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Water Tree Analysis and On-Line Detection Algorithm Using Time Domain Relectometry

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WATER TREE ANALYSIS AND ON-LINE DETECTION ALGORITHM USING TIME DOMAIN REFLECTOMETRY

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ABSTRACT

With the increasing amount of overhead lines being converted to underground cables in the distribution system, the need to be able to determine the health of these underground cables becomes imperative. Since the health of underground cables cannot be determined by visual means like overhead lines, an on-line measurement method is needed to determine the health of these cables. By sending a high frequency voltage pulse down the cable and measuring the return pulse, a method called time domain reflectomentry (TDR), an on-line measurement method becomes feasible.

One of the main causes of cable failure is known as water-trees, and they are formed through dielectric breakdown of the cables insulation. They are formed from electrical stress at the interface of the cables' insulation and conductors. To determine an on-line measurement method to detect water trees, an accurate model of water-trees in underground cables is developed. Two different cable types are modeled with water-trees, concentric neutral and tape shield cables. These models are developed in COMSOL Multiphysics®.

With this developed water-tree model, it is then integrated into a distribution feeder located along the coast of South Carolina, with parameters provided by Santee Cooper®. To perform TDR and monitor the health of all the three-phase cables in the distribution feeder an optimal pulse generators placement algorithm was used to determine the location of pulse generators to monitor all cables. Finally, an algorithm for monitoring every cable was created and the method tested in PSCAD®. Based on these results an on-line measurement water-tree detection method is presented.

DEDICATION

I would like to dedicate my thesis to my family and Keeli Fricks for all their help and support while pursuing my education and to my cousin Christopher D'Huyvetters, who passed away while I was working on my Masters.

ACKNOWLEDGMENTS

Special thanks to Keeli Fricks for being there with me when things got very difficult and for her help with editing my thesis. I would like to thank my parents Greg and Lynn Burkes for the importance they placed in getting an education. I want to thank my grandparents Robert and Maryland Kierspe and Lamar and Nell Burkes for all the love and support they have given me.

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CHAPTER ONE

WATER TREES

1.1 Introduction

The increasing use of underground residential distribution (URD) cables being installed in the power system gives the need for 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. 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. Therefore, a model of water trees is pertinent for better simulation and studying of their effect on the power system. Water trees are local deteriorations in polymeric insulations of medium voltage (MV) underground cables. Water trees grow in solid dielectric materials such as cross link polyethylene (XLPE) or ethylene propylene rubber (EPR). These water trees form at a very slow rate. It can take years for them to grow across the insulation and form electrical trees [1]. When electrical trees are formed the cable will experience voltage breakdown. The electrical trees and water trees grow with a tree-like appearance called Lichtenburg [1] figures, thus giving them their name. Water trees are an electrochemical breakdown of the insulation due to the presence of moisture in the insulation. They develop in the direction of the electric field from defects such as: impurities, micro cavities, or discontinuities in the conductor insulation interface [1-3].

1.2 Inception of Water Trees

The initiation of water trees is a very important aspect to study to better understand how to prevent or detect water trees in URD cables. Water trees will form when the humidity is greater than 65% [4]. However, at a depth of one meter soil has a relative humidity of 100% for most of the year [5]. Therefore, all cables even in conduit are capable of forming water trees due to the presence of moisture in the ground. Since all cables are susceptible to water tree growth, the mechanisms of the way in which water trees start is imperative for understanding water trees. There are several methods of water tree initiation and they can be formed through a combination of the multiple methods.

One such method is that water trees start from small voids or contaminants inside the insulation. These voids or contaminants create voltage stress at that location by increasing the electric field. This increase of electric field can be orders of magnitude higher than the rated electrical stress of the dielectric. This electrical stress at the voids or contaminants can be capable of eroding the dielectric in the surrounding locations [1-3].

Another method of water tree inception is that mechanical stress on a hot URD cable can produce high electric fields around this mechanical stress. The high electric fields cause fatigue in the cable which can lead to stress cracks forming and thus, water trees forming from these stress cracks [1,6,7].

The last known method of water tree inception is that chemical corrosion can occur around the tape shield due to ionic particles in the insulation. The high electric field within the insulation can raise chemical potentials. This promotes chemical reactions that break bonds, weaken material, and result in mechanical breakdown [1,2,8].

Neither one of these methods can explain exactly how all water trees are formed. However, all three of these methods have one single aspect in common that causes the water tree to start, which is an amplified electric field due to some process whether mechanical, chemical, or electrical. Many researchers have decided that a combination of these three mechanisms is the cause of water trees in field aged URD cables [1].

1.3 Growth of Water Trees

The most important part of the study of water trees is the way that water trees grow across the insulation. A better understanding of this allows for better knowledge on how to actively find water trees and determine the health of a cable. For example, water trees obviously grow faster as they get closer to the conductor. This is due to the increase in electric field as the water tree grows toward the conductor. This is an important factor in the physical appearance of water trees as well as their potential to create voltage breakdown in the cable. However, this will be discussed later in the chapter.

Water tree growth is similar to inception of water trees in that there are several methods by which water can penetrate through the insulation and cause cracks and micro voids. Also, it is not thought that these methods work individually to create water trees, but instead, that the combination is what allows water trees to grow. The three forces which explain the method by which moisture penetrates through the insulation are osmosis, electrophoresis, and dielectrophoresis [1,7]. Osmosis is the method with which water soluble substances in the micro-voids attract water from the environment [7].

Electrophoresis describes how charged particles move in an electric field. Positively charged particles move toward a negative electrode. Likewise, negatively charged particles move toward the positive electrode [1,7]. This is important because water trees that are growing from the tape shield or that are touching a neutral wire in concentric neutral cable will be grounded. Therefore, the ionic particles in the water tree are at a negative potential and are attracted to the conductor of higher potential. These water trees which are grounded will grow faster than non-grounded water trees, and their shape will be thinner than the water trees which are not grounded.

Dielectorphoresis describes the way in which uncharged but polarized particles move in an electric field. The positive part of the polar molecule is attracted to the negative conductor, and the negative part of the polar molecule is attracted to the positive conductor [1]. Because in a parallel plate's electric field, the electric field decreases as it moves from the positive conductor, the negative part of the polar molecule is in a stronger electric field and the attraction to the positively charged conductor is stronger than the attraction of the positive part of the polar molecule to the negative conductor. The polar molecule will migrate to the positive conductor. However, in an AC system where the conductor becomes negatively charged, the polarization process is reversed. Therefore, the particle is still attracted toward the conductor with higher electric field. This means that even in an AC system moisture will be drawn to the higher dielectric field regions [1]. This higher dielectric field region could be a void in the insulation or to the conductor.

1.4 Voltage Breakdown Due to Water Trees

The aspect by which cables experience voltage breakdown due to water trees is not as important as the way in which water trees start and grow. This is mainly because utility companies would rather know when a water tree was forming or has started in order to replace that section of cable instead of having a fully developed fault and then replacing the entire cable. However, studying the process by which water trees create voltage breakdown is useful in determining what has happened to the cable and, at least, in discovering how to locate the deteriorated region and remove it. However, if a cable is faulted from a water tree it is very likely that the entire cable is filled with many water trees and will probably fault very shortly from another water tree.

The interesting thing about water trees is that they actually do not cause voltage failure, but they are locations to trap electrons during switching transients, lightning surges, and test voltages. These entrapped electrons are the initiation sites of electrical trees [1]. Field aged cables show that water trees and electrical trees are not mutually exclusive [1,8-11]. Therefore, water trees and electrical trees cannot be separated into two categories, but they must be grouped together when discussing the breakdown of extruded dielectric cables.

The electrical tree by itself is the result of internal electrical discharges that decompose the organic material of the extruded dielectric cable. Moisture is not needed for electrical trees to grow, but instead, very high electrical stress causes partial discharges which then form the electrical trees [1,4,9,10]. The reason electrical trees follow the development of water trees is that a water tree location provides a weakening in the dielectric strength of the insulation, which then allows for the electrical stress needed to initiate electrical trees to be much less than the normal amount of electrical stress required [1]. Once electrical trees start to form in water trees, cable failure follows very shortly. This is due to the fact that electrical trees grow very fast, in a range of minutes to hours [10]. The results of cable failure due to a water tree and an electrical tree can be seen in Figure 1.1 and 1.2.

Figure 1.1: Short circuit in underground cable in conduit in Clemson

Figure 1.2: Another short circuited cable in Clemson

As it can be seen from the figures once an electrical tree forms the cable will be completely damaged. It can explode like Figure 1.1 or just blow a small part of the insulation like Figure 1.2. The reason it explodes the cable is that current starts to circulate and cause the cable to heat until the cable explodes from the heat.

The concept of the method by which water trees are converted into electrical trees can be called trapped space charges. When a lightning strike or capacitor discharge occurs in the system, electrons get trapped in water trees in the insulation. These electrons will stay dormant until they are supplied with a sufficient amount of energy to start to move. The electrons will travel to the closest metallic component, either the sheath or the conductor. This movement of the electron results in the electron drilling holes in the insulation. The electron will continue to move until it reaches the metallic component which thus creates an electrical tree [1]. An electrical tree coming out of a water tree is shown in Figure 1.3. Notice that the electrical tree starts inside the water tree then continues to grow until it is outside of the water tree moving toward the sheath.

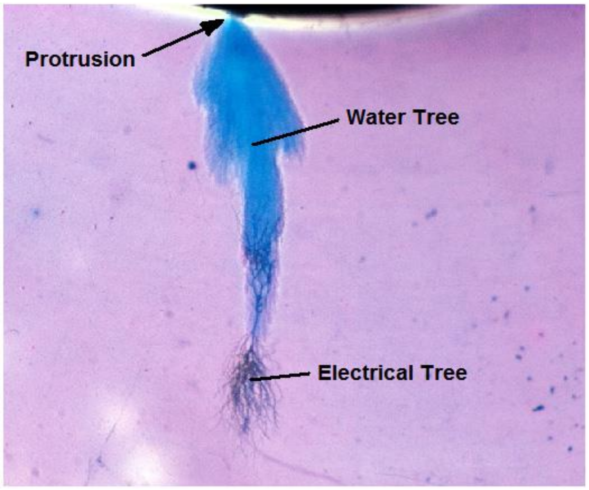
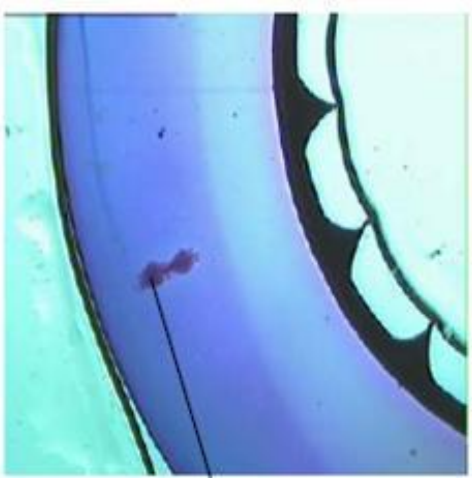


Figure 1.3: Electrical tree inside of water tree coming from tip [10]

1.5 Types of Water trees

There are two types of water trees that occur in URD cables: bowtie trees and vented trees [1- 3, 9]. Bowtie trees grow from impurities in the middle of the insulation and get their name from their shape [3,4]. The branches grow toward the conductor and sheath, giving them the look of a bowtie. They have a limited amount of moisture available. This is due to the fact that only a small amount of moisture is located around the particle in the middle of the insulation. Therefore, they do not have a large source of moisture to draw from and they cannot grow large enough to breach the insulation. This means that they will never cause cable failure and are not of interest when studying the cables health. A bowtie tree growing in the center of the insulation is presented in Figure 1.4. Notice how the branches of the bowtie tree are in line with the conductor and sheath. This is due to the fact that water trees grow in the direction of the electric field lines [2]. Unlike the bowtie tree, the vented trees are capable of growing large enough to cross the entire insulation. Vented trees can either grow from the conductor's surface or from the outside of the cable. Vented trees growing to the conductor are presented in Figure 1.5. Notice that the tip of the vented tree is very sharp. This is the cause of the amplified electric field due to the water tree and the reason that water trees continually grow.



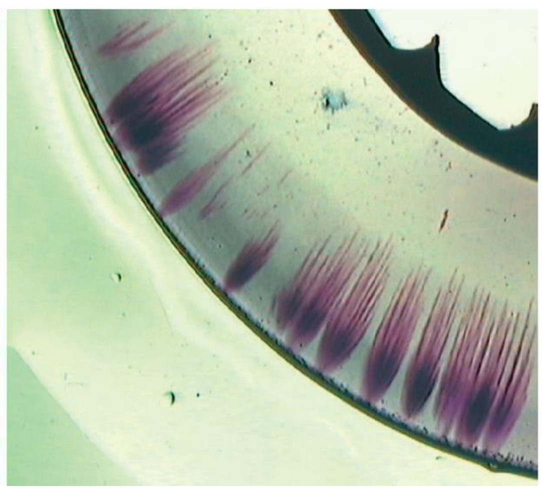


Figure 1.4: Bowtie water tree [12]   Figure 1.5: Vented Water trees [7]

There are two types of vented trees that grow in URD cables. There are those that start at the conductor and grow toward the sheath, and there are those that start at the sheath and grow toward the conductor [1,3]. The trees that grow from the conductor's surface are caused by some form of discontinuity or impurity between the conductor and insulation interface. The cause for this discontinuity or impurity is manufacture-based and is becoming more and more unlikely. This is due to the fact that cable manufacturing companies are improving their manufacturing techniques, are adding conductor screens, and are attempting to make the interface as smooth as possible [2].

Another important aspect of the vented trees growing from the conductor is that they rarely breach the insulation to cause cable failure. This is due to several reasons. First, there is a limited amount of moisture available at the conductor insulation interface. Therefore, the water tree does not have an endless supply of moisture which thus reduces the size of its growth. The second reason is that water trees grow in the direction of increasing electric field. Therefore, their growth slows as they move away from the conductor and they have more of a ball shape, as seen in Figure 1.6.

The water trees that grow from the outside of the cable to the inside are the most dangerous type of water trees. This is due to several reasons. The first reason is that these water trees have an endless supply of water from their connection to the outside of the cable and the moisture in the ground or conduit. Therefore, they can continue to grow as long as an electric field is present in the cable. The second reason is that these water trees are growing toward the increasing electric field. This allows for them to grow slowly during their initial life span and very fast as they approach the conductor. Their growth toward the conductor also dictates the shape of these water trees. Unlike the ball shaped trees growing from the conductor, these trees are pencil-thin because the electric field is pulling the water tree away from the sheath or outside layer [10], as seen in Figure 1.7.

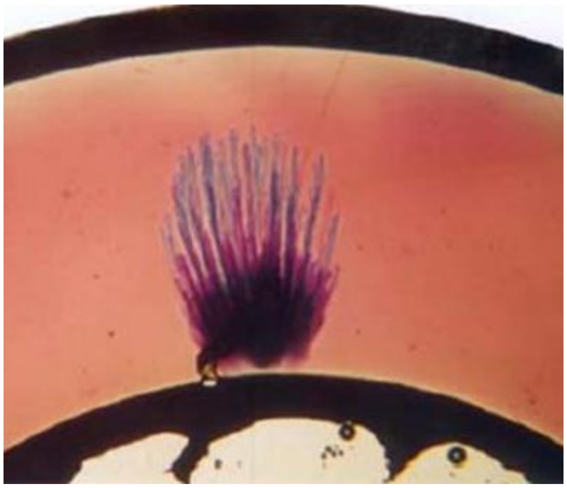


Figure 1.6: Water tree growing from conductor to sheath [13]

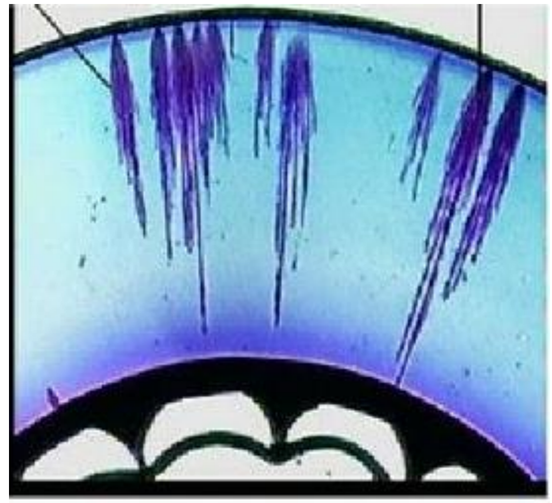


Figure 1.7: Water tree growing from sheath to conductor [12]

1.6 Current Cable Diagnostic Methods

There are several types of cable diagnostic tools that can be used to determine the age of the insulation and determine whether the cable will fail soon. Some of the techniques must be performed off-line while others can be performed on-line. One type of diagnostic technique is stress tests. If the cable fails during the stress test, it is conclusive that the cable was unhealthy. Other tests compile data over the lifetime of the cable and when a specific quantity found in the data passes a specified threshold, the cable is considered unhealthy and replaced.

1.6.1 Withstand Test

The withstand test is performed off-line. In the withstand test, the cable is disconnected from the grid and connected to a separate power supply. This test determines the cable's health by applying an increased voltage to the cable for duration of time. The test attempts to amplify weak points in the cable, thus causing the cable segment to fail. The voltage applied could be DC, very low frequencies (VLF), or power frequency. The main factor regarding this test is the amplification of the electric field inside the cable, which causes stress on the cable at its weak location. This test is intentionally destructive and not recommended as a cable diagnostic method because of the fact that it destroys the cable in most cases [9,10].

1.6.2 Depolarization Current and Recovery Voltage

The techniques of depolarization current and recovery voltage are used together to determine the cables health and are sensitive enough to detect deteriorations caused by water trees. The test is performed by disconnecting the cable from the grid and applying a DC voltage ranging from $0.5V_o$ to $2V_o$ for fifteen minutes, where V_o is the rated voltage for the cable. Once energized, the cable is then discharged through a ground resistor for two to five seconds. Then, the recovery voltage and depolarization current are measured for fifteen to thirty minutes. The depolarization current measures the time constant of the trapped current charge inside the insulation, and these time constants can be represented as an aging factor for specific cable designs. The recovery voltage analyzes the maximum value of the open circuit voltage. Healthy cables have proportionality to the maximum value and the energizing voltage, whereas unhealthy cables do not. These two tools help determine the health of the cable [7,10].

1.6.3 DC Current Measurement

DC current measurement method can be performed on-line by superimposing a DC voltage to the cable conductor through an inductance. The AC component of current that passes through the insulation is eliminated by a filter and the DC component is measured. An increase in the DC current indicates that the resistance of the insulation is decreasing and therefore, water trees are present in the cable [7,10,14].

1.6.4 Dissipation Factor

The dissipation factor test is a very well-known test and it measures the bulk health of the cable, and not the health from a specific defect. The dissipation factor is a measure of the degree of real power loss in the dielectric insulation in compared to the reactive power loss in the insulation. The dissipation factor is measured by disconnecting the cable from the grid and applying an AC voltage from a separate power supply. The phase difference of the voltage waveform and current wave form is measured. This angle is used to separate the total current into its charging current and loss current. The ratio of these two currents is used to determine the dissipation factor. It is also interchangeably called Tan δ, since it is the ratio of charging current over total current. The angle δ is from the phasor representation of the total and charging current and is the difference between the two currents [2,10,15]

The dissipation factor can be measured at the power frequency or at VLF. The sensitivity of the dissipation factor increases when performed at VLF because the charging current is dramatically affected. For example, the charging current at 60 Hz would be 600 times larger than the charging current at .1Hz. Therefore, the ratio of loss current to charging current increases and can be seen with the increase in dissipation factor [9,10].

The dissipation factor for a healthy cable should be zero since there theoretically should be no resistive current flowing through the insulation, only charging or capacitive current. This, in practice, is never true but it is the bases of the dissipation factor diagnostic method.

1.6.5 Partial Discharge Diagnostics

The technique of partial discharge diagnostics can be performed on-line or off-line. The measurement equipment for each method is different, though the concept is the same. Partial discharges are localized dielectric breakdown of a portion of the insulation. These charges do not breach the insulation, but they drill holes in the insulation [10]. A partial discharge test creates electrical trees at the location of the water trees. These electrical trees are then detected by the test, which therefore allows the test to detect water trees at the sight of the newly created electrical tree [9]. The tests detect electrical discharges from cavities in the insulation.

The measurement process for an off-line partial discharge test consists of connecting the cable to a high voltage power supply and measuring the return voltage through a coupling capacitor. The measurement equipment for an on-line partial discharge test consists of high frequency sensors to measure the partial discharges on the power signal. The sensors could be capacitive or inductive. The capacitive sensors consist of a capacitive tape that is placed over the cable that filters out the low frequency power signal [16,17]. The inductive sensors consist of a Rogowski coil that is placed on the cable after ground termination [17,18]. Partial discharge diagnostic measurements cannot be used to determine where, or if, water trees are in the cable since water trees do not produce partial discharges when they grow or are started.

1.6.6 Time Domain Reflectometry

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, you will get a reflection wave earlier than if the cable were healthy, which is how you can determine if there are water trees in the cable [7].

The way the proposed method works is that it superimposes a high frequency low voltage pulse to the power signal. The speed of the pulse is known and the time is measured from the time the pulse was sent to the time a reflection was received. With this information, the distance to a discontinuity in the cable can be determined [7]. There are, however, some issues with this method. Joints and spliced cables can cause reflection waves that could be misinterpreted as water trees; however, knowing the history of the cable, such as whether there are joints or spliced cables, should be available. This knowledge allows for the circumnavigation of this particular problem.

The on-line and off-line TDR signal can be measured with different types of sensors: capacitive and inductive. The capacitive sensors that can be used are a coupling capacitor or a capacitive strip sensor. The inductive sensors that can be used are an inductive strip sensor or a Rogowski coil. The coupling capacitor is connected between the conductor and the ground wire and acts as a filter to block the low 60 Hz frequency and measure the high frequency pulse. The coupling capacitor is very invasive and not the best solution for an on-line TDR [1,7,17].

The capacitive strip sensor is placed over the cable insulation where the neutral wires are pulled back. The semi-conductive material of the insulation screen at low frequencies acts as a screen for the MV electric field, but at high frequencies acts as a dielectric. This region entraps the 60 Hz MV electric field, while the high frequency pulse will penetrate the insulation screen and be detected by the capacitive strip sensor [7]. This method would be practical for on-line TDR because the sensors are cheap and would be added during installation. The negative aspects of using this method are that its sensitivity is proportional to the sensors' length and therefore, would need more room at the terminations of the cable than normally available.

The inductive strip sensor is placed over the neutral wires. The current flowing through the twisted neutral wires can be separated into axial and radial components. The axial magnetic field resulting from the radial current causes a voltage in the inductive strip sensor that acts as a one-turn transformer. This method would not be practical for on-line TDR because inductor strip sensors have low sensitivity [1,7].

The Rogowski coil is placed over the insulation with the neutral wires pulled back at the termination point. The current flowing through the conductor creates a magnetic field in the Rogowski coil and this magnetic field induces a voltage in the Rogowski coil that can be measured. The Rogowski coil is practical for on-line TDR because it has a large bandwidth, can be applied very easily, and it is noninvasive [7].

1.7 Overview of Thesis

Chapter 1 was an extensive introduction on the water tree: its formation, growth, and voltage breakdown. The first chapter also explains the types of water trees and current cable diagnostic methods. The rest of this thesis is presented in four more chapters in which simulations and results are presented. Each of the following chapters is briefly described in the following paragraphs.

Chapter 2 introduces the work performed in the software COMSOL Multiphysics, which combines a finite element analysis solver with 2D and 3D CAD drafting. The chapter starts with a model of a water droplet in insulation with a constant electric field. It then introduces a single phase cable, tape shield and concentric neutral, and displays the effect of a water tree to the electric field and voltage in the cable. Finally, the capacitance and resistance between the conductor and neutral is calculated as the water tree grows toward the conductor.

Chapter 3 utilizes the resistance and capacitance calculated in Chapter 2 by simulating a water tree in PSCAD. First, the water tree is moved down the line to determine if water tree location has an effect on its leakage current. Then, the length of the cable is varied to see if this has an effect on the leakage current. Finally, an electrical tree is simulated on the single line to see its effect on the leakage current.

