Study of Degradation Phenomena of Solid Insulation used in Extra High Voltage Cable under Alternating Voltage Stress

Subrata Karmakar

Department of Electrical Engineering
National Institute of Technology
Rourkela-769008, Odisha, India
E-mail: karmakar.subrata@gmail.com

***Abstract*— In order to balance the power demand against the population growth the applications of power cables are getting important role in the field of extra high voltage power transmission. Most of the power cables are insulated with Cross Linked Polyethylene (XLPE) as it offers high dielectric strength against the high voltage stress. Such power cables are failed to carry the huge power due to internal discharge i.e., partial discharge occur inside the insulation. Partial discharge in polymeric insulation of high voltage power cable causes cumulative damage that progressively deteriorates the insulation, leading to eventual failure. In view of the above, the condition monitoring of such power cables is very much essential to get early indication of degradation processes inside the XLPE insulation which leads to catastrophic failure in power system network and moreover to cope up with the huge power demand. In this work, the formation of electrical tree inside the XLPE insulation consider as one of the vital cause of insulation failure due to partial discharge has been conducted in high voltage laboratory.**

Keywords—Partial Discharge; Cross Linked Polyethylene; High Voltage; Power Cables

I. INTRODUCTION

Nowadays with fast increasing in population growth increases the power demand rapidly in exponential manner. In order to balance the power demand against the population growth the applications of power cables are getting importance role in the field of extra high voltage power transmission. Most of the power cables are insulated with Cross Linked Polyethylene (XLPE) as it offers high dielectric strength against the high voltage stress [1]. Therefore, the continuous monitoring of high voltage power cables is utmost requirement in order to cope up with the huge power demand. It is studied that most of the cables are failed to carry the huge power due to internal discharge i.e., partial discharge occur inside the insulation. Inception of partial discharge is a sign of ageing and degradation in solid insulating systems of power plants and can be detected in an external circuit as electrical current pulses related to individual discharges in the material [2, 3]. In view of the above, the condition monitoring of such power cables is very much essential to get early indication of degradation processes inside the XLPE insulation which leads to catastrophic failure in power system network.

In this work, an experimental study has been conducted on XLPE insulation used in the high voltage power cable. The formation of electrical tree inside the XPLE insulation due to presence of impurities is also discussed. The degradation/ageing processes of such XLPE insulations are done by conducting with the help of partial discharge test facility in the high voltage laboratory. Finally, the deformation structure and formation of electrical tree inside the insulation is investigated and analyzed using optical microscope.

II. DEGRADATION PHENOMENA OF SOLID INSULATION

In power system equipment, electrical tree formation prevention is very much crucial for reliable and long term operation of cable section. The growth mechanism of electrical tree in high voltage and extra high voltage dielectric system is needed for early identification, in order to defend against the complete insulation failure. There are many varieties of electrical tree structure can form from a weak region or an imperfection site in cable insulation. The point to plane sample geometry is the most commonly used technique to generate high field. The geometric field enhancement, ignoring space charge effects can be determined using Mason's equations

$$E_{tip} = \frac{2V}{r\ln[1+(4d/r)]} \quad (1)$$

Where, V is the applied voltage, r is the radius of the needle tip, d is the gap distance between the needle tip and the ground and E_{tip} is the calculated electric field at the needle tip due to electrode system geometry in the absence of space charge.

Electrical Tree

Electrical trees are micrometre scale defects which developed in high voltage solid polymeric insulating materials, and are

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precursor to long term failure. Treeing degradation is one of the most important physical evidence of internal damage to cable insulation caused by high electrical stress [4, 5]. Electrical treeing phenomena have been studied for many years, under both AC and DC conditions with the earliest publications reported to have emerged in 1912 [4].

The formation of electrical tree in polymers basically consists of three different phases like (i) Inception (ii) Propagation (iii) Final Breakdown/runaway

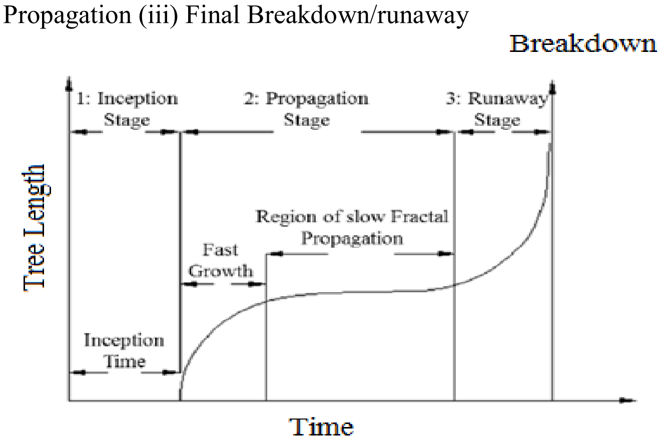

Fig. 1 Growth characteristic of electrical treeing

From the initiation of electrical tree formation to breakdown of the insulations, the three different tree formation stages are proposed by Dissado and Fothergill [6]. The essential time for formation of visible tree length about 10 μm with applied voltage is known as the initiation stage. The second stage of formation of electrical tree inside the insulation is starts very fast and compare to the end of the same stage. Finally, the dielectric strength decreases with increase of the tree length which leads to complete breakdown known as Runway stage as shown in Figure 1. The electrical trees are mainly categories in three way depending upon the structural formation [7-9] (i) Branch type (ii) Bush type and (iii) Bush-Branch type. Figure 2 shows the different type of electrical tree formation.

