Mechanism for Impulse Conversion of Water Trees to Electrical Trees in XLPE

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Abstract **A lightning impulse causes substantial capacitive current in a water tree channel which, as a result of its small cross section, has relatively low conductance. Transient, nonlinear finite element computations with coupled thermal and electric fields for the geometry of a 15 kV XLPE dielectric cable indicate that an 80 kV lightning impulse can cause the water within a water tree channel to boil over a range of four orders of magnitude in water conductivity, from 10^{-2} S/m to 10^{2} S/m. Boiling of the water in a water tree channel reduces substantially the yield stress of the XLPE, raises the pressure within the water tree channel, and is likely to leave a cavity which can support partial discharge resulting in electrical tree initiation.**

INTRODUCTION

Water (or electrochemical) trees are dendritic patterns which grow in hydrophobic polymers in the presence of ac electric field and water. Recent evidence [1] indicates that in the growth region, water trees consist of "tracks" of oxidized polymer which connect microvoids. The relevance of the microvoids is very likely statistical in nature, i.e., the likelihood of survival of a track is increased if it encounters a microvoid from which it can continue to grow.

In general, water trees do not cause failure of in-service XLPE cable, rather electrical trees initiate from water trees as a result of lightning surges. The circumstantial evidence for this assertion is strong, in that cable failures often occur days after heavy summer lightning activity in the southeast of the United States. Also, electrical trees have been found growing from water trees in XLPE cable removed from service[2].

In the present paper, we report computations which shed light on the means by which electrical trees are initiated from water trees. We believe that this occurs as a result of electro-thermo-mechanical phenomena induced by the lightning voltage surge. For moderate water conductivity, the high electric field caused by the combination of the lightning-induced voltage and the distortion of the electric field in the polymer by a large water tree results in power dissipation in water tree channels sufficient to boil the water therein, very likely generating a cavity sufficient to support partial discharge and initiate an electrical tree. For higher water conductivity, the water can act as a conductor and cause an electric field at the tip of a water tree sufficient to raise the temperature of the XLPE through the region in which the XLPE expands by about 20%. Such a temperature rise would cause (i) several orders of magnitude reduction in the yield stress of the XLPE, (ii) substantial electromechanical stresses as a result of the action of the space charge limited field in the XLPE (about 250 kV/mm at power frequency and proportional to the log of frequency) [3,4] with the space charge [5], and (iii) a mechanical shock wave as a result of the substantial thermal expansion of a micrometre region of the XLPE over a period of a few microseconds. Any of these phenomena would be sufficient to initiate an electrical tree from a water tree; however, we feel that heating of the water is the most likely mechanism under most impulse conditions.

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DIELECTRIC MODEL FOR A WATER TREE

At the growth front, water trees probably consist of tracks of oxidized (and therefore hydrophilic) polymer within the hydrophobic XLPE [6,7]. These oxidized, hydrophilic tracks result in condensation of water from the hydrophobic matrix into the hydrophilic track. Producing a chemical potential sufficient for water tree growth requires substantial conductivity in such very narrow tracks [6], which means that a substantial supply of ions is probably required. The growth front of the water tree is only visible as a series of water-filled microvoids; the tracks which connect these microvoids are not normally visible [1].

The visible tubules in the majority of the water tree are presumably tracks which have been oxidized to form water-filled channels. These channels will vary in thickness, with the greatest thickness near the base of the (vented) water tree. Thus the dielectric time constant will vary with the channel cross section, from relatively short near the base of the tree to long at the reaction front. At a given frequency, the field will be "ejected" from regions with a time constant short compared to the applied frequency and will therefore be concentrated in the regions of shorter time constant. Thus within the range of channel diameters and resulting dielectric time constants, conditions somewhere will be optimum for the processes described below for conversion of water trees to electrical trees.

