Study on Influence of SiO_2 Nano Particles on the Failure of XLPE Underground Cables due to Electrical Treeing

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Abstract – *In the present work, electrical treeing analysis of the pure and nano filled Cross Linked Polyethylene (XLPE) material has been studied. The electrical tree inception time, breakdown time and propagation speed of the nano filled XLPE insulation has been investigated. Nano Silicone Oxide (SiO_2) was used as a filler material. Nano-fillers were added at different concentrations of 1% and 3% by weight in the base material. Laboratory experiments were conducted as per IEC procedures at 12 kV AC voltage magnitude. Tree structure was observed for all the test samples. Scanning Electron Microscope (SEM) carried out for understanding the dispersion of nano fillers in the nano filled material. Thermo Gravimetric Analysis (TGA), volume resistivity, capacitance and dielectric constant test were carried out to understand the physical and chemical characteristics of the nano filled XLPE material.*

Keywords - *XLPE, electrical treeing, Dielectric Properties, breakdown time, nano filler.*

1. Introduction

Failure of underground cables due to electrical treeing phenomena in the polymeric insulating material is a major threat for the safe and reliable operation of power system network [1-4]. Hence many research works are being carried out in the development of high performance insulating materials for underground cables. Nano-composites are emerging as a new class of insulating materials for demanding application in all electrical equipment used in the electric power network. Both electrical and thermal properties are improved with the addition of nano fillers in the polymeric materials [5-6]. Electrical treeing causes early failure of electrical insulation structures under normal operating conditions. A tree-like tree structure or a bush type tree structure can form from the defect site and an increase in the applied voltage magnitude shows reduction in characteristic life of the insulation material. The development of high voltage XLPE cable requires fundamental understanding towards electrical treeing phenomenon of the insulation [7-11]. Electrical tree possibly starts from a weak point where the electric stress is concentrated, or as an extension of water trees. Some of the researchers have been reported that an increase in the applied voltage magnitude shows reduction in characteristic life of the insulation material. The incorporation of nanoparticles into polyethylene is seen to impart desirable dielectric properties when compared with conventional composites [12-15]. Electrical treeing is a stochastic phenomenon therefore a statistical investigation is important for analysis the experimental data [16-18]. The statistical analysis is essential for large population of high voltage insulation data interpretations [19-21]. Considering this, in this work, electrical tree inception, breakdown and propagation time of XLPE material at different nano filler concentration is studied.

2. Material and Sample Preparation

A silane grafted crosslinkable polyethylene compound was used in the present study as a base material. It is ensured that the base material has no filler of any type which may influence the experimental results. Silicone dioxide (SiO_2) of size <80 nm, purity >99% supplied by Hefei Jiankun Chemical Industry was used for making nano size filled XLPE specimens. The samples were prepared at 1% and 3% filler concentrations by weight of the nano size fillers. The base XLPE, catalyst and fillers were weighed accurately and mixed thoroughly by using brabender mixer. After mixing the mixer was poured into plastic extruder machine at 200°C heated by a hydraulic press. The finished product has all the properties associated with cross linked polyethylene. All samples were made using appropriate moulds. Samples were prepared from each composition for testing. The transparency of the specimen is required to a certain degree in order to view the tree structure formed during the testing.

3. Experimental Setup

Fig.1 shows the schematic diagram of the experimental setup and the electrode configuration used in the study. Needle-plane electrode was used for the examination of the electrical tree growth. Each sample had a dimension of 30mm x 15mm x 3mm and the distance between the needle tip and ground electrode was 3mm ±0.1mm.

