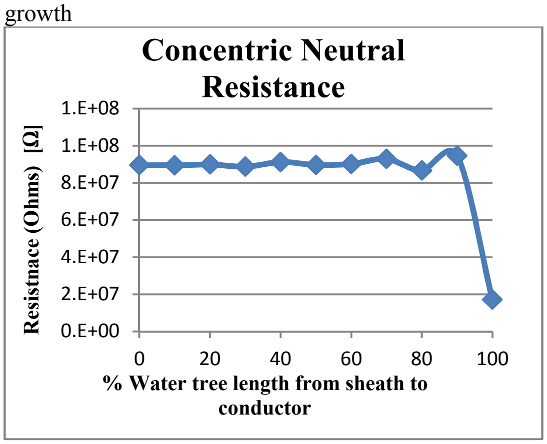

Figure 22: Concentric neutral resistance due to water tree growth

The resistance is constant until the time that the water tree touches the conductor. Since the water tree is not touching the conductor, no resistive current can leak out through the water tree, until the water tree touches the conductor.

5. Conclusion

The increase in the electric field at the tip of the water tree was shown using COMSOL and the effect of the water tree on the electric potential inside the insulation was also shown for both a tape shield and concentric neutral cable. This allows for visualization of what was already known about water trees. Also, the lumped parameters of water tree were calculated as the water tree moves across the insulation. This will allow for future simulation in PSCAD for continued research.

6. References

[1] W. A. Thue, “Treeing,” in *Electric Power Cable Engineering,* 3rd ed., Boca Ranton, FL: Taylor & Rancis Group, 2012, pp. 367-384.

[2] Z. Wang, P. Marcolongo, J. A. Lemberg, B. Panganiban, J. W. Evans, R. O. Ritchie, P. K. Wright, "Mechanical fatigue as a mechanism of water tree propagation in TR-XLPE," *IEEE Transactions on Dielectrics and Electrical Insulation,* vol.19, no.1, pp.321-330, February 2012.

[3] T, Toyoda, S. Mukai, Y. Ohki, Y. Li, T. Maeno, "Estimation of conductivity and permittivity of water trees in PE from space charge distribution measurements," *IEEE Trans. on Dielectrics and Electrical Insulation,* vol.8, no.1, pp.111-116, Mar 2001.

[4] M. Acedo, I. Radu, F. Frutos, J. C. Filippini, P. Notingher, “Water Treeing in Underground Power cables: modelling of the trees and calculation of electric field perturbation,” *ELSEVIER Journal of Electrostatics,* vol. 53, no. 4, pp.267-294, Oct. 2001.

[5] Y. Z. Arief, M. Shafanizam, Z. Adzis, M. Z. H. Makmud, "Degradation of polymeric power cable due to water treeing under AC and DC stress," *2012 IEEE International Conference on Power and Energy (PECon),* pp.950-955, 2-5 Dec. 2012.

[6] J. C. H. Mejia, “Characterization of Real Power Cable Defects by Diagnostic Measurements,” Ph.D. dissertation, Dept. Elect. and Comp. Eng., Georgia Institute of Technology, Atlanta, GA, 2008.

[7] S, Nakamura, J. Kawai, "Relative permittivity and conductivity of water-treed region in cross-linked polyethylene," *Proceedings of the 2001 IEEE 7th International Conference on Solid Dielectrics, 2001. ICSD '01*, pp.163-166, 2001.

9. Acknowledgements

This work was funded by Clemson University Electric Power Research Association (CUEPRA).