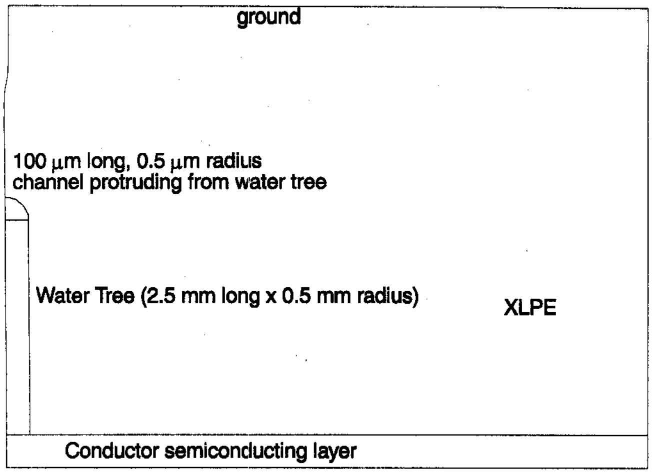

Figure 1. Geometric model employed for finite element analysis. The water tree channel protruding from the tip of the water tree is too fine to be visible.

In this paper, we model 15 kV XLPE cable with an insulation thickness of 4.51 mm (Figure 1). We take the bulk of the water tree as a cylinder with a hemispherical tip with its cylindrical axis perpendicular to the conductor semicon. We take this region to be 0.5 mm in radius and 2.5 mm long to the hemispherical tip. We assume that a water tree channel which is 0.5 µm in radius and 100 µm long is protruding from the tip of the water tree region. Obviously, we can model the treed region with a range of properties, from fully conducting, to dielectric constant of 80 with no conductivity, to intermediate values of conductivity and dielectric constant. Measured conductivities of water trees have generally indicated very low values. However, measurements were usually made on "dormant" trees (trees that had been unenergized for some time before making conductivity measurements), and the water in the tracks may have ceased to be continuous. The water tree need not have continuous conduction to enhance the electric fields as would a conductor. As long as the water tree polarizes nearly completely during the lightning impulse, it will "eject" the electric field from within the bulk of the water treed region and act as a conductor with regard to its effect on the regions surrounding it. For this reason, we model the heavily water treed region as conducting.

LIGHTNING SURGE-INDUCED PHENOMENA

Power Dissipation vs Water Conductivity

When a water-filled, partly conducting tubule is exposed to a transient high field, charge redistributes in the tubule to cancel the field within the partially conducting fluid (water). This occurs with a time constant which depends on the conductance of the tubule, i.e., the product of the water conductivity times the cross section of the tubule, and the geometry of the system. If the time constant is long compared to the duration of the impulse, then the current density is low and little power is dissipated.

If the time constant is comparable to the risetime of the impulse, then the current density is high and the resistance is appreciable, which results in substantial power dissipation in the water within the tubule. As well, charge accumulation at the ends of the tubule (one end where the tubule meets the XLPE and the other end where the tubule meets the high conductivity water tree region) along with the high dielectric constant of the water in the tubule relative to that of the XLPE result in substantial field enhancements at the ends of the tubule. This causes space charge injection in the XLPE, electromechanical forces, and heating as a result of $J{\cdot}E$ power dissipation therein.

If the time constant for redistribution of charge in the water of the tubule is very short, then the current density is high during the rise of the impulse, but resistance is very low, and little power is dissipated. However in this case, the water acts as a conducting protrusion, and the field at the tip of the tubule will be very high which results in substantial space charge formation, heating in the XLPE as a result of field-dependent conductivity and $J{\cdot}E$ (field times current density) power dissipation, and electromechanical forces as a result of the electric field acting on the injected space charge [5,8]. Given the reduction in the yield stress of the XLPE caused by the $J{\cdot}E$ heating, the XLPE is likely to yield.

From the above considerations, we expect the conductivity of the water in a channel must change in inverse proportion to the change channel cross section to maintain the time constant for redistribution of charge within the channel.

