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Fractal Cluster Based Aging Model of Electrical Treeing in Polymeric Insulation

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Abstract: The aim of this study was to develop an aging model based on the concept of generation of micro voids due to thermally-activated, electrically-enhanced breakage of bond structure of the polymeric insulation. Here, we have modeled electrical tree structures as fractal cluster which are formed due to coalescing of micro voids. In this study we have derived the electrical tree growth rate equation and formula for time of electrical tree propagation to failure. We have extended this approach for multifactor aging which can modify the bond breaking and repair energies of insulation under multi-stress conditions, which can eventually affect the electrical tree growth time to failure. We have provided an overview of phenomenological and physical aging models, the mechanism of formation of micro-voids from breaking of bond under combined thermal and electrical stress and the process of fractal clusters (electrical trees) formation due to coalescence of micro-voids.

Key words: Electrical treeing, micro voids, thermally-activated electrically-enhanced bond breaking, multi-stress aging

INTRODUCTION

The issue of the aging of insulation has been a hotly debated in high voltage engineering since its inception. In urban areas cables which are literally 40 to 50 years old still carry power. Similarly, transformers continue to operate well beyond their design life. For polymeric insulation potentially important electrical stress factors which affect electrical aging mechanisms include partial discharge, water treeing, electrical treeing and space charge. Some other factors which have contribution towards aging of insulation include peak value of voltage, wave shape, polarity and frequency. In addition, operation at higher loads and load cycling can change the thermal stress conditions. The presence of odd harmonics particularly, 3rd, 5th and 7th orders significantly influence the resultant wave shape of the power signal (Fabiani and Montanari, 2001). Harmonics voltages may significantly increase the peak and rms values of an electric field within the insulation, increasing dielectric loss. All these effects result in an insulation temperature rise which have effect on life of insulation (Guastavino *et al*., 2003). In addition to electrical aging factors, the material properties like morphology and crystalline structure have a profound effect on life of insulation. A more uniform cystallinity and small spherulites will enhance the resistance to electrical treeing and effectively the aging rate would be slower (Xie *et al*., 2009; Zheng *et al*., 2007).

Deterioration of insulation is an inevitable phenomenon in underground cables leading to insulation failures. The aging is caused by single or synergistic action of several aging factors which include thermal, electrical mechanical and environmental. These aging factors eventually make cable insulation to fail through a number of mechanisms summarized and listed in the Table 1.

The factors listed above can be represented as a function of some time yielding measurable form of stress on the insulation system. Examples of the measurable aging sub factors include temperature, mechanical strain, pressure, morphology, thermal history, radiation and electrical treeing. Activation of aging mechanisms either changes the bulk properties of the insulating materials referred as intrinsic aging or causes degradation known as extrinsic aging.

The researchers working in the field of high voltage insulation have a great concern in predicting the life of insulation at normal operating stresses. This is normally obtained from accelerated aging tests performed at higher than the normal operating stresses. Life prediction at normal operating stresses requires a mathematical model to extrapolate the accelerated aging data to lower stresses. Unfortunately, the life time of apparently identical specimens tested under the same conditions can vary by an order of magnitude from specimen to specimen. This

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Table 1: Summary of aging mechanisms in cables

Aging factors	Aging mechanisms
Thermal	
High temperature	Chemical reaction
Temperature cycling	Thermal expansion Diffusion Insulation melting
Low temperature	Cracking Thermal contraction
Electrical	
Voltage, AC, DC, impulse	Partial discharge Electrical trees Water trees Charge injection Intrinsic breakdown Dielectric losses
Current	Overheating
Mechanical	
Cyclic bending, vibration, fatigue, tensile, compressive and shear stresses	Yielding of material Cracking Rupture
Environmental	
Water, humidity	Electrical tracking
Contamination	Water treeing
Liquids, gases	Corrosion
Dielectric losses	
Radiation	Chemical reaction rate increases

Champions *et al.* (1994)

aspect promoted the research for physical models of insulation aging based on description of the specific degradation mechanism.

In this study, we have developed an aging model based on fractal clusters (i.e., electrical trees are modeled as fractal clusters) formed due to joining of micro-voids as a result of thermally activated electrically enhanced bond breakdown process.

