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A Review on Electrical Treeing in Solid Dielectrics

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Electrical trees constitute a cause for breakdown in solid dielectrics. Electrical trees are related with Partial Discharges (PD), enclosed defects, which in turn cannot be separated from faulty interfaces. In this review, certain aspects related to electrical treeing such as space charges, PD and enclosed voids are investigated. Charges related to electrical treeing must be classified in two categories. The charges that are redistributed continuously in the interior of the tree channels and charges that are moving and being trapped in the solid dielectric. The first category of charges constitute the PD charges and the second category charges are referred to as the space charges.

1.0 INTRODUCTION

Electrical treeing is one of the main causes for breakdown in electrical insulation. Electrical treeing can manifest itself as a network of gas-filled channels which emanate from already existing voids, asperities on electrode surfaces, interfaces, and/or contaminants. Generally speaking, as electrical treeing sources we can consider, under certain circumstances, any important deviation from the normal distribution of the electrical field accompanied with the appropriate amount of damage in regions of the solid dielectric. Such gas-filled channels form tree-like structures which, by increasing the electrical stress, grow in the direction of the electric field often causing the breakdown of insulation. Time also plays a dominant role in the development of electrical trees, since it is also with time that this phenomenon grows and leads to ultimate failure.

According to J H Mason [1], local breakdown which causes treeing channels occurs when the "intrinsic strength" is locally exceeded over the small volume next to the point electrode. Mason's interpretation points out implicitly to localised inhomogeneities of the insulating material, an interpretation considered by others [2] in their development of models or simulations of electrical trees. The notion of "intrinsic strength", however, is a notion challenged by later research [3].

Treeing is closely related to the breakdown of either laboratory specimens or industrial insulations. Trees can be classified into two main groups: (a) electrical trees which consist of narrow hollow channels which are branched and have the general appearance of a botanical tree (b) water trees having fuzzy appearance and consisting of water-filled microvoids [4]. It is the purpose of the present review to tackle questions related only to electrical trees and to study the various factors affecting their propagation.

2.0 EXPERIMENTAL EVIDENCE

Electrical trees grow due to high localised electrical stresses which have as sources,

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particles or fibers or asperities on the electrode surfaces. This was noted in one of the earlier works on treeing [5]. The researchers of the aforementioned work, studied the electrical treeing applying DC, AC and impulse voltage to the insulating samples. Moreover the time t is included in their experiments and more specifically they compare the time interval between the tree appearance and the total dielectric breakdown. Electrical trees, once formed, do not propagate uniformly towards the opposite electrode. Local dielectric environment around electrical tubules even in the inception stage or even in the propagation stage plays a dominant role in this behaviour. Normally, under ideal circumstances, the tree around an electrode inserted in a solid insulating material would be totally symmetrical. The solid insulating material is considered to be dielectrically homogeneous, so the expected electrical trees would result in a perfect symmetrical structure of electrical tree channels. The experimental results, however, differ from the above description. Electrical trees (which represent "theoretically" the motion of the "damaging" charges governed by electrical field lines), form various electrical tree structures with a lot of branches, which clearly deviate from the symmetrical description. Especially at low electric stresses, electrical trees may start and then stop growing [5]. This explains the numerous trees existing in samples after prolonged life tests.

Needle-plane or needle-needle electrodes were used in order to study electrical trees under laboratory conditions. In [6], trees were studied with respect to their behaviour in time and pressure. Trees imply the production of gas decomposition by-products. As the pressure of such by-products inside the tree channels increases, the tree stops growing. When the gaseous by-products leak away, PD activity will resume inside the tree channels. The behaviour of electrical trees, their dependence on the pressure in the tree channels, is similar to the pressure dependence of PD occurring in an enclosed cavity [6]. It goes without saying that electrical trees and PD occurring in the tree channels are intimately linked. In [6] it is also reported that turning the voltage off cannot extend the lifetime of insulation since that would allow the gas pressure to decrease to atmospheric pressure and hence set the right conditions for new discharges. These point out to another fact, namely, that in solid insulations gaseous by-products are important to the lifetime of such insulations.

Partial discharges cause extensions of trees and the two are inexorably linked together [7]. Research performed many years ago showed that a PD of 10 pC may cause erosion of 10^{-15} cm^3 of polyethylene and that can occur with plane-plane electrodes [8]. Tree initiation may be due to charge injection and extraction [9] under AC conditions. With the continuous injection and extraction of charges, polymer decomposition may occur which results in lower molecular weight by-products and gas, and finally in the formation of a hollow channel, large enough to accommodate gaseous PD. The relation between tree propagation and PD has also been reported in [10], where the author claimed that the electric potential of the needle electrode is transferred to the tip of the tree channel through the conductive plasma of gas discharge. In other publications as well, a discharge has been compared to a conducting extension of the electrode [1, 11]. Extension was assumed by a "localised intrinsic breakdown" at the tip of the electrode. Such views, however, were refuted by other researchers [3], who pointed out that a notion like "localised intrinsic breakdown" implies a preferential advance by the leading tubule, whereas electrical trees propagate rather randomly. According to our opinion, however, the localised advancement of the tree does not automatically refute the notion of preferential advancement. Some researchers found that trees emanate from voids and not necessarily from metallic surfaces [12]. Such a development, however, would require high values of fields, in excess of 3 $*10^8$ V/m in a void free insulation [13].