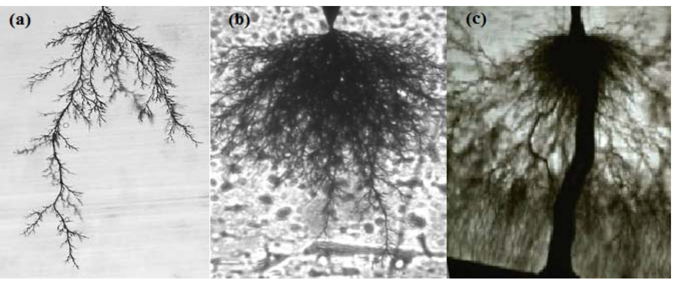

Fig. 2 Type of electrical treeing (a) branch type (b) bush type (c) bush-branch type

The degradation of the XLPE cable insulation can occur due to physical and chemical ageing in absence of applied electric field. However, with the application of high electric field the degradation processes is accelerated in both. Depending upon the type of the electric field and its magnitude as well as the thermal, mechanical and environmental factors influence the degree of degradation process in XLPE cable insulation. The table 1 depicts the ageing factors affecting extruded XLPE cable insulation.

TABLE I. AGING FACTOR AFFECTING EXTUREDED XLPE CABLE INSULATION

Thermal	Electrical	Environmental	Mechanical
Maximum T	Voltage (AC, DC, impulse)	Gasses (air, oxygen, etc)	Bending
Low, high ambient T	Frequency	Lubricants	Tension
Temperature gradient	Current	Water/humidity	Compression
Temperature cycling		Corrosive chemical	Torsion
		Radiation	Vibration

III. SAMPLE PREPERATION

At first the single conductor with XLPE insulation of 1 meter length was cut from a commercially available cable drum contains 100 meter power cable shown in Fig. 3 (a). The cable having conductors of 12 mm diameter and XLPE insulation of 11 mm thick cut axially along the cable conductor into small species of 5 mm thick shown in Fig. 3 (b). The thin black color semiconducting layer was removed from the outer periphery of the cable conductor shown in Fig. 3 (c). The inner semiconducting layer was also cleaned with the help of sharp knife and a hollow circular disk was obtained. There after white color XLPE insulation was cut into small rectangular shape of length 25 mm and width 10 mm shown in Fig. 3 (d). As XLPE cable insulation is very hard material and was kept on the hot plate in order to soften the material. The XLPE cable insulation was heated with 200°C in order to soften the material and two needles were inserted axially in opposite in direction keeping a gap 4 mm between them. The needles were of 2 μm tip radius each used as a high voltage and another one as ground electrode. The length of the stainless steel needle electrode used for this experiment was 40 mm.

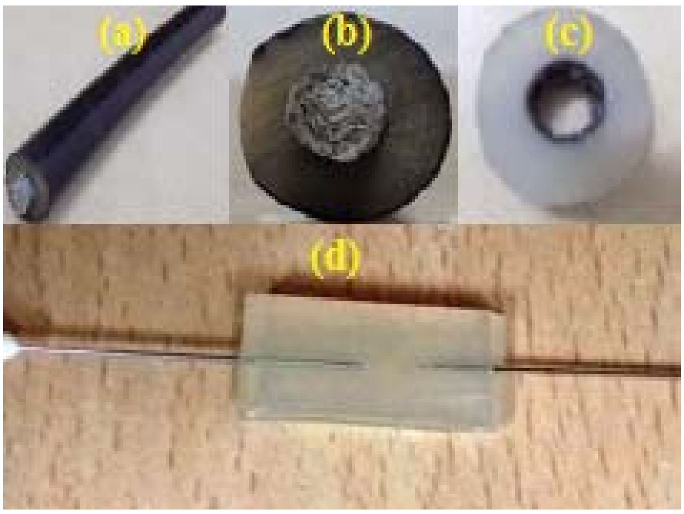

Fig. 3 XLPE cable insulation sample preparation process (a) 1 meter length XLPE taken from power cable coil, (b) Cross-sectional view of XLPE with conductor (c) Cross-sectional view of XLPE without conductor after removing the external semiconductor, (d) Small rectangular shape of XLPE cable along with needle electrode.

