Research Article

Water Trees in Solid Insulating Materials**Pavlos E. Stavroulakis and Michael G. Danikas****Democritus University of Thrace, Department of Electrical and Computer Engineering, School of Engineering, Power Systems Laboratory, 67100 Xanthi, Greece*

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Abstract

The process of degradation in cable insulation is a major problem in cable engineering. This happens because high and medium voltage cables are often exposed to water and moisture. The consequence of water on the cable insulation system results in changes in properties and treeing. This paper studies the phenomenon of water trees in solid cable insulation and how their presence affects an installation which is powered by degraded cable via Simulink software. Alternating electric field and humidity are the main factors which lead to appearance of water trees and their effect is studied. In addition, two basic methods are analyzed which are used in the detection of water trees, namely the method of dissipation factor $\tan\delta$ measurement, for which universal acceptable criteria have been established in the detection of water trees, and the method of DC leakage current measurement, for which some service providers have established criteria for assessing the condition of cables and have been universally accepted. The largest part of this paper shows the simulations which were performed in a single-phase system and a three-phase system using SIMULINK software which aims to study the differences in the behavior of a system with healthy cables and a system with degraded cables in the event of a fault, such as short circuit, lightning overvoltage, and in the event of interruption of the load supply from the network.

Keywords: Water Trees, Insulation Voids, Humidity, Cross-Linked Polyethylene (XLPE), Degraded Cable System, Healthy Cable System, Very Low Frequency (VLF), Diagnostic Methods for Water Trees, Simulation

1. Introduction

Water trees are diffuse bush-like structures in an insulating material that are developed in many different types of polymers [1]. This structure is known to consist of a dense network with extremely small water-filled channels which are defined by the natural crystalline structure of the polymer [1]. Water trees begin in a microscopic region near a defect. Then, they grow under the constant presence of a high electrical field and moisture. The presence of water and the development of trees change the distribution of the electric field. Water trees may eventually reach the point where they bridge the outer layer of the ground to the high voltage main conductor, thus the voltage is redistributed through insulation [1]. Water trees can cause a significant reduction in the breakdown strength of an affected cable. In particular, it has been proved that the breakdown strength of a cable is reduced with the presence of water trees [2]. Water treeing is a well-known phenomenon in underground cables, which plays an important role in the aging process and the degradation of their insulation. The reduction in the lifetime of cables due to water trees has been recognized as a major problem and a way of overcoming this issue should be found. The activation of water trees is one of the main aging mechanisms in cross-linked polyethylene (XLPE) cables, causing a reduced lifetime. Various factors affect the beginning and development of water trees [3, 4]. Moreover, it was noted in [3, 4] that wet aging conditions increase the dissipation factor and reduce the volume resistivity and that bow-tie trees

develop much easier with dynamic mechanical stresses than with static mechanical stresses.

In earlier research it was remarked that when steam cured XLPE cable insulation containing microvoids is heated, the voids become filled with low molecular weight polyethylene resembling “spherical particles” and that in most cases bow-tie tree generation is initiated more easily from filled rather than unfilled microvoids, suggesting that the water at the interface between a particle and its surrounding void acts as an electrode [5]. An extensive treatment of the mechanisms of water trees (dielectrophoresis, thermal expansion of water in voids due to a selective heating process, electrostrictive forces, water pressure due to change in chemical potential) was given in [6]. Countermeasures to protect cable insulation against water treeing were reported in [7].

It is the aim of the present paper to study – by using SIMULINK software – various faults appearing in cables and to report on the differences between the behavior of healthy cables and degraded cables.

2. The Impact of High Alternating Electric Field and Water Voids on the Emergence of Water Trees

Water trees have a somehow fuzzy appearance and consist of water filled microvoids [8]. The phenomenon of water trees is one of the main issues for the power cable industry. Researchers have made great efforts to find a solution to this phenomenon with improved insulating materials. The selection of less permeable materials in water may help delay the appearance of water trees. Water trees will start if the electric field exceeds a certain limit on condition that the cables are in a liquid environment. Water trees reduce the

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breakdown strength of insulation and can spread through it. Thus, the presence of water voids in the XLPE insulation causes non-uniform electric field distribution and insulation degradation [6, 7, 9].

Fig. 1. Electrical flux lines from positive to negative charge area.