The question as to whether the potential from the electrode is transferred to the tip of the tree was tackled in [3]. An argument against this simplified approach of the same potential at the electrode as well as the tip of the tree can be based on the fact that there are always charges deposited on the walls of the trees; therefore the uneven deposition renders the whole length of the tree not equipotential. Moreover, as is reported in [14], [15], discharges will result in heat dissipation, carbonisation of the wall surfaces and subsequent erosion, i.e. all this does not certainly imply an equal potential both at the electrode and at the tip of the tree channel. Such views are in agreement with earlier views expressed in [16], where it was argued that at first electro-chemical reactions take place when the charge density is sufficient. Such reactions lead to the production of free electrons and the rapid production of gas. The aforementioned papers point out to the fact that since reactions take place inside the tubules of a tree, it is most unlikely that there exists the same potential at the electrode and at the tip of the tree. This in turn brings us to the problem of space charges and/or surface charges.

It is true, however, that PD and electrical treeing are linked together. Several distinct phases are observed in the development of PD [17] and treeing as it is shown in Fig. 1 for the case of bush and branch like trees: (a) the number of the detected PD increases initially as the first microchannels appear at the electrode tip (b) a decrease in PD number is then observed, related to the appearance of a different kind of filament propagating with PD localised at their ends (c) a sudden increase of PD number and magnitude is observed as soon as a filament reaches the ground electrode, (d) breakdown ensues accompanied by an overall increase in the PD number. Stages (c) and (d) were also observed in [3]. Referring to [17], one may think that PD plays a most dominant role in expanding the tree channels since the PD behaviour observed in tree development is similar to the PD behaviour observed in enclosed cavities.

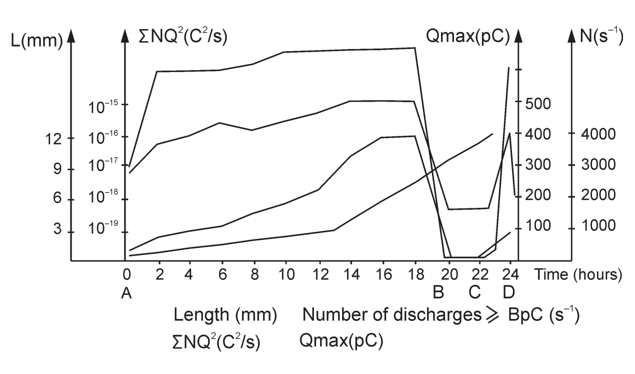


FIG. 1 NUMBER OF DISCHARGES AS A FUNCTION OF ELECTRICAL TREE EVOLUTION AND TREE LENGTH, IN THE CASE OF BUSH AND BRANCH LIKE TREES [SEE REF. 17]

L : Length of tree

LNQ^2 : Discharge quadratic flow

Q_{max} : Maximum discharge amplitude

N : Positive discharge number per second

The aforementioned four stages may slightly differ from the above description. PD and the total charge during the electrical tree propagation are affected by the type of the tree and the number of the produced branches. It is shown that branched type tree [18] is accompanied by PD events with a lot of peaks (Fig. 2). On the other hand a bush type dendrite is accompanied by PD events forming a more regular plateau in the graphical representation (Fig. 4). In the bush-branch trees, the result is mixed (Fig. 3).

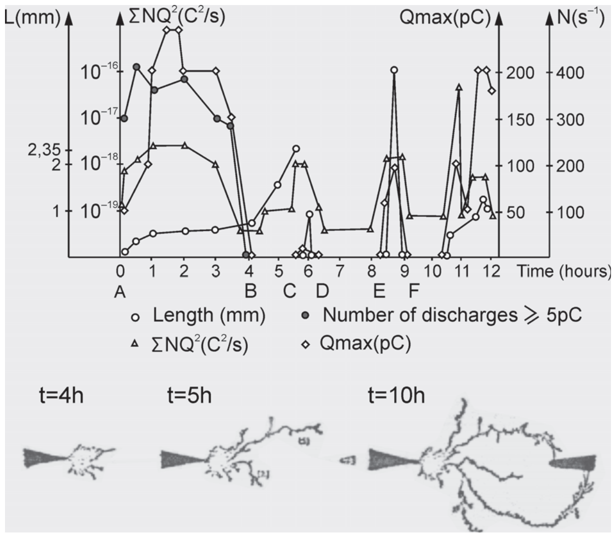


FIG. 2 DISCHARGE CHARACTERISTICS FOR A BRANCH LIKE TREE [SEE REF. 18]

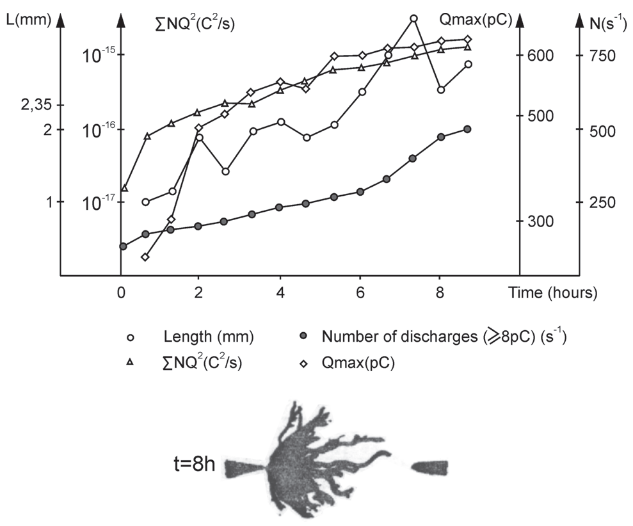


FIG. 3 DISCHARGE CHARACTERISTICS FOR A MIXED TYPE ELECTRICAL TREE (BUSH AND BRANCH LIKE DENDRITE) [SEE REF. 18]