Our choice of a 1 µm diameter water tree channel is dictated mainly by practical considerations associated with application of finite element analysis. For a 1 µm diameter channel, the smallest mesh elements must in the range of 0.1 µm in extent, while the largest dimension in the problem is about 5 mm. The range of geometry requires in the range of 2000 mesh elements. However, if we were to conduct the analysis for a 0.1 or 0.01 µm diameter channel, we would expect that the optimum water conductivity would be 100 or 10^4 times greater, but we would also expect a substantial temperature rise in the water over a greater range of water conductivity.

Space Charge Formation

In most solid dielectrics, space charge results from redistribution of charge within a dielectric. However, in the presence of a water tree, two forms of space charge will oscillate with the ac cycle. The dominant form is probably ionic space charge which forms and oscillates at the ends of the water tree tubules as the result of ion motion in the water during the ac cycle. The second form is space charge injected from the tip of the water three channels into the XLPE dielectric. The space charge density vs time for these two forms of space charge are predictable and will differ substantially.

MODEL FOR XLPE CONDUCTIVITY

Based on measurements [8] and data in the literature for XLPE cable dielectric [5], we employ the following formula for the conductivity, σ (S/m) of the XLPE vs temperature, T (K), and electric field, E (V/m).

$$\sigma(E,T) = \frac{62.24}{|E|}\exp\left(\frac{-6945.71}{T}\right)\exp\left(7.796x10^{-8}\,|E|\right) \quad (1)$$

As this equation diverges up at small E, we assume that $\sigma(E,T) = 0$ for $|E| < 10$ kV/mm. This formula is used in all computations but those of Figure 8. The extreme nonlinearity caused by XLPE conductivity can slow the computations greatly. We note that the above formula implies a trap depth of 0.83 eV and a distance between hopping sites of about 3.8 nm, which are reasonable values for XLPE. Obviously, the water tree will modify the XLPE conductivity in the immediate vicinity of the tree. Thus over some distance, the conductivity must go from that of the water to that of the untreed XLPE. However, data are not available which indicate the distance of which this transition takes place. We have therefore assumed a sharp transition from the conductivity of the water to that of dry XLPE. As indicated by comparing Figure 8 with the other figures, the details of this transition do not have a major impact on the resulting thermal computations.

COMPUTATIONAL TECHNIQUE

We compute the thermal and electric fields using a program for transient, nonlinear finite element analysis developed by one of us (JK). The program allows material properties to be a function of field parameters and the boundary conditions (e.g., applied voltage) to be time-dependent. We have verified the nonlinear electric field portion of the program through comparisons of our computations with published literature for charge injection into polyethylene from a needle electrode, and we have verified the coupled thermal and electric field portions of the program against analytic solutions during computations of electro-thermal effects in ZnO. We thus have high confidence in the computational procedure.

In the present analysis, system material properties are modeled as follows:

- XLPE Heat Capacity and Thermal Conductivity as a function of temperature are modeled as per Figure 2.
- XLPE Electrical Conductivity is modeled as per eq (1).
- Water Volumetric Heat Capacity is modeled by the eq. (2), the second term of which is a Gaussian with a standard deviation of 1 K centered at 373 K which integrates to the heat of vaporization of water.

$$RC(T) = 4.18\times10^{6} + 9\times10^{5}\exp\left(\frac{-(T-373)^{2}}{2}\right)\frac{\mathrm{J}}{\mathrm{m}^{3}\,\mathrm{K}} \quad (2)$$

- Water Thermal Conductivity is modeled by

$$K(T) = 6.1 + 0.01\,(T-300)\,\frac{\mathrm{W}}{\mathrm{m\,K}} \quad (3)$$

- Water Electrical Conductivity is modeled as increasing by 2.5%/K from a nominal value at 300 K, a typical temperature coefficient for ionic conductors. Thus the conductivity at 330 K is about 2.1 times and the conductivity at 373 K is 6.1 times the 300 K value given on the Figures.