IV. Experimental Setup

In this work, partial discharges were generated in a dielectric test cell (80mm × 120mm × 50mm) associated with needle-XLPE insulation arrangement. The cell was filled with new transformer oil in order to apply variable voltage among the needle. The ageing process of XLPE insulator was done in closed Acrylic chamber. The background noise 1.5 pC was recorded during experiment in doubled shielded HV laboratory. The experimental setup of PDs generation on XLPE insulation is shown in Figure 4.

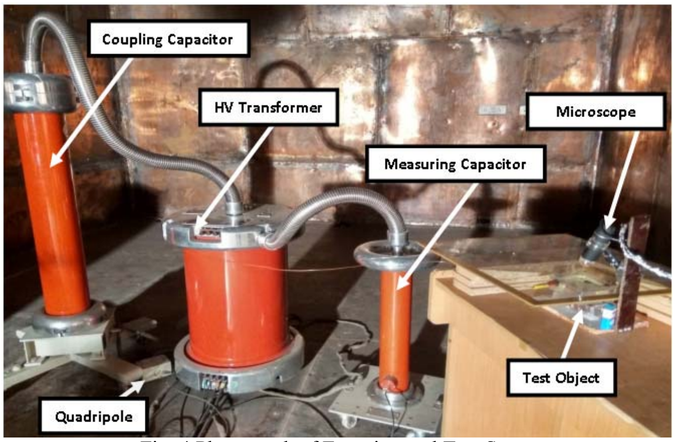

Fig. 4 Photograph of Experimental Test Setup

The partial discharges inside the XLPE insulation was generate from a computer control high voltage source of 20 kVA, 230V/100kV, 50 Hz. As per the standard IEC 60270 partial discharge test was conducted and voltage was increased from 0 to 15 kV, in 1 kV steps. The coupling capacitor (1000 pF) and capacitor type voltage divider (100 pF) was used to measure the applied voltage and the PD magnitude respectively. A digital storage oscilloscope DSO 2000C, having 100 MHz bandwidth and a sampling rate of 1 Giga samples/sec is used for data storage and further analysis. Finally, the degradation process of the XLPE insulation due to PD activity was analyzed by using digital microscope (make: Leica Model: DM750M). The image magnification varies in the range of 50x to 1000x. However, to verify the morphological structure of XLPE insulator after the PD activity inside the high voltage power cables such type facility is very much essential.

V. Result and Discussion

The partial discharge (PD) test was conducted as per the standard IEC 60270 [10]. The PDs inception voltage of 3.3 kV was observed. The partial discharge was detected with help of conventional electrical method. As the PDs were random in nature the frequency of the discharge signal were lies in the range of 40 kHz to 500 kHz shown in Fig. 5. The degradation of XLPE insulations are observed under high voltage stress of 9 kV shown in Figure 6.The growth of the electrical tree formation in XLPE insulation over a certain time period is observed. There is no tree formation is observed at the time of applied voltage shown in Fig. 6 (a).

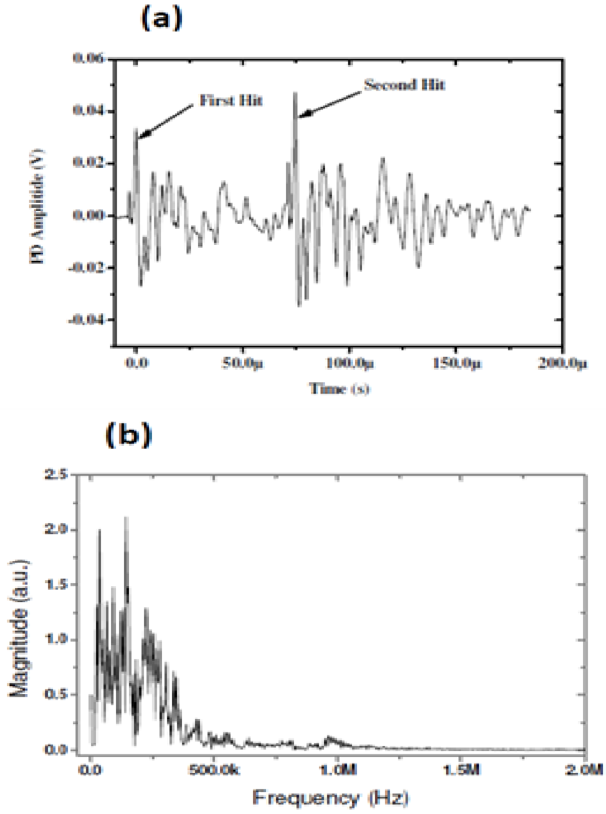

Fig. 5 Partial discharge signal recorded at an applied voltage of 9 kV (a) PD amplitude varies with Time (b) Spectrum of PD signal

However, with the increase of time and with same applied voltage different shape of electrical tree formation is visible. The Fig. 6 (b) and Fig. (c) shows the electrical tree formation at the time instance 5 minute and 10 minute respectively.