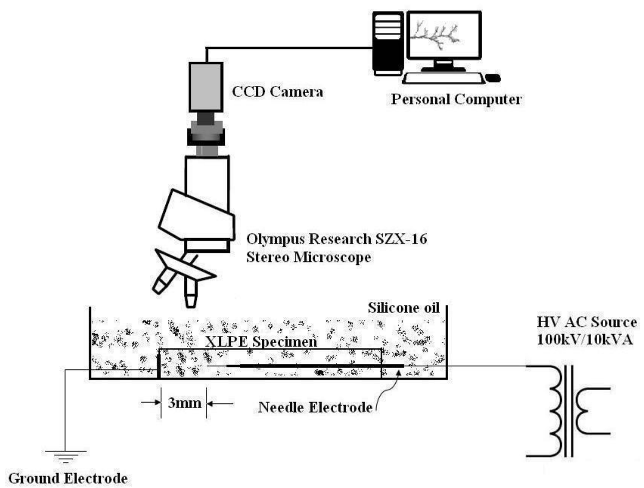


Fig. 1. Schematic diagram of electric treeing experimental setup

Steel needle electrode with tip radius < 10μm was used in this study. Experiments were conducted as per IEC procedures at 12 kV AC voltage magnitudes.A 100 kV, 10 kVA, 50 Hz high voltage transformer is used for the experiments. A needle electrode inserted in the specimen produces high electric field at the tip of the electrode. The experiment is conducted at the room temperature. Due to the very high electric field, tree developed in the specimen. The sample is viewed under digital microscope, Olympus SZX-16 Research Stereomicroscope equipped with CCD Camera. The microscope is interfaced with a personal computer. This helps to record the treeing images in the computer. The magnification and pixel level of the capturing device is adjusted to get the best view of the tree. The dimension and structure of the tree is noted and observed. Likewise, a number of samples were taken and treeing images were recorded.

4. Results and Discussion

4.1 Scanning Electron Microscope (SEM) Analysis

To examine the physical properties of the nano SiO_2 filled XLPE specimens, a detailed SEM investigation are made on the nano filled XLPE. Fig 2 shows the SEM photograph of 1 wt% and 3wt% of the nano filled XLPE specimens. It is observed that there is a significant difference in the dispersion of the nano particles.

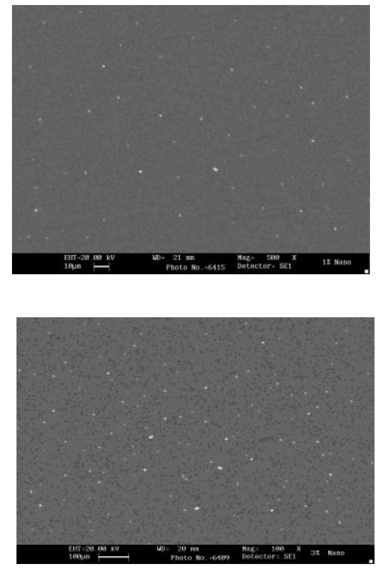


Fig. 2. SEM images of 1% SiO_2 and 3% SiO_2 filled XLPE Samples

There is small amount of particle appear in the 1% SiO_2 filled XLPE material whereas large number of particles are scattered over the entire area of 3% SiO_2 filled XLPE specimen. It is noted down that the particles are isolated and scattered uniformly over the area of specimen.

4.2 Tensile Strength Analysis

Fig.3 shows the variations in tensile strength of the nano composite XLPE material. It is noticed that the tensile strength of virgin material is less compared with other nano filled material. This clearly shows that when the filler concentration is increased the tensile strength of the material has been increased.

