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Influence of Silicon Carbide Composite Barrier on Electrical Tree Growth in Cross Linked Polyethylene Insulation

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Abstract: The aim of research is to study the interaction between electrical tree and nonlinear barrier. The propagation of electrical tree in solid insulation is of great particular concern for power engineering industry as it is regarded as most significant mechanism for dielectric breakdown in high voltage equipment. Composite material with barriers and surrounding matrix polymers are used to extend the breakdown time of the insulation. The major influence of barriers on propagation of electrical trees is investigated in this study with experiments and software simulation. The very low conductivities of modern insulating material do not permit the dissipation of accumulated space charge and charge at the extremities of the propagating electrical tree channel. High field non-linear conductivity characteristics of SiC were employed at the barrier to influence the electrical tree growth as they impinge upon on the barrier. The electrical tree growth was greatly reduced and time to breakdown extended. The tree propagation characteristics were studied by needle plane electrode geometry with five different concentration of SiC at the barrier (5, 10, 20, 40 and 60% by weight). The results show that propagating electrical tree channels did not penetrate the barrier when SiC has high field non-linear conductivity characteristics i.e., percolation threshold >35% SiC. As a result of this phenomenon, the tree growth and barrier penetration is inhibited, leading to extended lifetime of insulation.

Key words: Electrical treeing, nonlinear composite barrier, XLPE insulation breakdown

INTRODUCTION

XLPE has been used as an electrical insulating material in underground distribution and transmission cables for almost forty years because of its excellent dielectric strength, low dielectric permitivity and good dimensional stability and thermomechanical behavior. The life expectancy of high voltage cable is adversely affected by electrical treeing a pre breakdown phenomenon, which account for premature failure of cables in service even at operating voltages.

Consider a simple geometry consisting of 0.3 mm high, 5 μm tip radius of curvature, 30° cone angle, a needle shaped asperity on conducting plane. This would be a reasonable model for cable conductor protruding into the dielectric. Assuming no space charge, the field at the tip of the defect for pin-plane electrode is approximately calculated by Ding (2005):

$$E = \frac{2V}{r\ln(1+4R/r)} \tag{1}$$

where, V is the applied voltage across the sample, r is the pin radius of curvature and R is the pin plane separation.

Electric field would be 40 times the background field. If we consider a back ground field of about 10 kV mm^{-1}, as is the typical modern transmission class solid dielectric cable, the maximum field at the tip of the defect would be 400 MV m^{-1}. Organic polymer dielectrics will not withstand any where near the field and intrinsic local breakdown is inevitable and electric treeing starts.

For solid insulation of high voltage equipment, the electrical treeing is of high importance as it regarded as the most significant mechanism for dielectric breakdown in polymer material (Dissado and Fothergill, 1992; Auckland *et al*., 1992a). Therefore, the electrical treeing is widely studied extensively in classical needle plane geometry by Champion and Dodd (1995) and it was revealed that the major factors influencing tree inception and growth are needle radius, needle plane distance, voltage level, frequency, material and temperature (Mayoux, 2000; Abder-Razzaq *et al*., 1996). Discharge degradation and tree growth

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arise from the creation of intense electrical fields at the tips of conducting inhomogeneities, discharge channels and sites of stress concentration produced by partial discharge activity. If such an intense field could be relived, the lifetime and reliability of the insulation could be improved. There are two approaches aimed at producing a local raising of conductivity at high fields, which would redistribute space charge and charge, present at the extremities of electrical tree channels and prevent local intrinsic breakdown stress being achieved. One is to insert a nonlinear conductive barrier into the insulation. The other is to introduce nonlinear bulk conduction into the characteristics of the insulation. This study addresses the former approach by considering the effects of barrier on tree growth. There are many reports on electrical treeing in polymers but the tree propagation in polymers with barrier is only reported by Auckland *et al*. (1992b, 1995) and Vogelsang *et al*. (2006) so far. For industrial insulation systems, the effect of barrier upon tree propagation is of high importance as these materials are composite as a rule. Therefore, the objective of this research was to investigate the effect of barrier on electrical tree channels propagation by introducing an element of high field non-linear conductivity characteristics at the barrier. So, the high field produces local raising of conductivity and hence a redistribution of charge take place. This would resultantly lower the local electric field stress and consequently, partial discharge activity will be reduced. As already investigated by Dorris *et al*. (1996), analysis of their data suggests that measured partial discharge signals could produce a sudden 0.01 to 0.1 μm extension of tree channel. When the electric field stress is relieved due to high conductivity introduced at the barrier, the growth of the propagating tree channels would be retarded and longer breakdown time would be achieved to extend the life of the insulation.