The applied voltage is a standard lightning impulse (1.2 x 50 μs) of 80 kV magnitude which is appreciably less than the

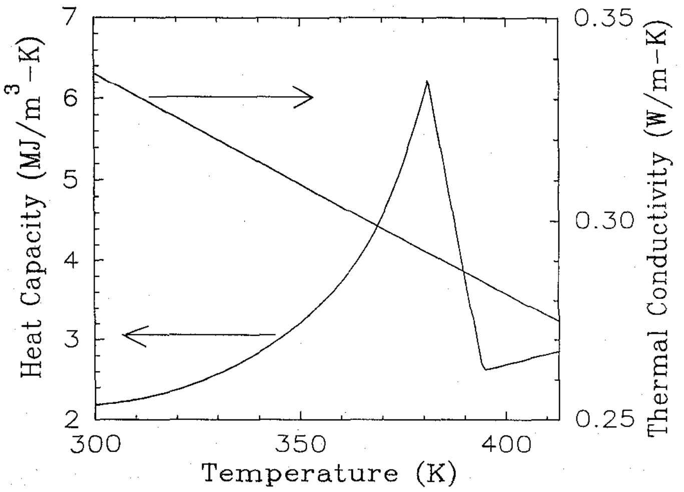

Figure 2. Heat capacity and thermal conductivity as a function of temperature as employed in the present computations.

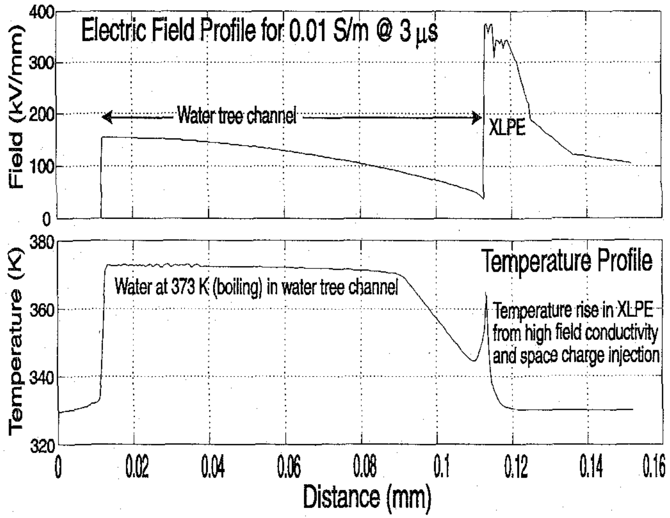

Figure 3. Electric field and temperature profiles on axis for water conductivity of 0.01 S/m at 3 μs into the lightning impulse waveform. The profiles run from just inside the conducting water tree region (left), through the axis of the water tree channel, and into the XLPE beyond the tip of the water tree channel. The temperature rise (from an initial 330 K) is greatest at the base of the water tree channel for reasons discussed in the text.

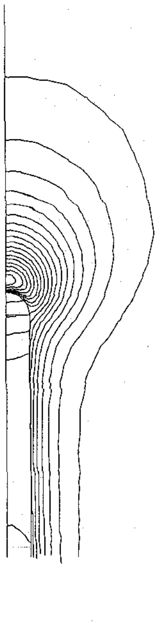

Figure 4. Equithermal plot at tip of water tree channel for the parameters of Figure 3. Note that the peak temperature at the tip of the water tree channel caused by high field conductivity in the XLPE occurs slightly off the tip, i.e., not at the point of highest electric field and power dissipation because the water in the tree channel acts as a heat sink. The temperature gradient along the water tree channel near the tip is clearly visible, as is the radial temperature gradient from the water into the XLPE. The channel radius is 0.5 μm.