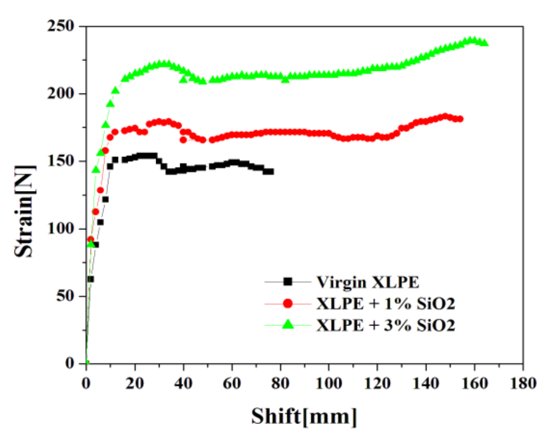


Fig. 3. Tensile strength of XLPE material

4.3 Thermo Gravimetric Analysis (TGA)

Thermo Gravimetric Analysis (TGA) was used to measure the thermal properties of different XLPE specimens. As the temperature is increased, a weight loss takes place due to the release of moisture or gases from the decomposition of the material. The measurements are taken in the ambient air and the temperature is increased at a rate of 20 °C/min from 250 to 800 °C. Fig 4 Shows the TGA curve of XLPE, 1wt% and 3wt% of the nano SiO_2 filled XLPE specimens. The result of the virgin XLPE material is compared with nano filled material. The samples without filler concentration decompose more quickly than those with filler concentration due to the influence of the nano fillers. The residual wt% of nano filled XLPE after the TGA test is higher than that of pure XLPE. The resultant residual weight is calculated by using the following formula.

$$\% \text{ Resultant residual weight} = (100\% - \text{Filler wt. }\%) \times \% \text{ Residual weight} \qquad (1)$$

The measured weight loss, calculated residual weight and resultant residual weight are shown in Table 1.

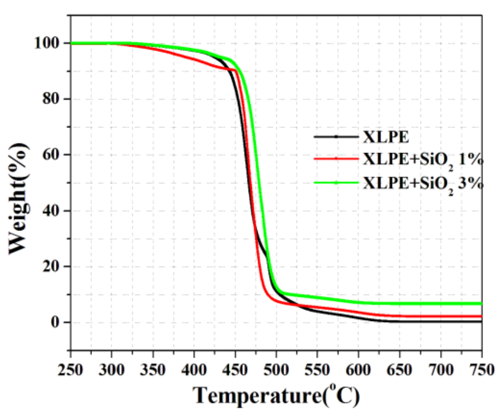


Fig. 4. Thermo Gravimetric Analysis of pure XLPE and nano XLPE

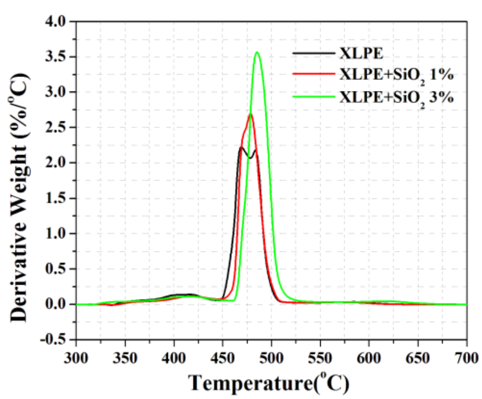


Fig. 5. DTG Analysis of Pure and nano XLPE

Table 1 % Weight Loss, % Residual Weight after the TGA Test and % Resultant Residual Weight of Pure, 1wt%, 3wt% XLPE.

Sample types	Pure	1wt%	3% wt
% Weight loss	99	96	92
% Residual weight After TGA	1	4	8
% Resultant Residual weight	-	3.96	7.76

It is observed that the weight loss have been reduced from 1wt% to 3wt% significantly, while increasing the % wt of filler the residual weight and resultant residual weight of the nano filled XLPE have been increased. It clearly shows that the thermal stability of the nano filled XLPE is naturally improved by increasing the filler concentration.

The DTG spectra of nano SiO_2 filled XLPE are shown in Fig 5. The TG curve shows that there is no weight loss up to 450°C and suddenly decreases the weight loss above 450°C to 600°C.This weight loss is due to the decomposing of the XLPE. After decomposition, the residual weight of the XLPE specimens has been noted. It is interestingly observed that there is no weight loss after 600°C, since SiO_2 itself should not decompose up to the 800°C. The weight loss, residual weight and weight loss rate are measured from the TG and DTG curves.

Considering the weight loss rate, it is reduced while increasing the filler concentration in all XLPE Specimens. It indicates that the inorganic components which in turn can restrain XLPE specimens from thermal degradation while increasing the filler weight percentage. Furthermore, the weight loss rate of pure XLPE is less compared non filled XLPE. However, the thermal stability of the nano filled XLPE is more than that of pure XLPE is observed.