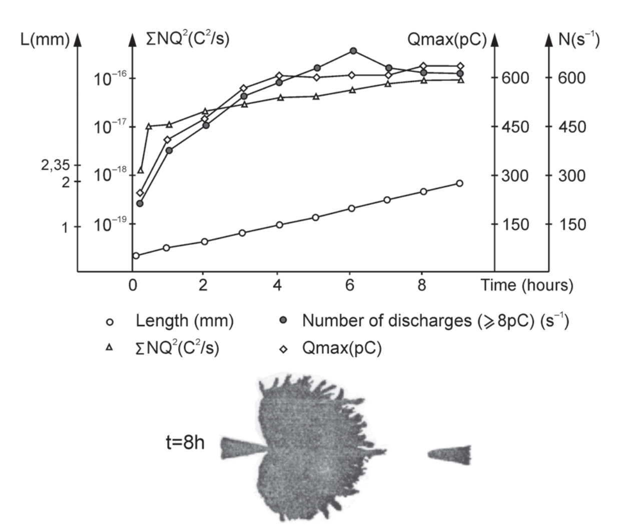


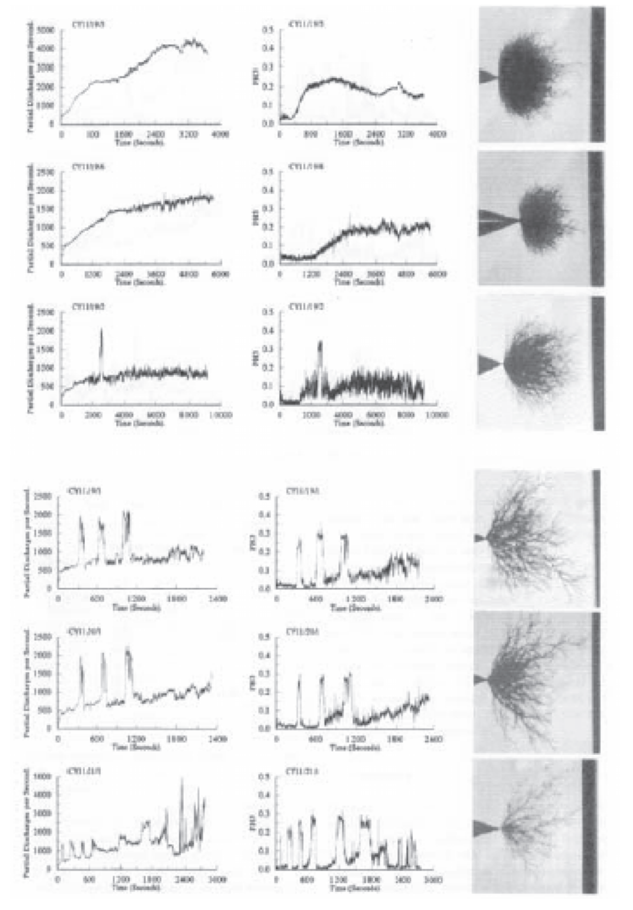
FIG. 4 DISCHARGE CHARACTERISTICS FOR A BUSH-TYPE DENDRITE [SEE REF. 18]

The same behaviour is also reported in [19]. In this paper, the phase shift is also studied, especially between the first and fourth quadrant and phase shift between the second and third quadrants (Fig. 5). This happens with the aid of two normalised phase displacement parameters:

$$PH1=Q4/(Q1+Q4)$$

$$PH2=Q2/(Q2+Q3)$$

The subject of PD and electrical treeing is vast and it is not the intention of this paper to deal indepth with all aspects of the phenomenon. In the context of this paper, it is fitting to mention that PD influences electrical treeing and that there are certain parameters related to the PD which indicate whether insulation is in an advanced stage of deterioration. Accordingly, successive PD pulses [20] cannot be considered to be independent events without correlation with preceding PD. Previous PD history determines pretty well the sort and amount of space charge existing in the insulation. The external applied field is by no means the only factor affecting tree propagation.



The effect of preceding and successive PD pulses is particularly strong in the early stages of treeing. Further support to the claims of Hoof and Patsch, suggesting a different average feature of how a large PD pulse occurs at a certain time after one pulse occurrence is available [21]. In this paper, however, a strong relation between the two phenomena is emphasised. It is good to know that the emphasis given [22-24] to the space charge phenomena has been suggested by other researchers in the past [second category charges].