Positively charged particles tend to move towards negatively charged particles (Fig. 1). Thus, the electric field lines are driven from phase B and C that have a positive charge to phase A where the electric field expands and then contracts [10]. Therefore, as the electric field is concentrated at this point there is an increase in the electric field, resulting in mechanical stress and consequently in the creation of water trees. It goes without saying that the high electrical field causes mechanical stress which leads to cracks along the insulation. If the field stress is increased, then the valence electrons of the dielectric material are removed. Then there will be free electrons available in the insulating material. Because of this, insulation loses its properties and becomes a conductor at a state of breakdown. Some partial discharges may occur in these cracks leading to the formation of trees. Insulating polymers permeable to moisture will become harmful [10].

From Fig. 1, it is evident that the distribution of the electric field in a cable insulation containing water voids shows that the electric field is high in the areas where these voids exist. This causes the creation of channels and then the formation of water trees that are growing slowly without causing a sudden collapse. They grow up for a long time and can eventually cause breakdown in the cable insulation.

3. Diagnostic Methods for the Detection of Water Trees

3.1 Dissipation Factor Measurement

One of the most common diagnostic methods is the measurement of capacitance (C), related to the Dissipation Factor (DF or $\tan\delta$) and to the conductivity of insulation at frequencies around power frequency or at low frequencies below 1 Hz. With this method, universally accepted criteria have been established in order to assess the condition of XLPE cables. The measurement shall be performed by applying an AC voltage and measuring the applied voltage and current through the insulation in question. Fig. 2 shows the measurement principle, the phase diagram and the definition of the Dissipation Factor [11].

Fig. 2. Measurement principle and definition of DF in phasor diagram.

For measurements on cables in service, the cable must be disconnected from the network and activated by a separate power supply, in other words this is an offline method. With an appropriate VLF experimental set-up, Dissipation Factor and leakage current can be measured, taking into account that polluted terminations may produce small derivative currents and thus may falsify $\tan\delta$ measurements to a significant extent. In addition, the required charge current shall be reduced by using the low frequency measurement, as a result the required equipment being smaller and easier to operate [12].

Fig. 3. Idealistic presentation of $\tan\delta$ for XLPE cables of varying ages.

Fig. 3 shows the results obtained with a VLF experimental setup in case of cables of different aging rates.

Typically, measurements for Dissipation Factor are usually performed at different voltage levels up to $2U_0$. Good-status insulation typically gives stable and low Dissipation Factor values that vary minimally with a voltage up to $2U_0$ and do not vary with time. Aging cables on the other hand show increases in Dissipation Factor sizes as the test voltage increases and can also show slow or rapid changes over time at a constant voltage [11, 12].

3.2 DC Leakage Current Measurement

DC leakage current test is an off-line method based on the application of a DC voltage and at the same time on the recording of DC leakage currents for a certain time period. The test voltage increases step by step. The maximum step voltage is usually twice the peak value of the rated voltage. This method concerns the dielectric response in time domain using only charge currents for diagnostic purposes. DC currents are usually much less than 1 mA, and therefore careful measurement techniques are used to avoid faults due to stray currents [11].

The experimental arrangement for the measurement of the DC leakage current is shown in Fig. 4. The device consists of the cable sample, a high voltage DC source, an insulating

holder and a measuring circuit. The HV source was rated at 140 kV DC, 5 kVA. The insulating holder was used to place the cable above the ground plane. The measurement circuit consists of a stable resistor, a protecting circuit and a digital voltmeter. The whole setup had one common ground [13]. The procedure for DC leakage current measurement is given in detail in [13].

Fig. 4. Experimental set-up for DC current measurement [13]

This procedure was repeated for all appropriate cables, both unused and used. The references state that if the slope of the characteristic voltage-current changes from linear to non-linear relationship, then this is a sign of the deterioration of the insulating material [13, 14]. Figs. 5 and 6 describe the slopes of used and unused cable samples [13]. It is evident that Fig. 5 indicates that in the cable sample no water trees were observed, whereas Fig. 6 indicates that water trees are present in the cable sample. Fig. 6 clearly shows a deterioration of the sample.

Fig. 5. Current-voltage characteristic for an unused 35 kV cable sample [13].