Chapter 4 uses time domain reflectometry to detect the water tree. First, the difference between cable splices and water trees will be shown. Second, a distribution feeder in Myrtle Beach South Carolina is modeled using PSCAD. Then, an optimal pulse generator algorithm is presented to determine the best location for the pulse generators to be placed on the distribution feeder to monitor all the cables in the system. Next, a water tree is placed on every three phase cable at different lengths along each cable to see if the entire feeder can be monitored. Finally, an algorithm to monitor all the cables in a distribution feeder is presented along with its results.

Conclusions are discussed in Chapter 5.

CHAPTER TWO

WATER TREE MODEL USING COMSOL

2.1 Introduction

Water treeing is simulated in a tape shield and concentric neutral cable using COMSOL Multiphysics. This was done in order to determine the value of the lumped components of the water tree. COMSOL Multiphysics is a finite element analysis (FEA) software that allows for two and three dimensional objects to be constructed in its graphical user interface (GUI). These objects can then have boundary conditions placed on them, and a meshed structure is created in order to perform the FEA simulation. This 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.

2.2 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. 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.

2.2.1 Single Spheroid Model

In 2012 Z. Wang from University of California looked at a single ellipsoid in the middle of the dielectric insulation [6]. 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 [6] 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 [6] and the insulation's relative permittivity is set to 2.3, the relative permittivity of XLPE. The results from the FEA simulation are presented in Figure 2.1.

The results from the FEA solutions 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.

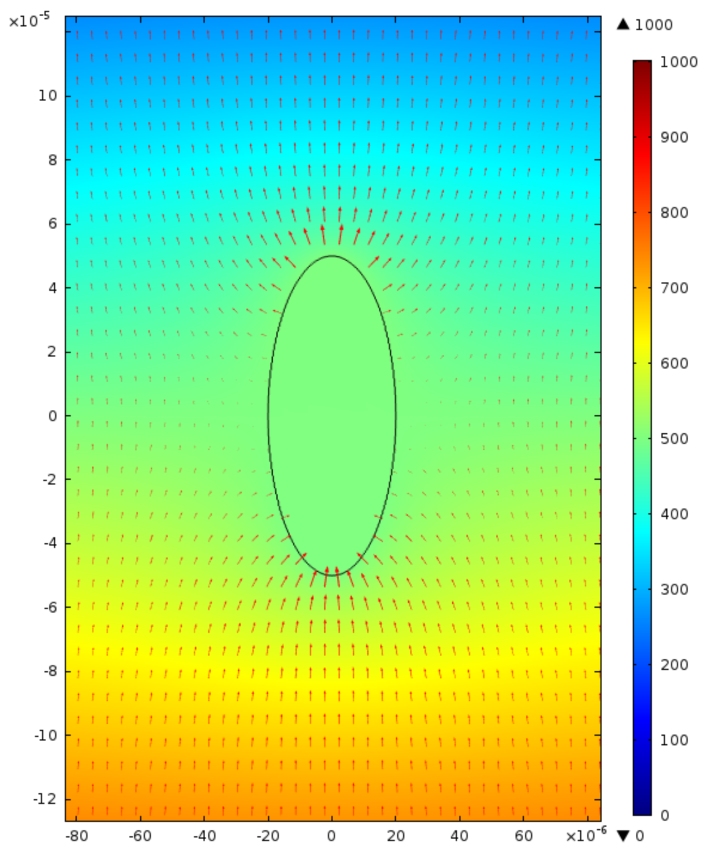


Figure 2.1: A single droplet of water tree in insulation with constant electric field

2.2.2 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 2.2. 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.

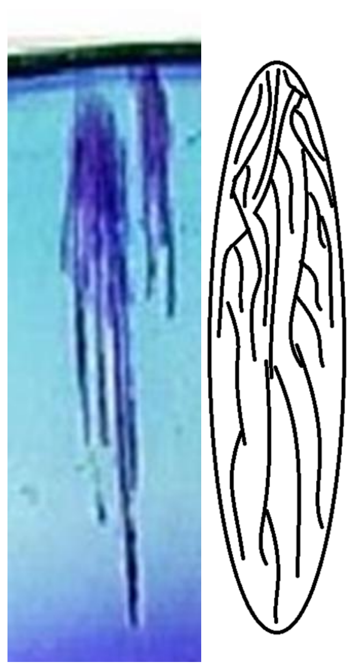


Figure 2.2: Single water tree and ellipsoid representation

2.2.3 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 [19]. 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 2.2, 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 2.3.

2.2.4 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 [2]. 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 [2]. 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 [2]. The relative permittivity can be seen in Figure 2.4.

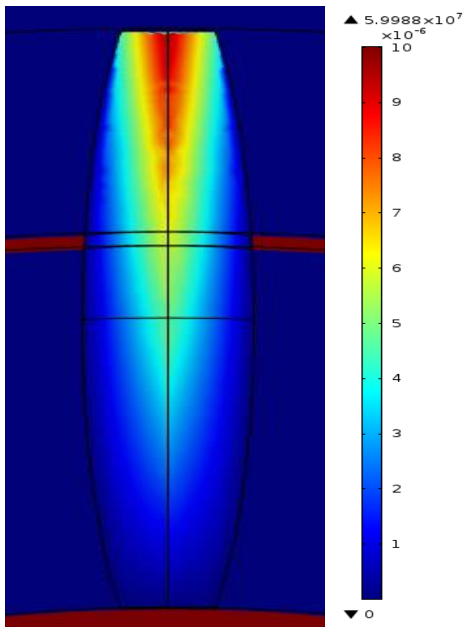


Figure 2.3: Electrical conductivity of water tree in COMSOL

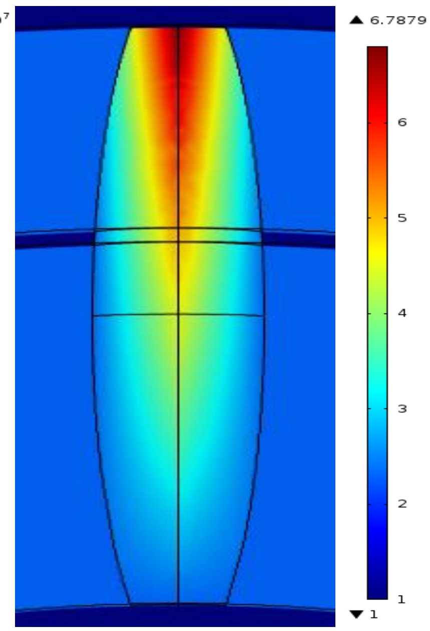


Figure 2.4: Relativive permittivty of water tree in COMSOL

The equation for the water tree's electrical conductivity and relative permittivity are shown in equation 2.1 and 2.2 below, respectively.

$$\varepsilon_r = \frac{(3\varepsilon_{XLPE} - \varepsilon_{XLPE})}{wt_L} \times [y - (Jacket_r - wt_L)] \times \left(1 - \frac{\sqrt{x^2 + z^2}}{\frac{wt_w}{2}}\right) + \varepsilon_{XLPE} \quad (2.1)$$

$$\sigma = \frac{(1^{10}\sigma_{XLPE} - \sigma_{XLPE})}{wt_L} \times [y - (Jacket_r - wt_L)] \times \left(1 - \frac{\sqrt{x^2+z^2}}{\frac{wt_w}{2}}\right) + \sigma_{XLPE} \quad (2.2)$$

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.

2.3 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 the final part of this research will involve implementing water trees into a distribution feeder in Myrtle Beach, South Carolina, and then the health of the cables in the system will be monitored. 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 2.5 for the tape shield, and Figure 2.6 for the concentric Neutral.

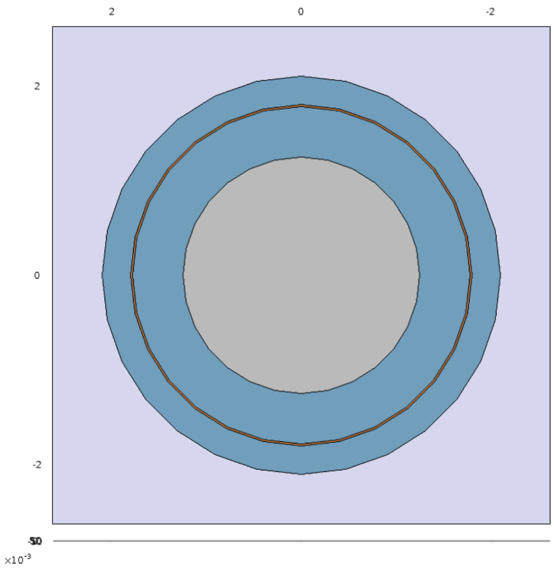


Figure 2.5: 750 kcmil tape shield cable

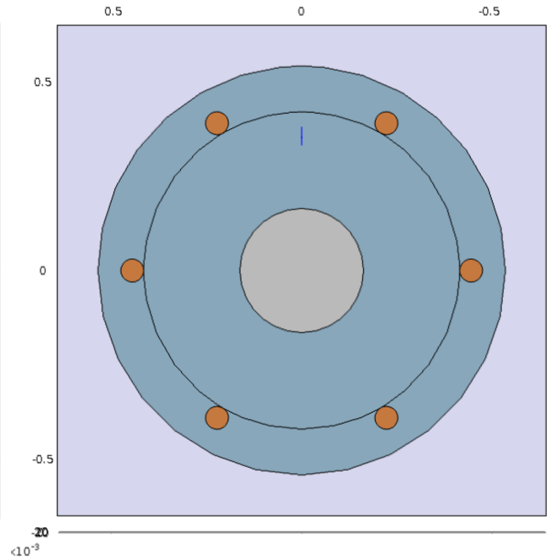


Figure 2.6 1/0 AWG concentric neutral cable

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 same as the distribution system which will be studied later. 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.

2.3.1 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. 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 2.7.

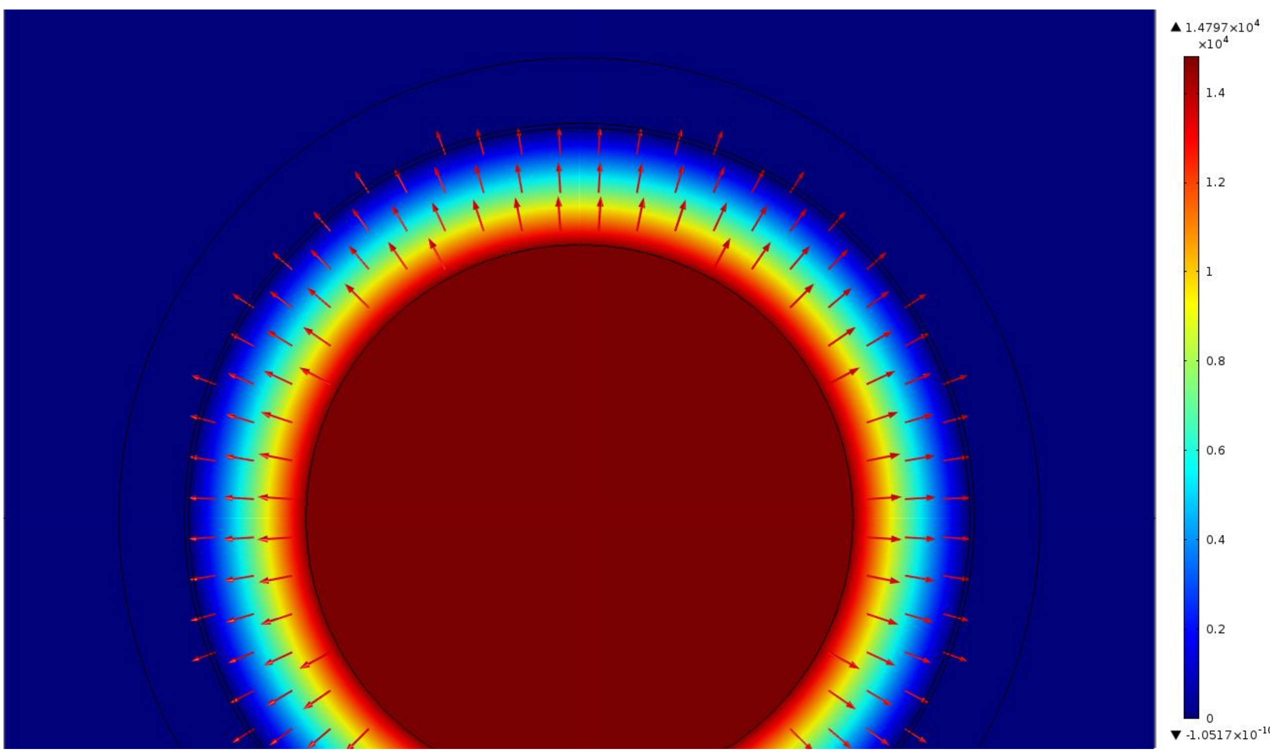


Figure 2.7: Tape shield cable with no water tree

Figure 2.7 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 2.8.

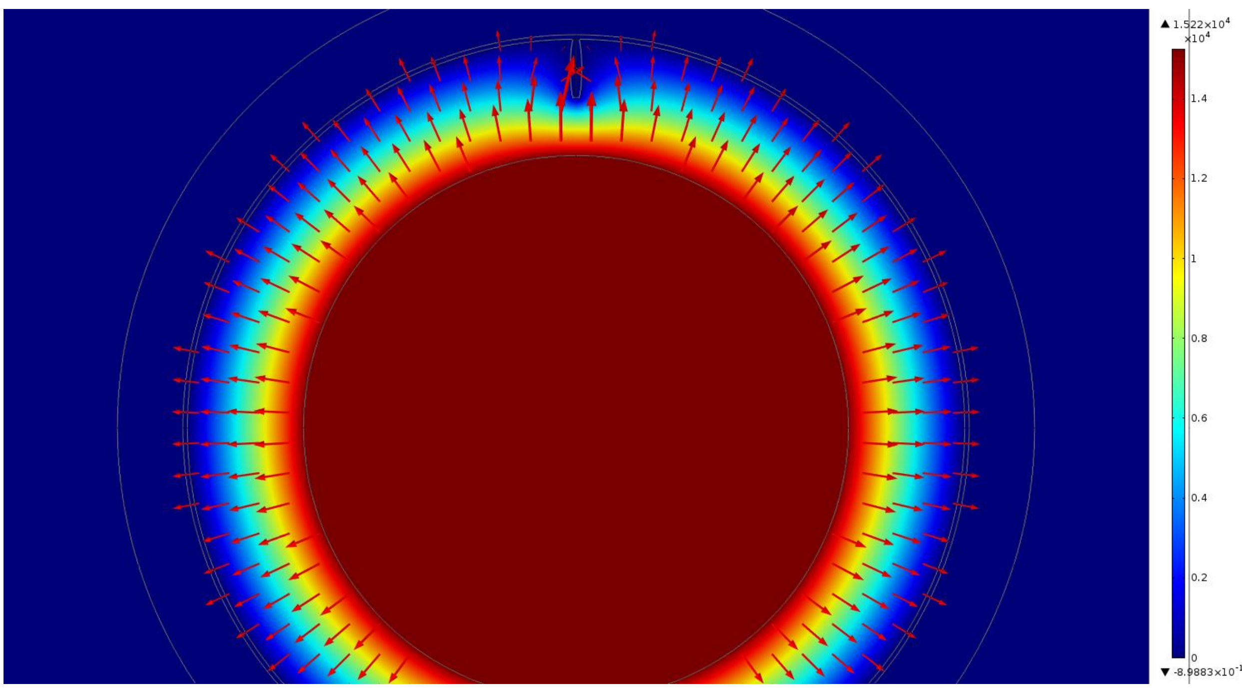


Figure 2.8: Tape shield cable with water tree crossing 50% of the insulation

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 2.9.

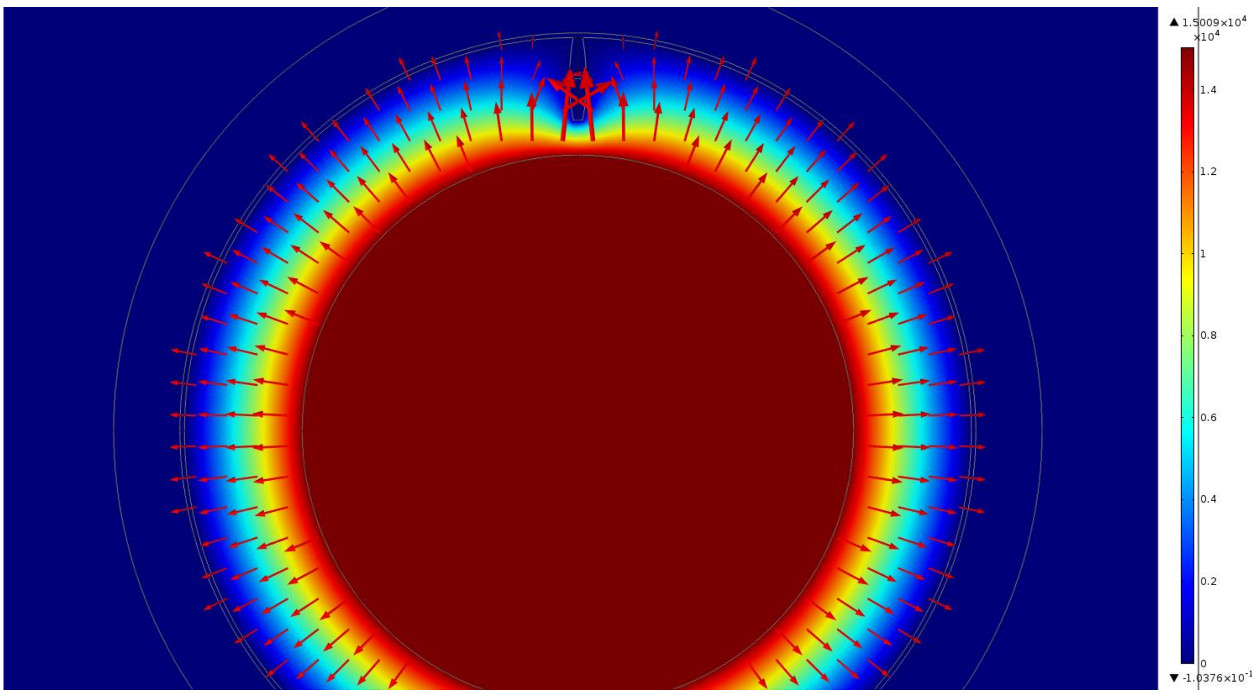


Figure 2.9: Water tree at 70% across tape shield insulation

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 2.10.

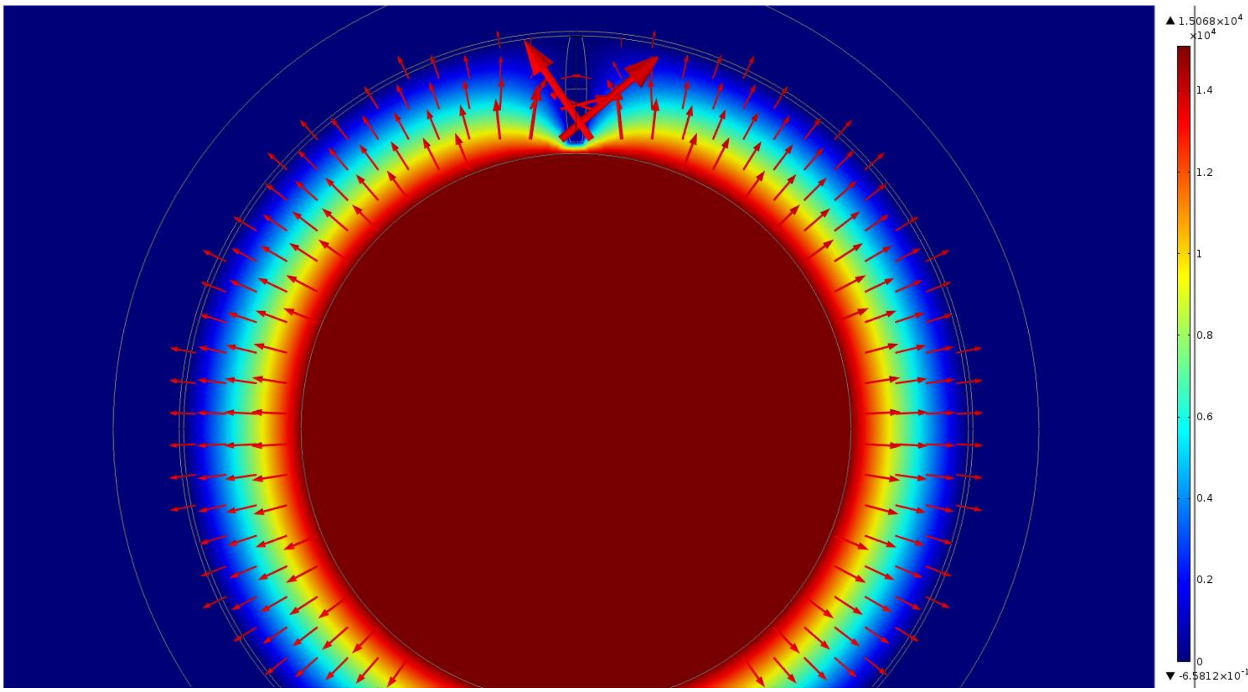


Figure 2.10: Water tree 90% across the insulation in tape shield cable

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. 2.11.

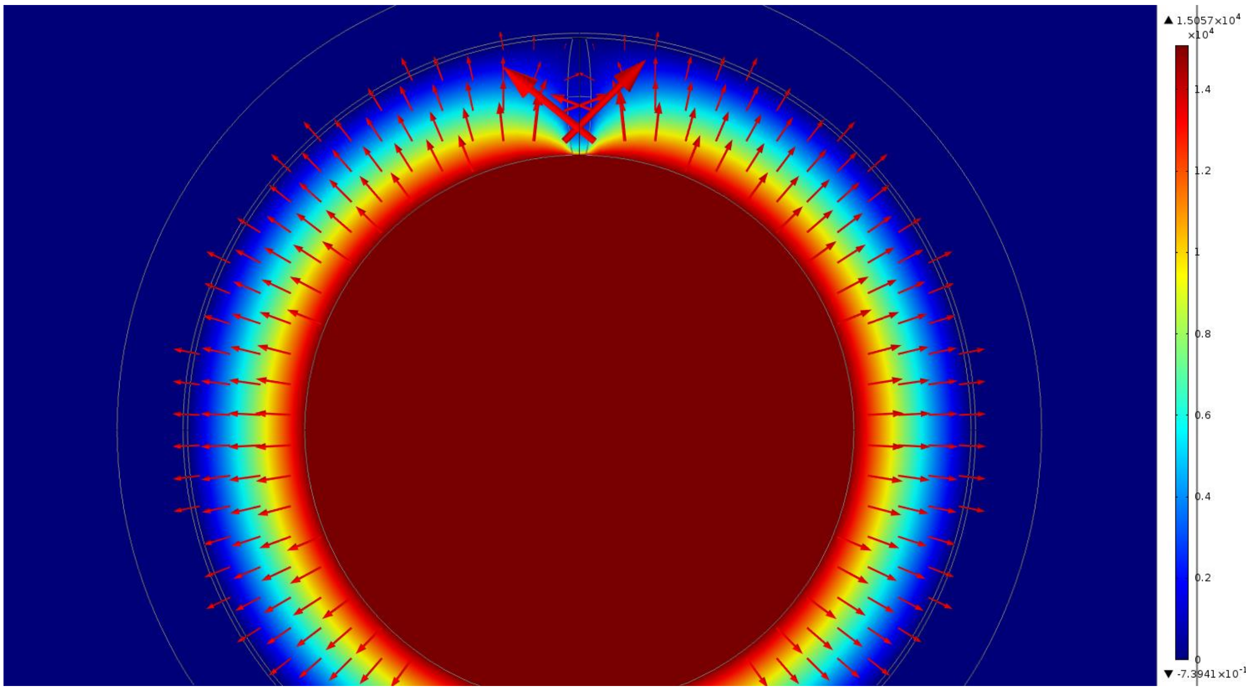


Figure 2.11: Water tree 100% across the insulation in tape shield cable.

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]

2.3.2 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. 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.

2.3.2.1 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 2.12.