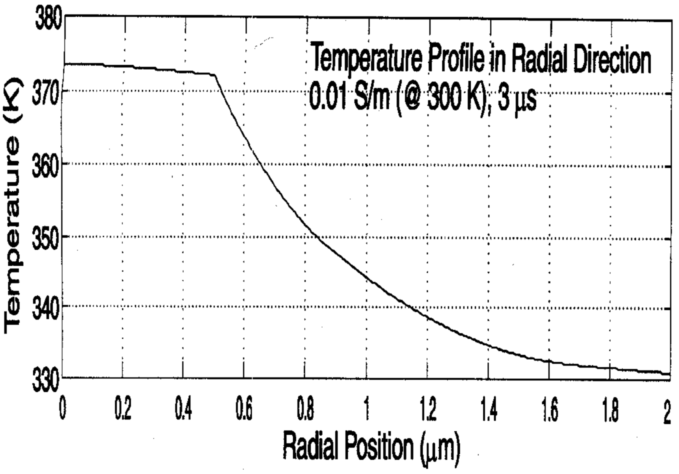

Figure 5. Profile of the temperature along a radial line through the water tree channel near the region of maximum temperature rise. The temperature (and electric field) are relatively constant through the 0.5 µm of water. Thermal diffusion is substantial

BIL of 15 kV cable (95 kV). Of course, the actual lightning-induced voltage waveform between conductor and ground depends on the lightning current waveform (highly variable in both current amplitude and risetime), proximity of the lightning strike to the cable, and surge protection applied to the cable. The industry has adopted the 1.2 x 50 µs lightning impulse voltage waveform as typical, for which reason we adopt it in this study, knowing full well that the actual lightning-induced voltage waveform can vary widely.

RESULTS

Figure 1 shows the model employed in these computations. As noted above, the 100 µm long, 0.5 µm radius channel protruding from the tip of the conducting water tree region is not visible in the Figure.

Figure 3 shows the electric field profile and temperature profile along the axis of the 100 µm long water tree channel, from slightly inside the conducting water tree region (to the left) to beyond the tip of the water tree channel for the case of 0.01 S/m water conductivity at 3 µs into a standard lightning impulse, near the 80 kV peak magnitude. Current is coupled into the water tree channel capacitively, so that the current increases from the tip of the water tree channel to the base, which results in the increasing electric field and increasing temperature from the tip to the base, as seen in Figure 3.

The field in the lower part of the water tree channel is about 150 kV/mm, which would result in a power dissipation (σE^2) of about 10^{16} W/m^3, taking into account the temperature dependence of the water conductivity. Over a period of 1 µs this would dissipate 7.9 nJ per µm of water tree channel length (for a 1 µm diameter water tree channel). Given a heat capacity for water of 4.18 x 10^6 J/K-m^3 and heat of vaporization of 2.26 x 10^9 J/m^3, 0.14 nJ per µm of channel length is required to take the water from 330 K to boiling, and 1.77 nJ per µm of channel length is required to vaporize the water in the channel. Thus we might expect the water to be vaporized, as would be indicated by a temperature above 373 K. However, the above computation overestimates the power dissipation as (i) the water conductivity increases with increasing water temperature, and (ii) the field increases during the impulse waveform and we have taken the value at the peak of the waveform. Figure 3 indicates that the water has reached the boiling point along most of the length of the water tree channel. The temperature and field drop near the tip of the channel as a result of reduced capacitively coupled current as mentioned above.