There are certain materials, like ZnO, $BaTiO_3$ and SiC, which show nonlinear field dependent conductivity characteristics and are studied by many researchers (Donnelly and Varlow, 2003; Auckland *et al*., 1997; Robertson and Varlow, 2005; Guo *et al*., 2006). SiC is an intrinsic semiconductor and it shows high conductivity at higher electric fields and it was chosen to employ as a composite barrier. SiC show highly nonlinear conductivity characteristics when concentration in the polymer matrix is beyond 35%. So, the samples with composite barrier of different SiC weight concentration (5, 10, 20, 40 and 60%) were prepared and stressed with high voltage in a test cell for electrical tree growth to obtain lifetime breakdown data. The results were analyzed with the help of two parameters Weibull-distribution. ElectNet a software simulation tool was used to obtain the electric field distribution in insulation model having composite nonlinear barrier.

MATERIALS AND METHODS

Sample preparation: Special mould were designed and manufactured for the preparation of samples. The carborundum powder with a diameter of less than 5 μm is used as nonlinear inorganic filler for making barrier material. SiC is intrinsic semiconductor with electric field dependent conductivity. The purity of the powder was 98% and it was supplied by Non Tong Shi Chemical Company, Jiangsu, China. The base polymer matrix was blended with carborundum powder on a roller mixer at 120°C for 30 min. All operation was manual and temperature of the roller mixer was controlled automatically around 120°C. Five different weight percentages were used and strips with variable thickness and cross sections were prepared which were later used to make thin composite barrier films of ~0.3 mm thickness in hot molding press.

Composite barrier films of SiC having 0.3 mm thickness were prepared by hot pressing machine at 160°C temperature. In order to remove the air bubble the pressure was gradually increased up to 10 MPa and kept constant for 10 min. Later on the moulds were shifted to cold press machine and let it to cool upto 40°C under 2.5 MPa pressure. Films were cut into required rectangular sections and were sandwiched between the two already prepared rectangular slabs of XLPE insulation. These rectangular slabs were prepared in two separate specially designed moulds of same cross sections but different thickness in hot pressing machines at 130°C temperature while gradually increasing pressure upto 10 MPa, later maintained this pressure for ten minutes and cooled down to 40°C in cold pressing machine at 2.5 MPa. Optical inspection was carried out to see ingression of air bubble. XLPE slabs were discarded in few instances due to ingression of air bubble. Finally, the SiC composite barrier films were sandwiched in a separate mould and was hot pressed at 10 MPa and temperature was raised to 170°C, needed for cross linking of polymer chain. Temperature was held constant for half an hour and later on heaters were turned off to let it cool naturally while keeping the pressure constant at 10 MPa. Finally, the test samples with composite barrier in the form of slab (20 mm long, 15 mm high and 5 mm thick) were cut. For easy optical detection of the trees, a fully transparent formulation was chosen.

Experimental setup: To initiate the treeing from the instant of voltage application, needle electrode with tip radius (~10 mm) were used. The relative distance of 3 mm was chosen between the point and plane electrode where, as the distance from the tip of point electrode to the barrier was ~0.7 mm. The base of samples was painted with conducting silver paint and all the experiments were conducted at room temperature. Test circuit consists of 5 kVA, 50 Hz, 240 V/50 kV, high voltage single-phase step up transformer. The test voltage was selected to be 20 kVrms as it produces an intrinsic breakdown at the tip of the needle electrodes leading to easily observed and repeatable tree growth in the dielectric. All the experiments were carried out in a test cell filled with transparent silicon oil to suppress extraneous surface discharges. The electrical tree propagation was observed with the help of telephoto lenses and CCD-camera (Charge Coupled Device) having interface with computer. Growing electrical tree images were recorded at different time interval. Time to breakdown values were analyzed with two parameters Weibull-distribution and discussed in detail in results and discussion section.

RESULTS AND DISCUSSION

Experimental observation: Due to high electric field at the tip of the electrode, the electrical tree inception occurred during the initial voltage rise to final value. In all the samples tree inception time was less than 30 sec. Once the first branch was created, the electrical tree grew into branches to ground the electrode. The growth characteristics were dominated by stochastic behavior where propagation alternates between the phases of growth and standstill as described by Dissado and Fothergill (1992). Because of the opaque nature of the barrier it was not possible to observe the growth inside the barrier. Observations of the growth characteristics were only possible when the tree emerges out of the barrier. In most of the instances the bush type trees appeared. When the tree touches the barrier, its growth slows down and in some instances it starts propagating along the barrier polymer interface to look for weaker region to penetrate. Discharges take place in small tree branches and their structure changes to hollow pipe shaped channel as described by Vogelsang *et al*. (2006). It was observed in the experiments that the final breakdown took place in the first channel and arc discharges may have caused final breakdown to the insulation. Some typical trees are shown at the time of breakdown in the Fig. 1.

