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Time Domain Reflectometry of a Water Tree inside an Underground Cable

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Abstract: Time domain reflectometry is widely used to detect defects throughout underground cables. It can be used to determine the specific location of the defect due to the wave reflection produced. One such common defect contained inside underground cables is a water tree. These water trees can grow across the insulation and not cause the cable to fault. Therefore, to better understand the reflections produced during time domain reflectometry from water trees COMSOL was used to simulate this occurrence using the RF Module.

Keywords: Water Tree, Time Domain Reflectometry, Underground Cable.

1. Introduction

The increasing practice of underground residential distribution (URD) cables being installed in the power system requires utility companies to know the health of these cables. Since the health of URD cables cannot be determined by visual methods like overhead lines, a better understanding of the power cable and its aging process is needed. Insulation of medium voltage URD power cables age from a phenomenon called water treeing **Figure 1**. Water trees are important to utility companies because they cannot be detected using traditional protection methods. Also, they can be growing in cables without any effect on the voltage or current. They are the main reason for URD cable failures. These water trees can grow across the insulation and not cause the cable to fault **[1]**. Also, they do not produce partial discharge **[2]**, a common cable diagnostic tool. Because of these two facts detecting them becomes very difficult and expensive.

Time Domain Reflectometry (TDR) is a traveling wave based method to determine whether water trees are present within the cable. TDR can be performed off-line or on-line. When a traveling wave is sent down a cable, it will have a reflection when it reaches the end of the cable or an element with different impedance. This can be used to locate water trees in a cable since the water treed region will change the impedance in that section. Therefore, an early reflection may indicate water trees in the cable **[3]**.

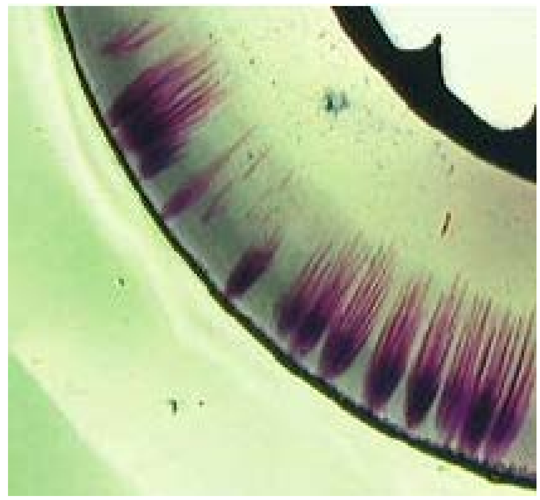

Figure 1: Water trees growing from the outside of cable [3]

2. Use of COMSOL Multiphysics® Software

The Radio Frequency and AC/DC tool boxes were used to perform a Time Dependent Study of the underground cable. The Electrostatics physics was used to determine the initial boundary conditions and define the electrical space for which the simulation takes place. Electromagnetic Waves, Transient physics was used to calculate the electric field flowing through the cable due to a high frequency input voltage pulse. The equations for calculating the electric field initially and traveling through the cable are:

$$\nabla \cdot (\varepsilon_0 \varepsilon_r \boldsymbol{E}) = \rho_v$$

$$\boldsymbol{E} = -\nabla V$$

$$\boldsymbol{\nabla} \times \boldsymbol{\mu}_r^{-1}(\boldsymbol{\nabla} \times A) + \boldsymbol{\mu_0} \boldsymbol{\sigma} \frac{\partial A}{\partial \boldsymbol{t}} + \boldsymbol{\mu_0} \frac{\partial}{\partial \boldsymbol{t}} \left(\boldsymbol{\varepsilon_0} \boldsymbol{\varepsilon}_r \frac{\partial A}{\partial \boldsymbol{t}} \right) = 0$$

Where

- ε_0 = *Permittivity of free space*
- μ_0 = *Permeability of free space*
- σ = *Conductivity of the material*
- ε_r = *Permittivity of the material*
- ρ_v = *Volume charge density*
- $\mathbf{E}$ = *Electric Field*
- $\mathbf{A}$ = *Magnetic Vector Potential*
- V = *Electric Potential*

3. Cable Model

The geometry of the cable was simplified from previous research **[4]**, and it consisted of two one meter cylinders to represent the conductor and insulation. A small 4 millimeter section around the center of the cable was inserted to represent the water tree, and the entire cable section was surrounded by a box to represent air for the electric field calculations **Figure 2**. The surface outside of the insulation was set to be a perfect electric conductor and was grounded; this was done in order to represent the shield of the underground cable. The conductor material was set to copper and the insulator material was set to crosslink polyethylene.