REVIEW ON ELECTRICAL TREEING AND PROPAGATION

Electrical treeing is a prebreakdown phenomenon and is a sort of degradation which progresses through an insulation structure under electrical stress so that when visible, its path resembles the picture of a tree. In solid polymers it has been recognized as the most likely mechanism of electrical insulation failure is due to this treeing process which does not occur promptly but rather appears as a result of an accumulative damage due to various stress factors (Dissado *et al*., 1997; Dissado and Fothergill, 1992). The primary cause of treeing in polymeric insulation is partial discharges under high electric stresses and moisture at lower electric stresses. Electrical treeing slowly propagates into insulation structure and degrades the ability to withstand the electrical stress. When electrical treeing bridges the gap between electrodes, breakdown occurs due to flow of large currents (Zheng *et al*., 2008).

While, the conventional explanations of the electrical treeing process is based on electronic and thermal mechanisms, there has been an accumulation of evidences demonstrating that the mechanical stress and mechanical properties of materials such as its elastic modulus, tensile strength and fracture toughness have a pronounced effect on initiation and propagation of electrical tree structures (Ding and Varlow, 2003a, b; Varlow and Auckland, 1998). However, most models based on partial discharge in the tree channel fail to consider and account for these experimental observations. Zeller and Schneider (1989) proposed that the growth of a PD channel in polymer is only possible if the release of electrostatic energy due to growth exceeds the formation energy of PD channel. Study carried out by Zeller and Schneider (1989) describes that electrical tree growth is an intrinsically mechanical phenomena, but it fails to describe a description of the formation of tree branching structure and tree growth kinetics.

BRIEF DESCRIPTION OF AGING AND LIFE MODELS

Let us consider a solid insulation system subjected to single stress that causes irreversible changes of material properties with time, thus reducing progressively the ability of insulation to endure the stress. This process is called aging and ends when the insulation is no more able to withstand the applied stress. If an insulation is subjected to single stress S (constant in time) and if P is the diagnostic property correlated to aging and it changes monotonically with time t, then a suitable function of P, F(P), can be found that increases with aging time and depends on applied stress, the following relation holds:

$$F(P) = K(S)t \tag{1}$$

where, K(S) is the aging rate constant with time as well as S.

Eventually, a situation is reached when material no more able to withstand the applied stress. This point is named as end point corresponds to a limiting value of P, P_L and the time to its achievement is called time to end point of material or life, L.

So, the life model achieved in explicit form:

$$L = \frac{F(P_L)}{K(S)} \tag{2}$$

If S_1 and S_2 are applied together, aging rate is $K(S_1, S_2)$ then the life model achieved in explicit form is:

$$L = \frac{F(P_L)}{K(S_1,S_2)} \tag{3}$$

The phenomenological life models are derived by processing failure times obtained from accelerated life tests and can not be directly measured as material properties. Life inference at service level stress can be obtained by extrapolating the data at test stress levels.

In this case, two phenomenological expressions have been considered in study i.e., (Simoni, 1983; Montanari and Simoni, 1993):

$$L = C_0 E^{-n} \qquad \text{(Inverse power model)} \qquad (4)$$

$$L = L_0 \exp(-hE) \qquad \text{(Exponential model)} \qquad (5)$$

In several cases, even if the model is conceived in order to describe a specific aging phenomenon, nevertheless the presence of coefficients that can not be derived directly by measuring physical properties makes the model actually phenomenological one. An example of such situation is the electrical life model developed to describe the electrical breakdown due to Partial Discharges (PD) given as under:

$$L = \frac{C_0}{(E - E_t)^n} \qquad (6)$$

This model is analogous to inverse power model with the addition of E_t, the so-called electrical threshold (i.e., an electrical field below which no degradation due to a given mechanism takes place). E_t can be measured, at least in principle, as the electrical field value corresponding to PD inception voltage, where as the coefficients C_0 and n can be determined only by accelerated life tests.