Having said this, one might argue that PD is preceded by space charge injection from the point electrode. Such a view is based on Zeller's seminal paper [25]. It is reported that electrical treeing is caused from injection of space charges. In fact, pre-breakdown currents penetrate at least twice as far in the dielectric compared to the homogeneous case. The current density reaches the NDR regime (Negative Differential Resistance) rendering thus the current distribution unstable and finally decaying into filaments. Zeller's paper makes clear that the cause of treeing is space charges and that PD comes afterwards. His approach is that the dielectric is first damaged by the space charge injection and the PD ensues. Such a view is not necessarily in contrast with other views expressed, but it stresses the notion of charge injection. A more general approach to electrical treeing, however, would probably be that charge injection is followed by the filaments which are in turn filled with gaseous by-products which again are subjected to PD. The latter may lead to the extension of filaments and the further damage of the dielectric.

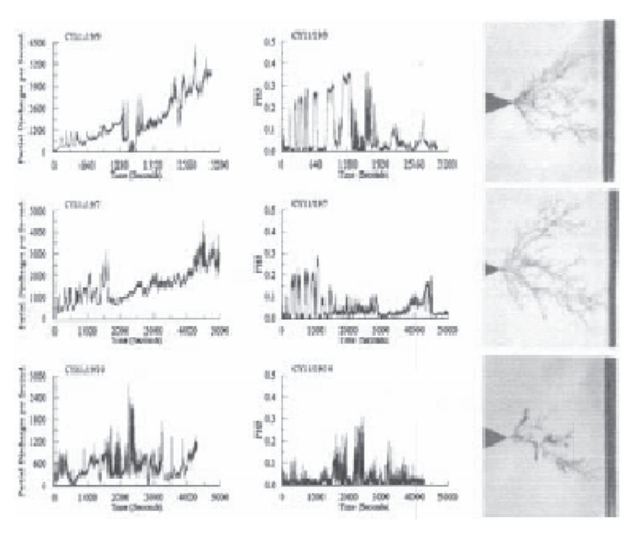


FIG. 5 DISCHARGE ACTIVITY AS A FUNCTION OF THE DENDRITE TYPE (FIRST AND THIRD COLUMN). AT THE SECOND COLUMN THERE IS A PRESENTATION OF THE NORMALISED PHASE DISPLACEMENT PARAMETER PH3 [SEE REF. 19]

3.0 FIELD EXPERIENCE WITH ELECTRICAL TREES

Industrial experience with electrical trees goes back to the early seventies, when there were a number of publications on polyethylene cables of 15 kV and 22 kV. Observations made by the authors [26-28] refer to trees in cables. These were, however, a mixture of both water and electrical trees. Various facts though, like the origin of trees from contaminants and voids, the growth of trees in the direction of the electric field were noted and are in accordance with those observed in electrical tree studies of laboratory samples. Interestingly, electrical treeing presents one of the weak aspects of extruded cables, which in [29] are referred to as "lack of resistance" from polyolefin. In the same paper [29], it was noted that for cables in excess of 400 kV, lapped PE/gas or polypropylene/paper laminate/oil insulation would be preferable to extruded insulation.

Interesting findings were reported in [30], the authors working on specimens of XLPE cable insulation, noticed that PD inside trees of magnitudes smaller than 200 pC can produce shorter times to breakdown than the PD of some thousands of pC because they penetrate the insulation more rapidly. Such findings, surprising at first, were contrary to the accepted belief that the lifetime of a specimen is inversely proportional to the PD magnitude.

LDPE and XLPE are extensively used for the insulation of cables up to 110 kV. However, minute cavities, in the range of 1–30 μm, are most of the time unavoidable during manufacturing and they may be the sources of PD and eventually lead to treeing [31]. Treeing from cavities was successfully simulated by Vardakis and Danikas [23, 32] and it was also observed in laboratory experiments [12], where treeing and breakdown emanate from a cavity in epoxy resin. Further evidence on treeing from cavities was offered elsewhere, where a mechanism is speculated, namely, that with the breakdown of a cavity, the surfaces of the insulation provide instantaneous cathode and anode, and therefore, with the respective bombardment of the cathode and the anode [33] by positive ions and electrons, a breakage of chemical bonds ensues. Channels and pits will be formed, which will eventually elongate. Gaseous by-products will also render the whole process easier, with the deterioration mechanism manifesting itself as slow erosion and with the result of a consequent reduction of the breakdown strength.

Ageing tests done on full size spacers of GIS showed that even small PD (in the range of ~ 1 pC) may cause deterioration and treeing [34]. Small degraded areas around a needle electrode are in the range of 10 μm in diameter. Small PD creates small pits on the surface of voids which in turn develop into tree-like deterioration. Such an approach brings us to the work performed by Bruning and colleagues [35], where it was mentioned that very small PD have indeed a deleterious effect on insulating materials.

Aspects of the question of small PD, their magnitude still capable of producing electrical treeing, the damage they cause, their relation to the capabilities of PD detecting equipment, was briefly mentioned in [36]. The conclusions are, however, that a PD detector cannot essentially detect all possible forms of PD phenomena since there is a variety of such PD types and, due to the complexity of the test objects, the time interval between two consecutive PD may differ. We understand that the whole problem of charge injection, microvoids, PD phenomena, PD detection and treeing, are all parts of material degradation and each one mentioned is very much related to the other. Having said that, it may be argued that PD alone cannot assure the quality of a solid dielectric cable, especially if the defects present in the insulation structure are marginal [37].