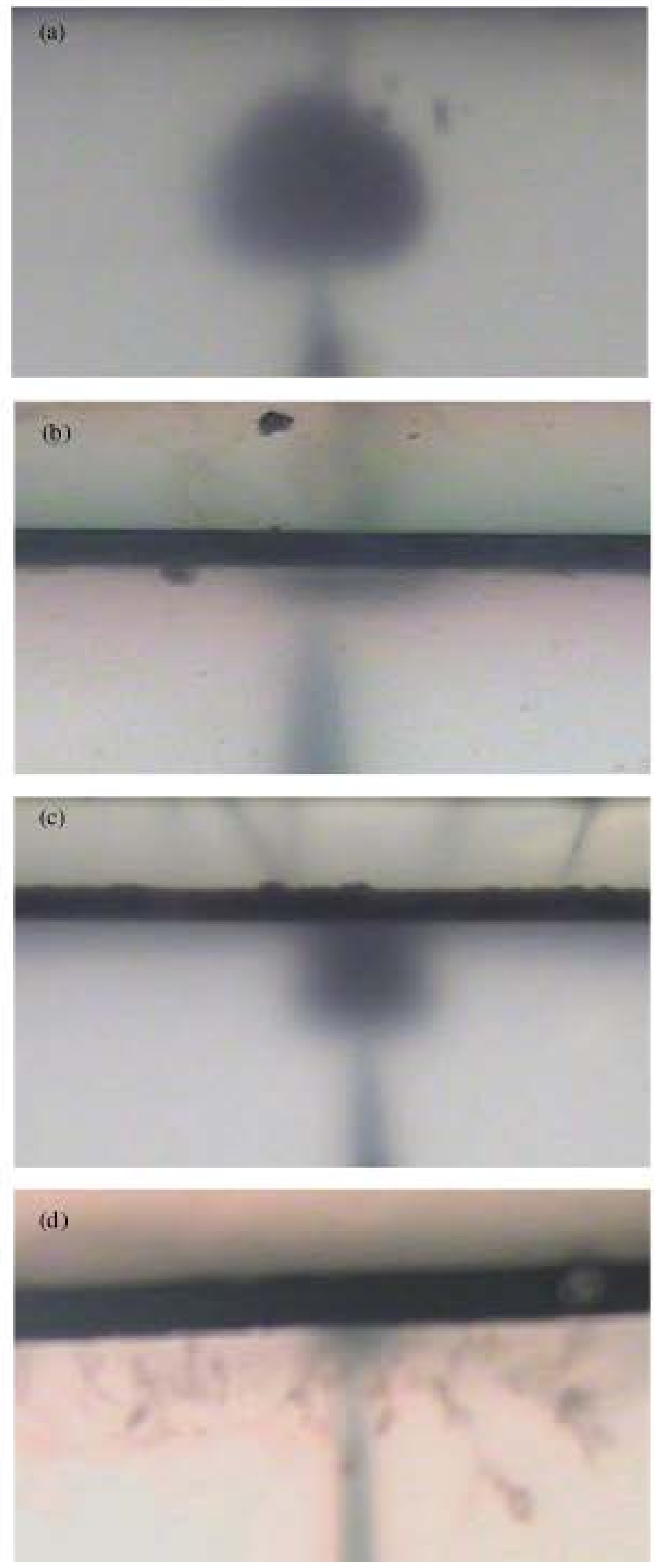

Fig. 1: Typical trees shown (a) without barrier at time of breakdown, (b) with barrier 5% SiC at the time of breakdown, (c) with barrier 20% SiC at the time of breakdown and (d) barrier 60% SiC can not penetrated by the tree

Computer simulation: ElectNet, an electric field software simulation tool was used to simulate the electric fields in a composite insulation with non-linear SiC barrier. ElectNet solves Maxwell's equations to find the electric field within the model. The aim is to demonstrate the difference in electric field values in the vicinity of needle tip for two cases, i.e., when needle is touching the barrier and when it is inserted above the barrier. The model of needle tip touching the barrier simulates the situation of electrical tree tip impinges upon the nonlinear barrier. Due to presence of high field conductivity characteristics of SiC at the barrier the electric field in the vicinity of needle tip within barrier would be lower because of redistribution