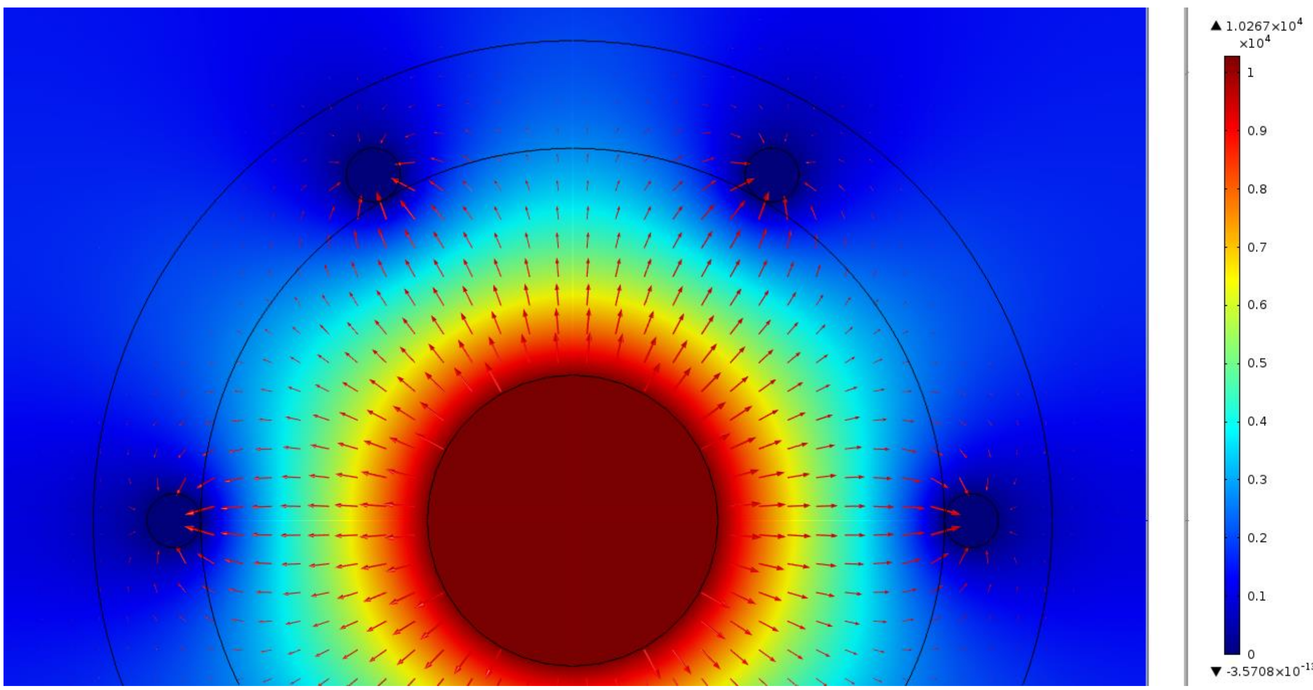


Figure 2.12: Healthy concentric neutral cable

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 2.13.

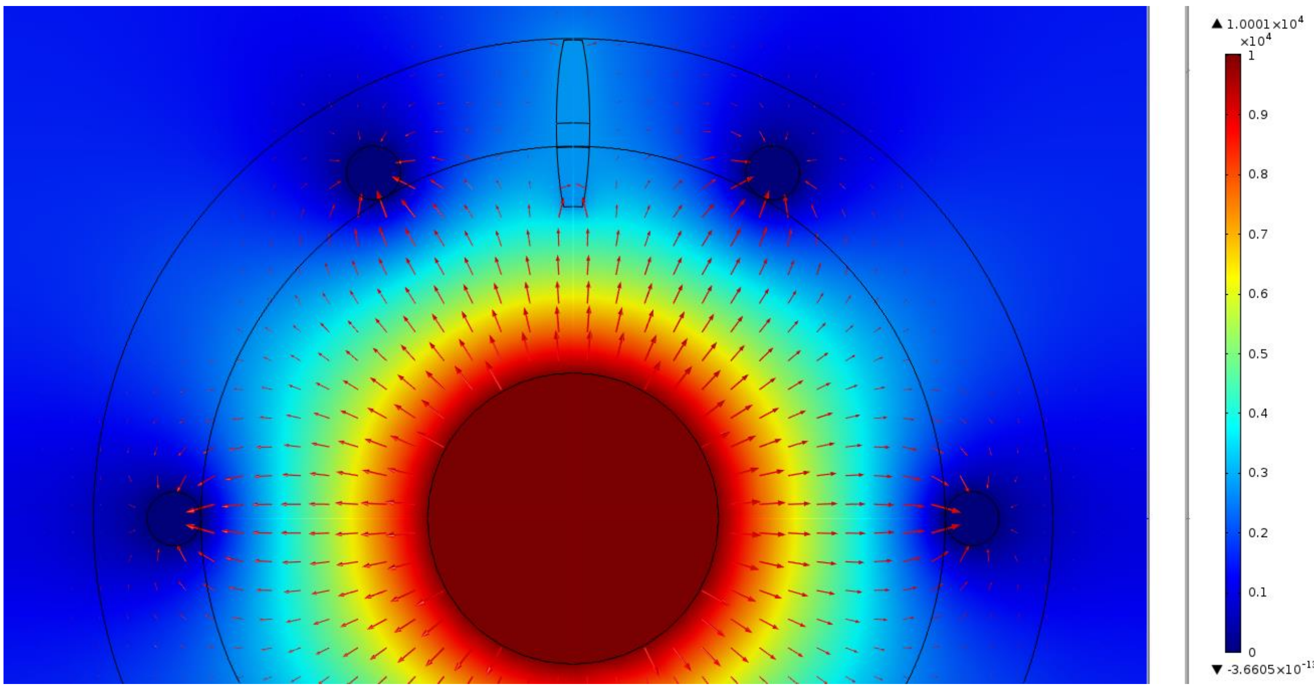


Figure 2.13: Water tree 50% across insulation for concentric neutral cable not grounded

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 2.14.

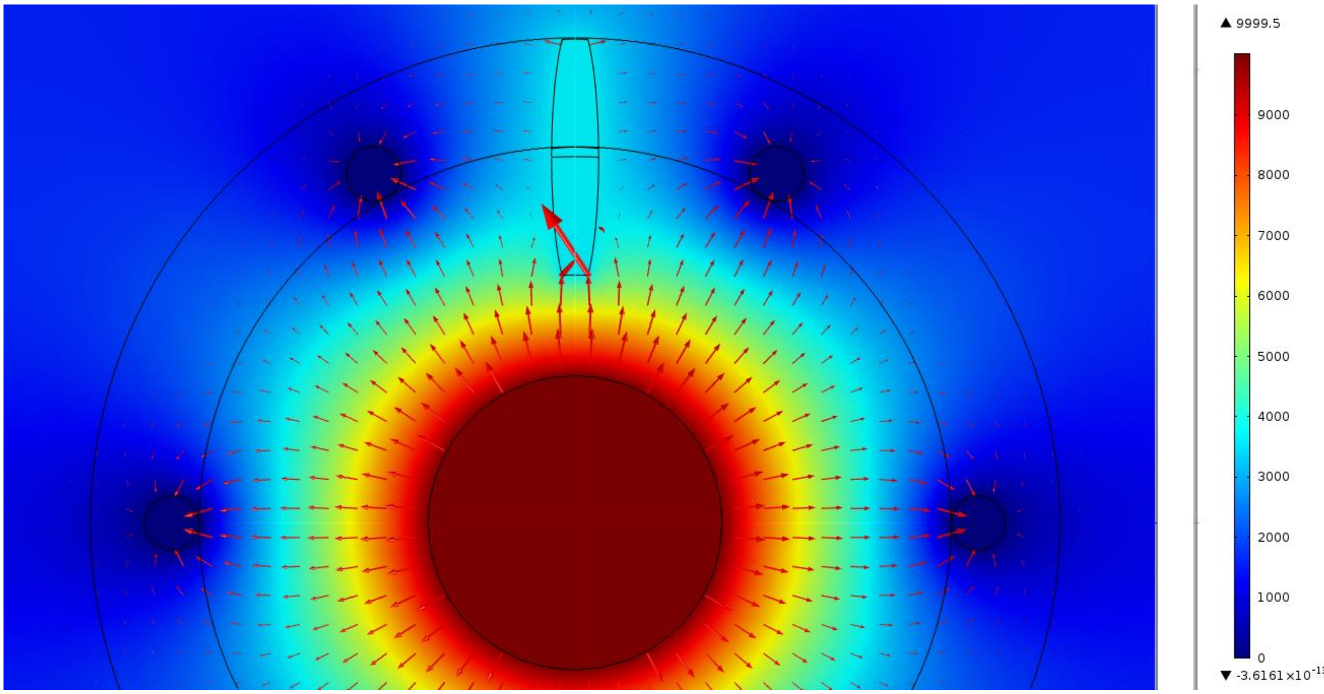


Figure 2.14: Water tree 70% across insulation in concentric neutral ungrounded

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 2.15.

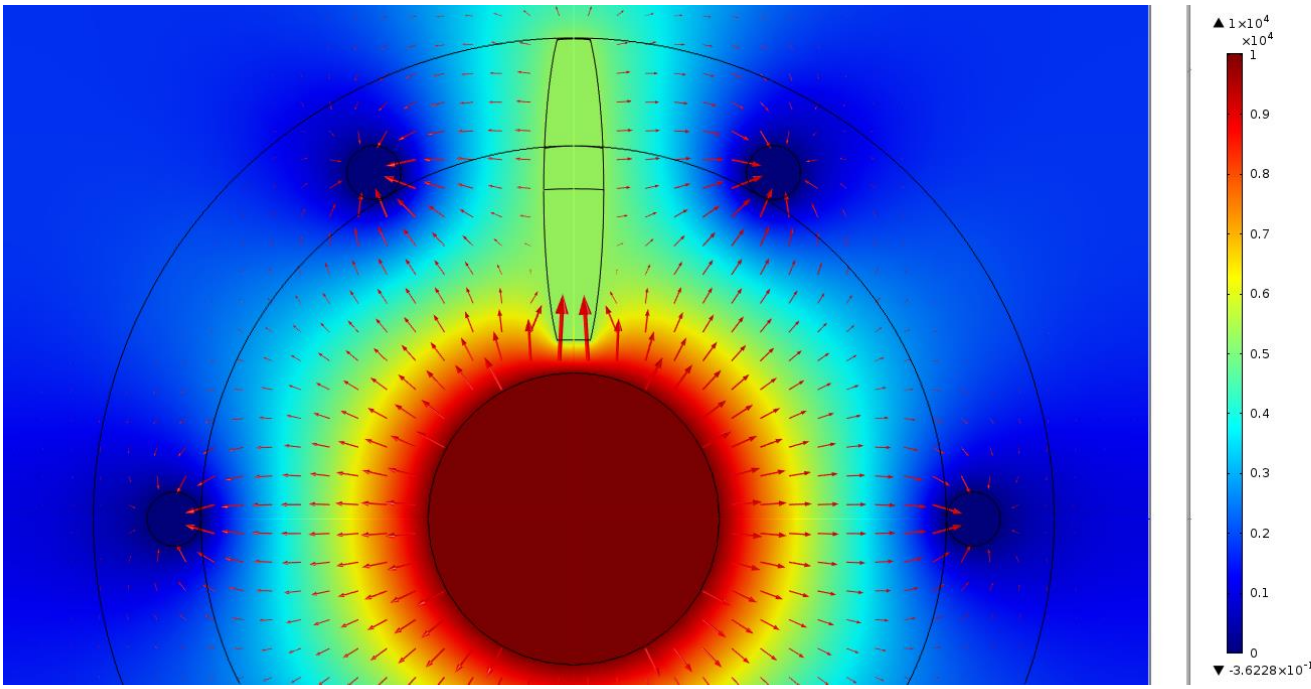


Figure 2.15: Water tree 90% across insulation in concentric neutral ungrounded

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 2.16.

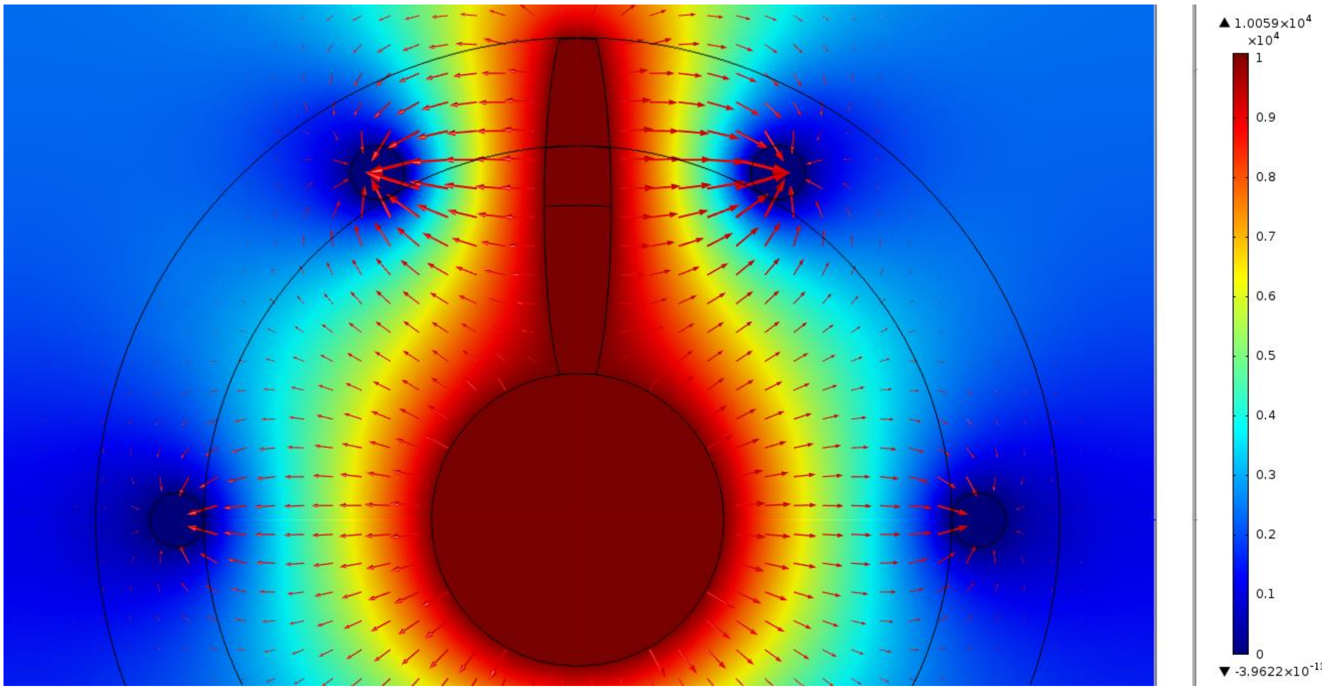


Figure 2.16: Water tree 100% across insulation in concentric neutral ungrounded

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.

2.3.2.2 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 2.17.

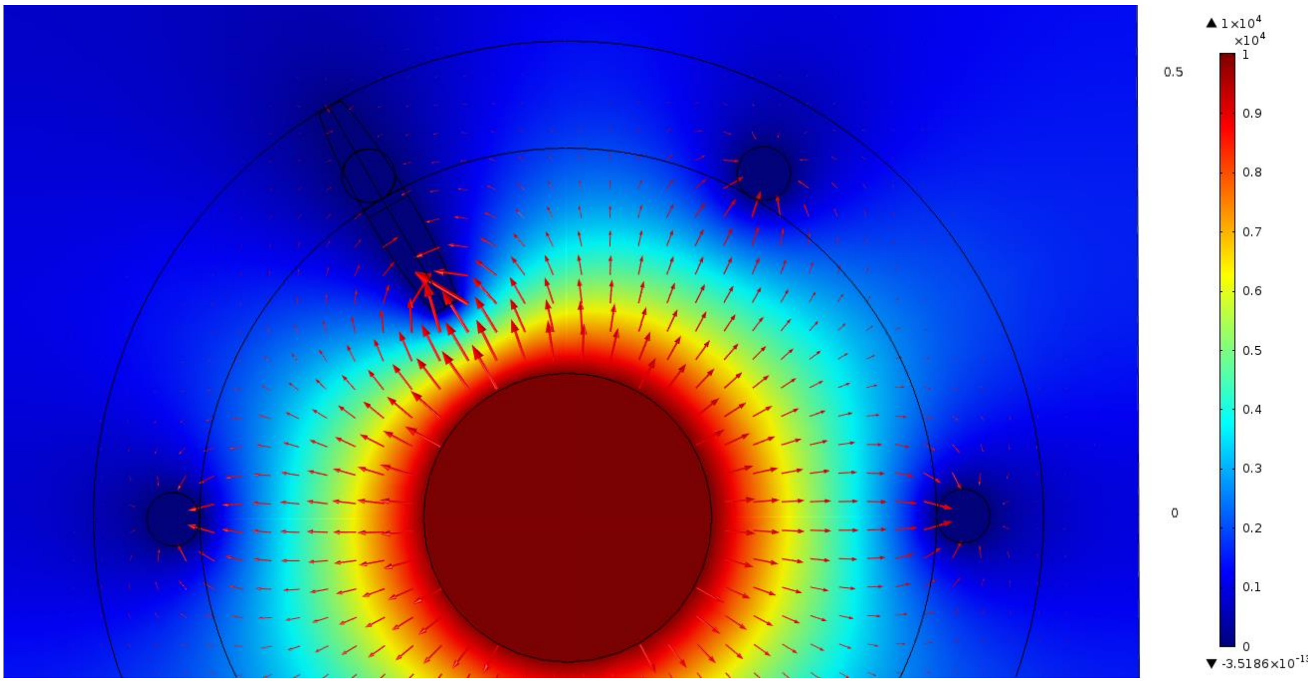


Figure 2.17: Water tree 70% across insulation in concentric neutral cable grounded

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 2.18

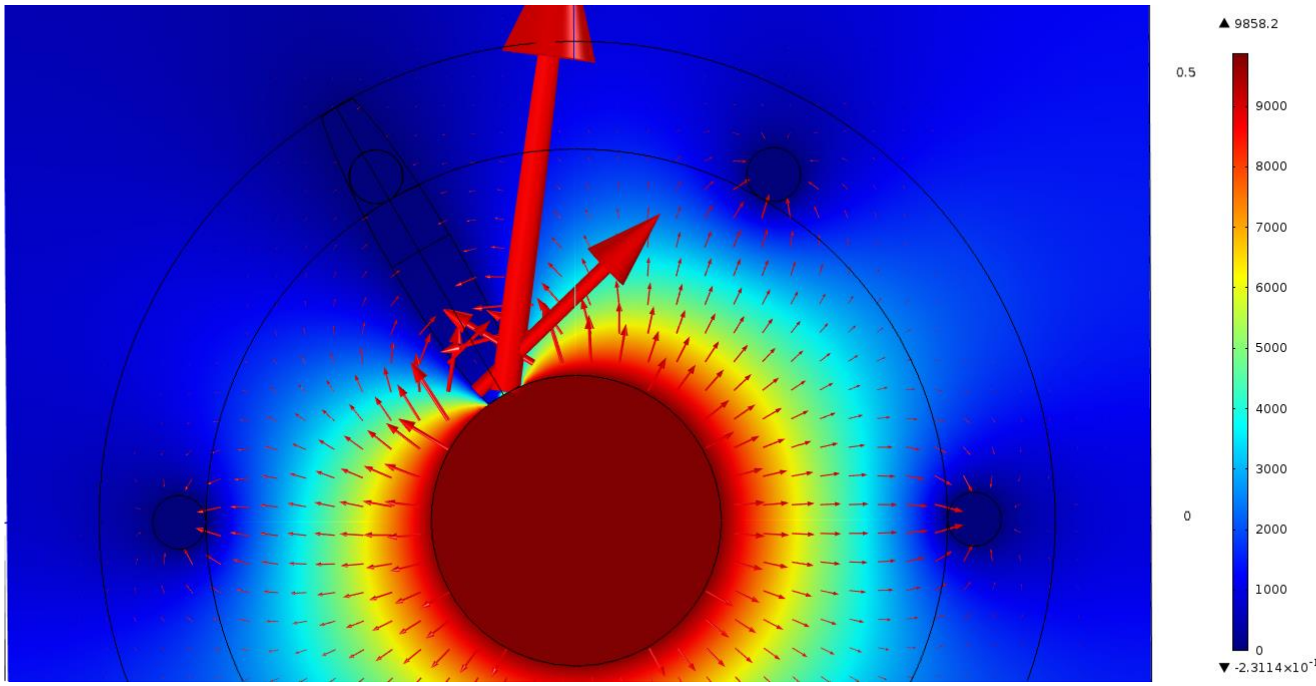


Figure 2.18: Water tree 100% across insulation in concentric neutral cable grounded

Notice that this water tree has breached the insulation, but the electric potential is still unchanged inside the cable. It is at 9.86 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.

2.4 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 [8,10,19,20]. Some use a model where the healthy insulation is a capacitance and then it is in series with the parallel resistance and capacitance [19]. 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.

2.4.1 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 2.3:

$$\frac{2\pi\varepsilon_r\varepsilon_o L}{\ln\left(\frac{r_2}{r_1}\right)} \quad (2.3)$$

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 2.19 for the tape shield cable and in Figure 2.20 for the concentric neutral cable.

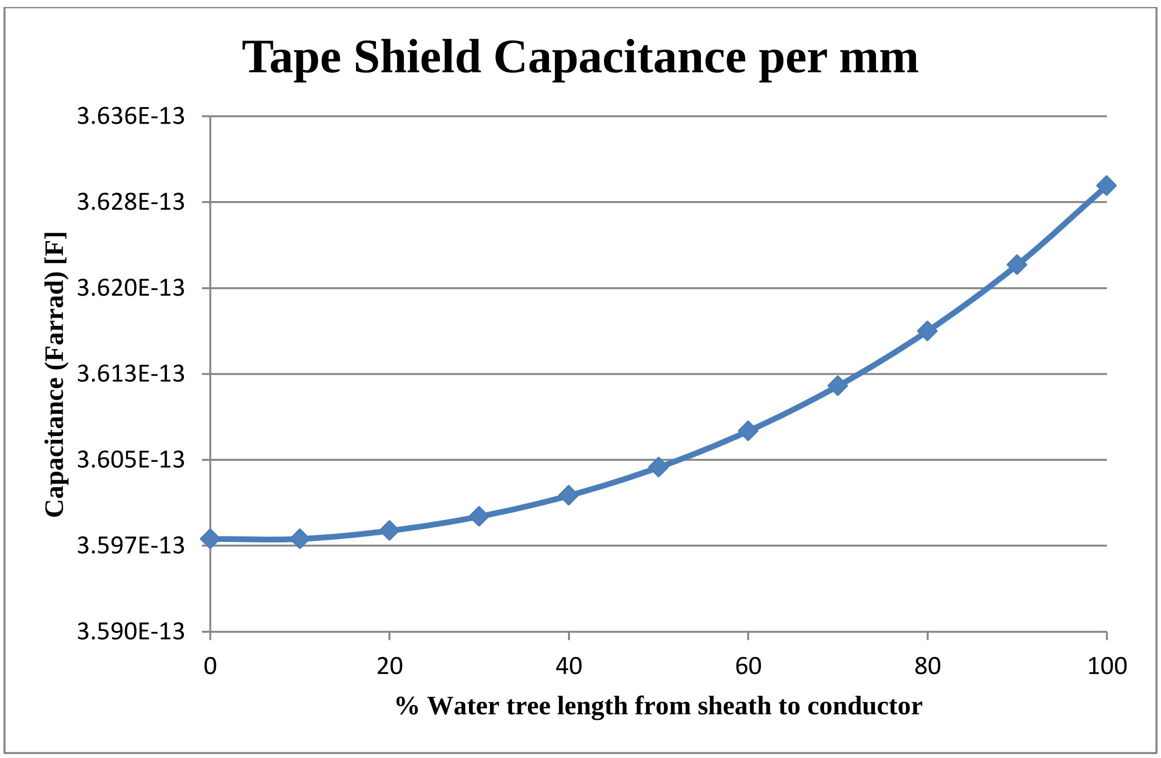


Figure 2.19: Tape shield capacitance from water tree growth

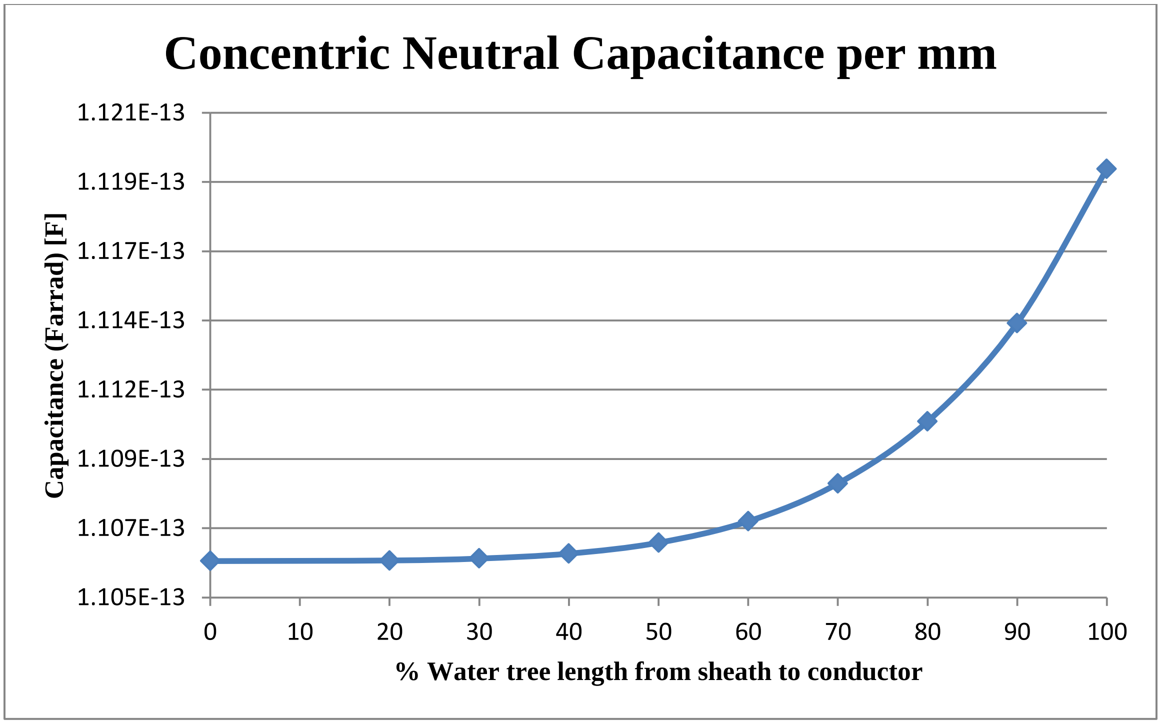


Figure 2.20: Concentric neutral capacitance for water tree growth

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, but the exponential shape will help with determining the size of water trees later in Chapter 4.