Figure 2: Geometry of the simulation

4. Method

TDR is first performed on a section of cable with no water tree model present. This allows for the comparison of cable reflections with and without water tree properties. Then a section of the cable's insulation electric permittivity is changed to match that of a section of cable with water trees growing from the outside inward. The electric permittivity equations have been adjusted from **[4]** to account for the water trees being represented as a concentric ring around the conductor.

$$\boldsymbol{\varepsilon} = \frac{3\boldsymbol{\varepsilon_{XLPE}}}{\boldsymbol{T_{ins}}} \times \left[\sqrt{\boldsymbol{y^2 + z^2}} - (\boldsymbol{r_{cab}})\right] + \boldsymbol{\varepsilon_{XLPE}}$$

Where:

- $\varepsilon_{XLPE} = 2.3$
- $\sigma_{XLPE} = 1 \times 10^{-15}$
- r_{cab} = *Cable radius*

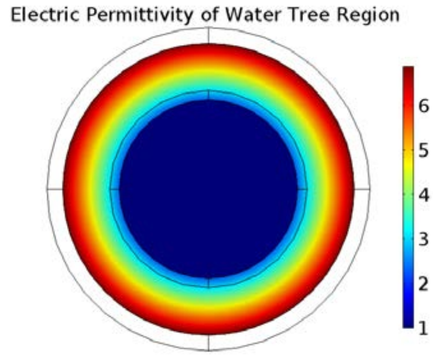

Figure 3: Electric permittivity of water tree region in underground cable

For both cables an exponential pulse is injected at one end of the cable.

$$\boldsymbol{V}(\boldsymbol{t}) = \boldsymbol{V}(\boldsymbol{e^{-\alpha t}} - \boldsymbol{e^{-\beta t}})$$

Where:

- t = *Time*
- V = *Magnitude of the pulse*
- $\alpha = 7\times10^{-8}$
- $\beta = 3\times 10^{-9}$

This exponential pulse travels down the cable and when it reaches a location of impedance mismatch a reflection is produced. When the pulse reaches the water tree section, a small reflection pulse is sent back to the sending end before the termination reflection. This reflected electric field helps determine locations within the cable which are damaged.

5. Results

The progression of the voltage pulse through the cable is shown in **Figure 4** below, and the electric field is represented by both the arrow and surface plots. The voltage pulse travels down the cable at a constant electric field until it reaches the water treed region. At this location the electric field's vector direction starts to point toward the water treed region. This can be seen at a time of 3 nanoseconds, and a larger image is located in the appendix.

It can be seen in **Figure 4** a very small amount of electric field lagging behind the main electric field at a time of 4 nanoseconds, highlighted in the black box. This small amount of electric field is the reflection from the water tree, and is not very strong because of the small size of the water tree region. Also, this reflection can be seen at a time of 5 nanoseconds because this is the time at which it reaches the beginning of the conductor.