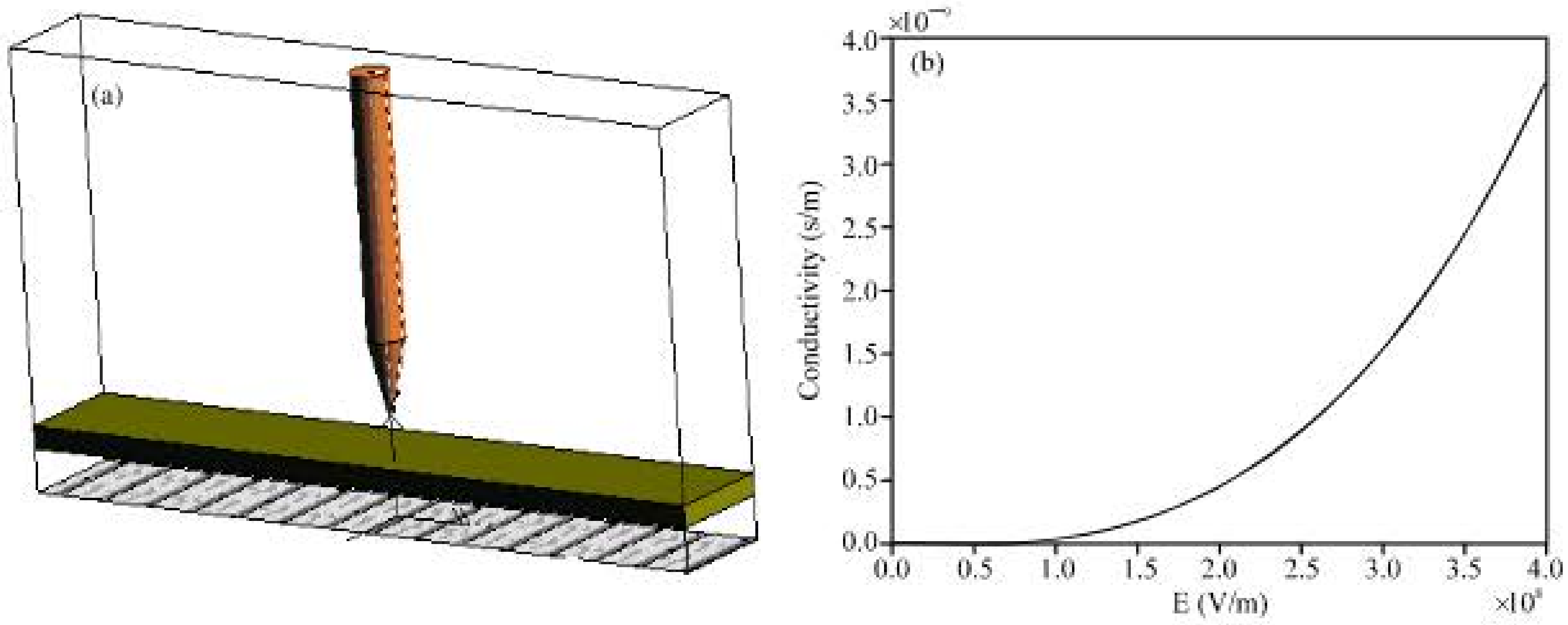

Fig. 2: (a) Model with needle electrode and non-linear barrier and (b) Electric field vs conductivity characteristics of SiC when filler concentration is more than percolation threshold

