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Investigating Thermal Effect on a Cross Linked Polyethylene Power Cable

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Abstract

One of the agents responsible of the degradation of power cables in electrical distribution network is the temperature. In this paper, numerical modelling of temperature effect on the cross linked polyethylene (XLPE) insulation of a medium voltage cable containing internal defects, which are air void cavity and water tree cavities, is developed by using the finite element method and simulated by COMSOL Multiphysics Software. The experimental investigation is conducted through studying parial discharge inception voltages in XLPE insulation before and after 23 heating cycles of a 7 meters sample of a medium voltage cable at 100°C and 120°C temperatures. Partial discharge inception voltages detection were performed using the IEC60270 test method. The simulation results and experimental measurements assessed the thermal effect on the degradation of XLPE insulation.

Keywords: *XLPE cable, temperature, Finite element method (FEM), pPartial discharge, IEC60270 test method*

1. Introduction

Underground XLPE insulated cables are widely used for transmission and distribution networks. Several problems in these cables are caused by external activities, but more than half of the damage is due to internal defects in the XLPE insulation system [1]. Although XLPE has good dielectric properties for high voltage applications, ageing of this insulation material cannot avoidable after long time in operation under various stress conditions, such as electrical stresses (due to voltage), thermal stresses (due to loss), mechanical stresses (due to vibration) and environmental stresses (due to pollution, humidity) [2]. In fact, several studies have shown that ageing of XLPE cables is related to the temperature of the insulation [3] and the insulation breakdown is closely related to partial discharge activities [4].

All XLPE cables contain antioxidants which protect the XLPE from oxidation during the extrusion and cross-linkng process, and also during the service life of the cable. The rate at which the antioxidant is used up is dependant on temperature. The normal maximum operating temperature of XLPE cables is (90±10)°C. Tests have shown that XLPE cables can operate at a temperature of 105°C for a limited time without significantly reducing the service life of cables. At temperatures in excess of 105°C deformation of XLPE readilly occurs, particularly at positions where the insulation is under mechanical stress. The maximum overload temperature of XLPE is limted to (105±10)°C [5, 6].

In the present work, a 2-dimensional model of a single phase medium voltage cable with XLPE insulation is developed based on the FEM. This cable model comprises internal defects in the insulation material which are air void cavity, vented water tree cavity and bow tie water tree cavity. The thermal effect is described by simulating the distributions of ambient temperature (30°C), the normal operating temperature (100°C), and the overload temperature (120°C) throughout the cable structure based on 3-dimensional modeling. An experimental study is subsequently carried out. A medium voltage cable sample of 7 meters issubjected to 23 cycles of heating at 100°C and 120°C. After that, an artificial defect is created by a needle in the insulation,heating cycles are repeated with the same conditions.Partial discharge inception voltages are measured continuously before and after heating periodsby the IEC60270 test

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method.Finally, the simulation and experimental results are used to demonstrate the effect of temperature on the insulation degradation and the cable breakdown.

2. Numerical Modelling of Thermal Effect on XLPE Cable

This section focuses on the numerical modelling of the temperature distribution in a medium voltage cable that contains internal defects wich are air void cavity and water trees. The model is implemented in the finite element method based on the software package COMSOL Multiphysics.

2.1. XLPE Medium Voltage Cable Description

The cable employed in this study is a medium voltage single phase cable of 18 kV.Its structure is shown in Figure 1. The cable is composed from a copper conductor (1), a semi-conducting layer (2), XLPE insulation (3), a semi-conducting shield (4), a copper tape screen serves as the earth conductor (5), a bedding (6), an aluminum wire armor (7) and a PVC ground sheath (8).

