Investigations of growth of Electrical Trees in XLPE Cable Insulation under Different Voltage Profiles

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***Abstract*-In the present work, electrical trees were generated under the composite voltages formed by superposing the AC voltage over the DC voltage. It is observed that the failure of insulation due to treeing is high under the AC voltage superposed with the positive DC voltage. The weibull parameter beta indicates that the mechanism of failure is almost the same under the composite voltage studied. The physicochemical test results indicate that only thermal characteristics of the material is altered due to electrical treeing and no new phases observed in the electrical treed zone.**

I. Introduction

In monolithic dielectric structure, under normal operating voltage stress, a series of partial pre-breakdown channels grows from a region of extremely high electrical stress due to imperfection present in the insulation structure especially, due to presence of asperities, gas cavities, conducting inclusions or intrusions. The pre-breakdown channel formed around the defect site in the dielectric structure resemble the branches of a tree and hence the name treeing is given to this deleterious process and since such an occurrence is purely due to electrical stress the mechanism is termed as **Electrical Treeing** [1]. Considerable work has been carried out to understand the dynamical aspects of electrical trees in XLPE insulation under AC voltages. At this stage it is essential to understand the dynamics of tree especially under the composite voltage formed by DC and AC voltages. A methodical study was formulated and the results acquired were discussed in this paper. Also certain additional physico-chemical diagnostic testings were carried out to understand the degradation caused in the material due to electrical tree formation especially through Wide Angle X-ray Diffraction and Differential Scanning Calorimetry study.

II. Experimental

The experimental setup for generating trees under AC voltage has been designed in such a way as to obtain the required database in a short time. For this purpose, the point from which tree can originate have been predetermined in implementing, defects of known geometry into the body. The specimens used for generation of electrical trees in laboratory were obtained from 33 kV XLPE cable. The outer semi-conducting layer of the cables was pealed off after applying heat pad over the surface. The samples of 2 cm length were cut from long length of cable. The specimens were stabilised by heating them about 90°C for 90 hours. A conducting defect was simulated by inserting a sharp metallic needle into the dielectric body. The trees were expected to initiate from this point. The needle used had a nominal tip radius of curvature, 5 μm. The selected pins were inserted into the insulation at 130°C and annealed for half an hour to relieve the residual strain at the tip of the needle. The effective thickness between the central conductor and the tip of the electrode was maintained between 3-5 mm. The space between the pin and the dielectric was effectively sealed with the cold setting araldite and the specimens were immersed in filtered, degassed mineral transformer oil ready for voltage application. The needle was connected to the high voltage source and the conductor of the cable was grounded. The high AC voltage of power frequency was produced from a transformer rated for 20KVA, 50 Hz, 20KV unit. The AC voltage was measured using the capacitance divider.

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Physico-Chemical Analysis

Wide Angle X-Ray Diffraction (WAXD)

This study helps in identifying any variation in percentage of crystallinity of the material or addition of new phases in the tree followed with the breakdown zone. Loss of crystallinity peaks is the indication of characteristic variation in the material. In the present work, WAXD measurements were done with Philips x-ray diffractometer. A scan rate of 2^0/min at 2000 cycles using CuKα radiation of wavelength 1.596 A^0 was applied. A radial scan of Bragg angle (2θ) vs. intensity was obtained with an accuracy of $\pm 0.25^0$ at the location of the peak.

Differential Scanning Calorimetry (DSC)

This technique involves the measurement of energy necessary to establish zero temperature difference between specimen and a reference material when the two specimens are subjected to identify thermal degradation. The melting behavior of the specimens was observed using Perkin Elmer model DSC-2C apparatus. The experiments were performed in nitrogen atmosphere, at a heating rate of 10^0C/min. Alumina was used as a standard.

III. Results and Discussion

Fig. 1 shows the optical photographs of different type of electrical trees formed in the XLPE cable specimen under the AC voltages. It is observed that Bush type of Tree (Fig. 1 a) and a Tree Like Tree (Fig 1b) structure are formed at the tip of the needle electrode which is connected to high voltages. Fig. 1c shows a typical breakdown path formed in the insulation structure due to propagation of electrical tree and terminating to the ground electrode. When high voltage is connected to the needle electrode, the local electrical field near the needle tip enhances and if the order of magnitude exceeds the maximum electric field of the material, causes