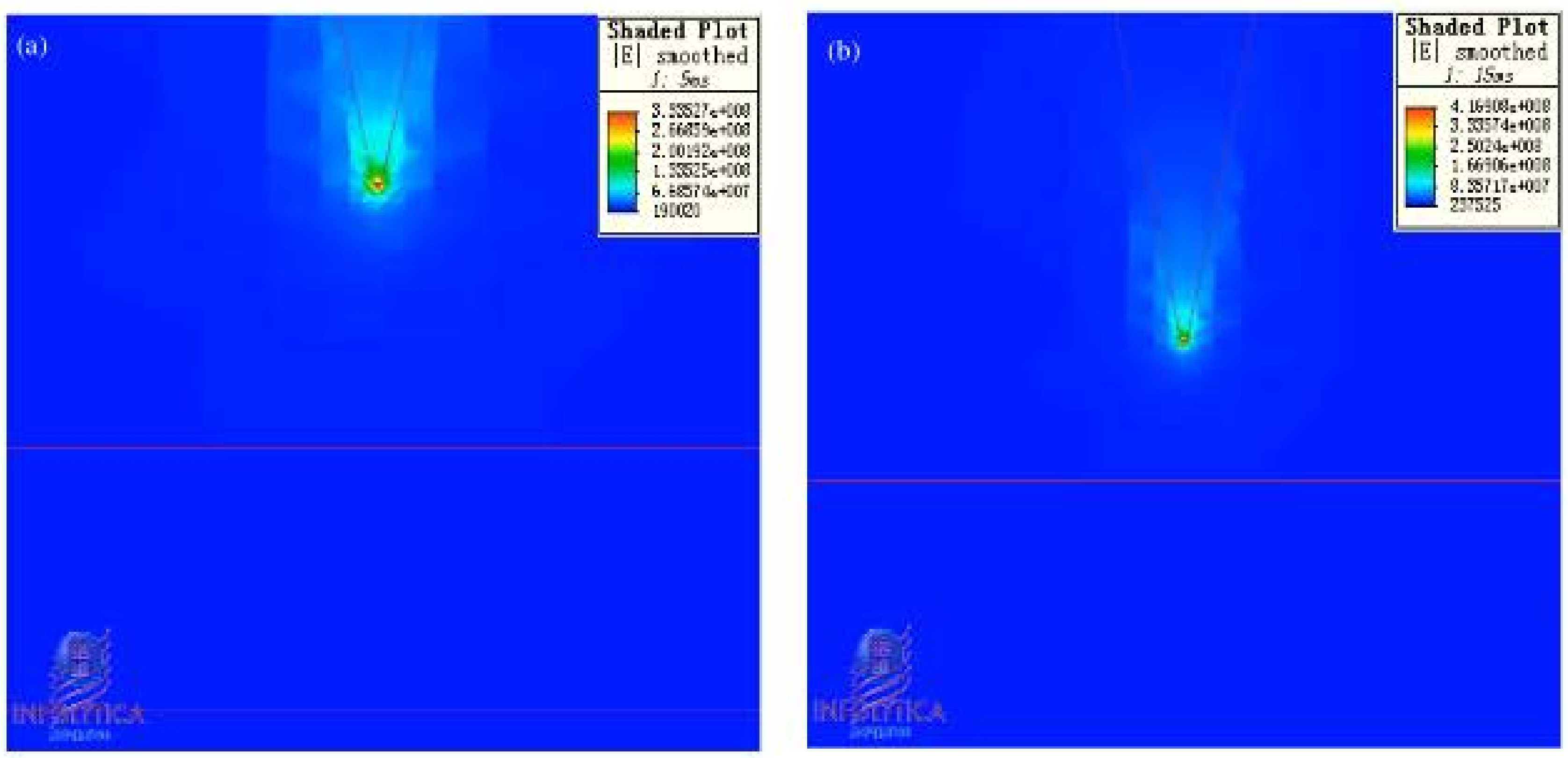

Fig. 3: (a) Shaded electric field plot at peak of positive cycle while electrode is stressed with 20 kV sinusoidal voltage and needle tip is placed 0.5 mm above the non linear barrier and (b) Shaded electric field plot at peak of negative cycle

and conduction of charges. A 3-D model was setup as shown in the Fig. 2a. Material properties and boundary conditions were applied. The non-linear characteristics of SiC used are shown in the Fig. 2b. The electrode was stressed by 20 kV and 50 Hz sinusoidal voltage.

A tetrahedral finite element mesh was selected for the model and a transient 3-D solution was run. The results are shown in the form of shaded plots.

Two models were solved; one with needle electrode of 10 µm tip radius was inserted 0.5 mm above the barrier. In other model the needle tip was deliberately made to touch the barrier to simulate the condition of an electric tree channel impinge upon the barrier, as the electric tree channels are considered to be the extension of electrode. The shaded plots are shown at the peaks of positive half cycle and negative half cycle in the Fig. 3 and 4.

These plots show that there exist difference between electric field values in the vicinity of needle tip when it is above the barrier and when it touches the barrier. This lowering in electric field is due to the redistribution of charges. This will result in lowering of partial discharge activity and hence longer time would be needed for the tree channel to bridge the gap between the electrodes, as the tree growth would be slower. Consequently, the degradation would be retarded and longer life for the insulation would be achieved.

To describe the influence on time to breakdown, tree propagation at the barrier of different SiC concentration were investigated. Generally, it can be stated that different time to breakdown values correlates with different conductivity characteristics at the barrier. On application of voltage, the time to breakdown of specimens were noted. In present study, the censored data analysis was