2.4.2 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 resistance plots are shown in Figure 2.21 for tape shield and 2.22 for concentric neutral.

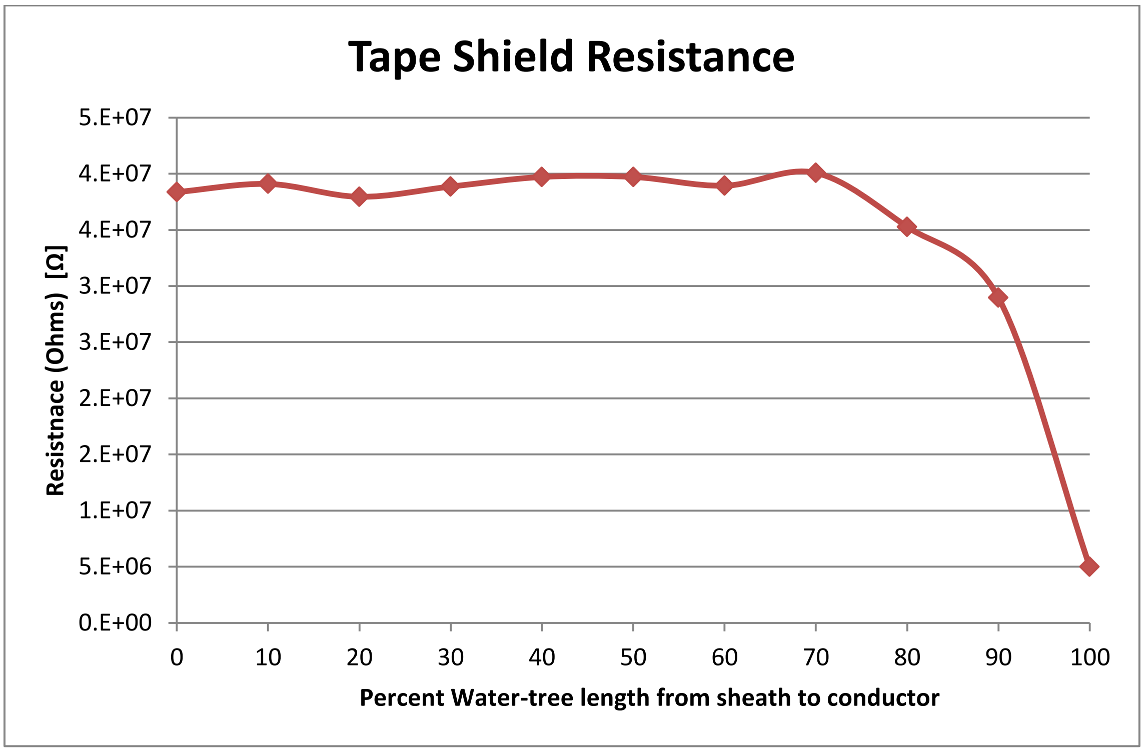


Figure 2.21: Tape shield resistance due to water tree growth

The conductance was solved with equation 2.4:

$$G = \frac{\sigma A}{l} \tag{2.4}$$

Where:

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

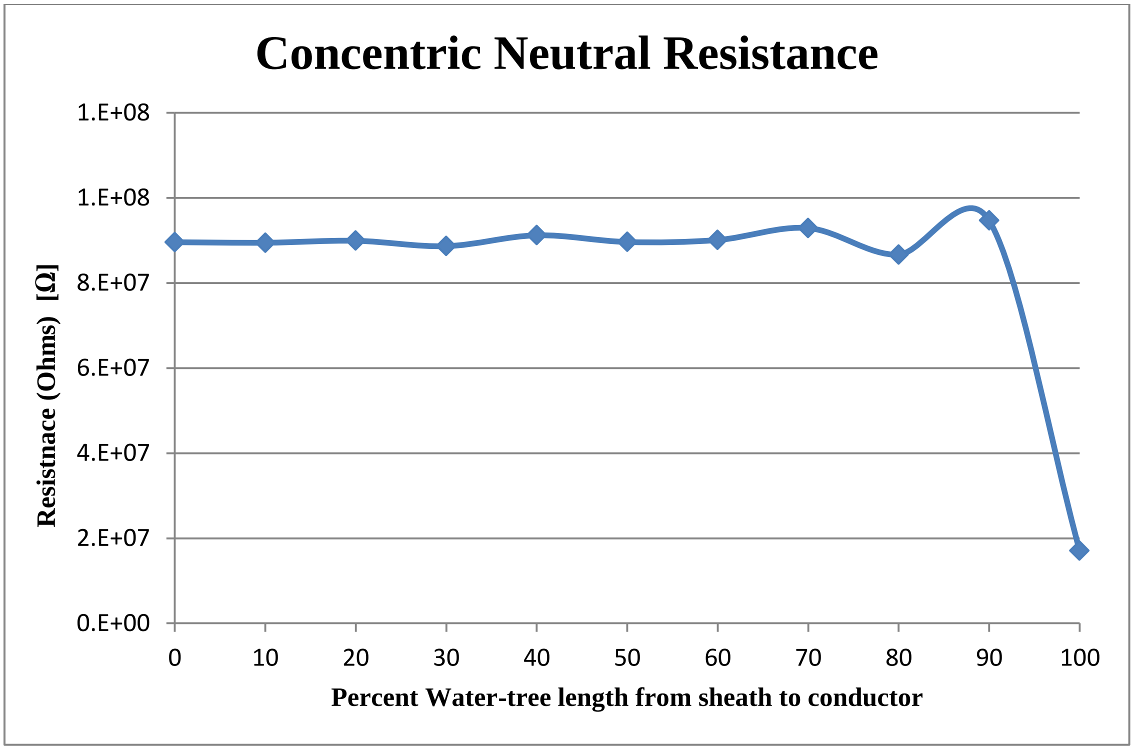


Figure 2.22: Concentric neutral resistance due to water tree growth

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. In Chapter 4, I will show that the resistance is not needed to detect water trees.

CHAPTER THREE

WATER TREE OBSERVATION WITH SYNCHROPHASORS OR SCADA

3.1 Introduction

The introduction of synchrophasors or phasor measurement units (PMUs) to the bulk energy system has allowed for improvements in many different areas, such as stability, protection, state estimation, and reliability. This is due to the fact that PMUs measure the voltage and current's magnitude and phase, which was otherwise unknown and had to be calculated. Due to the fact that PMUs have been used in these applications and have made improvements to speed and accuracy, one new application proposed in this thesis is to use the PMUs to detect water trees in underground cables. The PMU's accuracy and phase measurement is what is expected to be able to detect the water tree.

3.2 Cable Model

In order to model the water tree in PSCAD, the appropriate cable model must be used. PSCAD has a built-in cable model that uses traveling waves to simulate the model using EMTDC. However, because of the use of traveling waves, the simulation time step must be small enough to account for the time the signal takes to travel down the cable. In distribution systems the cables are very short, around 200 feet long, and therefore, the time step must also be very small, 10 percent of the traveling time of the cable [21]. Therefore, to reduce the simulation time it is proposed that using Carson's line equations to calculate the self-impedance, mutual-impedance, and self-capacitance, the time step can be increased and reduce simulation time.

3.2.1 Carson Line Equations

The Carson line equations can be found in [22], which also gives the self-capacitance equations. The equation for self-impedance is given in equation 3.1 below and the mutual-impedance is given in equation 3.2 below.

$$\hat{z}_{ii} = r_i + 0.0953 + j0.12134(\ln \frac{1}{GMR_i} + 7.93402)\Omega / mile \tag{3.1}$$

$$\hat{z}_{ij} = 0.09530 + j0.12134(\ln \frac{1}{D_{ij}} + 7.93402)\Omega / mile \tag{3.2}$$

The resistance of the conductor *i* in Ω/mile is r_i, and the geometric mean radius of conductor *i* in feet is GMR_i.

3.2.1.1 Concentric Neutral Cables

For concentric neutral cables, the GMR and resistance for the neutral wires are given in equations 3.3 and 3.4 respectively.

$$GMR_{cn} = \sqrt[k]{GMR_s \times k \times R^{k-1}}\ ft \tag{3.3}$$

$$r_{cn} = \frac{r_s}{k} \tag{3.4}$$

The geometric mean radius of a neutral strand in feet is GMR_s. The resistance of solid neutral strand in Ω/mile is r_s, and *k* is number of concentric neutral strands. Finally, *R* is the radius of a circle passing through the center of the concentric neutral strands as given in equation 3.5 in feet.

$$R = \frac{d_{od} - d_s}{24}\ ft \tag{3.5}$$

Where in this equation the nominal diameter over the concentric neutrals of the cable in inches is d_{od}, and the diameter of a concentric neutral strand in inches is d_s.

The shunt admittance equation for concentric neutral cables is given in equation 3.6 below.

$$Y_{ag} = j\frac{(2\pi)^2 f\varepsilon_0\varepsilon_r}{\ln\frac{R}{RD_c} - \frac{1}{k}\ln\frac{k\times RD_s}{R}}\mu S/mile \tag{3.6}$$

Where in this equation f is the frequency and ε_0 is the permittivity of free space. The relative permittivity is ε_r, and RD_c is the radius of the phase conductor in inches. The radius of the strand conductor in inches is RD_s, and the number of strands is k. Finally, R is calculated as previously stated, but in inches.

3.2.1.2 Tape Shield Cables

For tape shield cables, the GMR and resistance for the tape shield are given in equations 3.7 and 3.8 respectively.

$$GMR_{shield} = \frac{d_s - \frac{T}{1000}}{24} ft \tag{3.7}$$

$$r_{shield} = 7.9385\times10^8\times\frac{\rho}{d_s\times T}\Omega/mile \tag{3.8}$$

Where in this equation the outside diameter of the tape shield in inches is d_s, and the thickness of the tape shield in mils is T. Finally, the resistivity in Ω-meters at 50°C is ρ.

The shunt admittance equation for tape shield equations is given in equation 3.9 below, and all of its parameter have been previously explained.

$$Y_{ag} = j\frac{(2\pi)^2 f\varepsilon_0\varepsilon_r}{\ln\frac{d_s - \frac{T}{1000}}{2\times RD_c}}\mu S / mile \tag{3.9}$$

3.2.2 Comparison of Carson Line with PSCAD Model

Next, the Carson line model must be compared to the PSCAD cable model, to know whether the Carson line model is acceptable to use to represent the cable. If the comparison is okay it will reduce simulation time tremendously. The simulation time when using the cable model in PSCAD must be a tenth of the traveling time [21]. The sending and receiving end voltage and current of the Carson line equations or PI model were compared to the PSCAD cable model and shown in Figure 3.1.

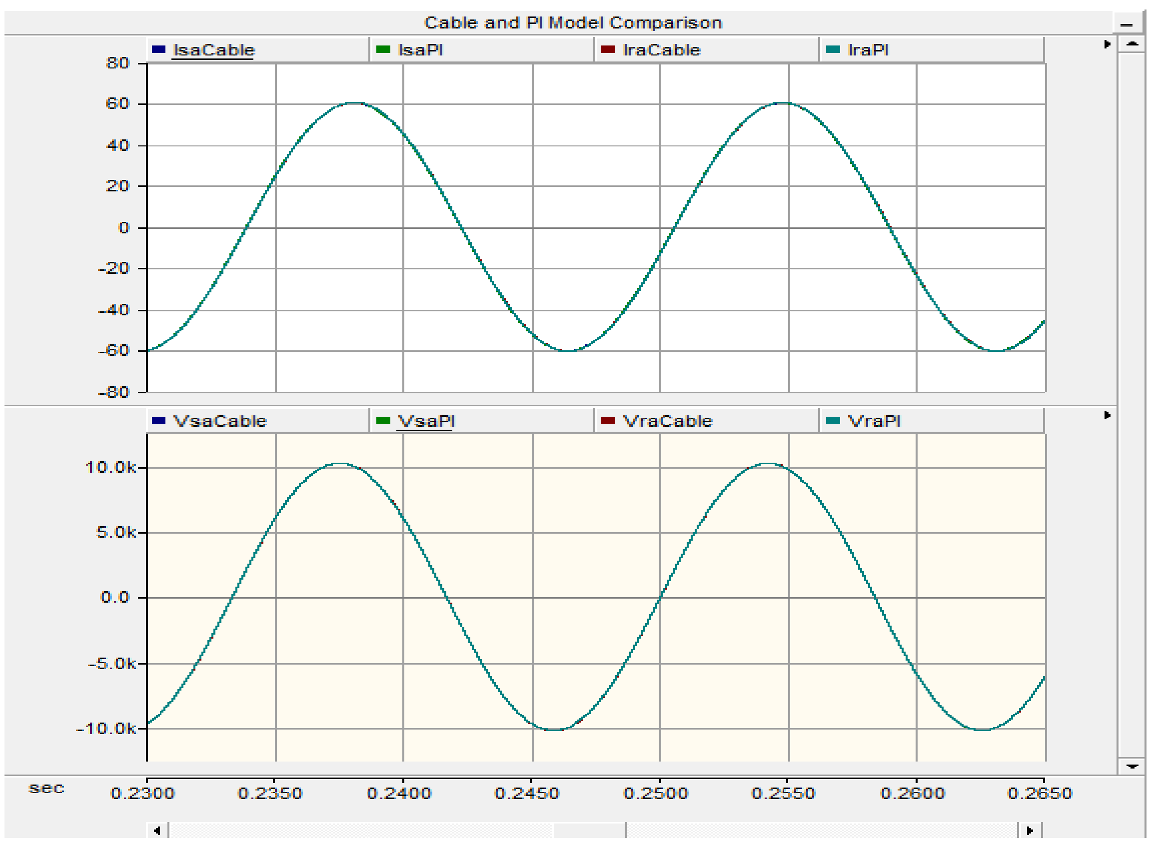


Figure 3.1: Voltage and current wave forms at sending and receiving ends of cable

From Figure 3.1, the wave forms look as if they are the same. This is because one cannot distinguish from the different signals in the plot since they are on top of each other. The sending and receiving end current is plotted in the same graph just like the voltage. Therefore, if the two models are the same, then the amount of current and voltage that are being lost in the two models should be the same. This is shown in Figures 3.2 and 3.3 respectively. The waveform and the phase are shown in the plots.

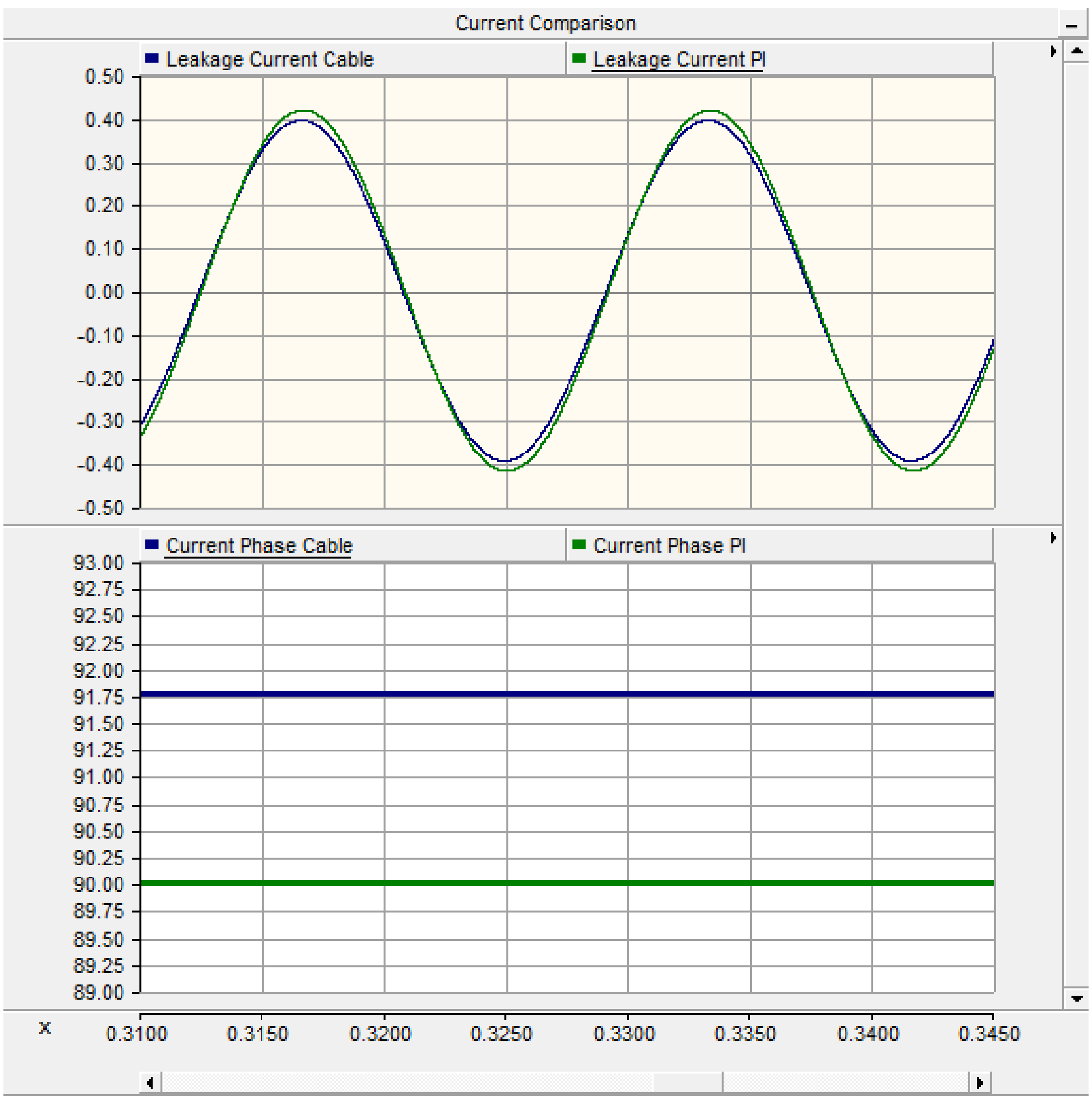


Figure 3.2: Leakage current comparison of cable and PI model wave form and phase

As it can be seen, the leakage current in the cable and in the PI model are fairly close to each other. The magnitude has about a 0.02 amps difference while the phase angle difference is about 1.75 degrees. Therefore, the leakage current in the PI model and cable model are close enough to substitute the PI model for the cable model. Finally, the leakage voltage for the two models was measured and shown in Figure 3.3.

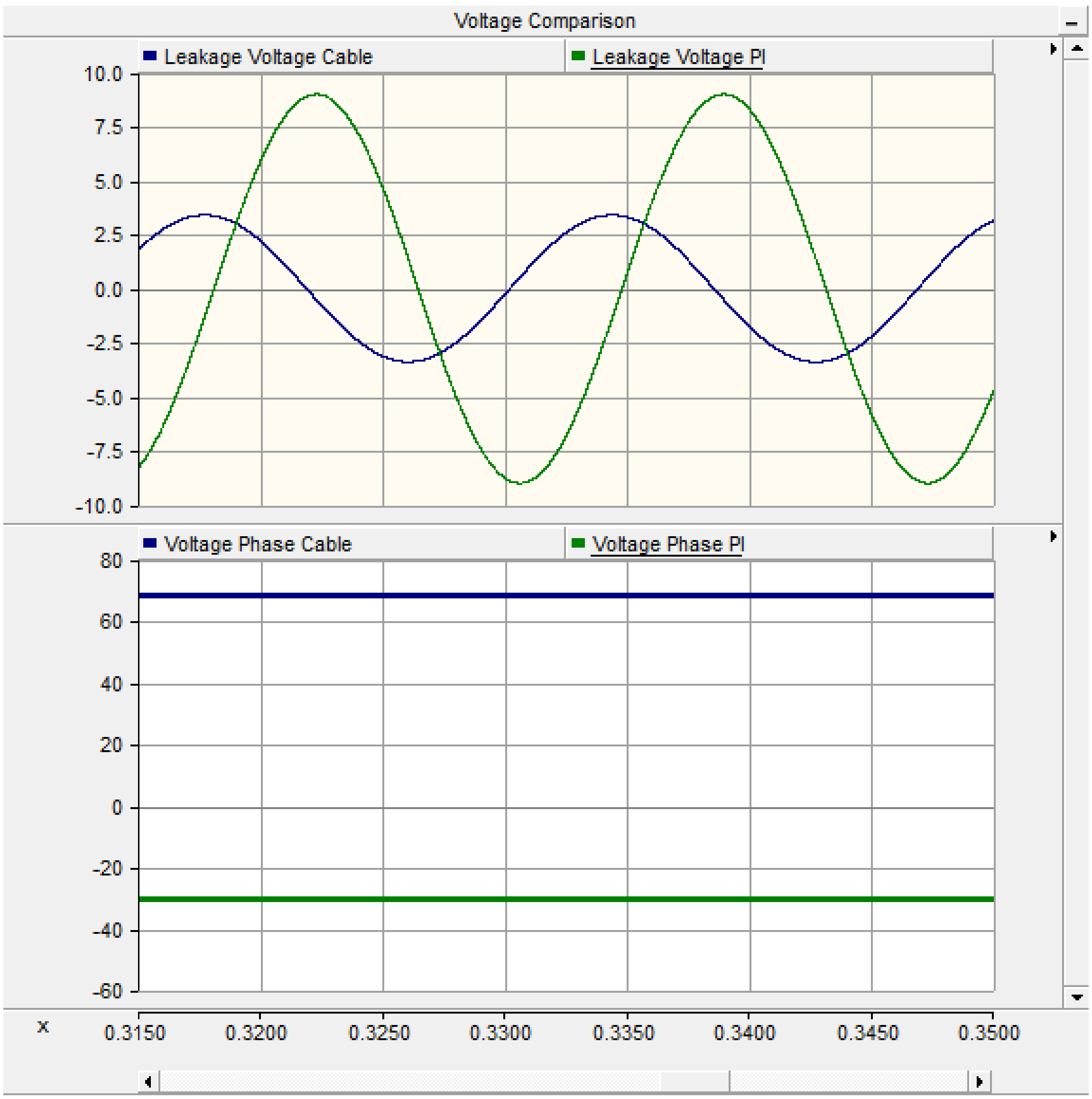


Figure 3.3: Leakage voltage comparison of cable and PI model wave form and phase

As it can be seen from Figure 3.3, the voltage wave form for the PI model is not only out of phase with the cable model by almost 100 degrees, but the PI model's magnitude is almost three times the magnitude of the cable model. The reason for this mismatch in voltage is believed to be from the mutually coupled model used in the PI model. The mutually coupled model in PSCAD does not take into account the mutual resistance of different phases and it can therefore account for the increase in voltage of the PI model. Therefore, because the leakage voltage in the PI model does not match that of the cable model, the cable model must be used and large simulation times due to small time steps cannot be avoided.