In the previously mentioned papers [34] it is also reported that charge injection has a crucial effect on tree development. The repetition of electron injection at the negative polarity and trapped electrons extracted towards the needle having positive polarity for AC voltage application is a phenomenon repeated in each cycle and has as a consequence the development of a small degraded area at first at the tip of the needle. This degraded area will eventually grow and become a void (or voids) which will lead to tree-like paths. One can also consider that electrical trees are the result of the link between small voids and/or cavities [11]. The above researchers have considered that in the interior of the solid insulating material there is a dense mesh of very minute channels. The dimensions of these channels can change if the electrons due to the electrical field move towards the walls of the channel.The continuous electron bombardment affects the channels dimensions forming channels with bigger dimensions or craters inside the material. The inner-atomic and the inter-atomic bonds of the solid insulating material break when electrons gain energy at the level of 10 eV.

4.0 ELECTRICAL TREES AND SPACE CHARGES

Space charges contribute significantly to the propagation of trees. Work [38] was among the first to consider that charges inside the electrical trees are responsible for tubule extension or even for radial extension. Someone may think that those charges belong to the first category (PD charges). A more careful study of the paper shows that the radial component of the electrical field near the surface of the tubule is referred to at space charges (second category charges).

During the application of AC voltage, negative homocharge around the needle tip (in a needle-plane arrangement) as well as the negative mobile charge carriers tend to move away as far as possible from the needle tip during the negative half cycle. When the voltage is at the positive half cycle, the field at the needle tip becomes very high since the negative space charge produced before may enhance the field toward the needle tip. There are two consequences of this: (a) it causes hole injection from the needle tip and, (b) it enhances the various recombination processes.

Such recombination processes release energy which eventually will break the chemical bonds of the polymer [39]. Such theories take into account the influence of space charges and they are reminiscent of a previous paper [9]. Space charges are injected from semicon tips (with a radius r of ~ 2 μm) and they produce Electroluminescence (EL), a phenomenon prior to PD [40]. EL is related to a degraded region next to a protrusion and it indicates that the polymer started degrading in that particular region. The degraded region is small and the whole phenomenon is due to charge injection. EL occurs prior to electrical treeing and prior to PD. It gives a good hint as to whether a particular region of polymer is degraded so that certain measures against degradation can be taken. EL inception *voltage* is certainly lower than PD inception and EL, as a phenomenon, can determine the effect of space charge during charge injection under AC, DC and impulse voltage [40]. This is again another indication that charge injection, EL, PD, treeing – are all inexorably linked together.

Moreover, light is also detected during the electrical tree propagation [17]. A photo-multiplier is used for better result categories namely (i) those which take place in the cavity and (ii) those taking place in the trees. The first category of discharges happen in a pre-propagation stage and the second happen during the propagation stage. The detected light has as source the regions where branches are created. During the formation of a bush-branch tree, photons are produced from the whole body of the tree. When branches are formed, deriving from the bush formation, the light is detected at the branches at the circumference of the bush-like tree.

In addition to this, there is discrimination between conducting and non-conducting channels [41]. The criterion for these two categories is the value of the constant RC of the channel. Conducting channels are considered as channels with small RC constant as compared to the period of the applied AC voltage.

The importance of space charges was emphasised [42], with double needle tests on high purity low density PE samples. It was suggested that there is a possible link between the concentration of space charges in the crystalline-amorphous interfacial regions and the subsequent formation and propagation of tree channels.

Generally speaking, electrons from the conducting needle electrode are injected into the solid dielectric from regions of high electric field (usually the tip of the needle). The work function of electrons from the electrode into the solid dielectric is in the order of eV, which is much lower than the work function of the electron from a metallic surface. This happens because at the interface between electrode and dielectric, there is the possibility of the existence of asperities and/or small cavities. The tunnelling effect plays a dominant role during this process.

The mean free path of the electrons during their injection inside the solid dielectric is very small. They continuously lose energy due to their collisions with the positive ions of the lattice. After these collisions, they become thermal electrons and finally they are trapped inside the lattice in the form of space charges.

These electrons inside the solid dielectric have two possible sources. The first is the injecting electrode itself. Even with the tunnelling effect or with the appropriate energy level, electrons belonging to the metallic electrode environment may appear inside the solid insulating material.

The second possible source is the electrons that may be produced from the bond breaking of the solid insulating material. Electron energies at the level of 3-5 eV, are sufficient enough to break bonds between C-C or/and C-H. The breaking of such bonds causes new energy release which in turn causes local melting process. A small air cavity can be formed with the possibility of propagating towards various directions with better paths those with smaller resistance (or smaller density). These channels can join with other tubes which can exist inside the solid dielectric due to manufacture procedures. The appropriate value of power density for local breaking of the solid insulating material is 10^{-5} Watt/mm^3.

The existence of these electrons inside the solid dielectric can cause an important value for electron conductivity (surface conductivity is easier to be measured), but cannot cause avalanches due to the restricted mean free path. The temperature increase generally shortens the mean free path. Avalanches may exist inside the conducting channels of the electrical dendrites which in turn exist inside the solid insulating material. The aforementioned does not imply that avalanches exist inside the solid insulating material [7].