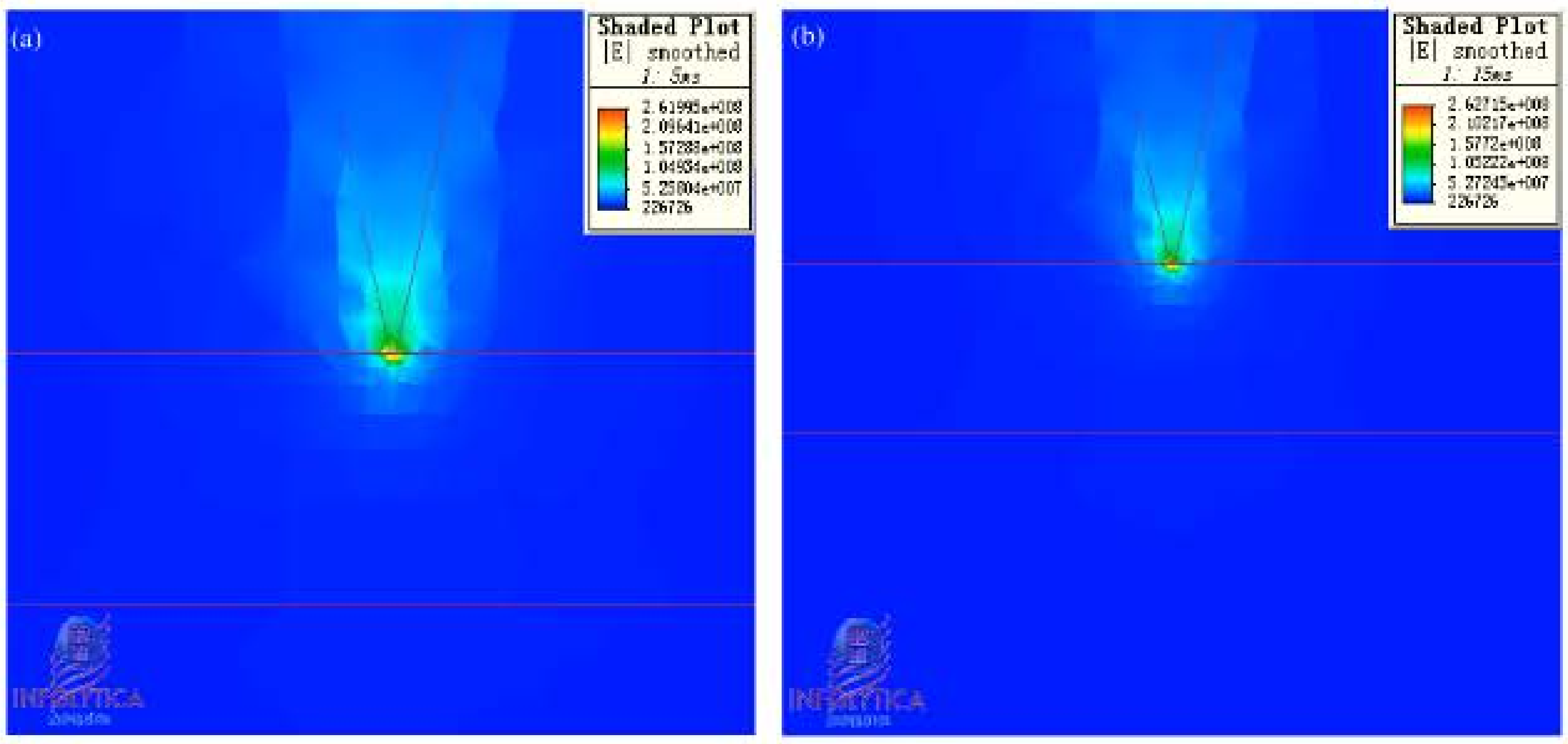

Fig. 4: (a) Shaded electric field plot at peak of positive cycle while electrode stressed with 20 kV sinusoidal voltage and needle tip touching the nonlinear barrier and (b) Shaded electric field plot at peak of negative cycle while electrode stressed with 20 kV sinusoidal voltage and needle tip touching the nonlinear barrier

used. The reason is that when tree grows from the tip of needle and impinge upon the barrier, its growth slows down. It sometimes propagates along the barrier polymer matrix interface. The injected charges cause reaction at some point surrounding the pin electrode, increasing the diameter of defect. Since specimen thickness was mere 5 mm for optical observation, in few instances the tree grew over top of the barrier and completely missing it, eventually bridging the specimen by forming a track around the edge. Larger thickness of the specimens if used could have avoided such situation but optical observation for tree propagation might not be possible. So for Weibull-distribution plots the lifetime data of those samples is used for which breakdown occurred from tip of electrode to plane electrode by penetrating through the barrier.

Even though the samples are identical for one type of barrier, the scatter in failure times of specimens is larger. It is essential to utilize statistical tools to understand the severity of the electrical stress and behavior of trees influence by the presence of nonlinear barrier. Weibull-distribution is of general nature, which can fit to wide variety of lifetime data (Fabiani and Simoni, 2005). So, when plotted on Weibull statistical model are expected to yield the stochastic behavior of electrical trees.

The cumulative Weibull-distribution function is given by:

$$F(t) = 1 - e^{-[(t-\gamma)/\alpha]^{\beta}} \tag{2}$$

where, α is the scale parameter which represent the time require for 63.2% of the tested units to fail. β is shape parameter; γ is location parameter; t is the random variable, usually time to breakdown. F(t) indicates the propagation of the specimen tested which fail by time t, the values of γ and α are represented in time whereas β is dimensionless parameter(number).

The cumulative probability F(t) was calculated using the following equation:

$$F(t) = \frac{i - 0.3}{N + 0.4} \tag{3}$$

where, i is the failure order number and N is the total sample size.

As seen from the Weibull plot in the Fig. 5a and b, the 63% value of time to breakdown for sample without barrier is only 27.3 min and for barrier with 5% concentration is 168.3 min. The conductivity characteristics of 5% SiC filler concentration are similar to that of unfilled insulation as described by Guo *et al*. (2006). The increase in time to breakdown may be due to the presence of strain at the interface as investigated by Auckland *et al*. (1995). Presence of such strain can retard the growth of electrical trees.