3.3 Method for Water Tree Detection

The method that is proposed to detect water trees is to monitor the current that is lost in the insulation or leakage current. This is done by measuring the current at the sending and receiving end of the cable and subtracting the receiving end current from the sending end current. As the water tree grows, the leakage current will become more resistive and its phase will reduce from the healthy cable's phase. By monitoring the phase of the leakage current, the health of the cable can be determined. This concept is called the dissipation factor or tan δ. In order to determine if this method would work for monitoring cables it must be simulated in PSCAD and several properties should be tested: the location of the water tree along the cable, the size of the cable, and the presence of an electrical tree with the water tree.

3.3.1 Location of Water Tree on the Cable

Knowing the location of the water tree on a cable is very important because it can allow for that section to be removed and the cable spliced together so that the utility company would not have to replace the whole cable. Therefore, several cables of the same length, 40 feet, were connected to a source in PSCAD. The water tree was placed at the sending end, 25% down the cable, 50% down the cable, 75% down the cable, and at the receiving end. Also, a healthy cable was connected to the source as well. The leakage current wave forms for all water tree locations are located in Figure 3.4.

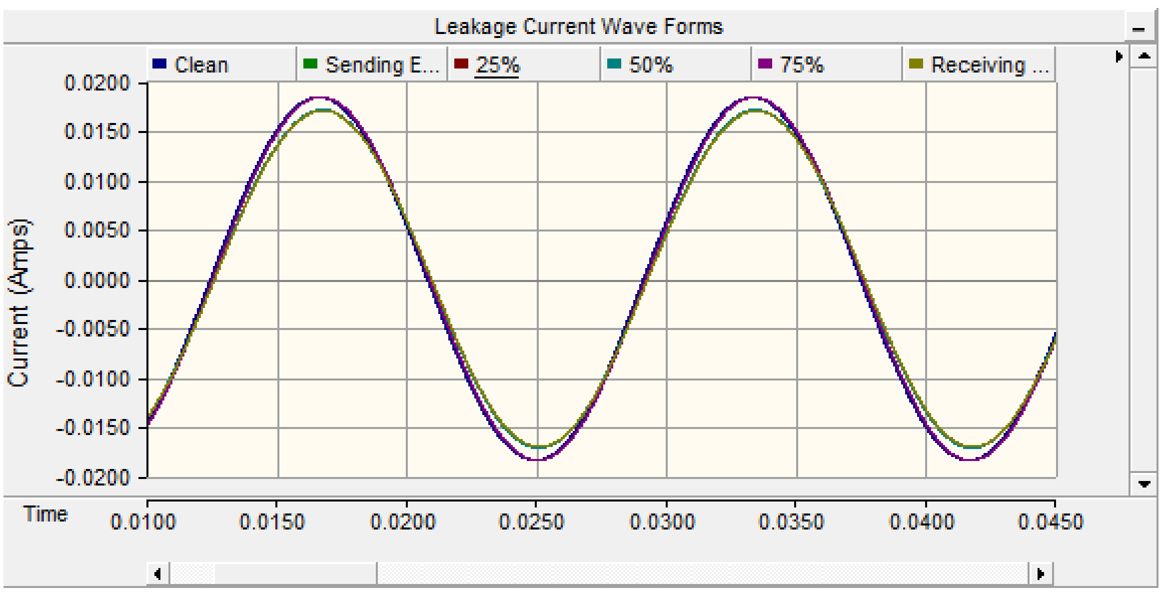


Figure 3.4: Leakage current wave forms when water trees are at different locations

The figure shows that there is no difference in magnitude of the leakage current wave forms as the water tree is placed in different location. This concludes that the leakage current magnitude is not an indicator of having a water tree in a cable or where the water tree is located. Therefore, the phase of the wave form was monitored in order to see whether, if the water tree is in a different location, the phase of the leakage current would change. The phases of the leakage current with the water trees at different positions are located in Figure 3.5.

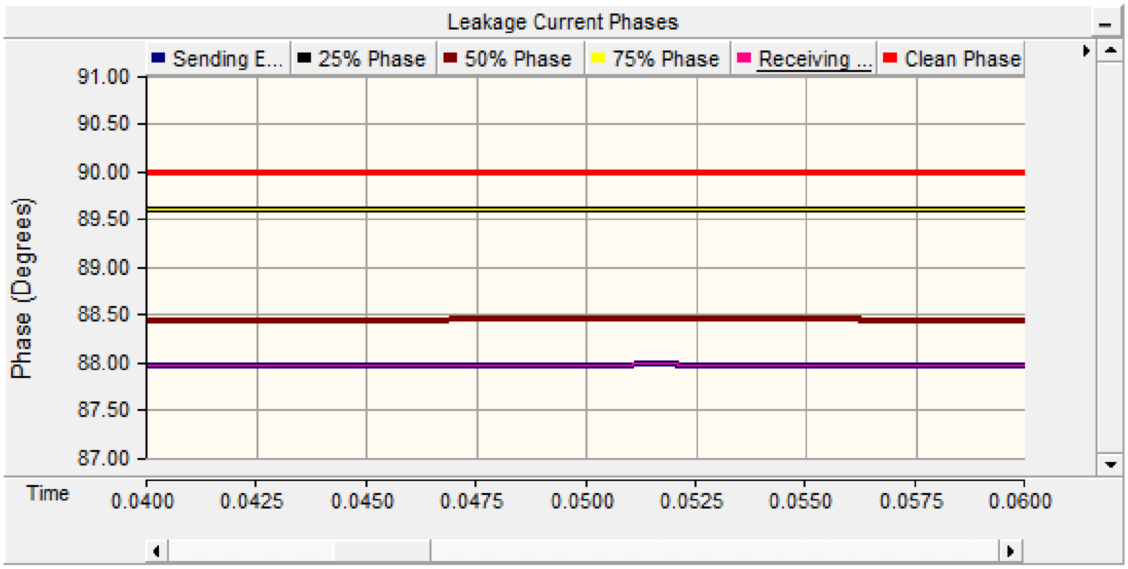


Figure 3.5: Leakage current phases when water trees are at different locations

From the figure you can see that when the water tree is added to the cable, the leakage current phase reduces because it becomes more resistive. This can be somewhat of an indicator. However, there is no method of indicating where the water tree is due to its phase. Also, when one water tree is located at the same distance from the sending end as another water tree is from the receiving end, the phase will be the same. This can be seen with water trees located at the sending end and receiving end as shown in blue and pink, respectively, and it can be seen with water trees at 25% and 75% along the cable as shown in black and yellow, respectively. Therefore, the leakage voltage was monitored to see if it can be used as some type of indicator. The leakage voltage wave form for all the locations are located in Figure 3.6.

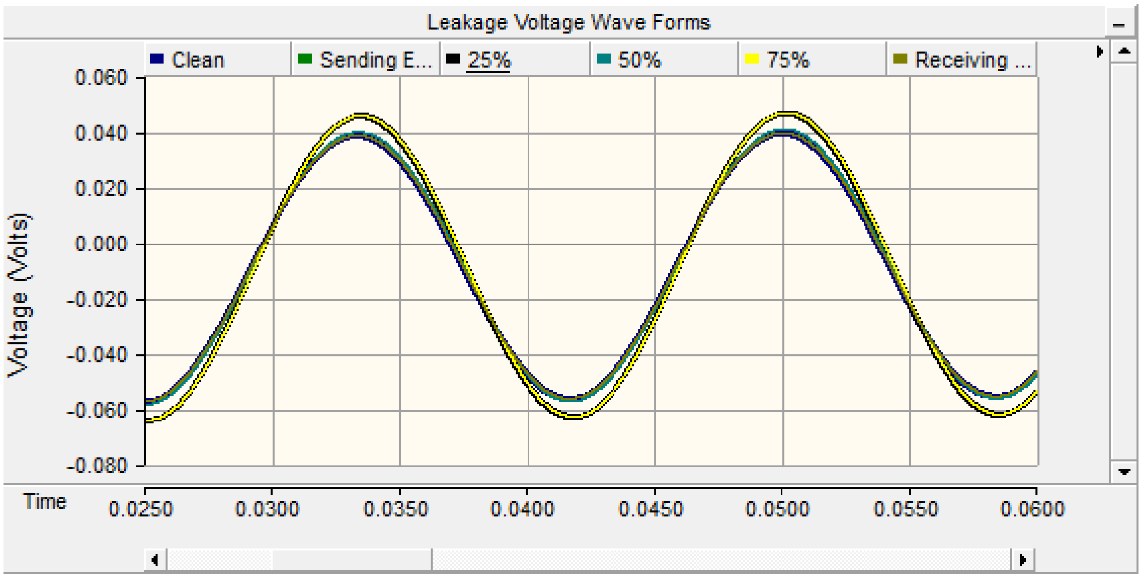


Figure 3.6: Leakage voltage wave forms for water trees at different locations

From the figure it can be seen that the water tree's magnitude of leakage voltage is the same as the cables with water trees. Also, there is still no indicator of the location of the water tree from the magnitude. Therefore, the phases of the leakage voltage were monitored, as shown in Figure 3.7.

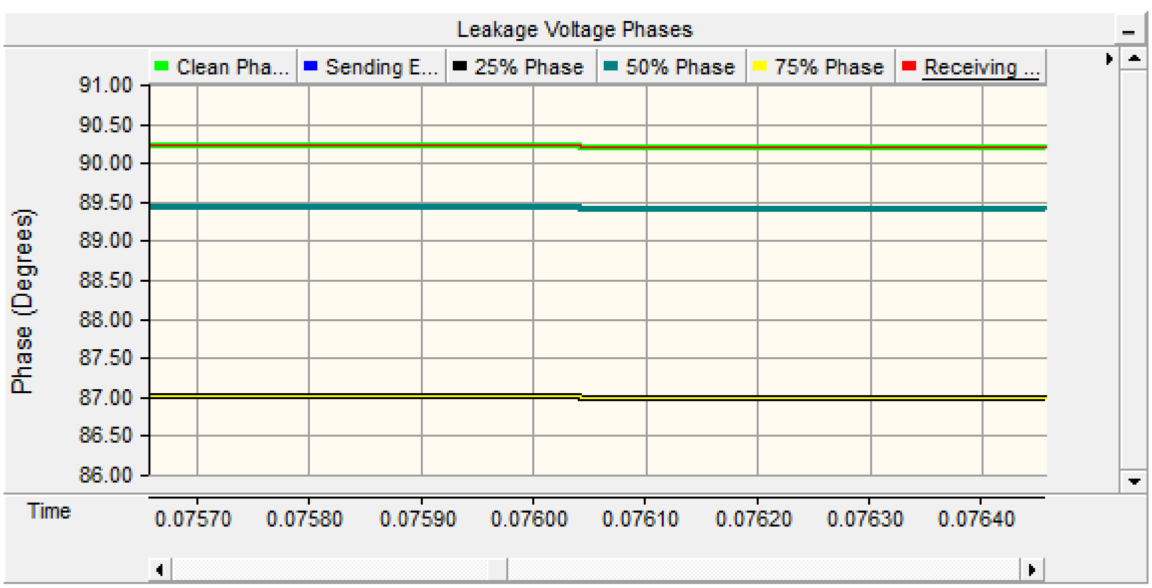


Figure 3.7: Leakage voltage phases for water trees at different locations

The leakage voltage phases were similar to the leakage current phases. That is the phase values are reduced if the water tree was added to the cable. However, the sending and receiving end phases did not change much from the clean cable. Also, the phases were the same for one water tree that was the same distance from the sending end as another water tree that is the same distance and the receiving end such as the water trees located 25% and 75% along the cables shown as black and yellow respectively in Figure 3.7.

3.3.2 Water Trees in Cables of Different Lengths

The length of the cable is important because distribution feeders have a variety of lengths. Therefore, if the water tree is to be monitored using the cable's leakage current phase, then the method must be able to detect changes in phase with cables up to 500 feet. Therefore, six cables were connected to a voltage source. The lengths of the cables in groups of two were 100 feet, 300 feet, and 500 feet. A water tree was placed on one of each of the pair of cables to see the change in leakage current phase due to the length of the line. The leakage current wave forms are not beneficial in determining if there is a water tree in the cable since the magnitude changes by about 1 mV. Therefore, the leakage current phase is monitored and compared with the healthy leakage current phase for that same length of cable in order to determine if there is a water tree. The leakage current phases for the 100 feet, 300 feet, and 500 feet cables are located in Figure 3.8, Figure 3.9, and Figure 3.10 respectively.

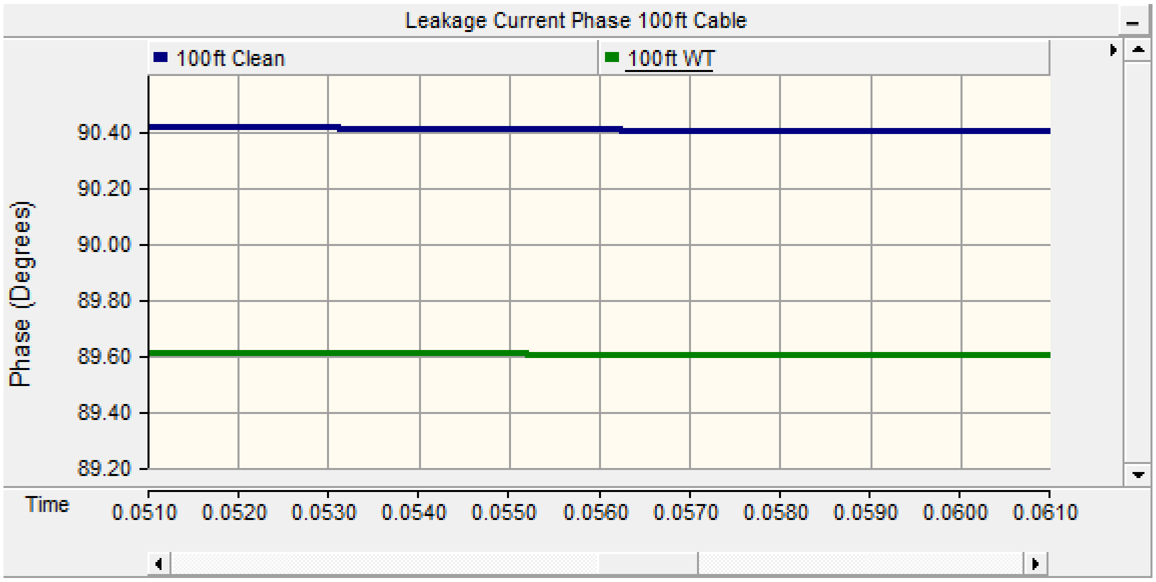


Figure 3.8: Leakage current phases for a 100 foot healthy cable and water treed cable

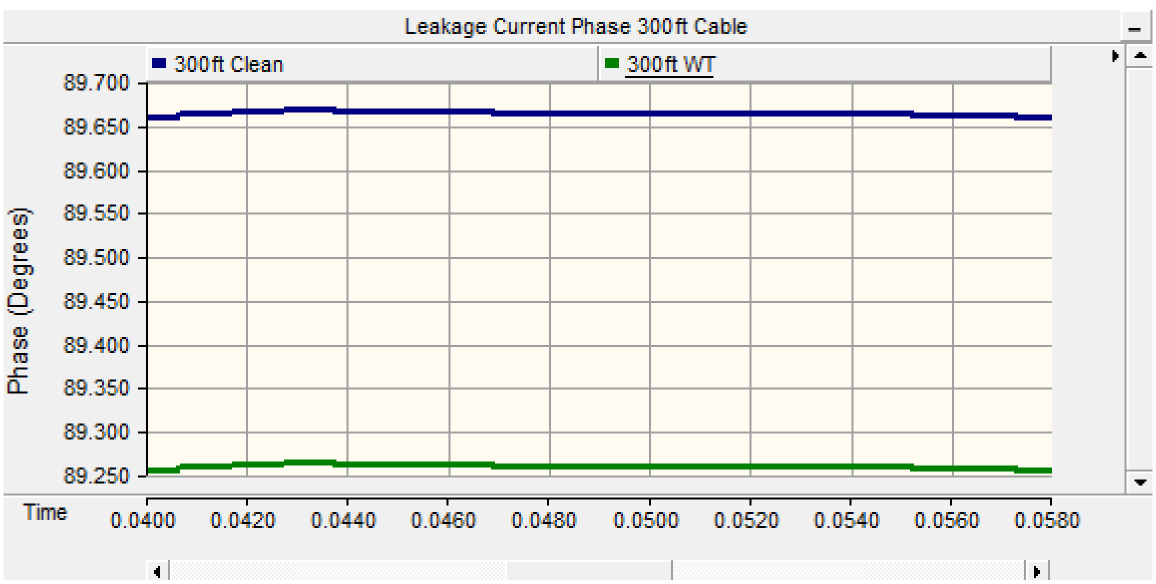


Figure 3.9: Leakage current phases for a 300 foot healthy cable and water treed cable

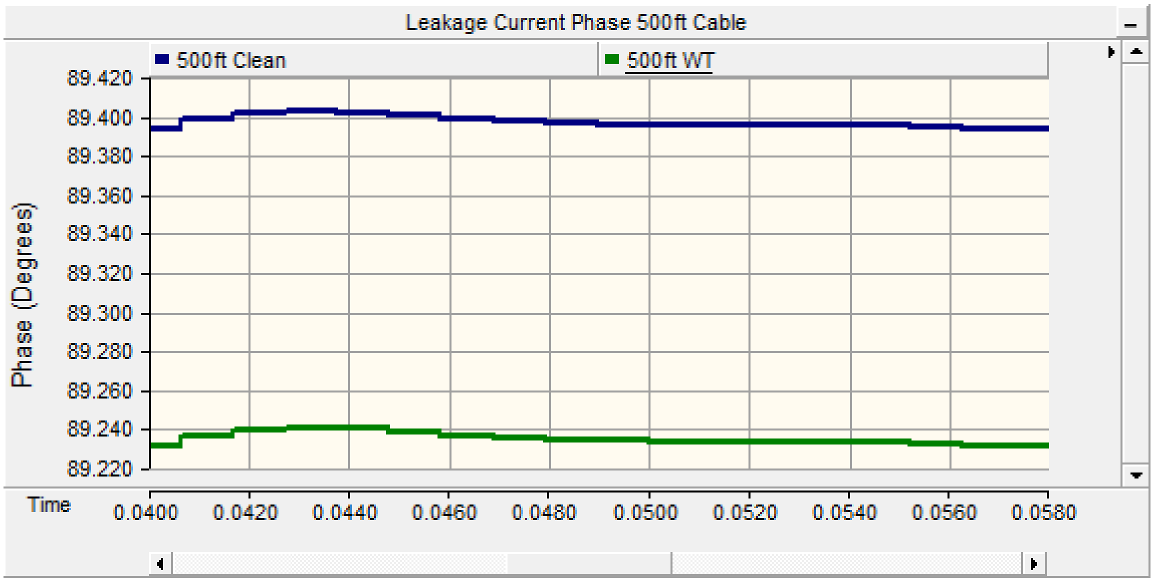


Figure 3.10: Leakage current phases for a 500 foot healthy cable and water treed cable

From the figures it can be seen that like what was expected the cable with the water tree's phase reduced due to the resistive nature of the water tree. However, with longer cables the amount of capacitance is increased. Therefore, with a small increase in resistance and a large capacitance due to length, the phase reduction from the water tree starts to become negligible and cannot distinguish a water tree. This can be seen in the figures where for the difference between healthy and water treed cables there is a 0.8 degrees difference for the 100 foot cables, a 0.4 degrees difference for the 300 foot cables, and a 0.16 degrees difference for the 500 foot cables. Also, using this method requires the knowledge of the healthy cables phase. Therefore, it cannot be used if the system has been installed for a while, and it cannot detect a water tree if there is an initial defect in the cable from manufacturing. Because of this it is not practical to detect water trees with this method.

3.3.3 Formation of Electrical Trees

Voltage breakdown of the cable is not due to water trees but to electrical trees [1]. However, electrical trees can break down the cable in a matter of seconds [10]. Therefore, the monitoring of electrical trees cannot save the cable's voltage breakdown, but it might give better knowledge of which cable was experiencing the electrical tree without wasting fuses. With this in mind, an electrical tree was added to the water tree model by adding a variable resistance in parallel with the water tree model. The variable resistance reduces as the water tree grows. The electrical tree's resistance starts at the same resistance as the water tree's and then it is assumed that in 0.15 seconds, the resistance reduces linearly to 1 kΩ, which is a sill a high impedance fault. The cable used is 40 feet long and the water tree is placed in the center of the cable. Figure 3.11 shows the leakage current wave form as the electrical tree grows.

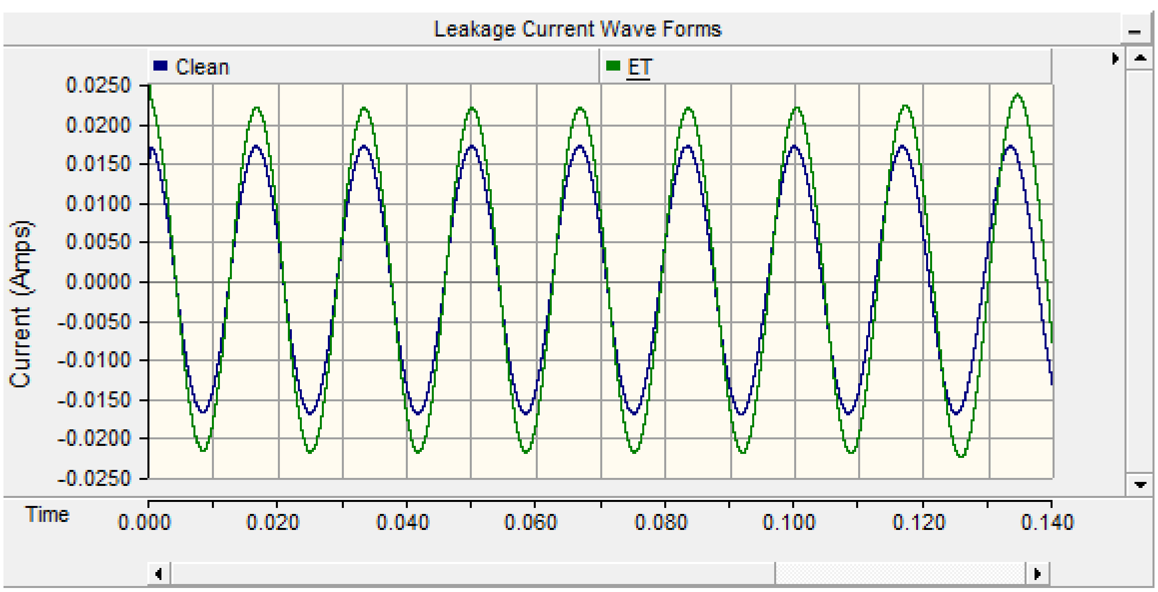


Figure 3.11: Leakage current wave forms for electrical tree formation and healthy cable

The figure does not show much change in the magnitude of the leakage current. However, the magnitude of the water tree is greater than the magnitude of the healthy cables, but it can be seen that the wave forms are starting to shift from each other which means that the phases are changing. The phases for the leakage current are plotted in Figure 3.12.