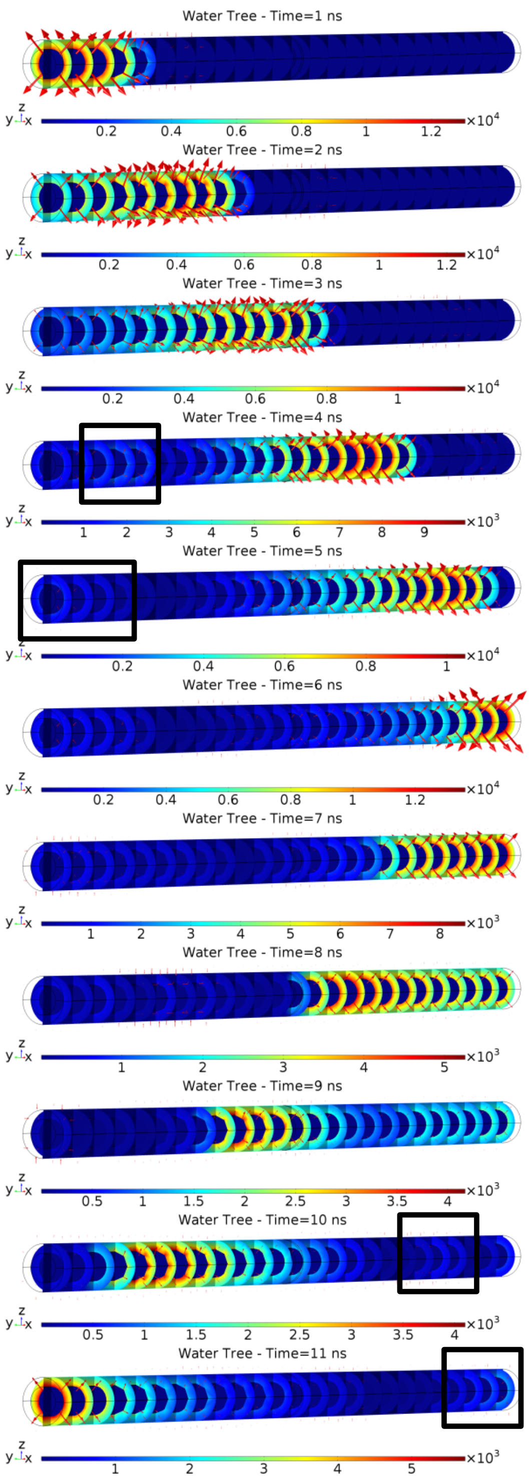

Figure 4: Progression of electric field through cable

Because mismatches in impedance cause reflection, when the main electric field pulse reflects off of the end of the cable and heads back to the beginning of the cable, it passes through the water tree medium again. This causes another reflection that is traveling in the direction toward the end of the cable. This reflection can be seen at the 10 and 11 nanosecond time frame. Larger images of the important times are located in the appendix.

The voltage, at the location where the exponential pulse was injected, was monitored to perform TDR. For a healthy cable the voltage shows an initial pulse with a decay to zero, and then the termination reflection pulse is measured. This is represented in **Figure 5**, and it is compared to an electromagnetic transient simulation (PSCAD) in **Figure 6**. The COMSOL simulation has some ringing right before the termination reflection pulse, but this is expected because it is more similar to experimental results. Also, the return reflection has been distorted due to the losses at the end of the cable when reflected.

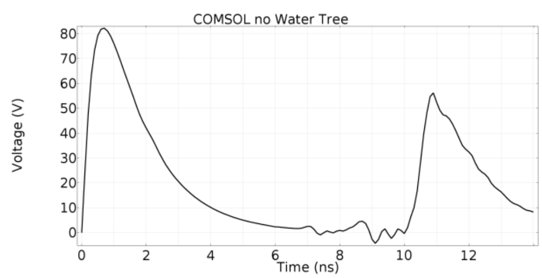

Figure 5: Input voltage in COMSOL simulation with no water tree

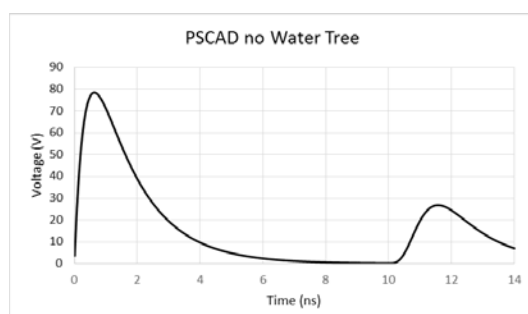

Figure 6: Input voltage in PSCAD simulation with no water tree

A water treed region was added to the cable and the voltage at the injection location is show

Figure 7. The water tree is located at the middle of the cable and it returns a negative voltage reflection. This is due to the capacitive nature of the water tree. The reflection pulse is also easily distinguished from the simulation with the healthy cable. As before this voltage profile is compared with the PSCAD simulation **Figure 8**.