The dynamic character of the phenomenon of electrical treeing is also shown during the application of AC voltage to the solid insulating material. During the negative voltage, electrons (and/or negative ions) cross the voltage barrier between electrode and solid insulating material and move away from the negative electrode (or reach the positive electrode). This movement of the negative ions is equivalent with the existence of a negative electronic cloud in front of the tip of the needle. During the polarity reversal, the resulting electrical field is extremely high and has two consequences.

Due to the high field, hole injection occurs from the positive electrode into the solid insulating material. Recombination between holes-electrons, electrons-positive charge, holes-negative charge takes place. During the recombination, energy release creates electrical channels of smaller density as described above. Of course, recombination effects take place continuously inside the solid dielectric. Electrons, negative ions, holes and positive ions may exist in small numbers inside the solid insulating material due to various reasons. One of them is the trapping and de-trapping phenomenon which is present in the whole dielectric volume.

The difference between the positive and negative breakdown strength is also reported by Mason [1] which is related to different ways that electrons accept energy (equivalently lose energy). Moreover, using impulse voltages, studies on space charge distributions in electrical treeing under positive and negative pulses, are correlated to the positive and negative impulse avalanches inside the conductive channels [43].

The space charge measurements are important tools for the electrical treeing studies, and are divided into two categories.

- The post-stressing techniques
- The measurements during the stress application.

The space charge measurement usually is independent from the electrical trees. The close relation between electrical trees and space charges shows the importance of such measurements. The first category measurements are mostly used but the second category measurements give more clear results due to the dynamic character of the electrical treeing phenomenon. The three main methods of the first category are:

- PWPM – Pressure Wave Propagation Method
- PEA – Pulse Electro Acoustic Method (Normally PEAM)
- LIPP – Laser Induced Pressure Pulse

The results of the aforementioned measurements are graphical representations of space charge densities (C/m^3) as it is shown in Figs. 6, 7 and current densities (A/m^2). These two physical quantities are usually measured as a function of time, space and temperature.

The above space charge distributions, may alter when various additives are inserted inside the dielectric volume.

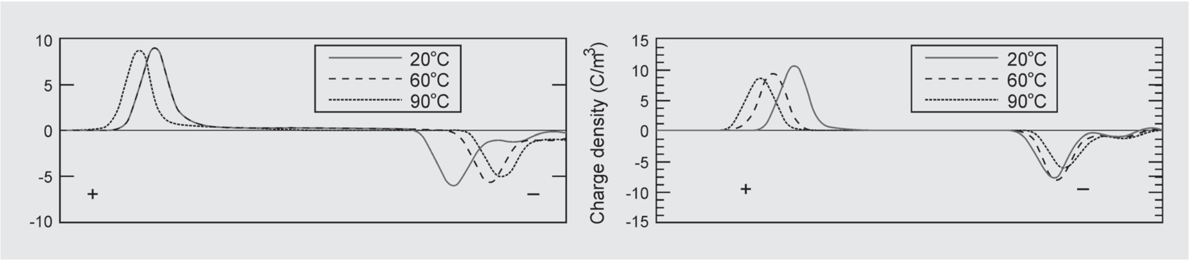


FIG. 6 MEASUREMENT OF SPACE CHARGE DENSITY (C/M^3) AS A FUNCTION OF THE POSITION AND TEMPERATURE, THE CHARGE DISTRIBUTIONS APPEAR AS TWO CHARACTERISTIC PEAKS. THE FIRST PEAK APPEARS NEAR THE ANODE AND THE SECOND PEAK NEAR THE CATHODE [SEE REF. 56]

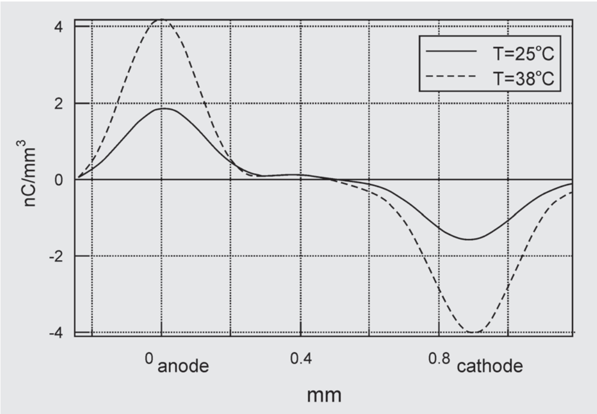


FIG. 7 MEASUREMENT OF SPACE CHARGE DENSITY (C/M^3) AS A FUNCTION OF THE POSITION AND TEMPERATURE. IT IS CLEARLY SHOWN THAT THE TEMPERATURE INCREASE RESULTS IN HIGHER CHARGE DENSITIES [SEE REF. 57]

Trees can arise from the application of impulse voltages (in fact chopped lightning impulse voltages [31]) and/or AC voltages. The role of space charges is emphasised, as it might weaken the field near the point electrode. Negative needle implies that electrons are injected into the material by external field emission and held there in traps by the formation of negative space charges.With positive DC to needle, charge electrons can be liberated from the valence band or from the traps by internal field emission and thus leave behind a positive space charge. The importance of the volume of the material near the point electrode is also emphasised in [44]. It is reported that treeing is related to the overcoming of local field strength through a process of electron multiplication and the deterioration of the energy balance between the electrons and the molecules of the material. Local instabilities as well as local field intensifications play a dominant role [22-24].