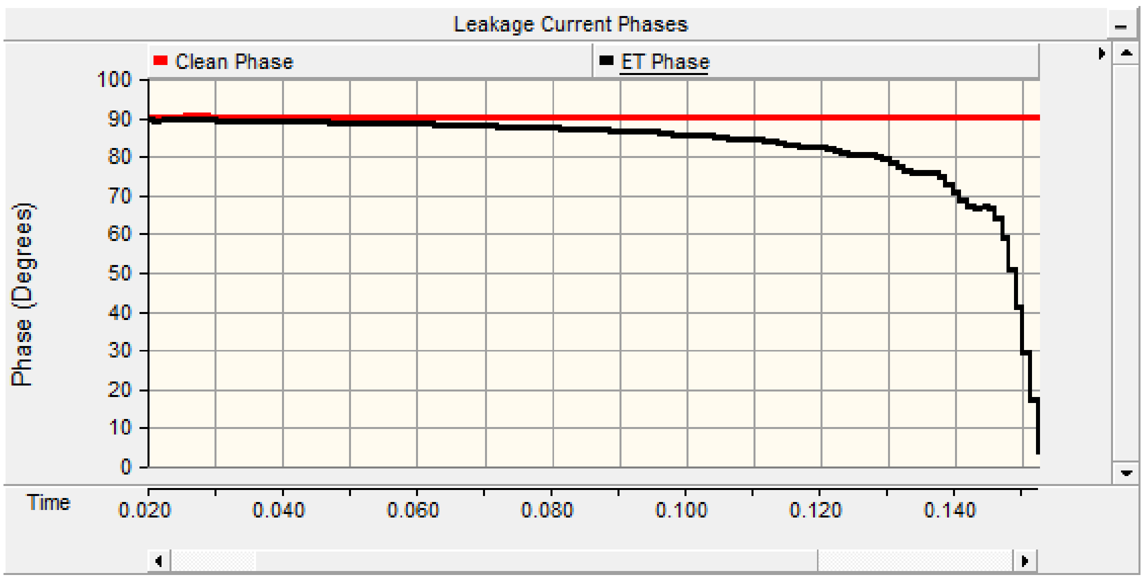


Figure 3.12: Leakage current phase for electrical tree formation and healthy cable

This figure shows that as the electrical tree grows, the phase starts to reduce because the resistance is decreasing, which allows for more resistive current to flow through the insulation. The phase has an exponential shape with the linear resistance. Therefore, as the resistance reduces to significantly smaller than the water tree resistance, the phase of the leakage current with an electrical tree starts to plummet and the difference can be to the order of 60 degrees. Therefore, an electrical tree can be detected by monitoring the phase of the leakage current. After it reaches a threshold, the cable can be disconnected. The leakage voltage is not shown because the electrical tree has no effect on its phase or magnitude.

3.4 Conclusion

Although the electrical tree can be monitored, it is not practical to do so. This is because in order to monitor the formation of electric trees, breakers would have to be placed on every cable, and distribution systems do not have breakers on every cable. Also, to place a PMU or a current transformer (CT) on the sending end and receiving end of every cable would not be feasible financially. Due to this practical and financial lack of feasibility, a more accurate and financial method of monitoring the cables is needed and explained in the next chapter.

CHAPTER FOUR

WATER TREE DETECTION USING TIME DOMAIN REFLECTOMETRY

4.1 Introduction

Time domain reflectometry (TDR) is one method that is proposed to detect water trees in underground cables, as mentioned previously [7]. TDR method consists of sending a high frequency voltage pulse down the cable and waiting for a voltage reflection to return. The voltage reflection is measured by a sensor on the sending end of the cable, as depicted in Figure 4.1.

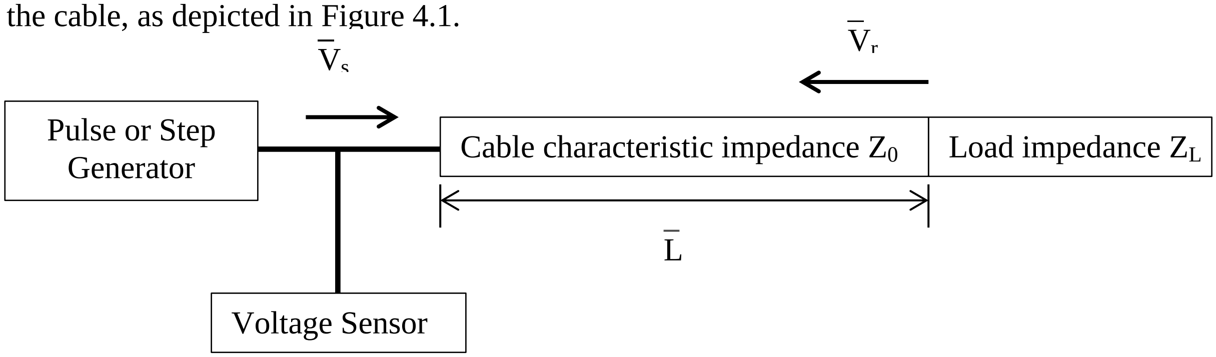


Figure 4.1: Diagram of TDR set up with one cable and load

This concept uses the traveling wave theory to detect the water tree. The high frequency pulse will travel through the cable. When it reaches an impedance mismatch such as a load or another cable, some of the high frequency pulse will transmit to the load or cable and continue traveling forward. However, depending on the voltage reflection coefficient there will be a reflected signal, which will travel back to the sending end and can be measured. The voltage reflection coefficient is the ratio of the reflected voltage and the sent voltage as expressed in 4.1.

$$\Gamma = \frac{V_r}{V_s} = \frac{Z_L - Z_0}{Z_L + Z_0} \tag{4.1}$$

Due to this ratio, no pulse would be seen if the cable were terminated with a load that has the same impedance as the cable, which is how infinitely long lines are simulated. Also, if the load impedance is less than the characteristic impedance of the line, then a negative reflection wave will be seen. Consequently, if the load impedance is more than the characteristic impedance of the line, a positive reflection wave will be seen. The probability that the load impedance will match the cable impedance is very small, so a reflected pulse from the interface of a load and cable will always be seen. Normally, the load impedance is larger than the characteristic impedance of the cable. Therefore, a positive reflection pulse is expected. Since the wave propagation velocity is known and the length of the cable is known, the time at which the reflection pulse will occur can be calculated using the following equation.

$$t_r = \frac{2 \times L}{v} \tag{4.2}$$

With this equation the reflection time for any cable can be calculated due to the cable's termination. Now with the reflection time known, any reflection seen before the termination reflection pulse is due to some type of impedance mismatch in the cable, such as water trees.

4.2 Water Tree Detection Method

When water trees form, they change the shunt impedance at the location that it formed, as explained previously, and the water tree is represented as a parallel resistance and capacitance. Therefore, this impedance change in the cable will cause a reflection pulse that will come before the termination reflection wave. This reflection pulse can be used to determine if there is a water tree inside the cable. However, there can be sections of cable that are spliced together with joints that would send reflection pulse back before the termination reflection pulse was measured as well. These reflection pulses could be mistaken for water trees. Therefore, the model of a cable joint was found in [23]. The model is represented as two shunt resistance and capacitance connected together with an inductance.

To compare whether or not the cable joint's reflection pulse will be the same as the water tree's, the characteristic impedance formula must be known. For an infinitely long line the characteristic impedance is calculated as follows in 4.3.

$$Z_0 = \frac{V(x)}{I(x)} = \sqrt{\frac{R + j\omega L}{G + j\omega C}} \tag{4.3}$$

At high frequencies, the resistance and conductance are negligible compared to the high frequency inductance and capacitance. Therefore, the characteristic impedance of a cable is represented by the square root of the inductance over the capacitance as seen in 4.4.

$$Z_0 = \sqrt{\frac{L}{C}} \tag{4.4}$$

From this equation it can be determined that when the inductance is increased in the cable, the impedance increases at that location and it is greater than the characteristic impedance. From equation 4.2, the reflection pulse would be positive. Also, when the capacitance is increased in the cable the impedance decreases at that location and is less than the characteristic impedance. From equation 4.2, the reflection pulse would be negative.

Since the cable joint's lumped parameters are mainly inductive, as explained above, it should produce a positive reflection pulse. This is due to the fact that the cable joint increases the impedance at that location. The model of the cable joint in [23] was implemented in PSCAD on a single phase of the cable. A high frequency pulse was placed on the cable and the results are shown in Figure 4.2.

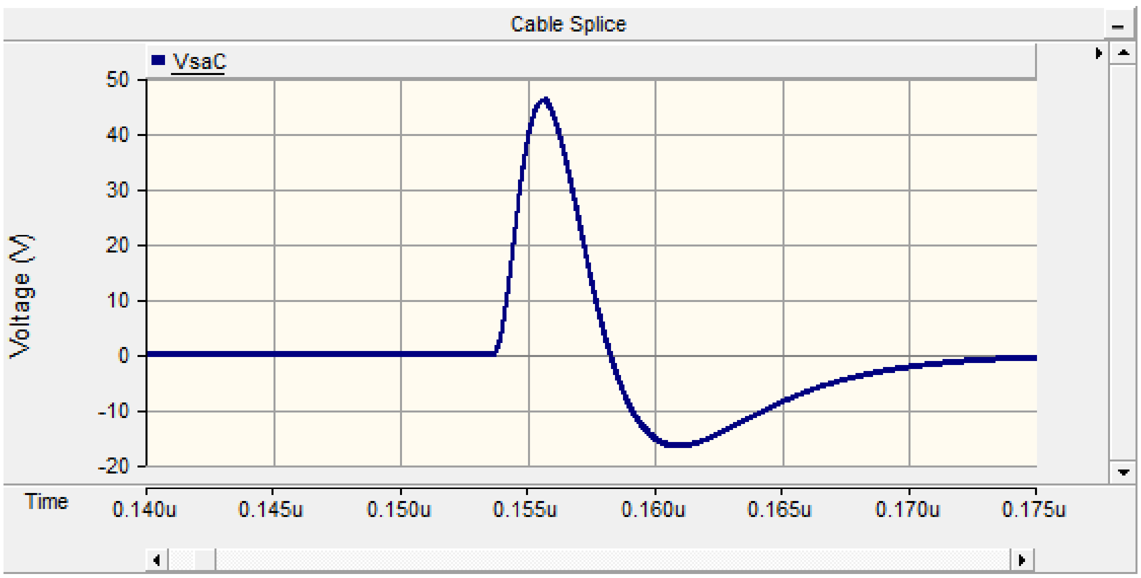


Figure 4.2: Reflection pulse due to splicing of a cable

Likewise, the water tree's lumped parameters are represented as a parallel resistance and capacitance, as stated previously. Therefore, there should be a negative reflection produced from the water tree. This is because the resistance does not have any affect during the high frequency pulse and the capacitance would reduce the characteristic impedance, as stated above. The water tree was simulated on a single cable to see the reflection pulse produced. The results from that simulation are shown in Figure 4.3.

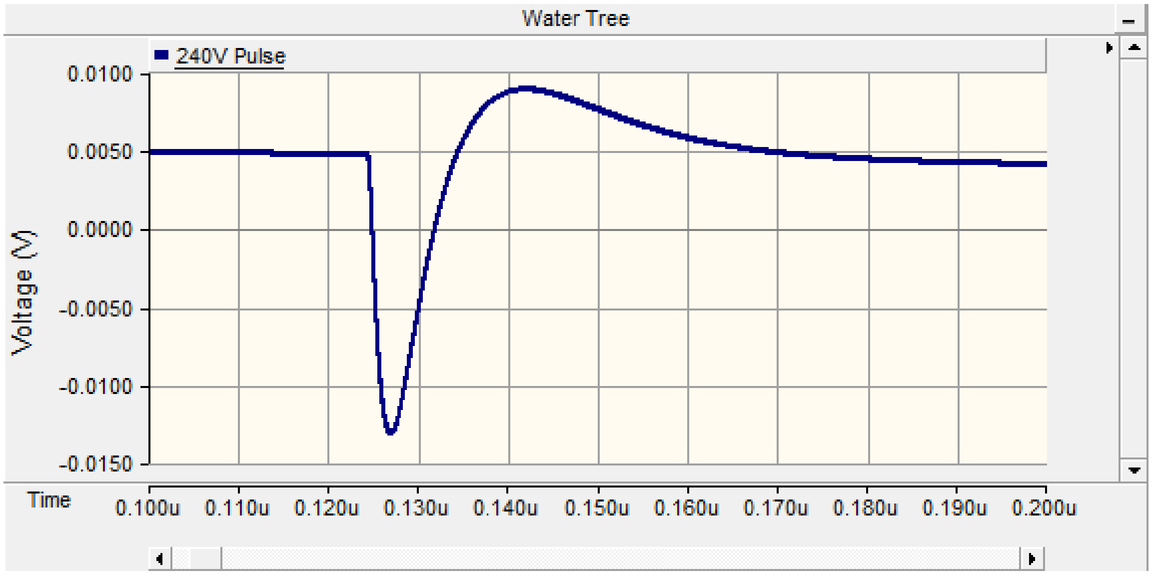


Figure 4.3: Water tree reflection pulse

The water tree produces a negative reflection pulse, like determined above, with a very small magnitude. Likewise, the cable joint produces a positive reflection pulse that is shown in Figure 4.2. Since the water tree's size is microscopic and the size of the cable joint is around a foot, the reflection magnitude of the water tree is much smaller than the reflection magnitude of the cable joint. A study of the two characteristics, amplitude and reflection direction, allows for distinguishing between a water tree and a cable joint. Therefore, water trees can be detected by TDR and not be confused with a cable joint.

4.3 Distribution Feeder

The statement that TDR can detect water trees was proven as demonstrated in this thesis. However, the next step is to determine if it can monitor the health of the cables in a distribution feeder. Therefore, a real distribution feeder was used for practicality. The distribution feeder is located along the coast of Myrtle Beach, South Carolina and it consists of mainly three phase loads. These loads are commercial loads, including hotels, restaurants, and shops. These businesses are vital customers for the utility company because if they lose power then they lose money, and furthermore, on the coast the main industry is tourism. Therefore, it makes the city look bad if the power cables fail and the hotels, restaurants, or shops are without power for any amount of time. Because of this, these locations are very important to the city and it would be very beneficial to monitor these locations. Another reason that a real distribution feeder was used is the fact that the distribution feeder configuration can be quite complex and looking at a test case or IEEE case system would not provide enough complexity. All the information was given by a local utility, Santee Cooper. The distribution feeder is shown in Figure 4.4 and a table of the number of loads and buses is given in Table 4.1.

Figure 4.4: Google Earth image of distribution feeder on the coast of South Carolina

Table 4.1

PARAMETERS FOR DISTRIBUTION SYSTEM

Number of Buses	29
Number of Loads	54
Number of Cables	78

4.4 Optimal Pulse Generator Placement

It is not financially feasible to place a pulse generator on every bus in a distribution feeder. Therefore, an optimal pulse generator placement scheme must be used to determine the location for pulse generators in the system. This optimal pulse generator scheme is very similar to optimal PMU placement because it allows for full observation of the system. Therefore, the method of optimal placement of PMUs by integer linear programing proposed in [24,25] will be used for determining the optimal location for the pulse generators placement in the distribution feeder. The optimal PMU placement algorithm uses the Y-bus matrix to implement this programing technique where all non-zero values are set to one. However, this does not take into account the fact that some buses are not connected to any underground cables and do not need to be part of the optimization. Therefore, this method needs to be modified and a new y-bus should be created, wherein a one in the diagonal row means that the bus is connected to a cable. For buses not connected to cable a zero is inserted into the diagonal row. For the elements not in the diagonal, a one represents the buses that are connected together through cables, and a zero means there is no connection or they are connected by overhead lines. This is stated in equation 4.5 below.

$$y_{i,j} = \begin{cases} 1, & \text{if } i = j \text{ and bus is connected to a cable} \\ 1, & \text{if } i \text{ and } j \text{ are connected by a cable} \\ 0, & \text{otherwise} \end{cases} \quad (4.5)$$

The optimal placement of pulse generators is formulated as follows in equation 4.6 [25].

$$\begin{aligned} & Min\sum_{i=1}^{n} x_i \\ & S.T.\_Y_{pulse} \times X \geq b \\ & X = [x_1; x_2; ...; x_n] \\ & x_i \in \{0,1\} \\ & b = [b_1; b_2; ...; b_n] \end{aligned} \quad (4.6)$$

In this equation, n is the number of buses, and b_i is equal to 1 if the bus is connected to cables, or 0 if it is not connected to any cables. The integer linear programing method proposed that 7 of the 23 buses connected to underground cables should have a pulse generator installed in order to minimize cost and allow for adequate monitoring of the health of all the cables as shown in Table 4.2 and Table 4.3.

Table 4.2
Results from Optimization

Bus Connected to Cables	5	6	7	8	11	13	14	15	16	17	18	19	20	21	22	23
Results	0	1	0	0	0	1	1	0	0	1	0	0	0	0	1	0

Table 4.3
Results from Optimization

Bus Connected to Cables	24	25	26	27	28	29
Results	1	0	0	0	1	0

The tables' columns are highlighted in different colors to represent what groups of buses are being monitored by the different pulse generators. As it can be seen, some buses are connected directly, or from a short distance, to multiple buses and can monitor three to four other buses, such as bus 24 and bus 17. There are also buses that only monitor themselves, such as bus 13, or just one adjacent bus, such as bus 22. This is simply due to the nature of this individual distribution feeder. For example, bus 13 has a single cable connected to it but is not connected to any other bus through a cable. Instead, it is connected to other buses with overhead lines. Therefore, if all three phase cables in the distribution feeder are to be monitored, then a pulse generator must be placed on bus 13 even though it can only monitor one cable. Furthermore, bus 22 is connected in between bus 24 and bus 20 through several cables in series with loads in between them and bus 20 is directly connected to bus 24 and 17. Therefore, bus 22 can only monitor bus 21 and the cables directly connected to bus 22 and bus 21. However, this pulse generator is needed because bus 24 cannot monitor bus 21 since it is too far away. From the tables it can be seen that there is a group of buses connected to the main system by overhead lines buses 5, 6, 7, and 8. If these buses are not supplying very important loads then they might not need to be monitored, thereby reducing the cost. However, they are monitored in the simulation to prove that all cables can be monitored.

4.5 Pulse Generator

The pulse generator used must have a fast rise time in order to monitor the health of very short cables. This is due to the fact that distribution feeders consist of very short cables connecting longer cables to each other and to the load. The pulse generator should be able to detect water trees in cables greater than 10 feet. The reason a length of 10 feet was picked is that in the simulated distribution feeder, the smallest cable is 12 feet long and therefore, 10 feet was picked as the shortest length. A cable 10 feet long will see its reflection after about 30ns. Therefore, the pulse generator needs to have a rise time of 1ns or less and a pulse width of less than 5 ns to be able to monitor cables as small as 10 feet as seen in Figure 4.5.

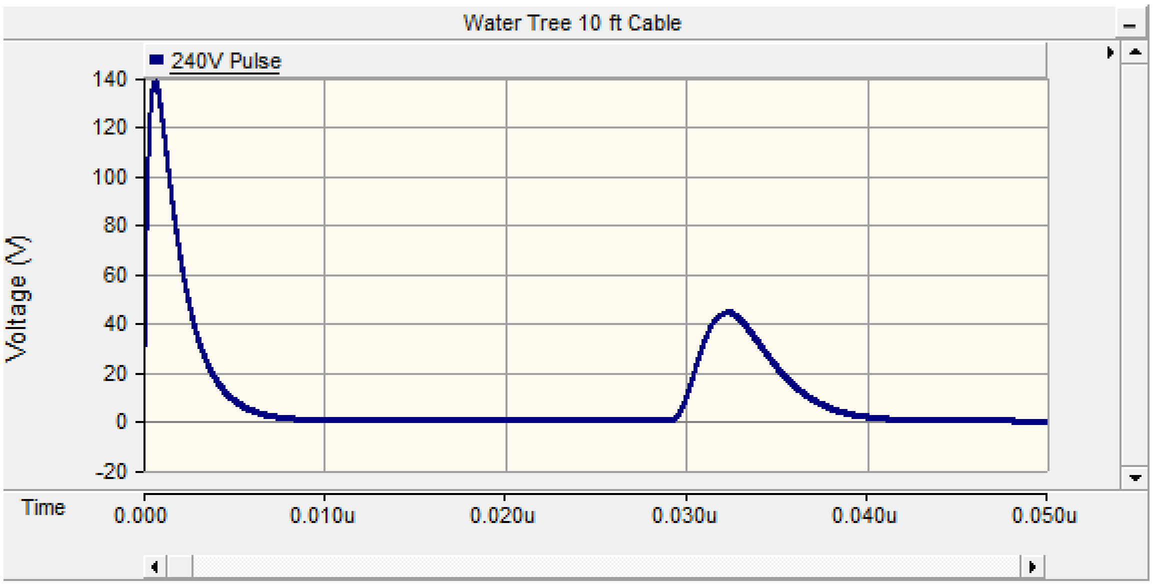


Figure 4.5: Generated pulse in 10 foot cable

The pulse generator's amplitude will determine the price of the pulse generator. Therefore, a study of the size of the pulse needed to detect the water tree was performed. Two pulse generators were studied. One, a 240V 1ns rise time pulse generator and the other, a 5kV 0.1ns rise time pulse generator. These two pulse generators are very different in amplitude and therefore the extreme cases can be studied. The two pulse generators were inputted into on a 100 foot long cable. The results from the two different simulations are shown in Figure 4.6.

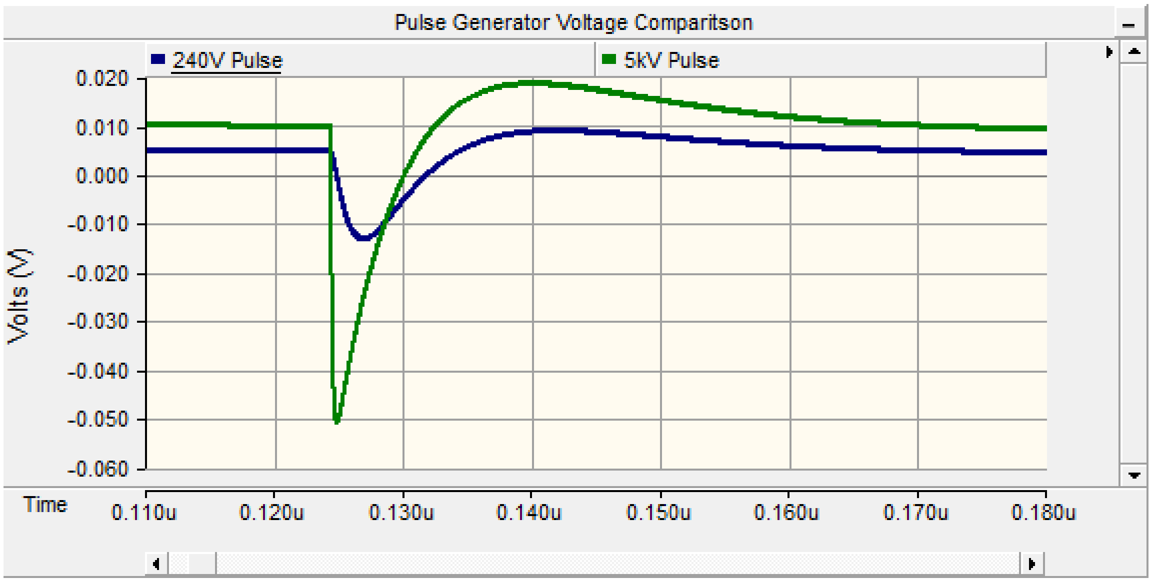


Figure 4.6: Water tree pulses for 240V and 5kV pulse generator in 100ft cable

As it can be seen in Figure 4.6, the voltage pulse of the water tree is not significantly increased. It is only increased by a factor of four. Further studies were performed on different lengths of cables to see if the length of the cable made a difference, as shown in Table 4.4.

Table 4.4
Pulse Amplitude Ratio

Length	**50ft**	**100ft**	**200ft**	**500ft**
Ratio 5kV Pulse amplitude to 240V Pulse	12.5	4	3.333	3.125

For cables smaller than 100 feet, the difference in the water tree's reflected pulse was much greater, making the higher voltage pulse generator worth using. An example of this would be the 50 foot cable, where the 5kV pulse generator's water tree reflected pulse had a magnitude more than 12 times the 240V pulse generator, as shown in Figure 4.7.