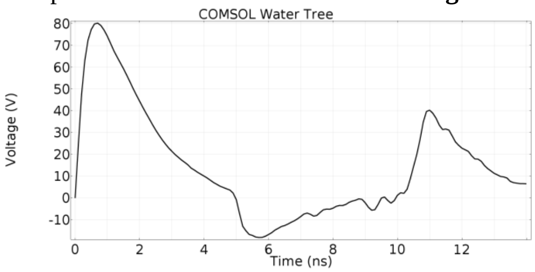

Figure 7: Input voltage in COMSOL with water tree

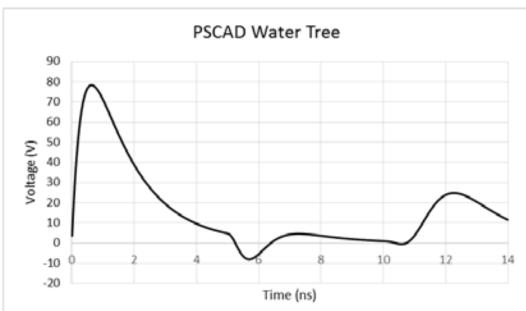

Figure 8: Input voltage in PSCAD simulation with water tree

6. Conclusion

The COMSOL and PSCAD simulations represented the same negative voltage reflection from the water tree with a similar magnitude and pulse width. This validates that the traditional model for a water tree is accurate and acceptable for simulation. Also, the progression of the electric field through the cable and the water tree's effect on the electric field correlates with previous research in a stationary electric field. This research will help further future research by simplifying simulations needed to understand the effect of a water tree on the reflection magnitude and pulse width. Allowing for development of future equipment to better detect and monitor the growth of water trees in underground cables.

7. References

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[3] V. Dubickas, *On-Line time domain reflectometry diagnostic of medium voltage XPE power cables,* Stockholm, Sweeden: Royal Institute of Technology, 2006.

[4] K. Burkes, E. Makram and R. Hadidi, "Modeling the Effect of a Water Tree inside Tape Shield and Concentric Neutral Cables," in *COMSOL Conference*, Boston, 2014.