But when barrier films of 10 and 20% SiC were used, there was increase in breakdown time. The 63%-quantiles of the time to breakdown values for samples with a barrier of 10 and 20% SiC is 308 and 285 min, respectively as shown in the Fig. 6a, b. Obviously, the time to breakdown is more than the unfilled and filled 5% SiC composite barrier. Since it is the conductivity

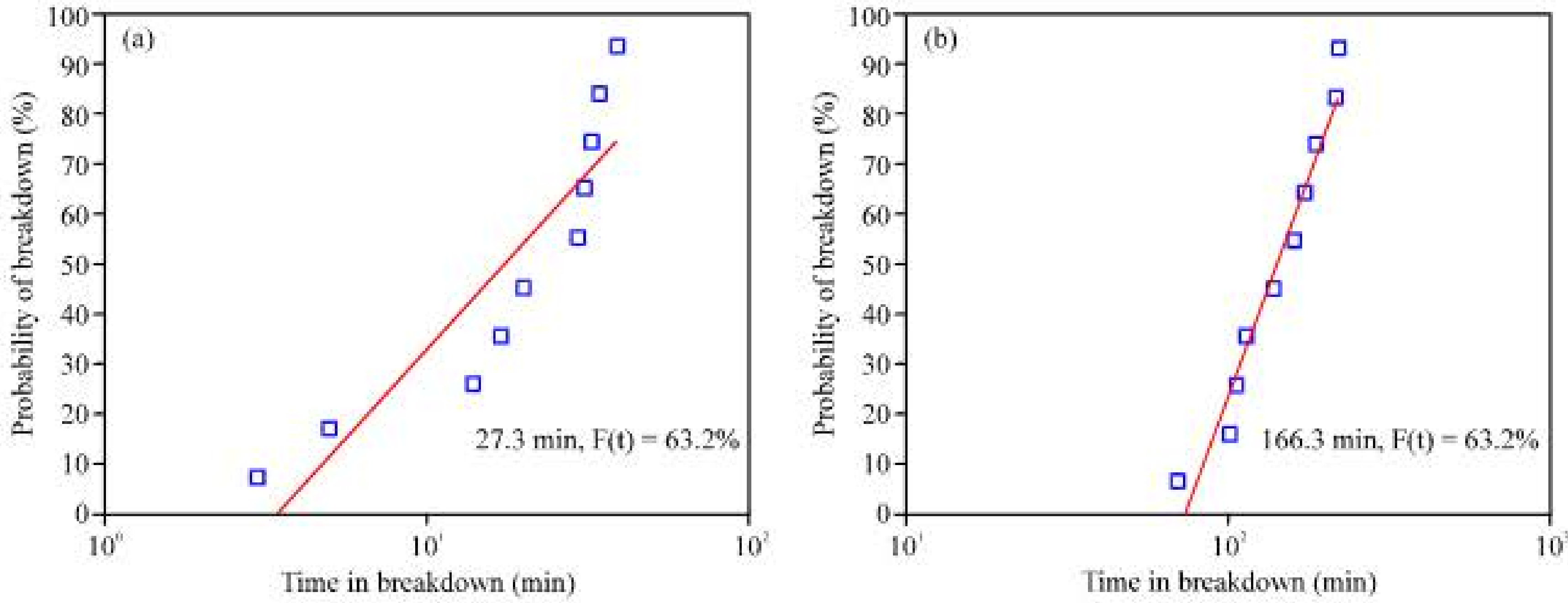

Fig. 5: (a) Weibull plot of time to breakdown of XLPE samples without barrier due to electrical treeing under AC voltages and (b)Weibull plot of time to breakdown of XLPE samples with 5% SiC barrier due to electrical treeing under AC voltages