Fig. 6. Current-voltage characteristic for a used 35 kV cable sample [13]

4. Simulations Using SIMULINK Software

4.1 General

The simulations were performed on the SIMULINK software in order to verify the effects of water trees on medium voltage power cables. In particular, it has been assessed how systems with cables containing or not containing water trees correspond in the event of a fault, such as a short circuit and a lightning overvoltage. In addition, it was studied what happens to each system in the event of a sudden interruption of the system's power from the network. These tests were carried out on a single-phase system as well as on a three-phase system.

Fig. 7. Dielectric model with resistances and capacitors in parallel and in series [15].

Volumes of the Water Tree Portion K_3 (%)	Capacitance Values (F)	Resistance Values (Ω)
4	$C_1 = 1.80 \times 10^{-4}$	$R_1 = 2.22 \times 10^{10}$
	$C_2 = 1.22 \times 10^{-5}$	$R_2 = 3.28 \times 10^{11}$
	$C_3 = 1.49 \times 10^{-5}$	$R_3 = 3.50 \times 10^{11}$
20	$C_1 = 1.40 \times 10^{-4}$	$R_1 = 2.85 \times 10^{10}$
	$C_2 = 1.86 \times 10^{-5}$	$R_2 = 2.15 \times 10^{11}$
	$C_3 = 1.80 \times 10^{-6}$	$R_3 = 2.24 \times 10^{15}$
45	$C_1 = 1.00 \times 10^{-4}$	$R_1 = 4.00 \times 10^{10}$
	$C_2 = 1.00 \times 10^{-5}$	$R_2 = 4.00 \times 10^{11}$
	$C_3 = 1.11 \times 10^{-6}$	$R_3 = 3.64 \times 10^{15}$

Fig. 8. Capacitance and resistance values for degradation rate of 4%, 20% and 45% from water trees [15]

Fig. 7 represents a cable which has been degraded by water trees and the simulations which are explained below are based on this model. Thus, in this model we can see some resistances and capacitors, where each element represents the following:

- C1: represents the capacity of the healthy part of the cable
- R1: represents the resistance of the healthy part of the cable
- C2: represents the capacity of the part of the cable in series with the part which is degraded by the water tree.
- R2: represents the resistance of the part of the cable in series with the part which is degraded by the water tree
- C3: represents the capacity of the water tree area
- R3: represents the resistance of the water tree area

In addition, reference [15] indicates the values of resistances and capacitances in case of healthy cable, which are: $R=2 \cdot 10^{10} \Omega$ and $C=2.005 \cdot 10^{-4} \text{ F}$. Fig. 8 shows values of resistances and capacitances for degraded cables with respective degradation rates of 4%, 20% and 45% from the presence of water trees.

4.2 Single-Phase System

4.2.1 General

In this section, single-phase simulations will be performed at the occurrence of a short circuit, lightning overvoltage and a sudden interruption of the system's power supply from the network. The cases of systems to be analyzed are as follows:

- The first circuit contains a healthy cable
- The second circuit contains 20% degraded cable from water trees
- The third circuit contains 45% degraded cable from water trees

Each circuit contains (Fig. 9):

- A single-phase alternating voltage source of 20 kV
- An internal source resistance
- An underground unipolar cable which has impacted a different degree of degradation in each case and has been simulated according to the models analyzed at the beginning of the chapter.
- A load consisting of a resistance and a coil
- A voltmeter for measuring the load voltage
- An ammeter for measuring the load current

As the differences in wave forms are small, in order to demonstrate fully the differences between the various cases, a comparison of the voltage-time and current-time waveforms of the healthy cable system will be made with each of the other two cases, which describe degraded cables. The voltage and current waveforms of the load belonging to the system with the healthy cable are presented with blue color, while the voltage and current waveforms of the loads belonging to the systems containing degraded cables from water trees are presented with yellow color (Fig. 10).

4.2.2 Short-Circuit

In the case of a short circuit, a one-phase circuit is simulated according to Fig. 9, and a short circuit for $t=0.1 \text{ sec}$ is created (closes the switch (S) at time $t_1=0.25 \text{ sec}$ and opens at time $t_2=0.35 \text{ sec}$) in order to examine how the load voltage behaves in each of the three cases.