The main shortcoming of phenomenological life models is that the model parameters can be estimated only after life tests, which often last for a very long time (even if aging is accelerated raising stress level with respect to the service conditions). Further, the life time of apparently identical samples tested under the same conditions can vary by an order of magnitude from specimen to specimen. This aspect promoted the research for physical models, based on description of specific degradation mechanisms assumed as predominant with in proper range of applied stresses. Such models are not only represented by mathematical formula and but also characterized by physical parameters that can, at least in principle, be determined by measuring directly physical quantities. Furthermore, these models have legible physical significance to understand aging mechanisms. Examples include, Field emission model developed by taking into account of the damage produced by charge injection and holds for higher electric field values (Cacciari and Montanari, 1992), Thermodynamic model which based on the concept of thermally activated degradation reactions that are responsible for material aging (Mazzanti and Montanari, 2005; Sanche, 1993), Electro-kinetic endurance model based on the formation of micro voids by means of chemical bond-breaking processes induced by voltage and temperature (Cooper *et al.*, 2005), space charge model assumed that space charge injected by electrodes and/or impurities is trapped within the insulation are responsible for electromechanical energy storage that, in turn, lowers the energy barrier, thus favoring degradation (Mazzanti *et al.*, 1999). We will not go into detail of these models and literature referred can be consulted for further understanding. We will focus our attention on developing of aging model based on fractal clusters created by micro-voids generation under thermally activated electrically enhanced bond breakdown mechanism in polymeric insulation.

MODEL DEVELOPMENT BASED ON FRACTAL CLUSTERS APPROACH

Electric field creates transverse mechanical tension: The application of an electric field to metal electrode-dielectric interface causes a mechanical strain (Lewis *et al.*, 1993). Such effect is explained by Lippmann equation which states that change in interfacial tension Δγ generated by the change in potential difference across the interface ΔV is given by:

$$\Delta\gamma = -q\Delta V \qquad (7)$$

This relation can be established in a general way by considering the balance of electrical and mechanical forces across the interface:

$$\Delta\gamma = -\int_0^d \varepsilon E^2 dz \qquad (8)$$

where, E is normal electric field, ε is permittivity at the position z at the interface and d is the width of interface.

Equation 8 shows that electric field normal to the interface creates a change in transverse mechanical tension which acts to expand the interface against the cohesive forces. At the same time it is possible to express the total transverse tensional change Δγ in term of plane stress, Δσ(z), where:

$$\Delta\gamma = \int_0^d \Delta\sigma(z) dz \qquad (9)$$

$$\Delta\sigma(z) = -\varepsilon(z) E^2(z) \qquad (10)$$

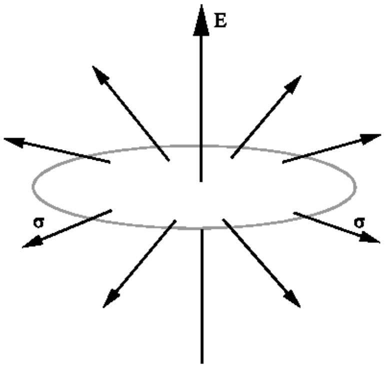

Fig. 1: The tensile stress σ(z) is orthogonal to E(z)

This result indicates that dielectric is everywhere subjected to a mechanical stress εE^2, tending to expand it against the cohesive forces in the directions orthogonal to the field E at every point as shown in the Fig. 1. The stress depends quadratically on E and so it would become particularly important in a situation where the field in the dielectric is enhanced by space charge. In an alternating field $E = E_0 \mathrm{Sin} wt$, the stress will give rise to alternating strains of frequency 2w.

Aging and tree development process: When the value of E is large, the generation of mechanical stress εE^2, could have important consequences on aging and breakdown of dielectric. Under this two aspects are more important, the field enhanced propagation of any existing cracks and generation of new cracks in the dielectric.

The stress εE^2 is a tensile one and if the imperfections in the form of submicroscopic cracks exist in the practical dielectric then energy associated with this stress might be sufficient to extend them. This situation is a fundamental one arising in the study of fracture mechanics of solids and leads to well known Griffith Criterion for crack propagation. In the case, of an elastic solid, the criteria is obtained by equating the amount of stored energy available in the neighborhood of an existing crack as a result of an applied mechanical stress to that required to increase the surface area of propagating crack. Propagation occurs by progressive breaking of the molecular bonds of material across the fracture path crack. The modification of stress field and consequent release of stored energy in the neighborhood of the propagating crack tip will derive it forward.

The initiation of crack growth leads to the development of a tree. Intrinsic cracks are likely to be present at the dielectric interface and propagation are likely to easier from those because of the lowered interfacial energies and enhanced surface fields.

A major factor likely to influence crack development is the existence of mechanical stress together with electrically induced stress. Growth would be inhibited by positive compressive pressure and enhanced by negative tensile one. Another factor influencing the tree growth will be the probable presence of space charge which can enhance local electrical field. If an applied voltage is alternating one, the tree growth would be intermittent, occurring only towards the peak of ac fields.