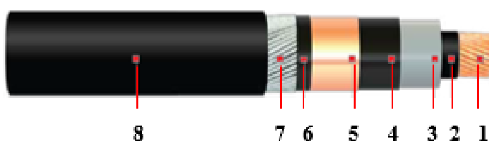

Figure 1. Physical Model of Single-Core 240 mm² XLPE Cable

2.2. Thermal Model of XLPE Cable

In Comsol Multiphysics software a 2D cable model is implemented. It is based on the Finite Element Method that transforms the designed model into a mesh of many elements. It is used to compute the values at every point in the model to get fine results. The software package is composed from many modules. In the present work, the Heat Transfer module is used by adding heat transfer in solids subdivision in it to determine the temperature distribution in the cable containing internal cavities. COMSOL's electrostatic application modes with sub domain settings solve Heat transfer equation:

$$\rho C\frac{\partial T}{\partial t} - \nabla.\left(k\nabla T\right) = Q + h.\left(T_{ext} - T\right) \quad (1)$$

where ρ is the mass specific (kg/m), C is the heat specific (J/m^3.K), k is the heat conductivity (W/m.K), T is the conductor temperature (K), Q is the heat source (W/m), h is the heat transfer conduction and T_{ext} is the external temperature (K).

2.3. Internal Cavities Model

The internal cavities used in this study are air void cavity and water tree cavities which are two types, vented water tree cavity and bow tie water tree cavity. Along the axis of the electric stress, the vented water tree is growing from the insulating material boundaries to the other side of the insulation as shown in Figure 2a. The possibility of vented tree initiation is due to irregularity in the semiconducting screen. It has a bad contact with the insulation [7].

Avented water tree is modeled as is depicted in Figure 2b to simulate the temperature distribution in this type of defect [8].

Bow tie water trees are the permanent structures that grow within the body of polymer insulation, they initiate from impurties and voids within the bulk insultaion and tend to grow in two directions [9].The term 'bow tie' is derived from the shape of the tree as shown in Figure 3a. A bow tie water tree is modeled as is depicted in Figure 3b [8].

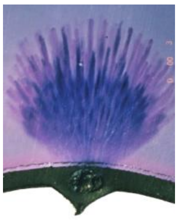

Figure 2a. Vented Water Tree

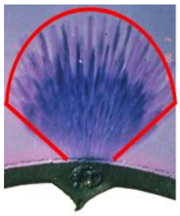

Figure 2b. Model used in Comsol

Figure 3a. Bow-Tie Water Tree [10]

Figure 3b. Model used in Comsol

2.4. Temperature Distributions in XLPE Cable

The distributions of ambient temperature, normal operating temperature and maximum overload temperature are shown in Figure 4a, Figure 4b and Figure 4c respectively.

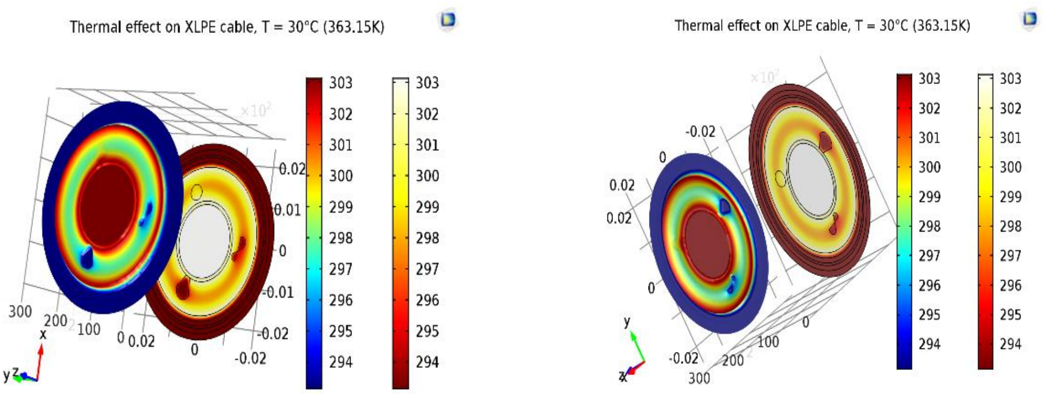

Figure 4a. Temperature Distributions in XLPE cable at Ambient Temperature: T= 30°C