According to Fig. 10, at the moment the short circuit ends, a larger overvoltage in the circuit containing the degraded cable with 20% is observed compared to the healthy system. To be more specific, the overvoltage observed in the load of the healthy system is $2.269 \cdot 10^4 \text{ V}$, while the overvoltage observed in the load of the system containing a 20% degraded cable is $2.46 \cdot 10^4 \text{ V}$.

According to Fig. 11, at the moment the short circuit ends, a larger overvoltage in the circuit containing the degraded cable with 45% is observed compared to the healthy system. More specifically, the overvoltage observed in the load of the healthy system is $2.269 \cdot 10^4 \text{ V}$, whereas while the overvoltage observed in the load of the system containing a 45% degraded cable is $2.63 \cdot 10^4 \text{ V}$.

Fig. 9. Simulations of healthy, 20% degraded and 45% degraded cables

Fig. 10. Load voltage-time wave forms of the healthy cable system and the degraded cable system with 20% water trees.

Fig. 11. Load voltage-time wave forms of the healthy cable system and the degraded cable system with 45% water trees.

4.2.3 Lightning Overvoltage

This case studies how the systems of the three aforementioned cases respond if a lightning overvoltage is suddenly applied at time $t=0.1 \text{ sec}$ to each system individually. It will be examined how the load voltage changes if lightning overvoltage suddenly occurs in each of the 3 cases and a comparison will be made between them. The system of Fig. 12 was used in this simulation.

Fig. 12. Simulation system

A controlled single-phase voltage source has been added to each circuit, introducing thus a lightning overvoltage on each system, via a Matlab function which is shown in Fig. 13, to examine how each system responds.

Fig. 13. Matlab function for lightning overvoltage simulation

The components of the MATLAB function consist of:

- A, which represents the impulse magnitude.
- alpha, which is the damping factor.
- t₁, which is the time when the impulse starts.
- t, which is the time function.
- u, which is the impulse rise step function.

Fig. 14. Load voltage-time wave forms of the healthy cable system and the degraded cable system by 20% from water trees focusing on the time interval when the lightning overvoltage occurs.

According to Fig. 14, it is evident that after application of this voltage a larger voltage is shown in the circuit containing

the degraded cable by 20% than the healthy system. In particular, the lightning overvoltage which is observed in the load of the healthy system shall be $1.1 \cdot 10^6$ V, while the overvoltage observed in the load of the system containing a 20% degraded cable shall be $1.19 \cdot 10^6$ V.

Fig. 15. Load voltage-time wave forms of the healthy cable system and the degraded cable system by 45% from water trees focusing on the time interval when the lightning overvoltage occurs.

According to Fig. 15, it is evident that after application of this voltage a larger voltage is shown in the circuit containing the degraded cable by 45% than the healthy system. In particular, the lightning overvoltage which is observed in the load of the healthy system shall be $1.1 \cdot 10^6$ V while the overvoltage observed in the load of the system containing a 45% degraded cable shall be $1.277 \cdot 10^6$ V.

4.2.4 Load Interruption from the Network

In this case, the single-phase system of the Fig. 16 is simulated. The power supply interruption from the source is achieved by a switch (S) which opens at time $t=0.1$ sec and the current and voltage load waveforms are observed from that time until the voltage and current go to zero in each of the above cases.

Fig. 16. Simulation system

Fig. 17. Load voltage-time wave forms of the healthy cable system and the degraded cable system by 20% from water trees.

According to Fig. 17, it is observed that the load voltage belonging to the system with the healthy cable declines slightly slower than the load voltage belonging to the system containing a degraded cable by 20% from water trees.

Fig. 18. Load voltage-time wave forms of the healthy cable system and the degraded cable system by 45% from water trees.

According to Fig. 18, it is observed that the load voltage belonging to the system containing a 45% degraded cable from water trees declines more rapidly than the load voltage belonging to the healthy system.

Fig. 19. Load current-time wave forms of the healthy cable system and the degraded cable system by 20% from water trees.

According to Fig. 19, it is observed that the load current belonging to the system with the healthy cable declines slightly slower than the load current belonging to the system containing a degraded cable by 20% from water trees. In conclusion, since the load voltage and current belonging to the system with the degraded cable by 20% decline more rapidly, the energy dissipation of that cable is greater than the energy dissipation of a healthy cable.