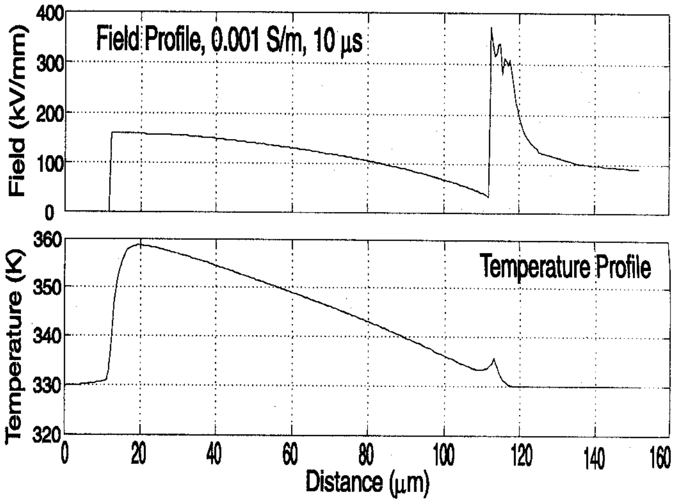

Figure 6. Electric field and temperature profiles for water conductivity of 0.001 S/m at 10 µs into a lightning impulse waveform. The temperature rise is modest at this relatively low water conductivity.

Figure 4 shows an equithermal plot of the tip region of the water tree channel. The longitudinal temperature gradient near the tip of the water tree channel is apparent, as is the high field conductivity-induced power dissipation in the XLPE at the tip of the water tree. Figure 5 shows a radial profile of the temperature near the location of maximum temperature rise along the water tree channel and indicates an appreciable effect from thermal diffusion.

The sudden change and peak in the electric field at about 0.115 mm in Figure 3 occurs at the transition from the water tree channel to the XLPE. The space charge limited field of about 350 kV/mm is typical for lightning impulse conditions. The high field conduction in the XLPE results in an appreciable temperature rise at the boundary between the two materials, as indicated by Figures 3 and 4.

Figure 6 shows similar data for a water conductivity of 0.001 S/m. The temperature rise is modest, at about 30 K and peaks at the base of the water tree channel as a result of the capacitive current coupling described above. The temperature rise at 10 µs is greater than that at 5 µs, which indicates that the dielectric time constant for redistribution of charge in the water tree channel is long compared to the risetime of the lightning impulse, so that substantial current continues to flow in the water tree channel even during the fall of the lightning impulse waveform. The temperature peak from high field conductivity of the XLPE is small, as a large voltage drop occurs along the water tree channel resulting in a modest field at the tip.

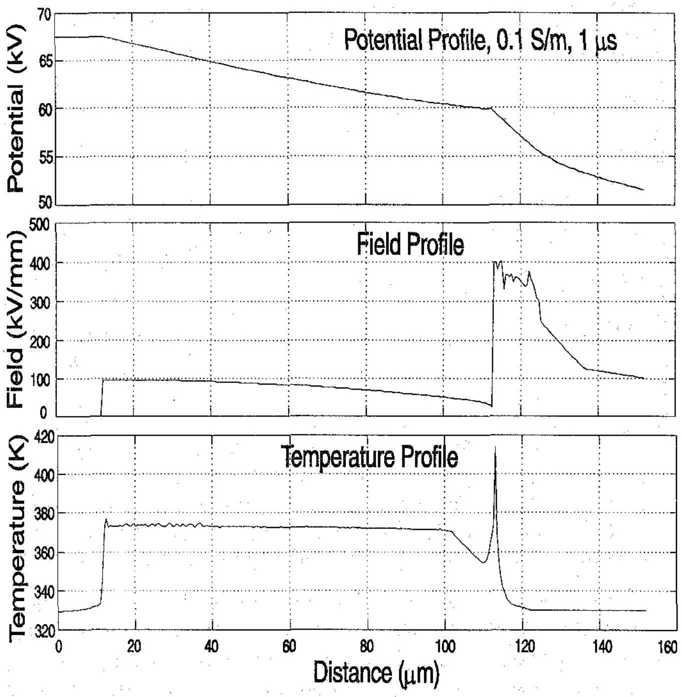

Figure 7. Electric potential, electric field, and temperature profiles for water conductivity of 0.1 S/m at 1 µs into the lightning impulse waveform for a computational model which includes high field conductivity in the XLPE. Even before the peak voltage of the impulse, the water is boiling over most of the tree channel length, and the high field conductivity-induced temperature rise in the XLPE at the tip of the water tree channel is over 140 °C.