incipient damage to the insulation structure. Further, the injection of charges from the high voltage electrode to the insulation structure were trapped near the defect site formed and the charges gets deposited in the surface of the damaged zone causing local reaction with the applied field reducing the electric field in the zone. Also, the decomposition products of the insulating materials subject to discharges are mainly gaseous but unsaturated hydrocarbons and conducting carbons are produced [2]. In general, depending on the electro negativity and the chemical reactivity of the gas contained in the microvoids, it can retard or accelerate the tree growth. Sometimes, the charges were also injected into the insulation structure through the defect formed zone-enhancing field at one point causing further enlargement of channel resulting in *"Tree-Like-Tree"* structure. Otherwise local discharges will occur causing increased diameter of the damage zone forming *"Bush Type"* of electrical tree.
Fig.2 shows the Weibull plot for the failure times of the insulation structure due to electrical trees under composite voltages. Table-1 shows the variation in the characteristic life of the insulation material and the shape parameter for the failure data caused due to electrical treeing. It is observed, under composite voltage, increase in magnitude of DC voltage shows a increase in the characteristic life of the material, irrespective of the polarity of the DC voltage. It is also observed that the failure of insulation due to electrical treeing, the rate of failure is high under AC superposed over positive DC voltage. It appears that the characteristic life of insulation material failure due to treeing is high under AC superposed with positive DC compared with the AC voltages. In addition, from Table- 1, it is noticed that the slope parameter (β) obtained under different electrical stress is varying. It is clear that if the β value is more than one, it is the indication that the failure of the insulation materials is due to local erosion and causing failure of insulation structure. When the electrical stress is high the value of β is less than one indicating that the failure causes intrinsic failure (puncture) of insulation structure. At lower voltage magnitudes, it is noticed, initially with the certain number of samples, the slope parameter is greater than one and as and when the number of failure of samples is increased, the value of β is reduced. Similar characteristics were observed by R. Bozzo et al., showing a reduction in the β values with respect to time [3]. This clearly indicates that, in the specimen which is stressed for a long time, especially in the electrical tree formation studies, the failure of the specimen is not only by the electrical stress but also any local condition formed, which alters the failure rate. It means that the local conditions aid the process of failure and cause failure of the materials at the early stage.

Carrying out experimental studies and understanding the failure times alone is not sufficient. It is essential to understand the physico-chemical changes that would occur in the treeing followed with breakdown zone. The local electric discharges cause considerable changes in the structure of the material surrounding in that volume. Among other things, carbonisation, chain scission and conversion of amorphous to crystalline phase are known to occur. The X-ray diffraction pattern of virgin XLPE material and the treeing followed with the breakdown zone are very similar and for the sake of brevity only the virgin XLPE sample WAXD is shown in Fig 3. The WAXD plot of the XLPE specimen showed two peaks at 21.5° and at 23.9° which are characteristics of 110 and 220 lattice plane [4]. The percentage of crystallinity of the material was calculated using Hinrichsens method [5] and for XLPE material it is calculated by the method as 56. The WAXD spectrum does not appear to show any change in the position of the peaks or their splitting throughout the scan range. This means that hardly any change has occurred in the crystallinity of the material or any new phase in the material.

The diagnosis of tree followed with the breakdown region has been made through differential scanning calorimeter. The DSC thermogram of the virgin and the tree followed with the breakdown path is shown in Fig.4. It is observed a reduction in the melting point of the material in the treed zone. Also a variation in the melting characteristics in the treed zone material indicating that material properties are changed in the treed zone. Now, It is very clear that the tree formation is due to degradation of materials forming free radicals in the zone, which could be explained by the following mechanism.

$$RH \xrightarrow{\text{Homolytic Cleavage}} H^*$$

(Free Radical)

$$R^* + O_2 \xrightarrow{\text{Oxidation}} ROO^*$$

(Alkyl Peroxy radical)

$$ROO^* + RH \longrightarrow ROOH + R^*$$

(Free Radical)

IV. Conclusions

It is observed that the characteristic life of insulation material due to electrical tree is less when the AC voltage is superposed over positive DC voltage compared to AC voltage of same stress. It is also noticed that the failure time is high with the negative DC voltage compared with positive DC voltage superposed with the AC voltage. It is also observed that the values of beta are relatively the same irrespective of the polarity of the DC voltage superposed with AC voltage.The WAXD results indicate no new phases has been observed in the treed zone. The DSC results indicate the thermal characteristics of the material are altered.

V. References

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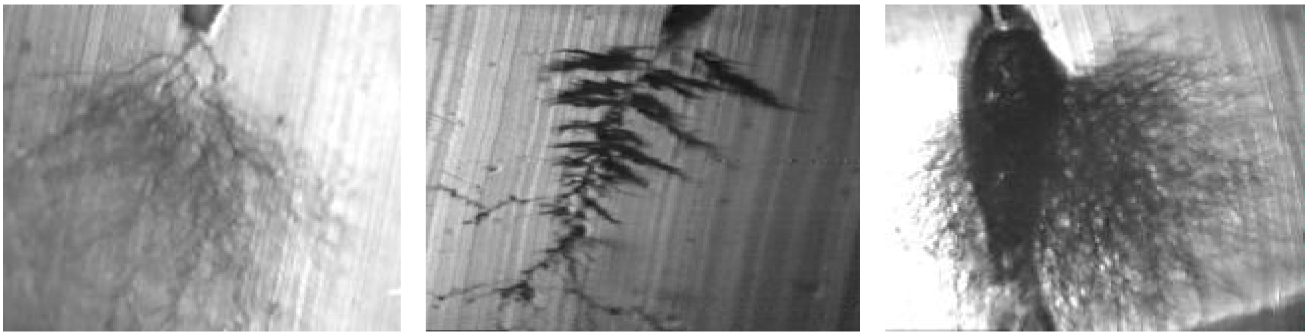