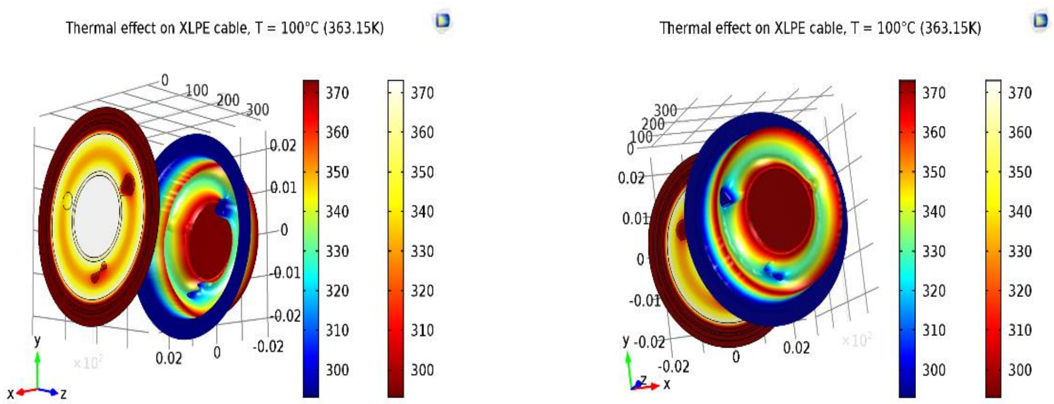

Figure 4b. Temperature Distributions in XLPE cable at Normal Operating Temperature: T= 100°C

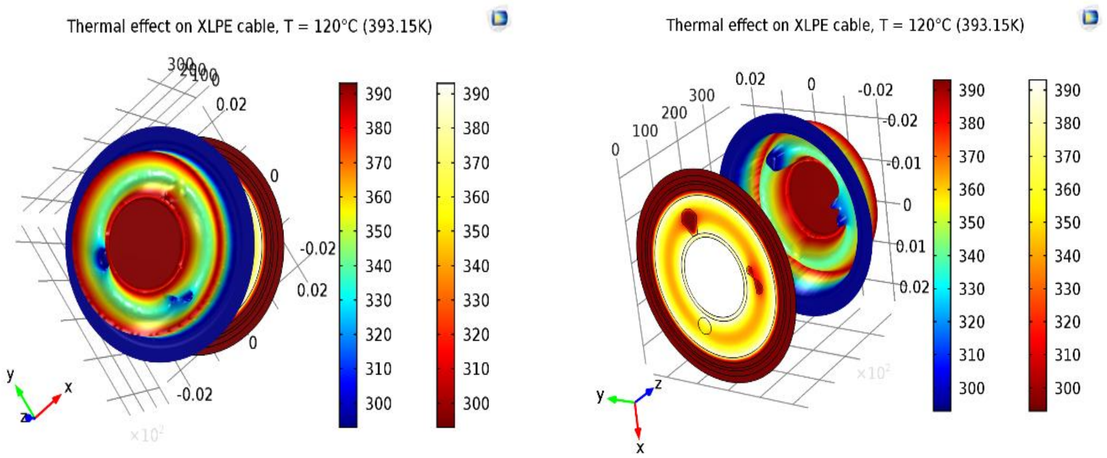

Figure 4c. Temperature distributions in XLPE cable at Maximum Overload Temperature: T= 120°C

The cable is heated for 23 days and thermal cycles are performed as follows [11]:

a) A test of 20 cycles of heating, 8 hours of heating at the temperature of 100 °C and 16 hours cooling in air at ambient temperature.
b) A test of three heating cycles, 8 hours of heating at the temperature of 120 °C and 16 hours cooling in air.

A load current transformer is used to heat the cable by applying a current of 1500 A as shown in Figure 5. Heating temperatures are chosen in accordance with IEC 60811-1-2 standard, which requires temperature (10±2) °C above the maximum conductor temperature of the cable in normal operation [12].

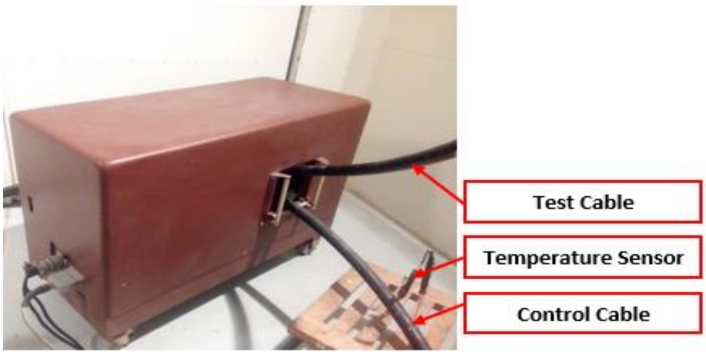

Figure 5. Load Current Transformer

A control cable is used to raise the temperature and allow the regulation of the current transformer, in order to ensure the good performance of heating cycle's tests.