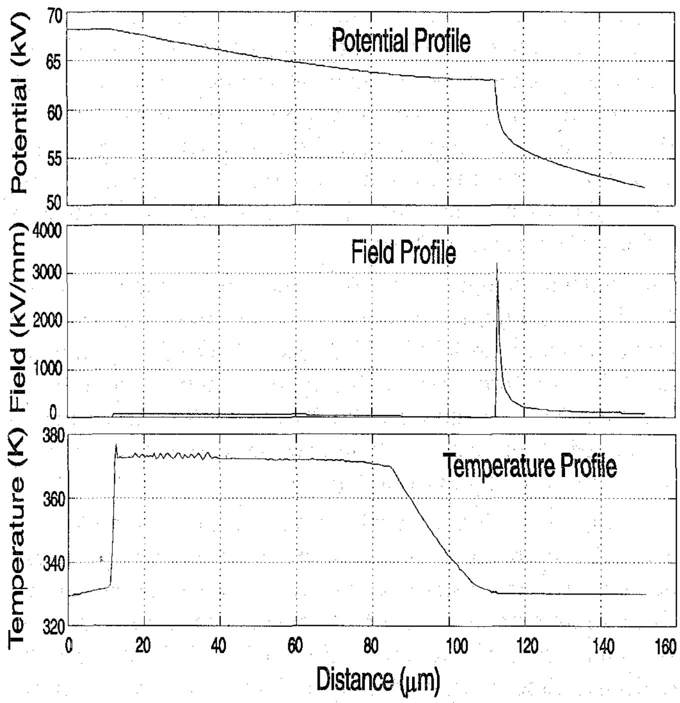

Figure 8. Electric field and temperature profiles for water conductivity of 0.1 S/m at 1 µs into the lightning impulse waveform for a computational model in which the XLPE conductivity is assumed to be zero. The data are unphysical in that XLPE cannot support a field of 3000 kV/mm. The large field at the tip distorts the field along the water tree channel and reduces power dissipation therein so that the water boils over a reduced longitudinal extent of the water tree channel relative to the data of Figure 7 which include the effect of high field conductivity in the XLPE.

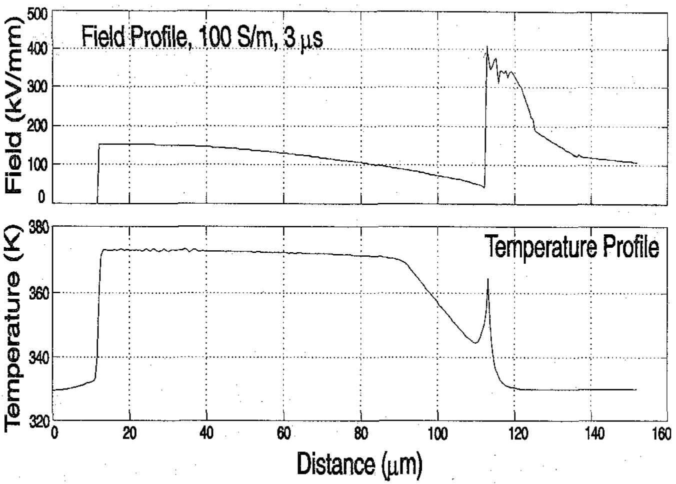

Figure 9. Electric field and temperature profiles on axis of a 1 µm diameter water tree channel for a water conductivity of 100 S/m at 3 µs into a standard lightning impulse of 80 kV magnitude. The water boils over most of the length of the water tree channel.