Although, crack propagation is essentially mechanical in nature but there are likely to be electrical processes associated with it which will assist propagation. A developing crack generates a momentarily low pressure path along the fracture path and in the field direction. Under these conditions electrical discharges can be expected. Electron avalanches are generated by collision ionization from adventitious initiating electrons occurrence. Since, a succession of breaking bonds must accompany crack propagation, generation of active chemical species, electrons, ions and radiations could be expected.

When electrical discharges occur, so that the crack path at least becomes momentarily conductive with a local field enhancement where field lines converge on the crack tips can be expected. This will encourage not only the advancement of primary cracks but also the tree like growth of secondary cracks along the field lines radiating out from its tips.

Bond breaking produces micro voids: For crack development through dielectric by a Griffith process it is necessary to establish a population initiating micro cracks of suitable size. We now consider how this population of micro cracks might arise in an electrically stressed polymeric insulation and this will lead to a development of fractal cluster based approach model of aging.

The population of initiating cracks will be increased by thermally-activated electrically-enhanced breakage of bond structure of the dielectric. The bonds involve in this may be a weak van der waal inter-molecular bonds or stronger intra-molecular chemical bonds. In either case, the breaking process will be a statistical one requiring the chance concentration of thermal energy at a bond site in order to rupture it. The rate of breaking of bonds through thermally activated process is given by Lewis *et al*. (1996):

$$K_b = w \exp(-U_b/kT) \tag{11}$$

where, w = kT/h is so-called attempt frequency which is about 6×10^{12} sec^{-1}, U_b is the activation energy require to break a bond, k is Boltzmann constant, h is a Plancks constant.

In the presence of field enhanced tensile stress εE^2, the energy to break the bond will be reduced and bond breaking rate will become:

$$K_b(E) = w\exp\left(-(U_b - \gamma_b \varepsilon E^2)/kT\right) \tag{12}$$

The factor γ_b takes account of any local enhancement of the field E but more importantly represents the effective volume change, i.e., strain, at the bond site caused by tensile stress εE^2.

There is always a finite chance that by thermal activation, a broken bond will be repaired and structure regains its original form. For this to occur, an activation energy U_r again modified by the stress εE^2 will be required. The rate of bond repair rate can be expressed as:

$$K_r(E) = w\exp\left(-(U_r + \gamma_r \varepsilon E^2)/kT\right) \tag{13}$$

where, γ_r is equivalent to γ_b

The differential equation determining the concentration of broken bonds can be written as:

$$\frac{dn}{dt} = K_b(N-n) - K_r n \tag{14}$$

where, N is the initial concentration of bonds and n is the concentration of broken bonds

Fractal cluster approach of electrical trees: Electrical trees are usually initiated at a point of high and divergent electrical stress. Due to divergence of local electrical field and stress and the non linear properties of local material behavior, the process of trees becomes complex. As the tree channel front moves, the intense electric field near the front moves the electrons and ions irreversibly in the region beyond the tree channel tips, where the electromechanical, thermal and chemical effects takes place and this area is referred as damaged process zone (Ding and Varlow, 2003a, b). During the tree propagation process, the damaged process zone is visualized to evolve in a self similar fashion and evolves through the transformation of dielectric from some initial morphology to a damaged morphology. In this way, the characteristics of the damaged zone is intrinsically related to microstructure of the dielectric. The damage in the damaged zone may manifest itself as an ensemble of micro defects in the form of voids, cracks or other features. The formation and growth of micro voids in the zone ahead of tree channel tips on submicroscopic level can be explained as follows: the polymer degradation process starts from the chain scission and free radical formation due to charge carrier injection, electromechanical, thermal and chemical effects. Thus, causing few weak regions to develop. Because the electrical stresses in the polymers are highest in the damaged process zone ahead of tree tips, each site of broken chain may lead to successive breakage of its neighbors by the local electrical field concentration according to a thermally activated bond breakdown mechanism (Ding and Varlow, 2005).