According to Fig. 20, it is observed that the load current belonging to the system with the healthy cable declines slightly slower than the load current belonging to the system containing a degraded cable by 45% from water trees. Therefore, since the load voltage and current belonging to the system with the degraded cable by 45% declines more rapidly, then energy dissipation of that cable is greater than energy dissipation of a healthy cable.

Fig. 20. Load current-time wave forms of the healthy cable system and the degraded cable system by 45% from water trees .

4.3 Three-Phase System

4.3.1 General

In this section, three-phase system simulations will be performed for the case of a short circuit, lightning overvoltage and sudden load supply interruption from the network, as mentioned before. The cases of the circuits which will be analyzed are the following:

- The first circuit contains three healthy unipolar cables.
- The second circuit contains three unipolar degraded cables by 20% from water trees.
- The third circuit contains three unipolar degraded cables by 45% from water trees.

It has to be noted that the case of the short circuit which is studied in section 4.3.2, used a system with three healthy unipolar cables, three degraded unipolar cables by 4% from water trees and three degraded unipolar cables by 20% from water trees. Each circuit contains:

- A three-phase alternating voltage source of 6 kV.
- Three underground unipolar cables which have impacted a different degree of degradation in each case and have been simulated according to the models analyzed at the beginning of the chapter.
- Two similar three-phase induction motors, which each has output power 250kW, rated at 6 kV.

Supposing that we have three underground 10Km cables which supply two similar three-phase induction motors, each having output power 250kW and operating at rated voltage 6kV. Induction motors data was derived from a technical list of ASEA BROWN BOVERI (ABB) for high voltage induction motors [16].

Then, three underground unipolar cables 185mm² were selected from the technical list of HELUKABEL [17]. In order to use the cables successfully, it is necessary to check the voltage drop that will occur when the two loads are supplied to establish that it will be within the permissible limits, i.e., $\Delta V \leq 4\%$. The type for voltage drop was derived from training review for energy inspectors of the Technical Chamber of Greece[18].

Therefore, the voltage drop will be:

$$\Delta V = \frac{\sqrt{3} * I * L * (R'_L * \cos\varphi + X'_L * \sin\varphi)}{U_n}$$

where,

ΔV : voltage drop (V)

I : current of cables (A)

L : length of cables (Km)

R'_L : resistance of cables (Ω/Km)

X'_L : inductive resistance of cables (Ω/Km)

φ : phase angle between current and voltage
 U_n : rated voltage
 Thus,

$$\Delta V = \frac{\sqrt{3} * 62 * 10 * (0.101 * \cos(34.915) + 0.110 * \sin(34.915))}{6000}$$

$$\Delta V = 0.026 \Rightarrow \Delta V = 2.6\% \text{ acceptable value}$$

Therefore, three unipolar cables with cable cross-section 185mm² can be used.

The voltage and current waveforms of the motors with yellow color represent the system that contains cables with the highest degradation rate and the voltage and current waveforms of the motors with blue color represent the system

that contains cables with the lower degradation rate in each case.

4.3.2 Short-Circuit

In this case, a permanent short circuit is created in the middle of the power line at time $t=4$ sec and the induction motor circuit breaker is assumed to open at time $t=4.014$ sec, as according to the reference [15], the response time of the circuit breakers is 10-100 msec. It will be examined how the load voltage and current behave in each of the 3 cases. A comparison will be made of the voltage-time and current-time load waveforms between the system containing healthy cables and the system containing degraded cables by 20% from water trees, and a comparison of the current-time and voltage-time wave forms between the system containing degraded cables by 20% from water trees and the system containing degraded cables by 45% from water trees. The total used system is shown in the Fig. 21.

Fig. 21. Simulation system

It is necessary to note that the self-excited effect of motors which is observed after supply interruption by the circuit breaker, will be analyzed in more detail in section 4.3.4.

Fig. 22. Motor voltage-time wave forms of the healthy cable system and the degraded cable system by 4% from water trees.

According to Fig. 22, when the circuit breaker opens, there is a larger overvoltage at the motors which are powered by the degraded cables than the motors of the healthy system. In particular, the maximum voltage which is observed at the motors belonging to the system with healthy cables is $1.249 \cdot 10^4$ V, whereas the maximum voltage which is observed at the motors powered by the 4% degraded cables is $1.428 \cdot 10^4$ V.

Fig. 23. Motor current-time wave forms of the healthy cable system and the degraded cable system by 4% from water trees.