8. Acknowledgements

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9. Appendix

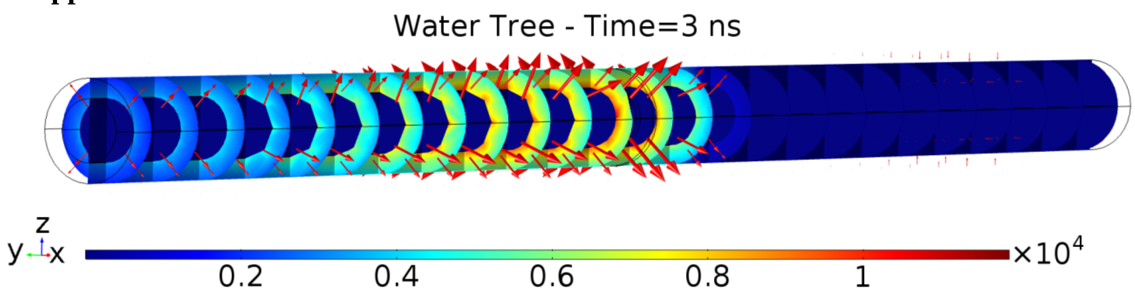

Figure 9: Electric field vectors in the water tree region of the insulation

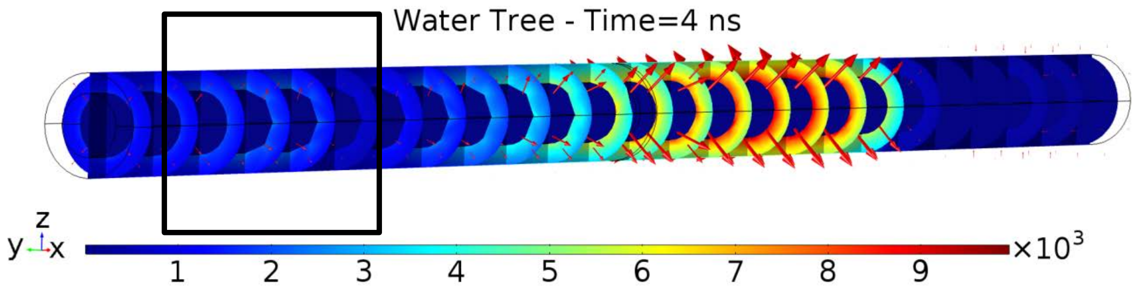

Figure 10: Water tree reflection heading to the beginning of the cable

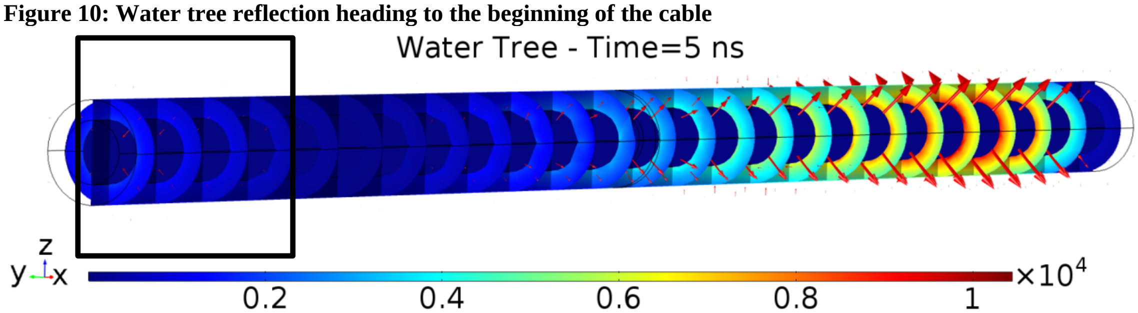

Figure 11: Water tree reflection at the beginning of the cable

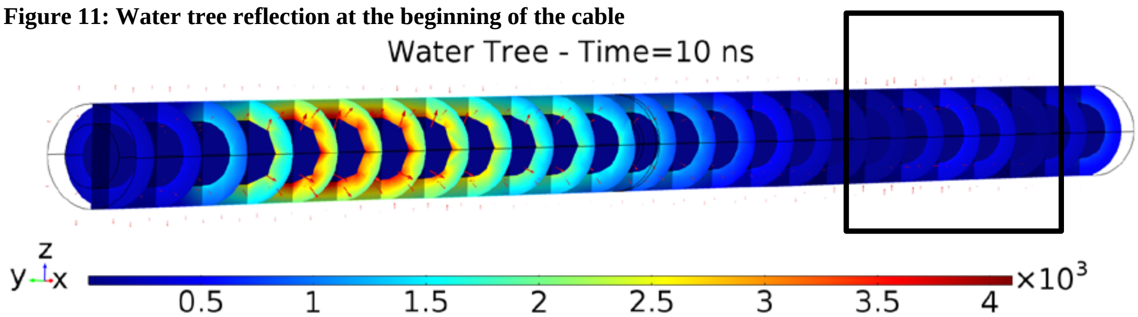

Figure 12: Water tree reflection heading back to the end of the cable

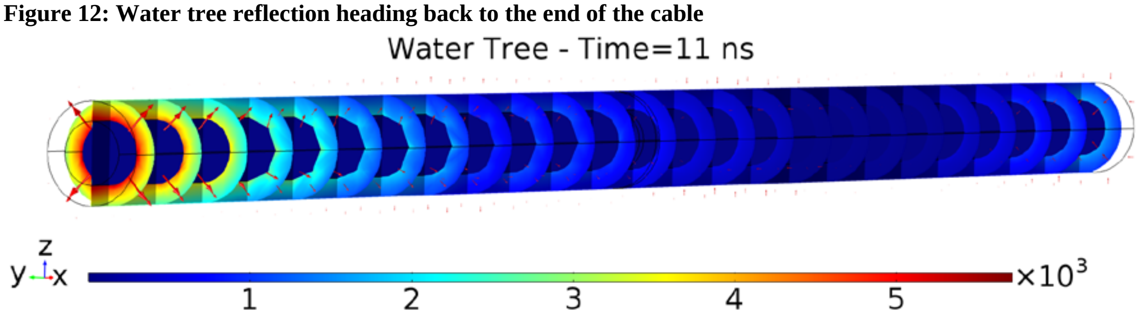

Figure 13: Water tree reflection at the end of the cable