Throughout the different heating cycles, a voltage Uo of 18kV at an industrial frequency of 50 Hz is applied between the conductor and the metallic screen (earth conductor).

The activity of PD is continuously measured by the test circuit shown in Figure 6, [13].

Figure 6a. Partial Discharge Measurement Circuit

Figure 6b. Parial Discharge Detector

In a second phase and in order to produce an artificial cavity inside the insulation, a steel needle-plane geometry is opted. This approach is widely used in research for simulaing the electrical stress enhancements and initiating the electrical treeing inside the polymeric insulation. The insertion of the sharp needle inside the polymer creates a micro-void at the tip of the needle resulting in the inception of partial discharge activity at relatively low voltages [14]. Heating cycles are repeated with the same conditions and partial discharge activities are measured continuously.

3. Results and Discussion

The partial discharge voltage is measured over a period of 20 ms each test day during 23 days of heating. Measurement data are recorded in the form of Excel tables, and partial discharge voltage changes over time have been represented on Matlab software. In Figure 7 is shown an example of partial discharge activities evolutions before and after the heating cycles at 120 °C for the twentieth day.

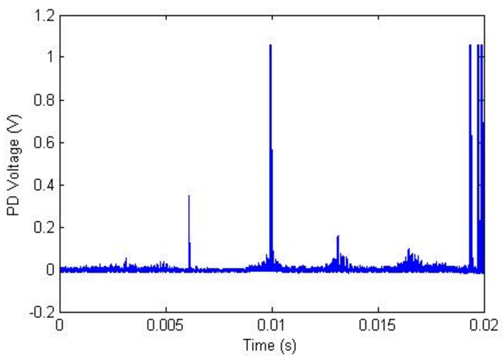

Figure 7a. Partial Discharge Activity before Heating Cycle at 120°C

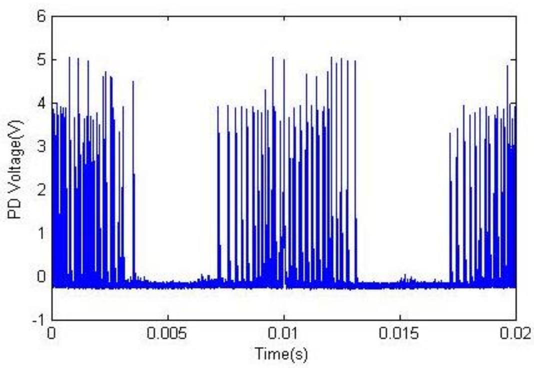

Figure 7b. Partial Discharge Activity after Heating Cycle at 120°C

PD signals have increased after heating cycles of 100°C and 120°C. Figures 4 and 5 show that PD voltage peaks passed from the range between 300mVand 400 mV to the range between 4V and 5 V by increasing the heating temperature.

PD activity evolution during 23 heating cycles is shown in Figure 8 and Figure 9.

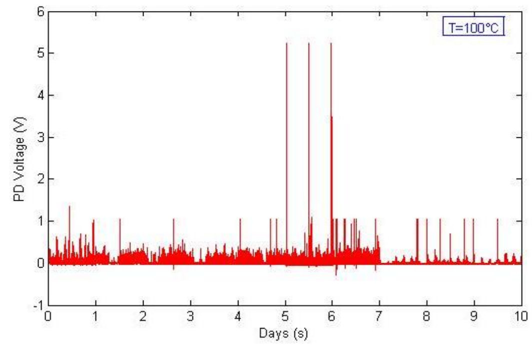

Figure 8a. PD voltage evolution during the heating cycles of 100°C: during the first ten days