4.4 Evaluation of Electrical Treeing Analysis

In order to understand the breakdown strength of the nano composite XLPE material Electrical Treeing analyses were conducted at 12kV AC voltage for pure and Nano filled XLPE samples.

Table.2 Breakdown time of XLPE Nano composites @ 12kV

S.No	Material	Breakdown Time (hr)	Improvement
1	Virgin XLPE	16	-
2	XLPE+ 1%SiO_2	18	12.5%
3	XLPE+ 3%SiO_2	21	31.25%

As per the test procedure the test voltage has been applied to the needle electrode, due the high electrical stress at the tip of the needle electrode the tree propagates towards the ground electrode. The electrical treeing inception and breakdown time were noted likewise. The propagation of tree growth was recorded for further analysis.

It is observed from Table 2 by addition of silica nano particle in the base material the breakdown time of the material has been tremendously increased. Approximately 12.5% of improvement has been identified by adding 1% of nano silica fillers and 31.25% for 3% of nano silica fillers at 12kV AC voltage stress.

The fig.6 shows the Step by step electrical tree development images for pure material at 12kV voltage stress. A branch tree and tree like tree structure has been observed. At 12kV voltage stress for unfilled XLPE samples the electrical tree propagate towards ground electrodes in a narrow manner, mostly one or two branches reached the ground electrode. The width of the tree is very small.

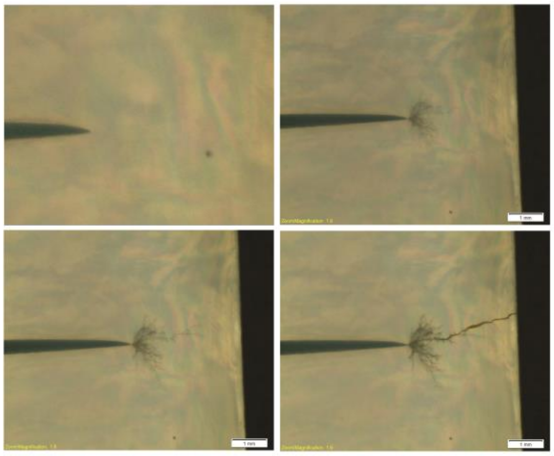


Fig. 6. Electrical tree growth images for pure XLPE at 12kV voltage Stress

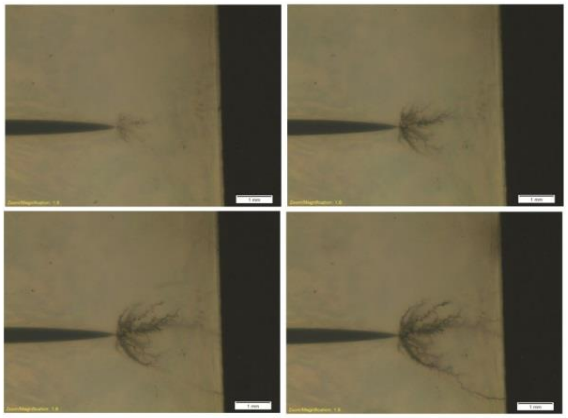


Fig. 7. Electrical tree growth images for 1wt% SiO_2 filled XLPE at 12kV voltage Stress

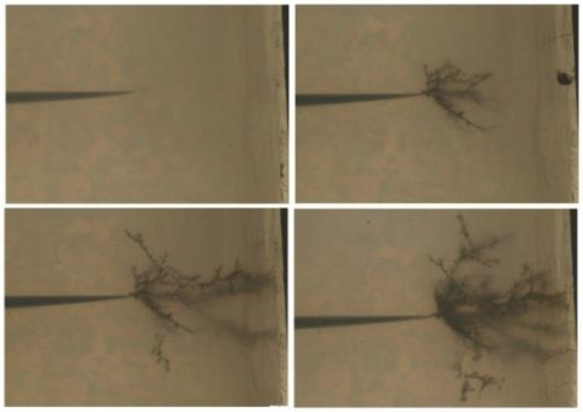


Fig. 8. Electrical tree growth images for 3wt% SiO_2 filled XLPE at 12kV voltage Stress

Fig.7 and 8 shows the step by step tree growth images for 1 wt % and 3 wt % nano SiO_2 filled samples correspondingly. For 1 wt % material a branch type tree has been observed and the propagation speed of the tree has been reduced compare to pure XLPE sample. Branch tree and tree like tree has been observed for 3wt% material, the tree inception and breakdown time has been increased significantly compare to 1wt% filled material due to filler material properties

After addition of filler material the tree width has been increased progressively from 1wt% to 3wt%. Different types of tree structure has been found for nano filled samples. Due to influences of nano SiO_2 material the tree propagation bath has been erratic and width of the tree has been increased.