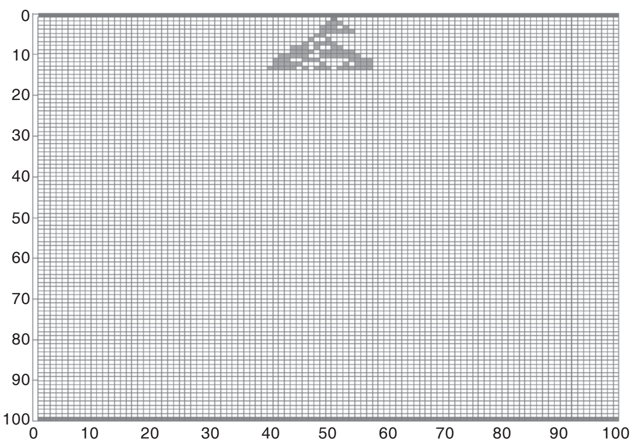


FIG. 8 SIMULATION OF ELECTRICAL TREE PROPAGATION IN POLYETHYLENE BETWEEN PLANE-PLANE ELECTRODE ARRANGEMENT. 250 kV IS APPLIED AT THE UPPER ELECTRODE AND ρ=+80 C/M^3 IS CONSIDERED AS SPACE CHARGE DENSITY [SEE REF. 24].

In Figs. 8, 9 and 10, simulations of the electrical tree propagation are shown in the interior of solid insulating material which is considered to be polyethylene. 250 kV is applied at the upper plane electrode and 0 kV at the opposite plane electrode. The simulation has the space charge density as parameter. As it is evident, the various values for the space charge density strongly modify the electrical field which in turn influences the form of the electrical tree patterns. In Fig. 8, a space charge density of similar sign (homo-charges) is considered, in Fig. 9 no space charge is considered and finally in Fig. 10 a space charge density of the opposite sign (compared with the polarity of the injected upper electrode) is considered.

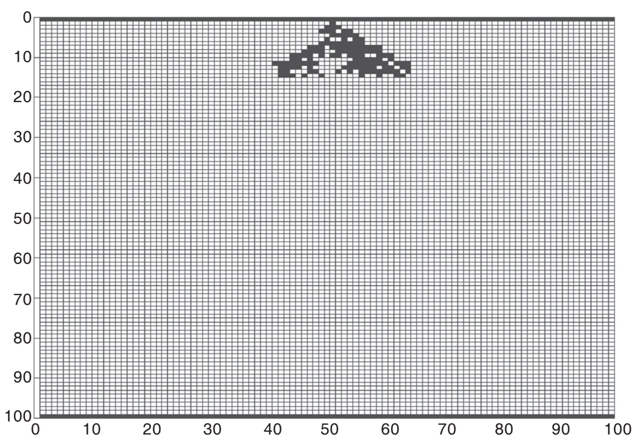


FIG. 9. SIMULATION OF ELECTRICAL TREE PROPAGATION IN POLYETHYLENE BETWEEN PLANE-PLANE ELECTRODE ARRANGEMENTS. 250 kV IS APPLIED AT THE UPPER ELECTRODE AND NO SPACE CHARGE IS CONSIDERED IN THE INTERIOR OF THE INSULATING MATERIAL [SEE REF. 58]

As it is clear the electrical trees of Figs. 8 and 9 belong to the branched category, whereas the electrical tree simulated in Fig. 10 belongs to the bush category.

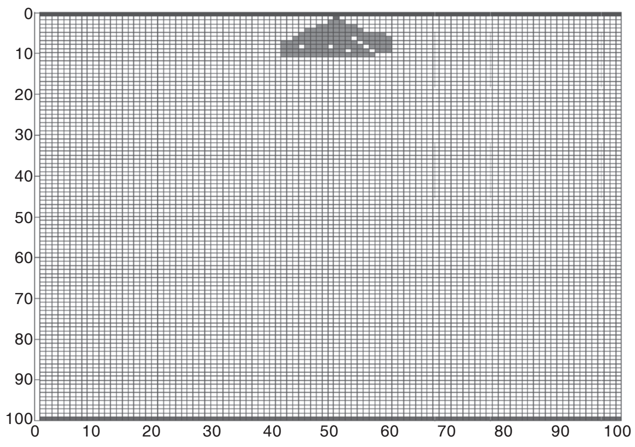


FIG. 10 SIMULATION OF ELECTRICAL TREE PROPAGATION IN POLYETHYLENE BETWEEN PLANE-PLANE ELECTRODE ARRANGEMENTS. 250 kV IS APPLIED AT THE UPPER ELECTRODE AND $\rho=-80$ C/M^3 IS CONSIDERED AS SPACE CHARGE DENSITY. THE DENDRITE CLEARLY BELONGS TO THE BUSH-TYPE [SEE REF. 24]

5.0 FACTORS AFFECTING THE PROPAGATION AND INCEPTION OF ELECTRICAL TREES

Mechanical stressing can affect tree inception. A repeated Maxwell stresses that $\varepsilon E^2/2$, (with ε being the relative permittivity of the insulation and E the applied electric stress) is induced around the needle point by the applied AC voltage. Subsequently, a compression force is applied to the polymer. A mechanical stress perpendicular to the direction of the electric field appears causing crazing when a critical value is reached.