According to Fig. 23, it is observed that the current of motors which are powered by healthy cables is the same as that of motors of the system powered by the degraded cables with 4% water trees. Therefore, water trees do not affect motors current until they are stopped by the circuit breaker.

Fig. 24. Motor voltage-time wave forms of the degraded cable system by 4% and the degraded cable system by 20% from water trees.

According to Fig. 24, when the circuit breaker opens, there is a larger overvoltage at motors powered by 20%

degraded cables relative to motors belonging to the system with 4% degraded cables. In particular, the maximum voltage which is observed at motors belonging to the system with the degraded cables by 4% is $1.428 \cdot 10^4$ V, while the maximum voltage which is observed at motors powered by the 20% degraded cables is $2.395 \cdot 10^4$ V.

Fig. 25. Motor current-time wave forms of the degraded cable system by 4% and the degraded cable system by 20% from water trees.

According to Figure 25, it is observed that the current of motors which are powered by 4% degraded cables is the same as that of motors powered by 20% degraded cables. Therefore, water trees do not affect motors current until they are stopped by the circuit breaker.

4.3.3 Lightning Overvoltage

This case studies how the systems of the three different cases - which are mentioned above - respond if lightning overvoltage is suddenly applied to one phase at time $t=2$ sec on each system individually. Consideration will be given how motors voltage changes for applying a voltage of 10^7 V at each of the three cases and a comparison will be done between them. The entire system used is shown in the Fig. 26.

Fig. 26. Simulation system

A MATLAB function that is intended to simulate the lightning overvoltage has been analyzed in section 4.2.3.

Fig. 27. Motor voltage-time wave forms of the healthy cable system and the degraded cable system by 20% from water trees focusing on the time interval when the lightning overvoltage occurs.

According to Fig. 27, the maximum voltage at the beginning of the phenomenon occurring at the motors terminals of the system with the 20% degraded cables is $1.2657 \cdot 10^7$ V and the maximum voltage at the motors terminals of the healthy system is $1.26 \cdot 10^7$ V. In addition, it is observed that the motors voltage of the healthy system is declining more rapidly than the motors voltage powered by the 20% degraded cables.

Fig. 28. Motor voltage-time wave forms of the degraded cable system by 20% and the degraded cable system by 45% from water trees focusing on the time interval when the lightning overvoltage occurs.

According to Fig. 28, the maximum voltage at the beginning of the phenomenon occurring at the motors terminals of the system with degraded cables by 45% is $1.27 \cdot 10^7$ V and the maximum voltage at the motors terminals of the system with the 20% degraded cables as mentioned above is $1.2657 \cdot 10^7$ V. In addition, it is observed that the motors voltage powered by the 20% degraded cables is declining more rapidly than the motors voltage powered by the 45% degraded cables.

4.3.4 Load Interruption from the Network

If an error occurs in the network, then the switches, which exist on departure of the line, open in 0.15 sec. However, as soon as 0.45 sec after opening, they close again, and this process may repeat in cycles, called "OCO" reset cycles. The voltage at the terminals of the asynchronous motor, however, is not immediately eliminated, but with a time constant which in large motors (MW) may take seconds. This is due both to the rotor time constant L/R and to the large inertia of the motor resulting in continuing its rotation. In other words, the motor induces a voltage at its terminals which is greater if there are connected capacitors at its poles, resulting in self-excited effects. However, when the network voltage comes back after the first reset and the motor has not been disconnected from the network, then the motor and the network may have a large phase difference equivalent to a short circuit [19].

Fig. 29. Reset cycles of circuit breaker (after [20])

Fig. 29 shows the times when switches on the network open and close in case of an error [20]. We assume that an error occurs in the network, which is not cleared up to time t_3 but after time t_4 . Therefore, after the t_3 time the switches open for 5 sec. This simulation studies motor voltage and current from the time t_3 to a few seconds after the time of fault clearance for the three reported cases (Fig. 30). The circuit breaker shall be assumed to open from 8 seconds to 13 seconds. At the end of 13 seconds the error is cleared up.

Fig. 30. Simulation system

Fig. 31. Motor voltage-time wave forms of the healthy cable system and the degraded cable system by 20% from water trees focusing on the time interval when the circuit breaker is open.