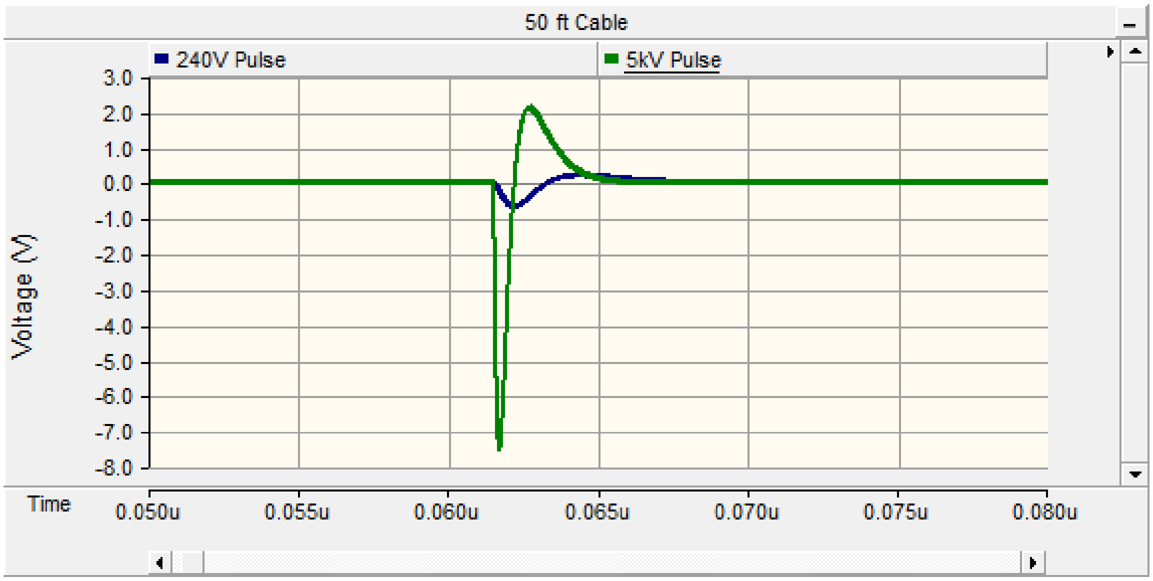


Figure 4.7: Water tree reflected pulse for 240V pulse and 5kV pulse in 50ft cable

However, the average length for the cables in the distribution feeder used is 250 feet, and the breakdown of cable lengths is shown in Table 4.5. The maximum number of cables is between 100 feet and 200 feet and the percentage of cables above 100 feet long is 76.9%.

Table 4.5
Breakdown of Cable Lengths

Length of cable (ft)	0-50	50-100	100-200	200-300	300-400	400-500	500-600	600-700	700-800	800-1000
Amount of Cables	9	6	18	15	6	4	3	2	1	1

Prices were found for the pulse generators with those properties. They are shown in Table 4.6.

Table 4.6
Prices for Pulse Generators

	240V 1nsec	5kV 0.1nsec
Cost of 1 Unit	$11,596 [26]	$29,660 [27]
Cost of 7 Units	$81,172	$207,620

The price for the high voltage pulse generator is three times more than the low voltage. Therefore, the total cost of implementing a TDR water tree monitoring system with a 5kV pulse generator would be three times more than a system with a 240V pulse generator. For this distribution feeder, with 76.9% of its cables being longer than 100 feet, it is proposed to use the low voltage pulse generator to save money. However, this decision was made without knowing the importance of the loads being supplied by the cables. For high-priority loads connected through a short cable, a high voltage pulse generator should be placed at that bus only, and the rest of the buses could have low voltage pulse generators connected to them, which would increase security with minimal cost.

4.6 Cable Monitoring Algorithm for a Distribution Feeder

With the pulse generators in place, the next step is to determine which cables will be monitored by each pulse generator. This is done by firing each pulse generator individually and sending a pulse for each phase individually at the zero crossing of each phase. Also, it should be noted that this is not taking place every cycle and is not a real time monitoring method. However, theses pulses would be sent quarterly each year and the information stored for monitoring. Also, if a water tree pulse is found, the cable will not get immediately remove due to the fact that water trees grow very slowly and take years to cause cable faults. However, the size of the water tree can be monitored from the size of the reflected pulse. This can be used to determine when the cable should be replaced.

First, if the cable is connected directly to the bus, which the pulse generator is connected to, the cable can be monitored and the water tree detected. Therefore, every cable connected to the bus which the pulse generator is connected to can be monitored. Cables that are connected to the pulse generator bus through multiple cables cannot be monitored directly without manipulation. This is due to the fact that there will be reflections from other cables that will be transmitted into the cable before its termination reflection is seen. Therefore, to remove these reflections, a cable connected at the same bus will have the same type of reflection disturbance.

Using this, the two cables' signals can be subtracted from each other in order to remove these unwanted transmitted signals. Therefore, the cables can be monitored and water trees can be detected. If there are not two cables connected at a bus, but there is a single-phase cable connected to one of the phases at the junction, the single-phase cable can be monitored and its pulse can be stored to subtract from each phase. Therefore, each phase of the three-phase cable can be monitored at the junction. However, if there is a load connected at the junction, there is nothing to subtract from the cable signal, which therefore causes that cable to not be capable of being monitored by the current pulse generator.

Therefore, in order to monitor that cable, the pulse should be sent from the opposite direction. Instead of being fed the pulse through a cable, it now may be connected to a bus with another cable. Therefore, these two cables' measured pulses can be subtracted from each other and then the two cables can be monitored. However, if the cable is connected from both ends to buses by cables, this method does not work. Therefore, if a single-phase cable is connected at the junction of the two cables, the single-phase cable's signal can be measured, stored, and subtracted from all three phases to monitor the cable.

However, if there is no single-phase cable but, there is a load, there is still a method to detect the water trees in the cable. The signal from all three phases will be stored and subtracted from each other to get six subtracted signals. This will be done from the pulse generator on both sides of the cable individually to see which reflection pulse is bigger. The pulse generator that produces the largest reflection pulse will be chosen to monitor the cable since it will produce a larger water tree reflection pulse. This method will work because three-phase cables are bundled together in conduit. Therefore, either the water tree is initiated through some protrusion in a single cable or there is some defect that causes two water trees to form in two cables at the same location. Thus, if the two signals were subtracted from each other they would remove the water tree pulse. However, the third phase would not have a water tree in this location. Therefore, when this signal is subtracted from both of the water treed signals, the water trees in the other two phases could be detected. The formation of the two water trees is depicted in Figure 4.8.

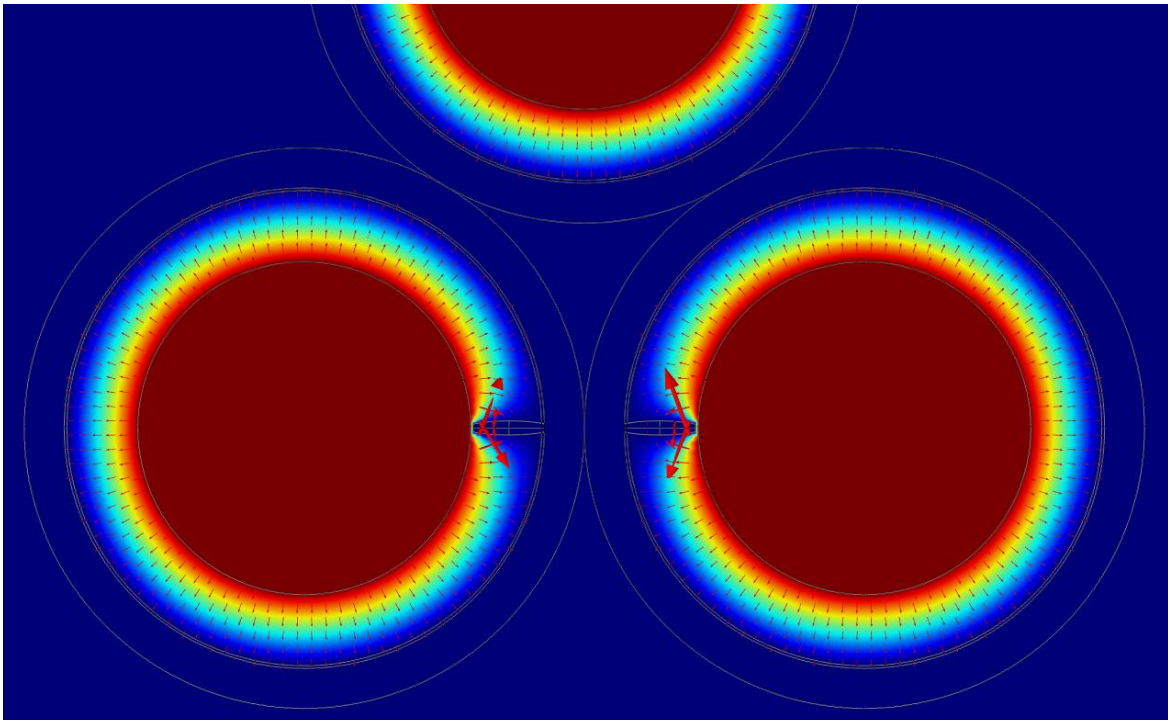


Figure 4.8: Water tree at same location in two cables

With these steps, all possibilities of cable configurations can be monitored. From that a general algorithm can be constructed and is located in Figure 4.9.

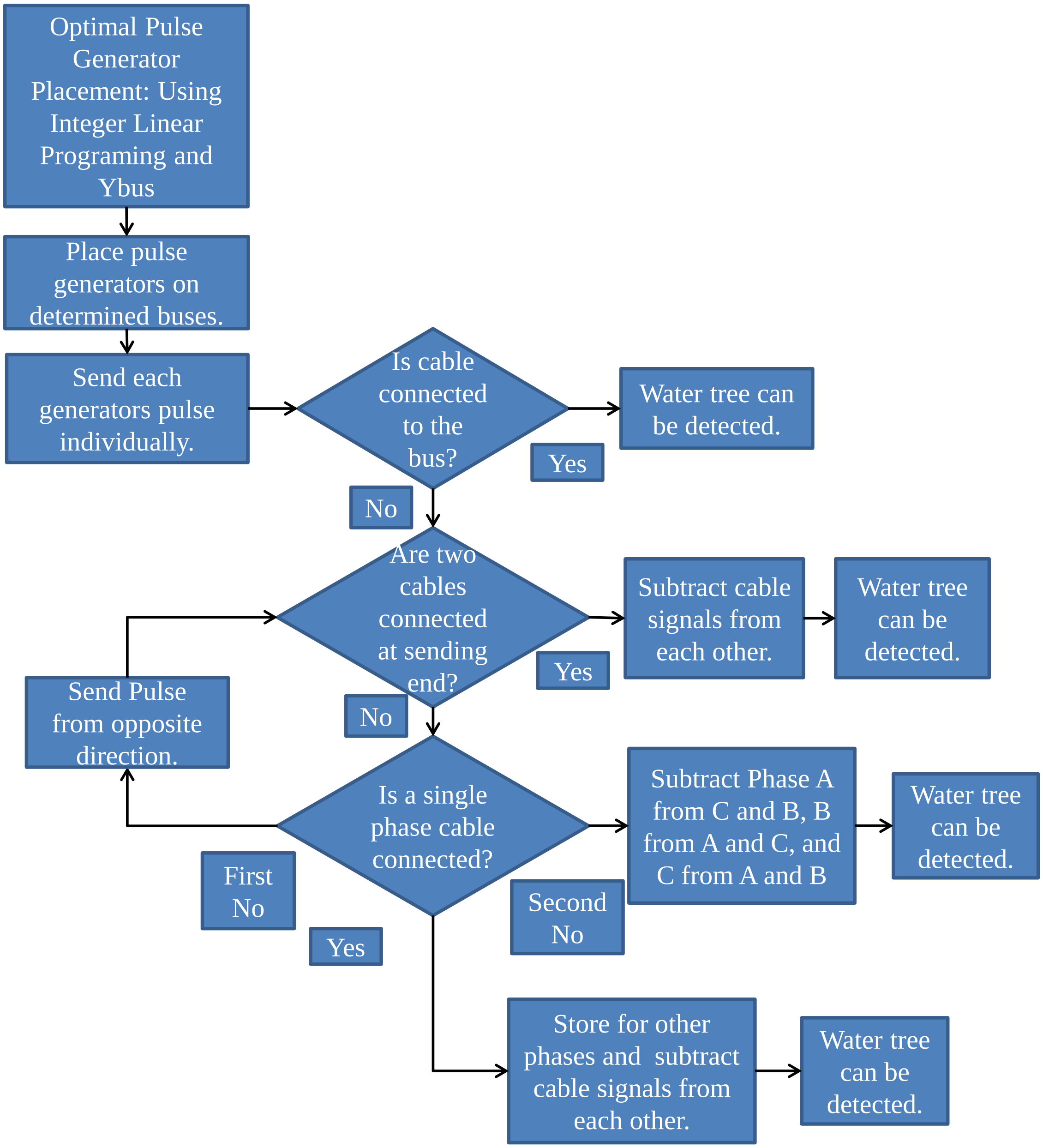


Figure 4.9: General algorithm for monitoring cables in a distribution feeder

4.7 Results

Water trees were placed on every cable in the distribution feeder to determine if the proposed method allows for full observation of the system. The pulse generators were also added to the system. Water trees were placed at different percentages of the length of each cable in order to be certain that the water tree can be detected at any location along a cable. Then a series of test were performed. Each pulse generator was activated individually in order to not have pulses from other generators affect the measured signal. Therefore, seven simulations were performed, one for each bus.

4.7.1 Cable is Connected Directly to Pulse Generator Bus

The water tree can be detected in the cables that are directly connected to the bus with the pulse generator. The value of the water tree reflected pulse for cables connected to the pulse generator was a magnitude of 10^{-1} to 10^{-2} volts. One of the return pulses is located in Figure 4.10.

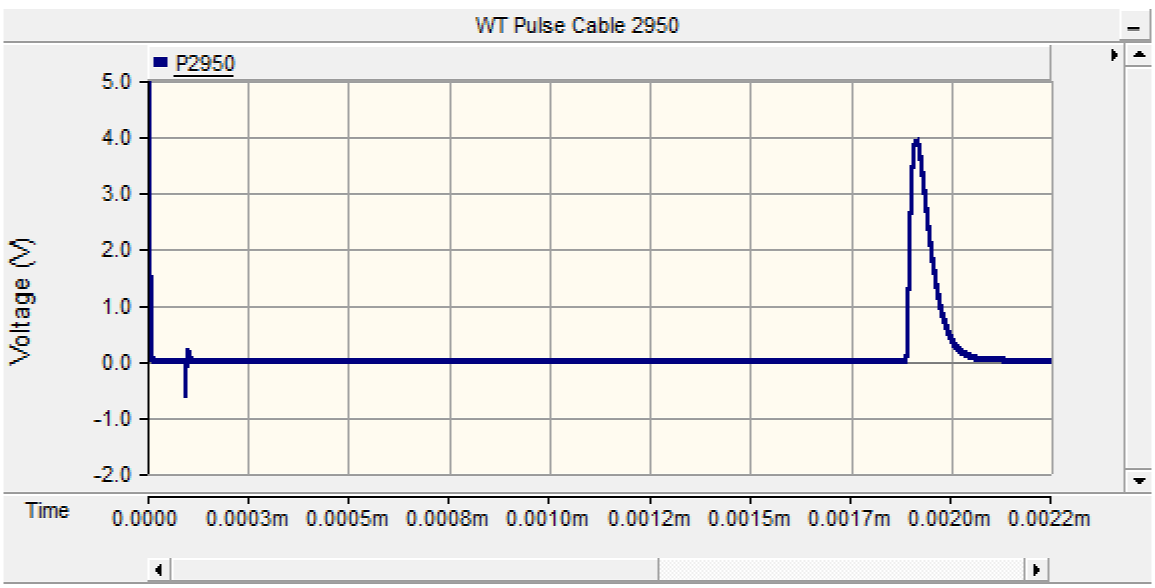


Figure 4.10: Signal sent in cable connected directly to the pulse generator bus

It can be seen in the figure that the reflected pulse is at a magnitude of 4 volts and the water tree reflection can be seen when zoomed in on the reflected signal. This cable is 622 feet long and the water tree is located at 5% down the length of the cable. A zoomed in plot of the water tree reflection pulse is shown in Figure 4.11.

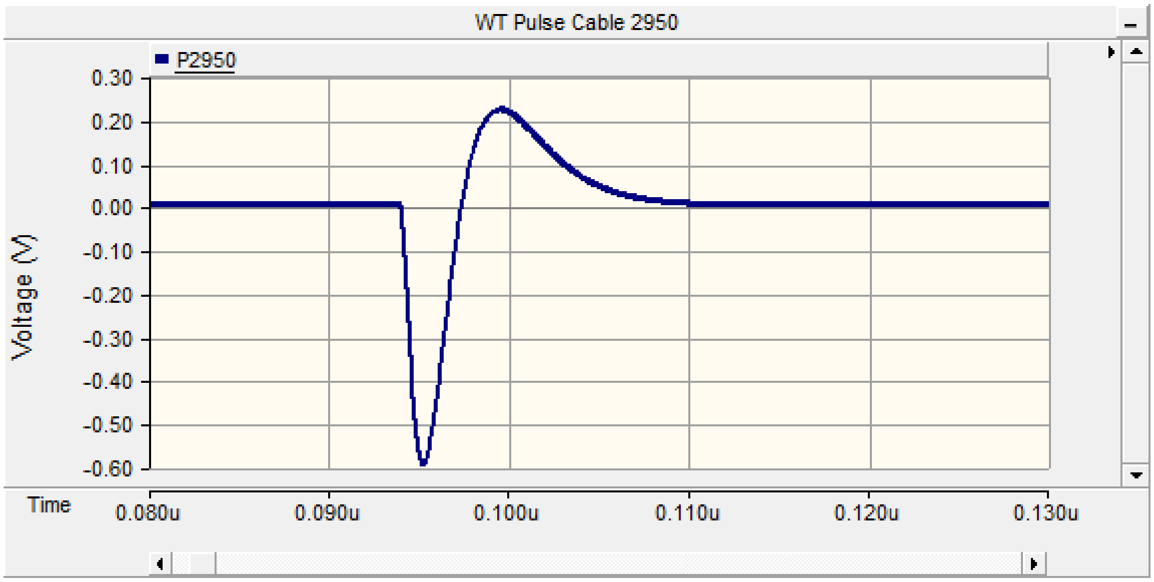


Figure 4.11: Water tree reflection pulse from cable connected to the pulse generator bus

From the figure the water tree's reflection pulse is about 0.6V which can be filtered from noise and detected with simple sensors. The other cables that are connected to the pulse generator bus are similar and therefore, the water tree can be detected in cables that are directly connected to the pulse generator bus.

4.7.2 Subtraction of Cables Connected to Pulse Generator Bus through a Cable

Even though cables directly connected to the pulse generator bus can be detected, cables that were connected to the bus with a pulse generator through other cables could not directly measure the water tree. This was due to the fact that reflections from other cables in the system would cause pulses that affected the detection of the water tree. Therefore, if there are two cables which are connected to the pulse generator by the same cable, these two cables will be subject to the same pulses that affect detecting the water tree. The cable signals before subtraction are shown in Figure 4.12.

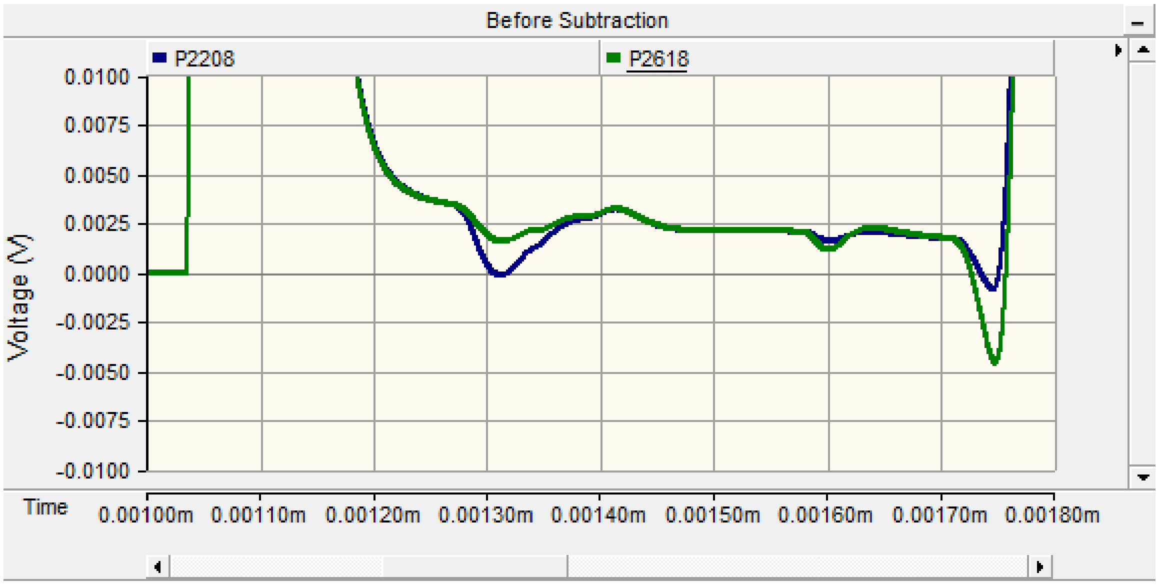


Figure 4.12: Cable signals before subtraction of the two cables

As it can be seen, there is no possible way to determine if there is a water tree in the two cables. However, their signals have similar values except in specific places. Because of this, the signals were subtracted from each other and then water trees were capable of being detected in both cables. This is shown in Figure 4.13.

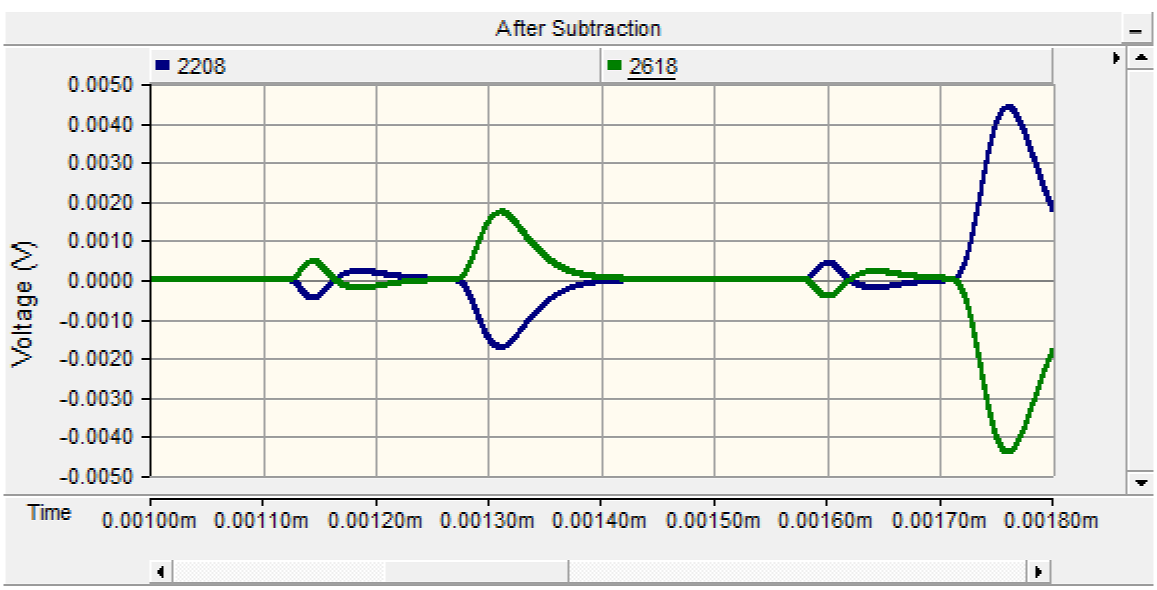


Figure 4.13: Water trees in cables after subtraction

It can be seen in Figure 4.13 that the proposed method will produce a positive pulse in the cable that does not have a water tree and a negative pulse in the cable that does. This could be mistaken for a cable joint. However, the location of a cable joint would be known and therefore, if there is no known cable joint on the cable it can be determined that this reflection is due to the subtraction of the cable with a water tree. Also, the proposed methods capable of detecting water trees on cables that are not the same length. Furthermore, the water tree can still be monitored after the smallest cable's reflected pulse has returned. The magnitude of the subtracted cables' water tree is from 10^{-3} to 10^{-2} volts as seen in Figure 4.13 and can be detected by sensors.