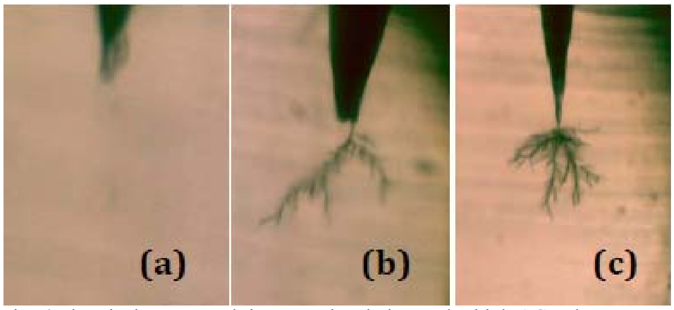

Fig. 6 Electrical tree growth in XLPE insulation under high AC voltage stress. (a) without tree 9 kV 0 Min (b) with tree at 9 kV 5 Min. (c) with tree at 9 kV 10 Min.

For a certain applied electrical field, the electrical tree length is increases with the increase of time. Figure 7 shows that at different time instances the growth of electrical tree increases and the degradation process of XLPE insulation is continue. The electrical tree width and the area were measured at different time instance along with the tree length which is depicted in table 2. It is clear that with increase of time duration for formation of electrical tree the width as well as area is also an increase along with the increase of tree length.

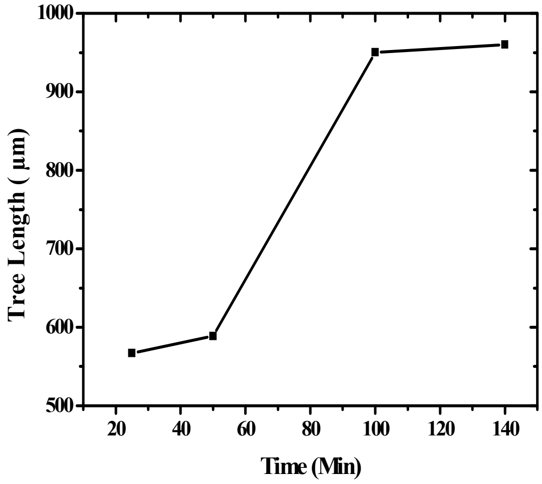

Fig. 7 Variation of electrical tree length with the time at 9 kV.

Similarly, at different applied voltage (8 kV and 10 kV) the growth of electrical tree are also measured which is shown in Fig. 8. The results shows that with the higher applied voltage the length of the tree are increases much compare to lower applied voltage.

TABLE II. ELECTRICAL TREE GROWTH AT 9 KV APPLIED VOLTAGE

Sl. No.	Duration of Tree Formation (Min.)	Tree Length (µm)	Tree Width (µm)	Tree Area (μm^2)
1	25	567.324	495.731	299550
2	50	588.912	520.046	308917
3	100	950.079	1140.543	1107817
4	140	960.192	1164.849	1178748

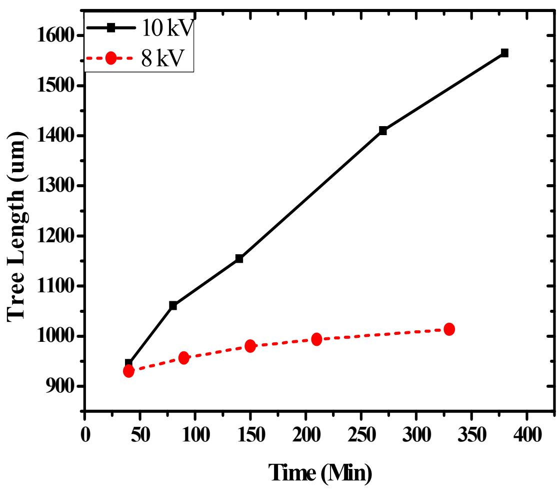

Fig. 8 Variation of electrical tree length with time at different applied voltage.

VI. CONCLUSSIONS

In this work, an experimental study has been conducted on XLPE insulation used in the high voltage power cable. The formation of electrical tree inside the XLPE insulation due to presence of impurities is also discussed. The degradation/ ageing processes of such XLPE insulations are done by conducting with the help of partial discharge test facility in the high voltage laboratory. The Ageing and deterioration of insulation is due partial discharge activity inside the high voltage power cable. The discharge activity inside the XLPE cable insulation for long period of time is one of the cause of insulation failure. Finally, the deformation structure and formation of electrical tree inside the insulation is investigated and analyzed using optical microscope.

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