Fig. 31 shows that if the motors are powered by 20% degraded cables from water trees, they induce a larger voltage at their terminals than if they are powered by healthy cables. It is noted that the maximum voltage displayed at the motors terminals of the healthy system is $3263 \cdot 10^5$ V, whereas the maximum voltage displayed at the motors terminals powered by the 20% degraded cables is $4417 \cdot 10^5$ V as shown in Fig. 31.

Fig. 32. Motor current-time wave forms of the healthy cable system and the degraded cable system by 20% from water trees focusing on the time interval when the circuit breaker is open.

Fig. 32 shows that if motors are powered by 20% degraded cables from water trees, then they absorb a larger current of the self-excited period than if they are powered by healthy cables. We note that the maximum current absorbed by each motor of the system with the healthy cables is 465.983 A, whereas with the 20% degraded system is 524.673 A, as shown in Fig. 32.

In addition, after the circuit breaker has been successfully closed at time $t=13$ sec, a very high current is observed for a minimum of time. In the case of the system with degraded cables 20%, this current is up to 1.855 kA, and in the case of the system with healthy cables the current is up to 1.409 kA.

Fig. 33. Motor voltage-time wave forms of the degraded cable system by 20% and the degraded cable system by 45% from water trees focusing on the time interval when the circuit breaker is open.

Fig. 33 shows that if the motors are powered by 45% degraded cables from water trees, they induce a greater voltage at their terminals than if they are powered by 20% degraded cables. Noting that the maximum voltage displayed at the motors terminals of the system with the degraded cables by 45% is $5937 \cdot 10^5$ V, while the maximum voltage displayed at the motors terminals powered by 20% degraded cables is $4417 \cdot 10^5$ V.

Fig. 34. Motor current-time wave forms of the degraded cable system by 20% and the degraded cable system by 45% from water trees focusing on the time interval when the circuit breaker is open.

Fig. 34 shows that if motors are powered by 45% degraded cables from water trees, then they absorb a greater

current of the self-stimulation period than if they are powered by 20% degraded cables. Noting that the maximum current absorbed by each motor in the system with the degraded cables by 45% is 589.098 A, while the maximum current absorbed by each motor powered by 20% degraded cables is 524.673 A.

In addition, after the circuit breaker has been successfully closed at time $t=13$ sec, a very high current is observed for a minimum of time. In the case of the system with degraded cables 45%, this current is up to 1.855 kA, and in the case of the system with degraded cables by 20% the current is up to 1.409 kA.

It is evident from the above that degradation of cable insulation plays a decisive role in determining the performance of the cable. The adequacy of the simulation data presented in this paper is validated from the very fact that the ever increasing degradation rates of the cables give worse results than the healthy cable. In this work an effort was made – with the aid of simulations – to show the destructive effect of water trees. What was presented here is an indication as to the effects water and moisture have, based – we repeat – on simulations. What is currently missing is a direct comparison between the simulation results presented here and experimental data but ample experimental evidence exists regarding the deteriorating effects of water trees in previously published work [6-11]. Needless to say that it is our aim in the near future to collect experimental data, so that a comparison with the simulation results will be possible.

5. Conclusions

• Theoretical Conclusions

- Alternating electric field and humidity are the main factors which lead to the emergence of water trees.
- The measurement of the loss factor at Very Low Frequency (VLF) is a very useful practical method.

• Simulations Conclusions

- In normal operation of all investigated systems no differences in electrical behavior were observed.

• Single phase system

- The higher the degree of deterioration of the cable, the greater the surge observed after the short circuit.
- The higher the rate of cable degradation due to water trees, the greater the excess pressure observed at the load ends at the time of lightning overvoltage.
- The higher the rate of cable degradation, the faster the decline of voltage and current of the load powered by the cable.
- The higher the degradation rate of cables, the greater the loss of energy present in these cables.

• Three phase system

- The higher the cable degradation rate due to water trees, the greater the hypertension appears at the motors terminals at the time the short circuit is stopped by the circuit breaker. The motor current is the same in all cases.
- The higher the cable degradation rate due to water trees, the greater the excess in the motor terminals at the time of lightning overvoltage.
- The higher the rate of deterioration of the cables due to the water trees, the greater the voltage induced at the motor terminals and

the current leaking the motors during the self-stimulation period and the time when the network circuit breakers reclose by resetting the voltage.

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