4.6 Evaluation of Electrical Treeing Length

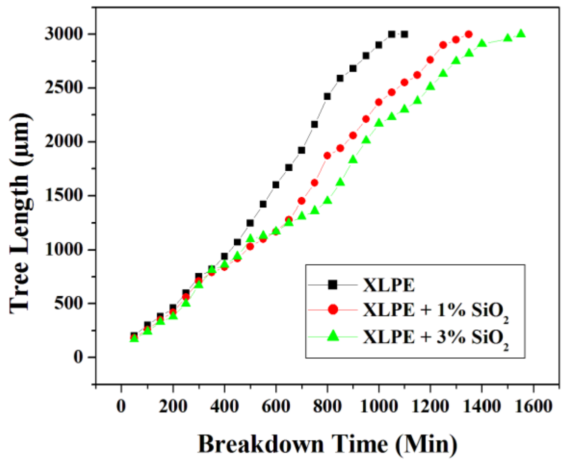
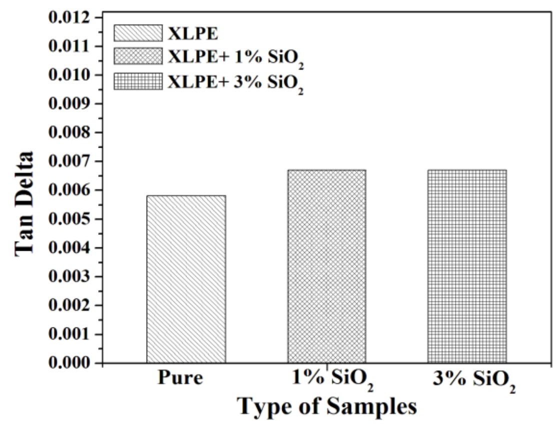


Fig. 9. Electrical tree length of pure and nano filled XLPE samples at 12kV voltage magnitude

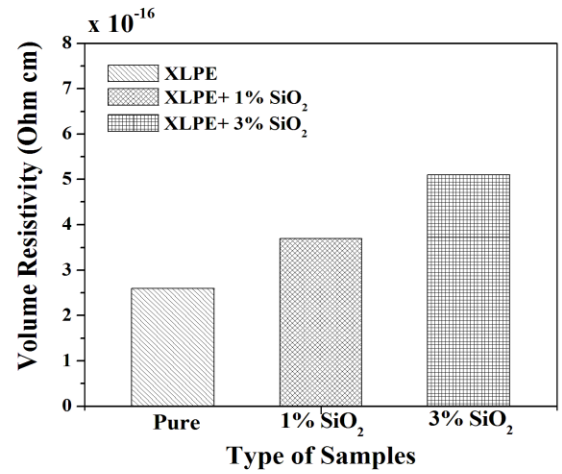
Electrical treeing lengths were noted all the test samples by using research stereo microscope for analyzing purpose. Electrical treeing length and propagation speed of the electrical tree plays an important role for determine the life time of the material. Fig.9 shows the electrical tree length of pure and nano filled samples at 12kV voltage stress. In this fig all samples takes certain time period for initiation. The initiation time for nano filled samples has been greater than pure sample. After initiation the tree gradually propagate towards the ground electrode for certain time period. Nearer to the breakdown the growth rate is very high. Finally the tree bridges the gap. These results confirm that the nano particles will enhance the life time of the materials.