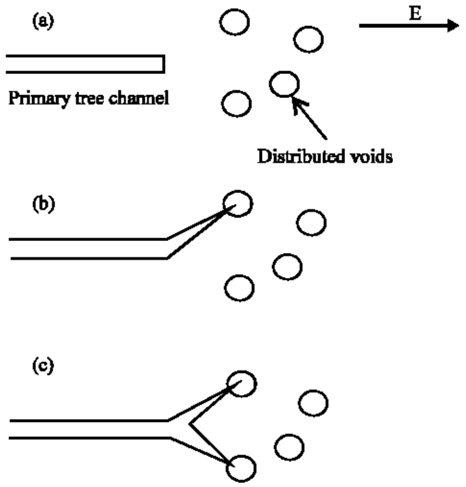

Fig. 2: A propagating electrical tree channel, (a) microvoids initiate in the DPZ ahead of tree tip when local field intensity exceeds some critical level (b) the primary tree channel deviates from its original straight path to join to a neighboring micro-void and (c) another neighboring micro-void is absorbed by the main tree channel to form branching tree channels

Accumulation of bond breakages originating from one site during a period of voltage application can be considered as void. This is stage of submicroscopic void formation. Then, in these submicroscopic voids the local electrical field intensity increases therefore, causing more and successive bond breaking which is the stage of submicroscopic void growth. Eventually, a number of these submicroscopic voids coalesce into macroscopic tree branches as shown in Fig. 2. The characteristics of micro voids density and its distribution in the damaged zone depend upon material, specimen geometry and loading conditions. The interval between two consecutive increments of tree propagation depends also on the random distribution of micro voids in the damaged zone.

With this approach we may consider the tree propagation to be a random process and tree structures can be modeled as fractal clusters that consists of growing micro voids. It is also noted here that the term fractal clusters was used by Mandelbrot (1977) to describe the geometry of objects that too irregular to be modeled by simple Euclidean geometry. According to Mandelbrot explanation, a fractal is a shape made of parts similar to the whole in same way. The concept of fractal has been applied to microstructure of materials by describing various phenomena including fractal behavior of dielectric aging (Barclay *et al.*, 1990).

Fractal clusters can be represented by the relationship between L, the linear size of the cluster and D, the total number of branch elements from which the cluster has been formed. Their relationship is a power law with non-integer exponent d_f:

$$D = \left(\frac{L}{L_b}\right)^{d_f} \qquad (15)$$

where, d_f is called the fractal dimensions, L_b is therefore the average increment in tree length due to joining of growing micro voids.

Since, the tree structure here modeled as a fractal clusters that consist of growing micro voids, the micro voids growth frequency determined from the Eq. 14 in term of successive bond breakdown mechanism, will then control the rate of tree structure growth which is dD/dt, i.e., the rate of treeing damage.

If m be the average of number broken bonds, which is needed to form a void and M_v be the number of growing micro voids necessary to allow a branch of length L_b, then we can calculate the rate of formation of new branches from the micro voids formation and growth as:

$$\frac{dD}{dt} = \frac{1}{mM_v}[K_b(N-n) - K_r n] \qquad (16)$$

The rate of over all treeing damage can thus be generally determined as:

$$\frac{dD}{dt} = \frac{w}{mM_v}\begin{bmatrix}(N-n)\exp\left[-\left(U_b - \gamma_b \varepsilon E^2\right)/kT\right] - n\exp \\ \left[-\left(U_r + \gamma_r \varepsilon E^2\right)/kT\right]\end{bmatrix} \qquad (17)$$

Equation 17 represents the electrical treeing damage evolution law which has been derived on the basis of bond breakdown rate and subsequent growth of micro voids in a dielectric. It is clearly seen that electrical treeing damage evolution law depends not only on the specific physical mechanism of formation and growth rate, but also on material microstructure characteristics and loading condition.

Substituting $D = \left(\frac{L}{L_b}\right)^{d_f}$ in Eq. 17 we can obtain electrical tree growth rate equation as:

$$\frac{dL}{dt} = \frac{L_b{}^{d_f} w}{md_f M_v}\begin{bmatrix}(N-n)\exp\left[-\left(U_b - \gamma_b \varepsilon E^2\right)/kT\right] - n\exp \\ \left[-\left(U_r + \gamma_r \varepsilon E^2\right)/kT\right]\end{bmatrix}(L)^{(1-d_f)} \qquad (18)$$

By integrating the Eq. 18:

$$L = \left(\frac{w}{mM_v}\right)^{1/d_f} L_b\begin{bmatrix}(N-n)t\exp\left[-\left(U_b - \gamma_b \varepsilon E^2\right)/kT\right] - nt\exp \\ \left[-\left(U_r + \gamma_r \varepsilon E^2\right)/kT\right]\end{bmatrix}^{1/d_f} \qquad (19)$$