Crazing develops to a void-crack and gas discharges expand the tree channel even further [45]. Repeated mechanical stresses, as factors affecting electrical trees, were pointed out also in [46]. The type of material used is of great importance. It was shown in [2, 22, 23, 24, 32, 47, and 58] that even slight localised permittivity variations may be responsible for tree propagation.

So, we are led to believe that both external factors and material properties (ε, micro-defects, etc.) may influence tree propagation. Usually, electrical trees are the interplay between external factors and material properties. External factors may determine to a certain extent the conditions in which insulation has to function (voltage waveform, type of voltage, mechanical stress), whereas material properties determine the way the material may respond to these external stresses. PD, intimately related to treeing, do also to a certain degree depend on material properties. The tree propagation length depends on the waveform of the applied voltage [48]. In this work [51], it is remarkable to know that the tree length depends on the number of voltage applications, as shown in Fig. 11.

In [49] it was reported that the rate of rise of voltage has a certain influence on tree propagation, namely, that rising at a constant rate, the maximum length of a tree channel is related to the maximum charge pulses which accompany the tree growth. The total length of the tree channel is also related to the power of discharges. Their conclusions were not different from those of [50] where the tree pattern is reported to depend on the magnitude and duration of the applied voltage. Evidence was also presented in the said paper that temporal changes of tree patterns from branch-like to bush-like or fan-like in void-less specimens of PMMA are associated with the occurrence of localised cracks.

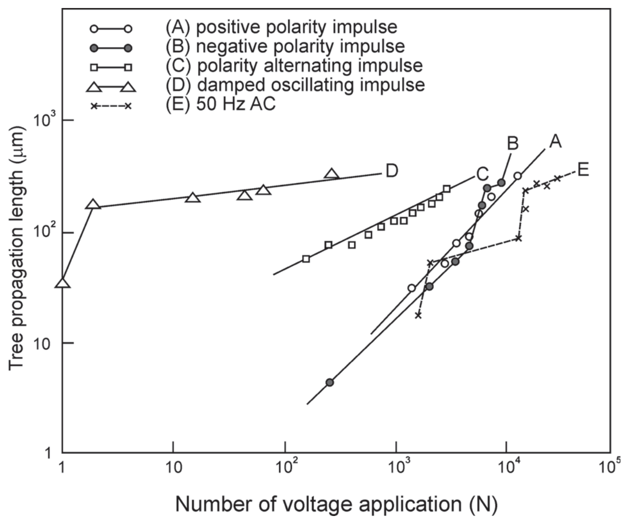


FIG. 11 THE EFFECT OF WAVEFORMS ON TREE PROPAGATION CHARACTERISTICS [SEE REF. 51].

Regarding laboratory experiments, moulded needles are preferred over inserted needles. The former forbids the formation of voids very near to the needle electrode, which might give spurious results. The increasing voltage level reduces the initiation time and increases the growth rate and the magnitude of the PD involved. Tree growth may not necessarily agree with the increase of PD activity and be restrained. The tree grows as filaments at first, then as bush-like and in the last phase some filaments (branches) come closer to the ground electrode [51]. Such a phenomenon is not in contradiction with the PD variation reported in [17].

A factor affecting the origin of treeing is the way the cable conductor shield is constructed. Tests on miniature polyethylene and XLPE cables with tape type conductor shield and with extruded conductor shield showed that the former are extremely vulnerable to the formation of trees from the conductor shield whereas the latter exhibit little tendency to develop trees from the same point [52].

The extrusion process – referred to the insulation of a cable – is important (to a great extent) for the avoidance of gas inclusions and/or of imperfect interfaces. This process, however, cannot completely avoid imperfect interfaces, gas cavities, foreign particles, foreign fibers, and asperities on the surface of the conductor. An interesting datum is that the intensification of the field is in phase with the injection of the space charge and also with the maximum of PD activity, a point which brings us to the conclusion that PD and space charge are intimately linked and that the aforementioned quantities are also related to the treeing process [53]. Another factor coming into play is the surface resistivity of the inner void walls. It has been reported that as the material deteriorates, the surface resistivity of the inner wall surfaces is reduced and thus the electric field will increase at the boundary of this area, which will eventually lead to further deterioration and probably to an extension of the area [54]. We see no reason why such an extension of the damaged area should not go deeper into the material, with the consequence of provoking trees.

Ionisation and excitation in small cavities can also be damaging in the long run for insulation. Although such phenomena are due to a small number of charged and excited particles (in cavities of about 5 ì m in diameter) – not to be confused with partial discharges – and their effect is limited (bond scission in a limited scale), in the long run they may be deleterious to the insulation since low degrees of ionisation and excitation will probably result in sufficient accumulated damage of the solid insulation [55].

6.0 CONCLUSIONS

In this review, some aspects of electrical treeing are discussed. Electrical treeing is a complex phenomenon which is influenced by external stresses as well as material properties. It is obvious that space charges and partial discharges are strongly related with electrical tree propagation. These three phenomena are, under certain circumstances, factors indicating, among others, the insulating capability of any insulating system. The detection of at least one of the above factors (or all of them), may be a sign that the insulating system is somehow degraded. Further investigation towards the study of the above mentioned interrelated phenomena is needed.

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