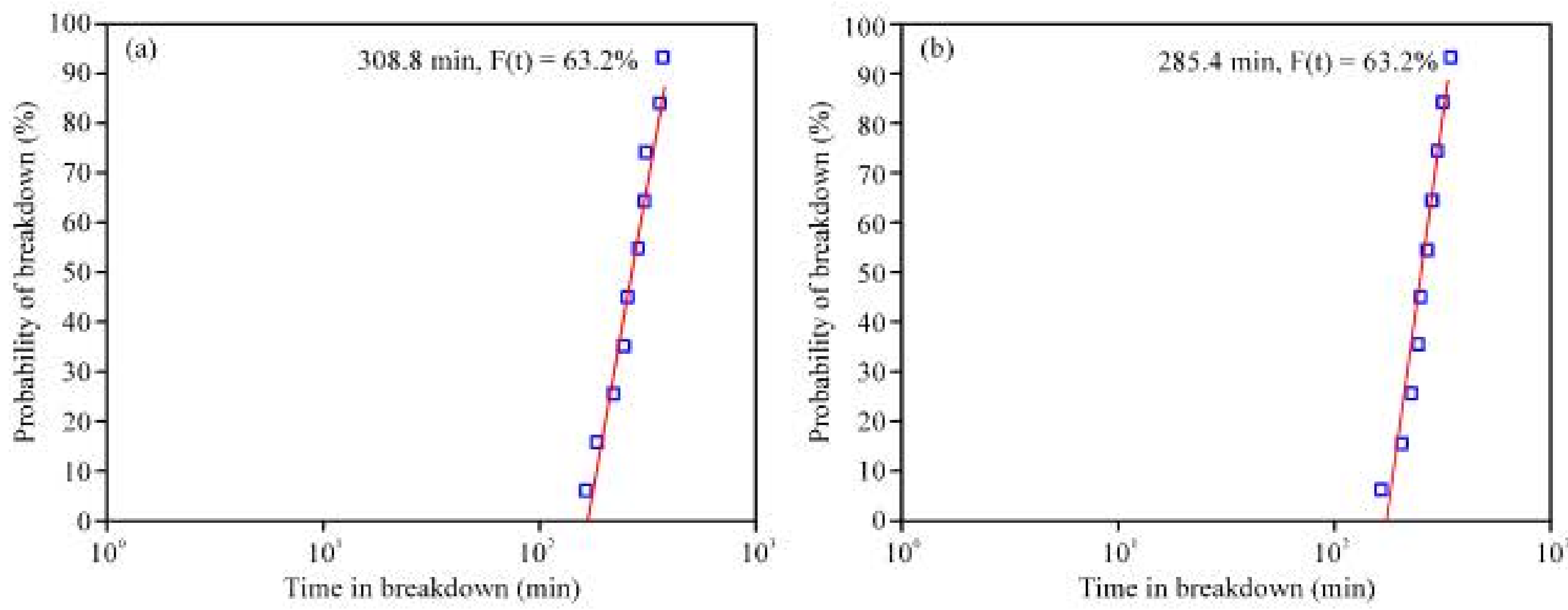

Fig. 6: (a) Weibull plot of time to breakdown of XLPE samples with 10% SiC barrier under AC voltages and (b)Weibull plot of time to breakdown of XLPE samples with 20% SiC barrier under AC voltages

Table 1: The Weibull parameters for breakdown time analysis of samples

Specimen type	β	α (min)
Without barrier	1.22	27.3
5% SiC barrier	2.95	166.3
10% SiC barrier	3.99	308.8
20% SiC barrier	5.20	285.4

characteristics, which determine the magnitude of the charge distribution, so having higher field conductivity characteristics when filler concentration is increased, the electric field at the tip of the propagating electric tree channels will be less compared to the 5% SiC or unfilled. Consequently, the partial discharge activity will be less, which means that the growth rate would be slow and time to breakdown would be prolonged significantly and longer life of the insulation will be achieved. As shown in the Table 1, the characteristics life values for 10% SiC and 20% SiC are almost similar, which may be attributed to conductivity characteristics, which are nearly same at high fields (Auckland *et al*., 1997).

When the SiC filler concentration is greater than percolation threshold, the conductivity rises so sharply that it is six to seven order of magnitude more than the unfilled insulation. When the samples with 40 and 60% SiC were tested, the growing electrical tree channels hit the barrier, their advancement is virtually stopped. Not a single sample was penetrated by the tree at the barrier even after 10 h for all of the tested samples (time 10 h is chosen due to constraint of thickness of samples otherwise breakdown occur from top of barrier). This behavior possibly may be explained by assuming that when SiC contents are more than the percolation threshold, the barrier dissipates the charges at the extremities of the tree channels as postulated earlier. When tree channels hit the barrier its granules in the vicinity starts conducting in accordance with electric field and current density characteristics (Auckland *et al*., 1997), reducing the concentration of the field at the tip of the tree channels and hence stop further development. Direct comparison is not possible in case of composite barrier having SiC contents greater than percolation threshold as no time did a tree channel penetrate the barrier. But one thing is obvious that for all tested samples of 40 and 60% SiC composite barrier the lifetime of the insulation is more than that of rest of the tested groups.

CONCLUSION

The enhanced conductivity of SiC when the filler concentration is greater than the percolation threshold permits the dissipation of space charge and the charge present at the extremities of the electric tree channels as they impinge upon the barrier, thereby reducing the electric field. This lowering in electric field results in decrease in partial discharge activity. As a result of this phenomenon, tree growth and penetration of barrier is inhibited, leading to extended life of the insulation. The tree growth and characteristics life of 10 and 20% SiC composite barrier are nearly same which may be attributed to same conductivity characteristic at higher fields. But when the composite barrier filler concentration is over percolation threshold, the conductivity rises so sharply and reducing field at tips of tree channel, which result in slowing down of tree growth and virtually stopping it giving extended life of the insulation. Consequently, unlike barrier as investigated by Auckland *et al.* (1995) which provides a barrier to tree growth due to its high adhesive bond strength and fracture toughness, SiC composite barrier with contents greater than percolation threshold provide an additional enhancement to tree resistance because of its nonlinear properties and its ability to redistribute accumulated space charges and charge at the extremities of tree channel. Although the study described here was to provide experimental foundation for understanding the interaction between electrical trees and composite barrier of non-linear characteristics. As it is shown, using semi conducting filler material with nonlinear characteristics can increase tree resistance. In this way the energy of the tree channel is dissipated and concentration of charge and subsequent tree growth being avoided. If such a material employed in practice it may not improve tree resistance but at the same time absorb switching and other transients in power system. Thus by choosing certain nonlinear characteristics the insulation could be designed having integral surge suppression.

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