If we assume initial tree length L = 0 and failure occurs when the tree length has approached a critical length, i.e., L_f, then by integrating the above equation from initial tree length to a final tree length we get the time of tree growth to failure t_g as:

$$t_g = \frac{mM_v}{w}\left(\frac{L_f}{L_b}\right)^{d_f}\begin{bmatrix}(N-n)\exp\left[-\left(U_b - \gamma_b \varepsilon E^2\right)/kT\right] - n\exp \\ \left[-\left(U_r + \gamma_r \varepsilon E^2\right)/kT\right]\end{bmatrix}^{-1} \qquad (20)$$

This is a fundamental relationship which shows the dependence of life time with electric field strength, the temperature and the fractal dimension of tree structure in one equation. If we neglect contribution of bond repair rate being small compared to the bond breaking rate at higher electrical field conditions then time of tree growth to failure reduced to:

$$t_g = \frac{mM_v}{w(N-n)}\left(\frac{L_f}{L_b}\right)^{d_f}\left[\exp\left[-\left(-U_b + \gamma_b \varepsilon E^2\right)/kT\right]\right] \qquad (21)$$

It is clear that the life time will decrease exponentially as E increases; longer the fractal dimension of tree longer is the insulation life time. The insulation life time is shorter for higher temperature.

MULTI-STRESS FACTORS AGING

As we have shown that the bond breaking and repair energies can be modified by an electric field. Equally the energies could be modified by chemical means which would modify the bonds involved and also by temperature. Thus we can write a total combined bond breaking rate under chemical, mechanical and electrical stress as follows:

$$K_b{}^t = w\exp\left(-(U_b \pm U_c \pm \gamma_{bm}\sigma_m - \gamma_{be}\varepsilon E^2)/kT\right) \qquad (22)$$

where, $\pm U_c$ represents the chemical modification of bond energy, γ_{bm} and γ_{be} are factors for mechanical and electrical modification of bond energy.

A similar expression can be written for combined bond repair rate as:

$$K_r{}^t = w\exp\left(-(U_r \pm U_c \pm \gamma_{rm}\sigma_m + \gamma_{re}\varepsilon E^2)/kT\right) \qquad (23)$$

With the Eq. 22 and 23, we can determine the rate of accumulation of broken bonds under multi-stress conditions and we can further develop the relationship for rate of growth of micro voids and applying the concept of fractal clusters we can obtain the formula for time of tree growth to failure.

$$t_g = \frac{mM_v}{w}\left(\frac{L_f}{L_b}\right)^{d_f}\begin{bmatrix}(N-n)\exp\left[-\left(U_b \pm U_c \pm \gamma_{bm}\sigma_m - \gamma_{be}\varepsilon E^2\right)/kT\right] - n\exp \\ \left[-\left(U_r \pm U_c \pm \gamma_{rm}\sigma_m + \gamma_{re}\varepsilon E^2\right)/kT\right]\end{bmatrix}^{-1} \qquad (24)$$

If we neglect the effect of bond repair rate then the relation reduces to:

$$t_g = \frac{w}{mM_v(N-n)}\left(\frac{L_f}{L_b}\right)^{d_f}\left[\exp\left[-\left(-U_b \pm U_c \pm \gamma_{bm}\sigma_m + \gamma_{be}\varepsilon E^2\right)/kT\right]\right] \qquad (25)$$

CONCLUSION

In the first part of this study, we have developed electric treeing growth model based on the concepts of thermally-activated electrically-enhanced bond breakdown mechanism and fractal nature of electrical trees in a solid polymeric insulation. The relationship represents a tree growth law and a life time formula of tree growth to failure and contains a number of features which distinguish it from other models. The model provides a link between micro structural properties of materials and electrical treeing morphology. The model combines both microscopic and macroscopic approaches to describe the local damage features around the tree tip. The model can also be extended to multi-stress factor aging by redefining the bond breakdown rate and bond repair rate. The life time formula of tree growth to failure relates the local electrical stress, the temperature, physical properties of the dielectric, the structure of the electrical tree and electrical tree propagation characteristics. The new model predicts that the total time to tree growth to failure is longer for larger fractal dimension of an electrical tree. The life time decrease exponentially as electrical stress increase. The insulation life time is shorter for higher temperature. In the second part, we are working on experimental verification of this model.

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