Fig. 1 Electrical Trees under AC voltage (a) Bush Type Tree (b) Tree-Like-Tree (c) Tree Followed with Breakdown

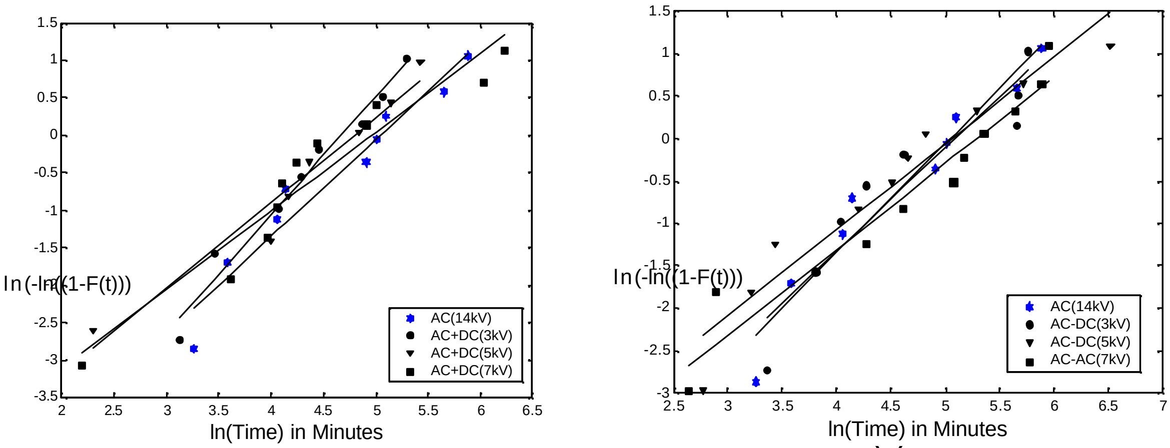

Fig.2 Weibull Plot of Times to Failure of XLPE Specimen due to Electrical Tree Under Composite Voltages (a) Positive DC (b) Negative DC

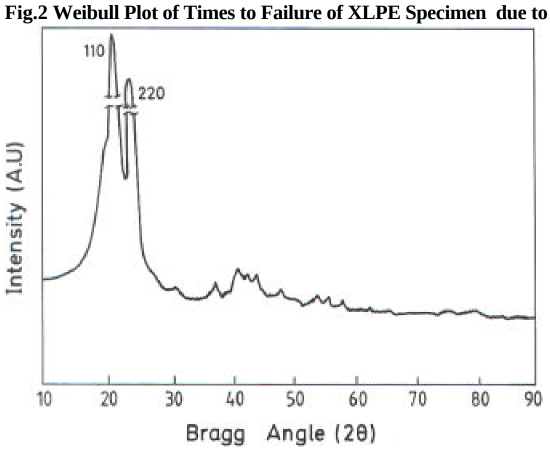

Fig. 3 WAXD Pattern of XLPE Specimen

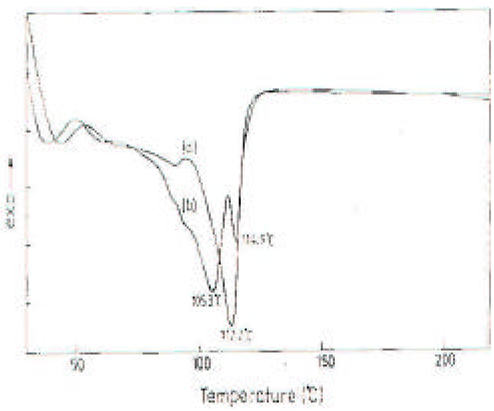

Fig.4 DSC Thermogram

(a) Virgin (b) Treed Zone

Table-1 Variation in Characteristic life and shape parameter at different voltage Levels

Voltage Magnitude	Time in Minutes	Shape Parameter(ß)
14kV AC	155	1.2969
14 kV AC+3 kV DC	108	1.57
14 kV AC+5 kV DC	121	1.13
14 kV AC+7 kV DC	147	1.05
14 kV AC-3 kV DC	163	1.21
14 kV AC-5 kV DC	157	1.01
14 kV AC-7 kV DC	199	1.00