4.7.3 Water Trees with Similar Reflection Times

The proposed method can furthermore detect water trees that are close in position on the cable of cables with similar length. The cables pulse subtracted from each other is shown in Figure 4.14

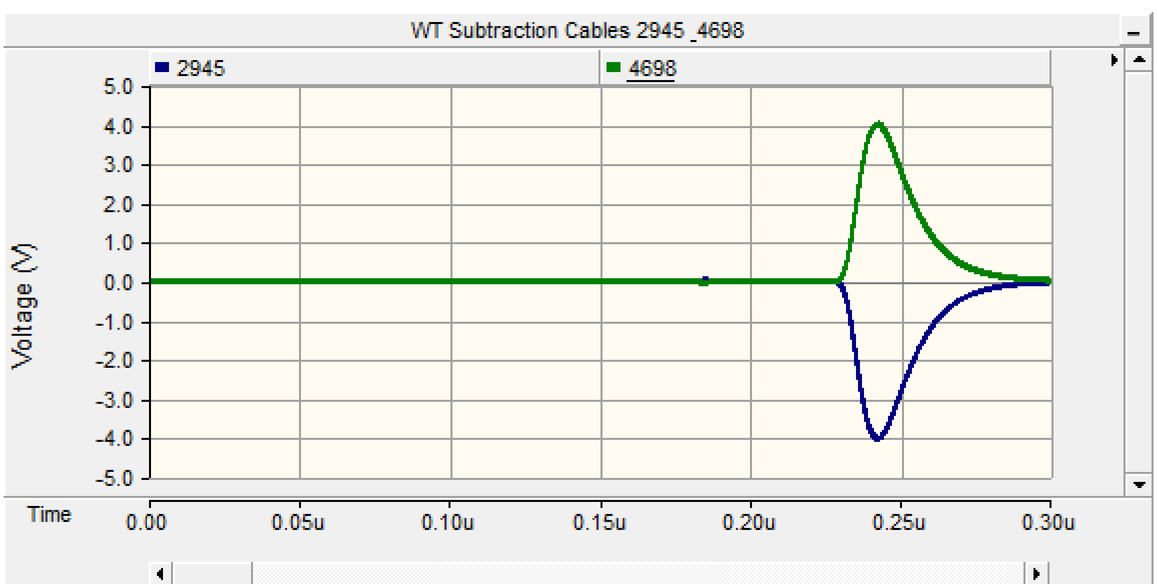


Figure 4.14: Cables subtracted from each other

From Figure 4.14, it can be seen that cables that are connected to the pulse generator through a common cable have much smaller water tree reflection pulses. This is due to the fact that the pulse energy is being split into the two cables, depending on the impedance of each cable. A zoomed-in plot of the water trees with similar reflection times is shown in Figure 4.15.

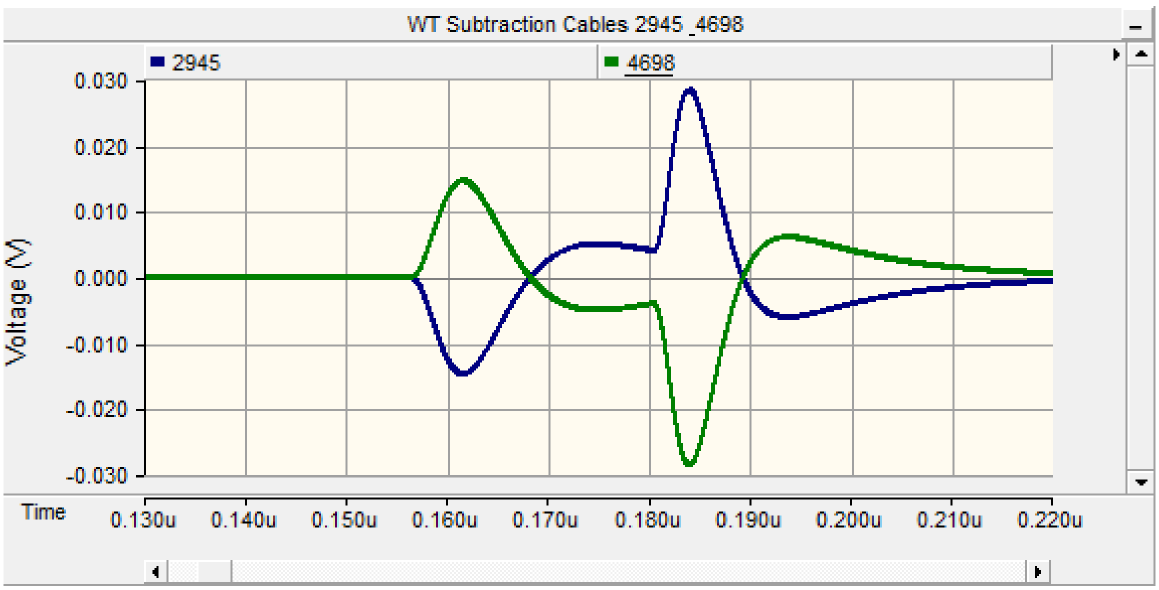


Figure 4.15: Water trees with similar reflection times

What occurs is that the signal of the cable with the first water tree is normal but as the second water tree is reached, the two signals jump to follow the second water tree, as depicted in Figure 4.15. Therefore, one water tree does not keep the other water tree from being seen and their magnitudes are measureable with sensors.

4.7.4 Water Tree Connected to Pulse Generator through Multiple Cables

When a secondary cable is connected to the pulse generator through multiple cables, it will receive the same out of phase voltage pulses as the cables connected to it. This is seen in Figure 4.16.

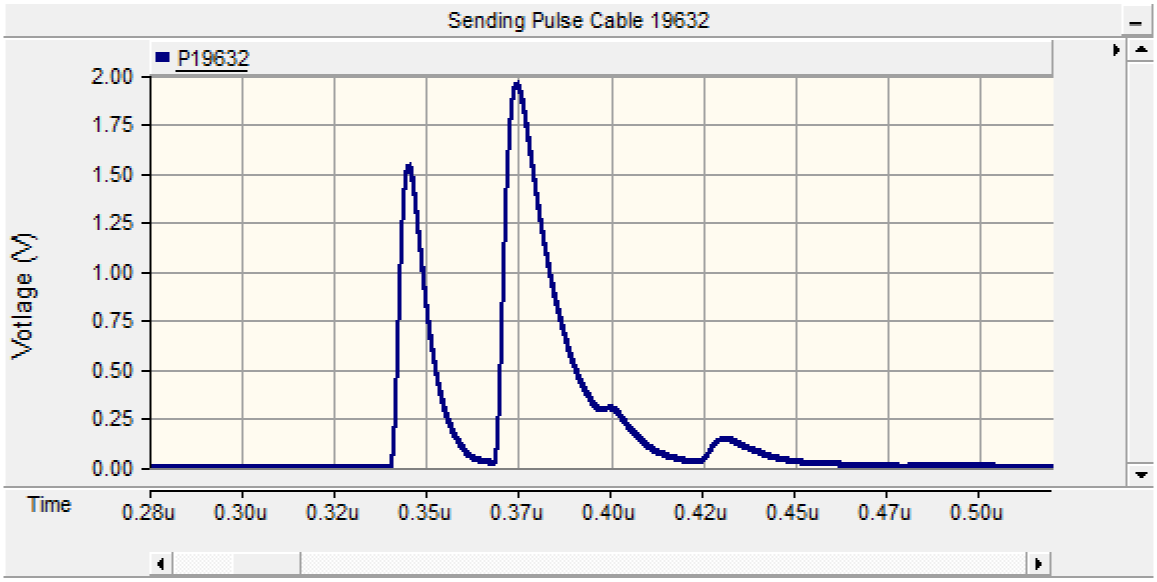


Figure 4.16: Multiple sent pulses due to multiple cables

Notice that the cable has two large pulses and a small pulse after them. This will cause three water tree reflections to be present as seen in Figure 4.17.

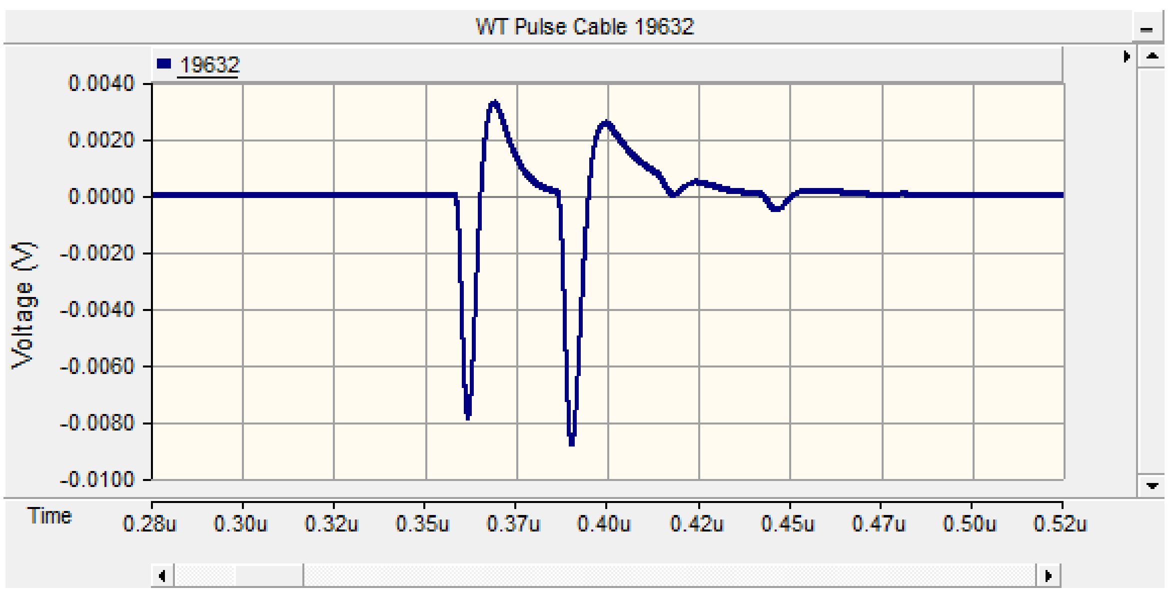


Figure 4.17: Water tree reflection pulses due to multiple sent pulses

As it can be seen, the water tree reflection pulse has the same duration between them as the sent pulses. This will not indicate multiple water trees because the time difference of the multiple pulses is known and it can be verified that these water tree reflections are from one water tree with the same number of pulses.

4.7.5 Cables with Three Phase Subtraction Detection

The cables that cannot be monitored by the subtraction method would then have each three phase signal stored. Then they should be subtracted from each other like previously stated. This is simulated by placing water trees on the A and C phase of the cable. The individual signals for each phase are located in Figure 4.18.

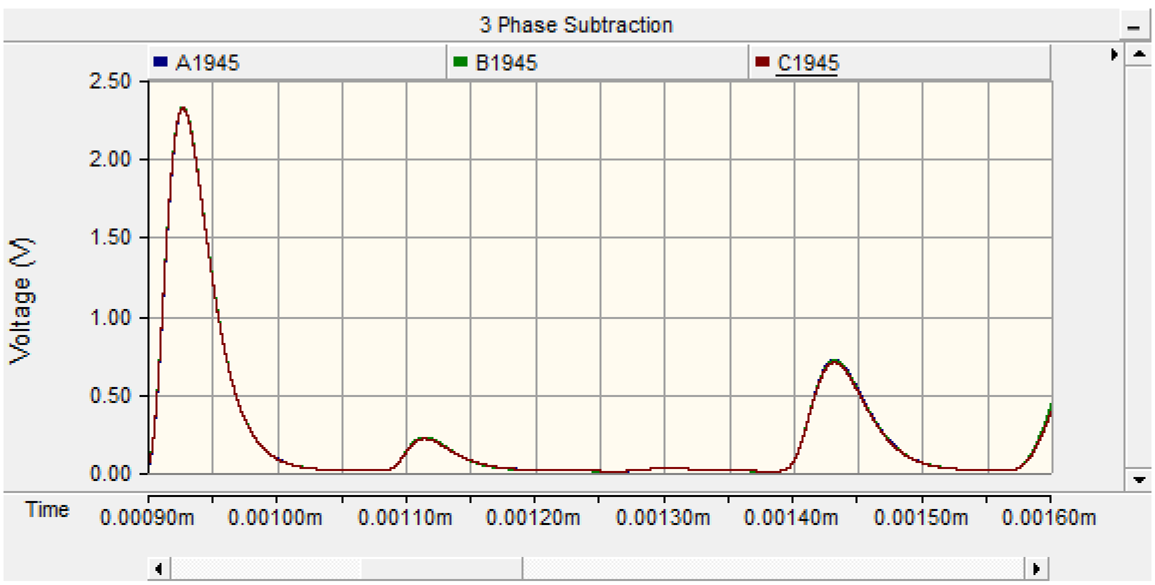


Figure 4.18: All three phases of a cable before subtraction

It can be seen that there is not any difference in the signals for each phase. Therefore, the phases could be subtracted from each other using the same concept as the two cables connected at the same bus. The subtraction of phase A and C is shown in Figure 4.19.

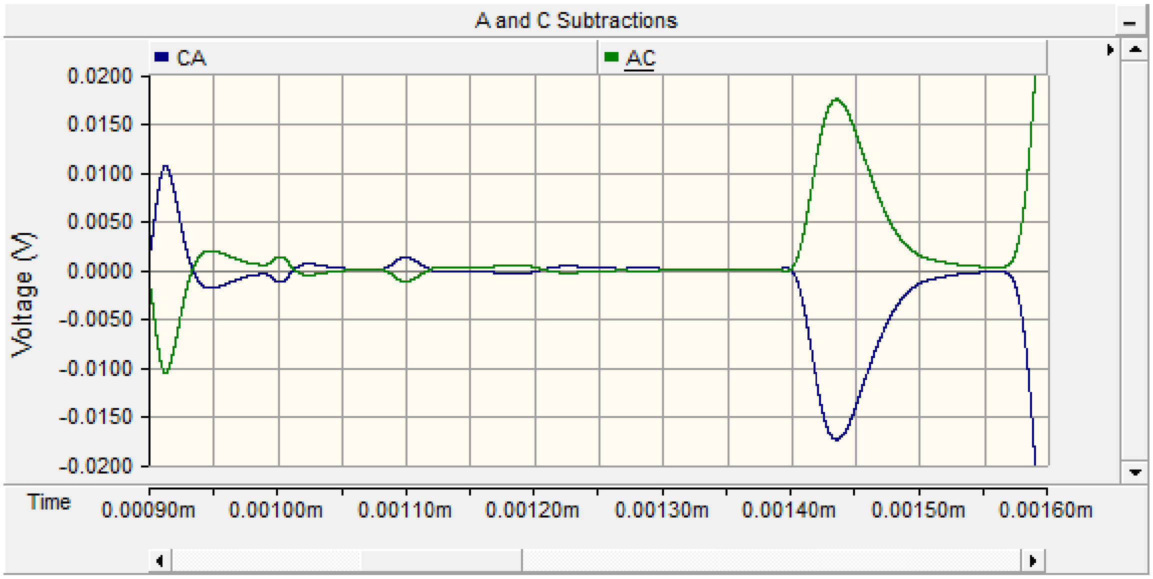


Figure 4.19: Subtracted signals for phase A and C

There are some small fluctuations in the signal in between the sending pulse and the reflection pulse, but nothing with the same shape as the water tree pulse. This is because both these cables have the same size water tree at the same location. Figure 4.20 and Figure 4.21 show when phase B is subtracted from phase A and C.

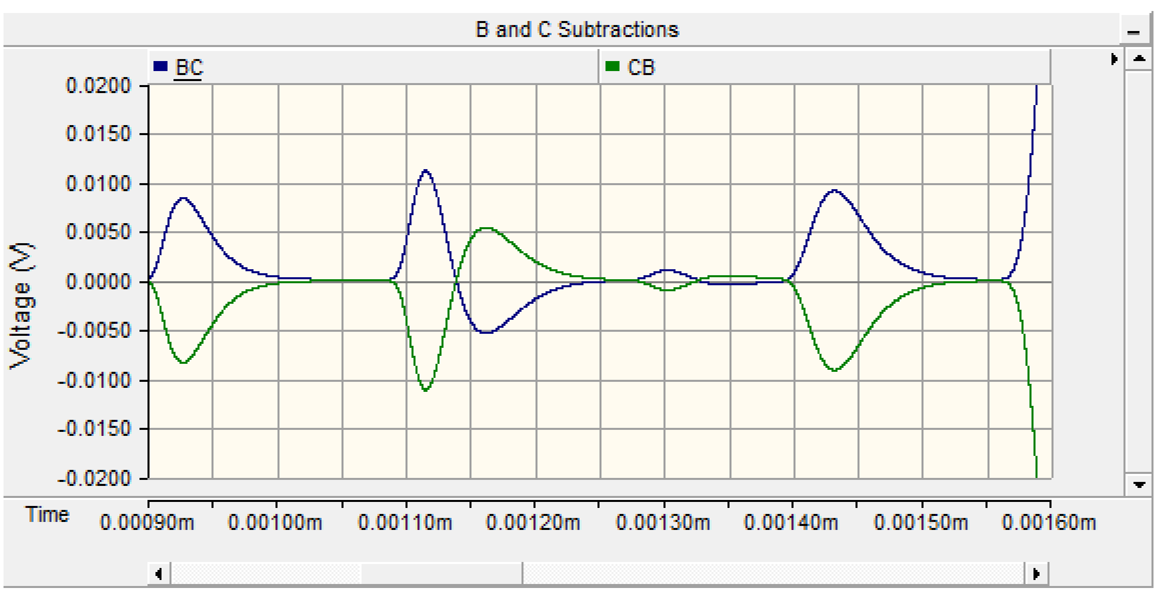


Figure: 4.20: Phase C and B subtraction signals

The plot when phase B is subtracted from phase A or C is shown in green and it can be seen that the water tree can be detected in both phase A and C. It can be verified that the water tree pulses should be present at the same time, which can help with detection. Unlike when the cables connected to the same bus are subtracted from each other, there is still a pulse after subtraction. The water tree pulse was large enough to be detected by sensors and the three-phase subtraction method works to monitor cables that cannot be monitored using the previous determined subtraction method.

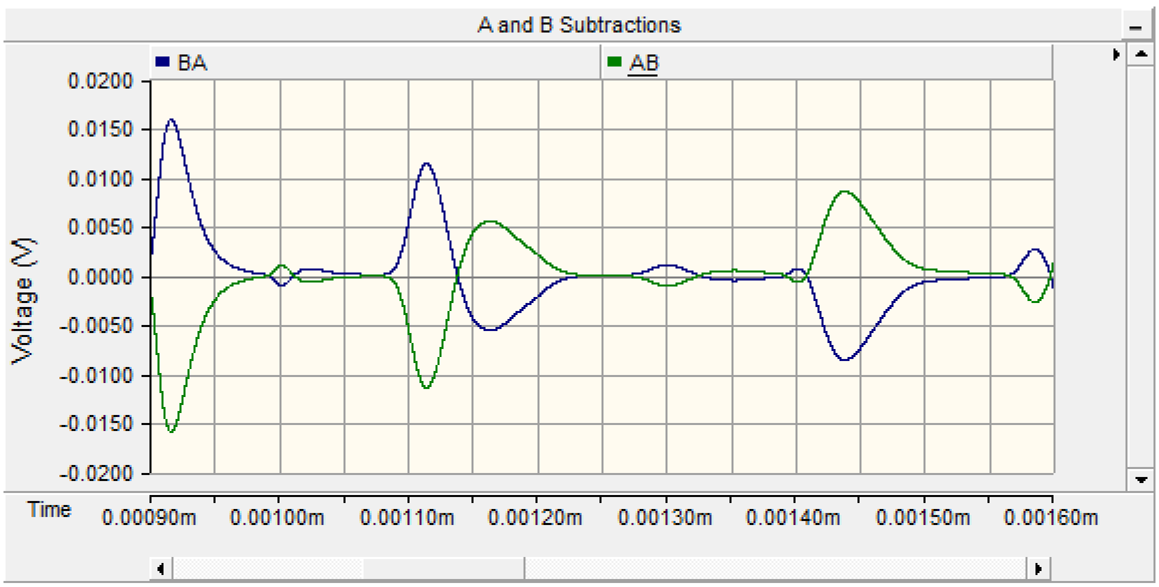


Figure 4.21: Phase A and B subtraction signals

CHAPTER FIVE

CONCLUSION AND FUTURE WORK

5.1 Conclusion

In this thesis, a water tree was modelled in COMSOL. The water tree model was implemented into a distribution feeder in Myrtle Beach, South Carolina. PMUs and traditional CT and VT measurements were proven to not be feasible equipment to detect water trees and monitor a distribution feeder's health. Therefore, TDR was shown to have the ability to detect water trees in a cable and that it could determine the location of the water tree. An optimal pulse generator placement algorithm was used to determine the most cost effective positions for pulse generators to monitor the entire distribution feeder. Then an algorithm for monitoring all the three-phase cables in the distribution feeder was created. From the results an on-line water tree detection method or on-line cable monitoring system was proven to be capable using TDR successfully.

The water tree model was built using parameters based on a literary review. The effect of the water tree on the electric field and electric potential was shown and the results matched the previous research preformed on water trees. COMSOL was used to calculate the resistance and capacitance of the lumped parameter water tree model. The resistance did not change until the water tree breached the insulation. This is what would be expected because there is no conducting path that allows for resistive current to flow. The capacitance changed with an exponential growth. This is what would be expected because the capacitance would increase as the water tree got closer due to the fact that the conducting plates are getting closer in that region.

The water tree model was added to an underground cable model in PSCAD. The phase leakage current of the water tree was proven to be the only method of detecting a water tree using traditional measurements and PMUs. However, the phase of the leakage current experienced a very small amount of change, so small that it was almost non-detectable. Therefore, an electrical tree was added to the water tree model and its effect on the phase of the leakage current could be an identification of breakdown. However, electrical trees break down in minutes so there is no way to replace the cable before it explodes.

Therefore, a new method for water tree detection was chosen: TDR. The proposed method is performed on-line by sending a high frequency pulse down the cable when the power signal is at the zero crossing. The frequency of the pulse is so fast that the power signal doesn't change and the reflection of the high frequency signal can be measured. Reflections happen at impedance mismatches. Therefore, a reflection will occur when the cable terminates. However, if a reflection is seen before the termination reflection then this is due to an impedance mismatch in the cable or water tree, and the reflected pulse is negative because the capacitive nature of the water tree reduces the characteristic impedance which results in a negative reflection. The water tree reflection is on the magnitude of volts to millivolts and can be detected by inexpensive sensors.

To monitor the distribution feeder, pulse generators were added with an optimal pulse generating algorithm to find the least expensive amount of pulse generators needed to monitor the distribution feeder. The algorithm is similar to optimal PMU placement algorithms and uses binary linear programing. Furthermore, the pulse generators magnitude was tested to reduce the cost. The pulse generators tested voltages were 5kV and 240V. The cost of the high voltage pulse generator was three times the cost of the low voltage pulse generator. The ratio of the 5kV pulse and the 240V pulse increases as the cable length decreases. However, for the test feeder used the majority of cables are 100 feet to 300 feet. For these lengths of cable the ratio of the 5kV pulse over the 240V pulse is not enough to justify the cost of the high voltage pulse generator. Therefore, for this specific feeder a pulse generator with a 240 volt pulse with 1 nanosecond rise time was sufficient to monitor all the cables.

An algorithm was created to monitor all the cables in the distribution feeder. For the monitoring algorithm, each pulse generator is sent at a separate time and for each phase the pulse is sent at each phases zero crossing. The algorithm consisted of, first, all cables can be monitored and water trees detected if they are connected to the bus with the pulse generator. Then cables that are connected to the pulse generator bus through the same cable can be subtracted from each other and then they can be monitored. If there are not two cables connected, and if there is a single-phase and three-phase cable connected to the pulse generator bus through a cable, the single-phase cable can be stored and used to subtract from all three-phases of the three-phase cable, and the cable can be monitored. However, if there is no single phase cable, the pulse should be sent from a pulse generator connected on the opposite side of the cable and the process above repeated. If this process does not work, then all three phase signals can be stored and subtracted from each other and now that cable can be monitored. The results from this algorithm showed that the distribution's three-phase cables can be monitored.

The proposed method of using TDR can be installed on existing systems. This is due to the fact that it does not require knowledge of the healthy system as a bench mark to determine when the system is becoming unhealthy. By preforming the proposed method periodically throughout the year and storing the results, the system's health can be monitored. If a water tree is seen in a cable it does not have to be removed immediately. This is because the water tree takes a long time to grow and the cable can operate for several years safely after the growth of water trees. When failure is close the cable can be removed and the utility company will save money from not removing the cable immediately.

By using TDR the exact location on the cable of the water tree can be determined. With this knowledge the section of that cable can be removed and a cable joint added to the cable. Therefore, the utility company does not have to pay the full price for removing the cable. Also, multiple water trees on a cable can be detected using this method. Furthermore, water trees can be detected in cables that are unequal in length, and water trees can be detected when their reflection time is similar.

The proposed method of using TDR, optimal pulse generator placement, and subtraction of cables with similar measured pulses is an inexpensive way to monitor the health of critical distribution feeders. The proposed method will allow for utility companies to keep their underground infrastructure of the distribution feeder safe from water tree and electrical tree faults.

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