4.7 Evaluation of Dielectric Characteristics of Pure and Nano Filled XLPE Material

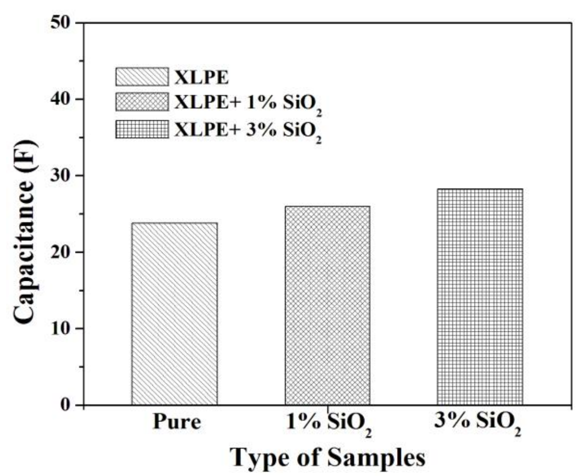
Tan δ and capacitance are most important factors to determine the quality of the XLPE insulation. In order to find out the dielectric parameters such as Dielectric constant, Tan Delta, Capacitance and Resistivity, ELTEL Make ODTR-3K model dielectric properties measuring test system is used. Fig.10a shows the tan delta values for pure and nano filled XLPE materials. 1wt% and 3wt% filled material tan delta values are nearly same as pure XLPE, there’s no losses found adding lesser amount of nano fillers. The volume resistivity was assessed with the DC leakage current value measured 1 minute after the measurement was begun. The applied DC voltage was 500 Volts.



(a)



(b)



(c)

Fig.10. Comparison of pure and nano SiO_2 filled XLPE materials (a) Tan-Delta (b) Volume Resistivity (c) Capacitance

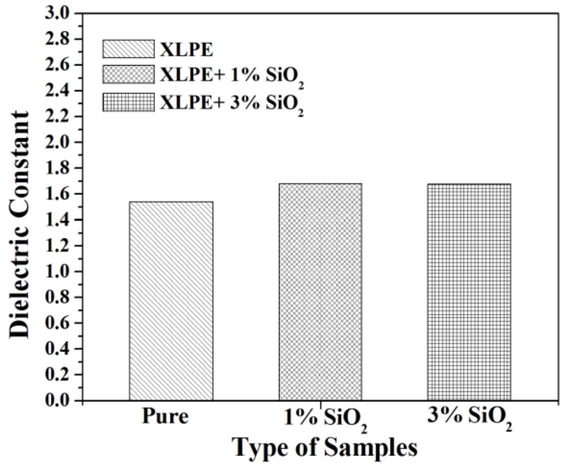


Fig. 11 . Dielectric constant values of pure and nano filled XLPE materials

Measured volume resistivity's are shown in Fig.10b. From the fig it clearly shows addition of Nano SiO_2 fillers will enhance the volume resistivity values of the nano filled samples. Volume resistivity have been increased from pure to 1wt% & 3wt%. Fig.10c shows the capacitance values of pure and nano filled XLPE specimens, there is considerable improvement in 1wt% and 3wt% material. Fig.11 shows the dielectric constant values of pure and nano SiO_2 filled XLPE samples, the values are gradually increased from 1% and 3% filler concentration. The increment signifies the addition of nano filler wt% will enhance the properties of the material.

5. CONCLUSION

Experimental results on electrical treeing characteristics of virgin XLPE material and XLPE filled with 1% and 3% nano size SiO_2 fillers at 12kV voltage magnitudes have been presented in this paper. The propagation speed of the treeing has been relatively reduced for nano filled material. The breakdown strength has been increasing gradually from 1wt% to 3wt% nano filled materials. In general, nano filled material has good breakdown strength by increasing filler concentration levels. The tan delta losses is same for both pure and nano filled samples. Volume resistivity values are gradually increased from pure sample to 3wt% filled sample. Capacitance and dielectric constant values have been improved gradually from pure to 3wt% samples. In overall conclusion, it is found that the incorporation of nano SiO_2 fillers in XLPE specimens will enhance their electrical, mechanical and physicochemical properties.

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