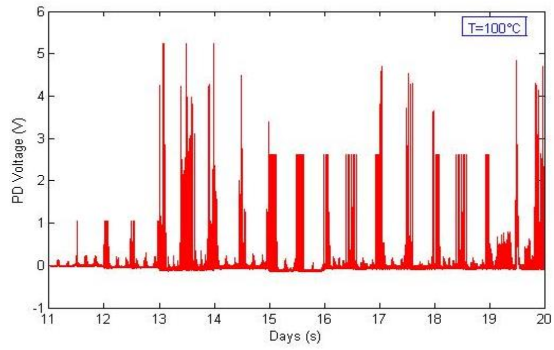

Figure 8b. Partial discharge activity after heating cycle at 120°C: during the last ten days

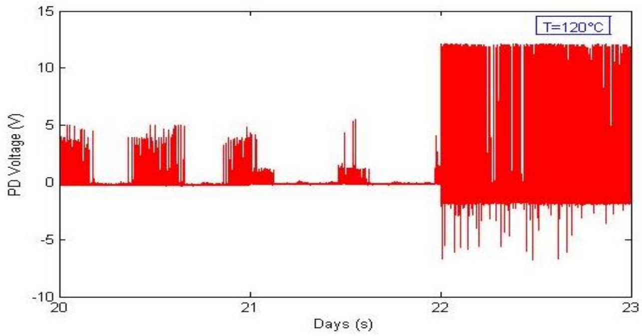

Figure 9. PD voltage evolution during the heating cycles of 120°C

As it can be seen, the partial discharge voltage tends to increase after heating cycles. Figure 9 shows that between days 22 and 23, the discharge pulses are characterized by very high- intensity discharge activity, and the partial discharge voltage reaches 14V whereas it did not exceed a few volts at the beginning of the heating cycle at 100 ° C like is shown at Figure 8.a.

This indicates the increase in surface conductivity of the cavity wall due to the erosion and chemical reactions creating dissociation products of air. This results in roughness of the surface and formation of more localized solid by-products, for example, the formation of hydrated oxalic acid crystals [15, 16].

We can notice that the shape of partial discharge pulse changes significantly over the prolonged insulation ageing. Discharge pulses with extremely short rise time and pulse width are observed at the beginning of heating cycles, it is the initial phase of electrical tree inside the insulation [17].

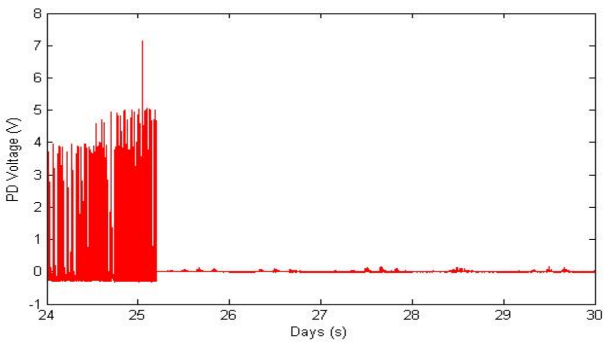

Figure 10. PD Voltage Evolution in the Sample with Artificial Cavity

Partial discharge activity continued with the artificial cavity for only six days as is shown in Figure 10 and then the cable was destroyed.PD voltage drops to almost zero for few days before the cable breakdown. According to research [18], this may take place as a result of carbonization of the partial discharges inside the void.

This phenomenon prevents the voltage build up across the void and creating a very low resistive path for very high currents flows. These high current pulses are known as ‘tiny arcs’. It results in increased heating and severe insulation deterioration.

The intense heat can cause molecular and chemical breakdown of the insulation which further accelerates the deterioration process as depicted at Figure 11.

Figure 11. Damage of XLPE insulation due to accelerated ageing

4. Conclusion

In this paper, the effect of temperature on XLPE insultaion of a medium voltage cable has been studied. This study is based on a finite element model of temperature distribution in the cable containing internal defects, and on an experimental measurements of the evolution of the inception voltage of partial discharge activity in a cableundergoing heating cycles.

According to the simulation results, we can see that internal defects in the insulation are accentuated with the temperature increase, these structural changes in the cross linked polyethylene morphologie due to thermal ageing generate changesin dielectric properties of the XLPE cable which are confirmed by experimental measurements.

This work is still in development and research field is oriented on the analysis and the exploitation of partial discharge signals in order to build up a fundamental basis for the development of an accurate remaining lifetime diagnostics of power cables.

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