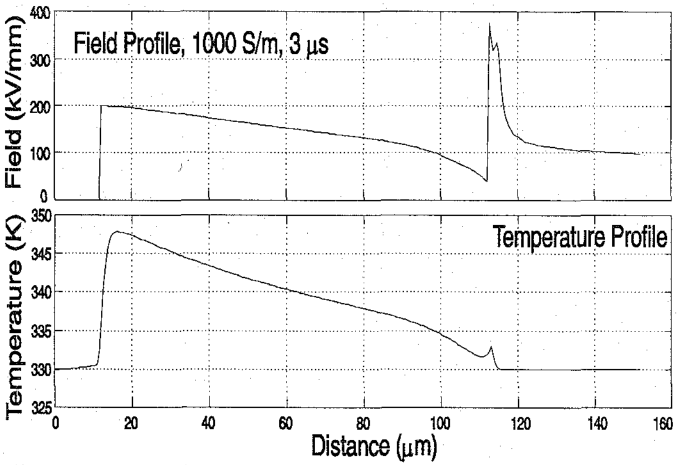

Figure 10. Electric field and temperature profiles on axis of a 1 µm diameter water tree channel for a water conductivity of 1000 S/m at 3 µs into a standard lightning impulse of 80 kV magnitude. The conductivity is sufficiently high that the water does not boil during the lightning impulse.

Figures 7 and 8 show electric field and temperature profiles for a water conductivity of 0.1 S/m (@ 300 K) and 1 µs into an 80 kV lightning impulse. The data of Figure 7 were computed with field dependent conductivity for the XLPE, while those of Figure 8 were computed with zero conductivity assumed for the XLPE. Comparing the two figures, we see that assuming zero conductivity for the XLPE results in unphysical data and substantially different results. Without high field conductivity in the XLPE, the field must drop suddenly at the tip of the water tree channel where charge accumulates as a result of the much larger conductivity in the water tree channel relative to the XLPE. This results in a field of over 3000 kV/mm in the XLPE at the tip of the water tree, which is totally unphysical. The large field results in a change in the field distribution which reduces the capacitively coupled current near the tip of the tree with a resulting reduction in the temperature in the tip region relative to Figure 7. Thus in Figure 7, the water is boiling over a larger longitudinal extent of the tree channel, and the peak temperature occurs in the

XLPE at the tip of the water tree where the peak temperature of about 415 K (142 °C) would probably reduce the yield stress of the XLPE sufficiently that it will yield as a result of the boiling water-induced pressure and the electromechanical forces. We are presently modifying our program to compute electro-thermo-mechanical stresses and should be in a position to address this point sometime in the future.

Data have also been computed for a water conductivity of 1 S/m, for which the water is already boiling at 0.44 μs into the lightning impulse, at which time the peak temperature in the XLPE is about 420 K. The water also boils for a water conductivity of 100 S/m (Figure 9); however, it does not boil for a conductivity of 1000 S/m (Figure 10). In none of the cases examined, does the computation "run away" in the sense that the water vaporizes totally and the temperature increases rapidly thereafter. However, for all conductivities between 10^{-2} and 100 S/m, the water boils over most of the tree channel length. This very broad range of conditions suggests that lightning impulse-induced boiling of the water in water tree channels could create cavities capable of supporting partial discharge and initiating an electrical tree.

The above water conductivities are very reasonable. For example, at low to moderate NaCl concentrations, the derivative of the conductivity with respect to ion concentration is about 540, so that a concentration of 20 ppm NaCl results in a conductivity of about 0.01 S/m at 300 K. Thus the above conductivities are easily achieved and do not require a very high ion concentrations.

CONCLUSION

The above results suggest a mechanism for conversion of water trees to electrical trees under impulse conditions. The impulse voltage-induced transient current can cause the water in a tree channel to boil, the temperature of the surrounding XLPE to increase sufficiently to reduce yield stress substantially, a temperature increase at the tip of the water tree channel as a result of high field conductivity in the XLPE, and substantial electro-mechanical forces as a result of the action of the field on the space charge. The overall result is yielding of the XLPE, generation of a cavity which can sustain partial discharge, and initiation of an electrical tree.

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