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Influence of ageing and water treeing to degradation of XLPE insulation

***Abstract**. XLPE is modern material widely used as insulation material for power cables. Many studies and experiments show a significant infulence of ageing and water treeing to degradation of XLPE insulation.This article deals with a short review about XLPE and processes of ageing and water treeing in XLPE cable insulation.These processes, together with a crosslinkingand amount of peroxide and antioxidants affect to quality and properties of XLPE insulation.The measurement of dielectric parameters of XLPE cable sample was carried out by the method of dielectric relaxation spectroscopy (DRS) in frequency domain. It was observed a change of parameters in consequence of additional ageing.*

Keywords: insulation, XLPE cable, ageing of XLPE, water treeing, TRXLPE.

Introduction

Power cables are very important and sensitive devices in the power system, and they play an important role in the safety of thepower load and reliable transmission of electricity.

Nowadays, the majority of power cables are insulated with polymeric materials. Cross-linkedpolyethylene(XLPE), as the main polymeric insulation,is widelyusedaselectricalinsulation materialforhigh-voltagedistribution power cables. This insulation material provides excellentphysical, chemicalandelectrical properties.

Thepower cables may be exposed to high currents and voltages and they are critical parts of the transmission infrastructure. Therefore, is expected their high resistance against possible failures [1]. Damage of insulation can lead to equipment failureandotherdisorders.

The insulation degradation is inevitable during the operation and the failure rate of XLPE cable increases with the service time [16].The cables are permanently exposed to thermal ageing during operation. It may cause change in dielectric parameters of cables and also irreversible damage of cable insulation. The primary initiators for the degradation of cable insulation are high currents, voltage, mechanical, chemical and thermal stress and pollution of environment. Interaction various factors together may significantly speed up the degradation processes. Process of ageing of insulation is the most acting on the parameters and quality of insulation.

In most casesfailures in the insulation are related to integral degradation of the insulation like water treeing in XLPE cables.It is also known, that the insulation failuresmay be caused by lower dielectric strength due to ageing processes or by internal defects in the insulation system.[1]

In a wet environment, XLPE insulation materials are subject to water treeing which is still an important cause of cable failures.Water tree degradation is one of the most serious faults that can occur at XLPE cables andit is a prebreakdown phenomenon associated with dielectric cable failure.Many studies have been performed concerning water trees in XLPE based materials.[12, 13]

This paper presents a short review about ageing and water treeing in XLPE cable insulation.

About XLPE

Polyethylene (PE) is a long chain semicrystallinepolymer manufactured through the polymerization of ethylene gas. PE was very popular, compared to paper insulation, as insulation for cables because of its low cost, good electrical properties(low dielectric constant, low dielectric loss, and high breakdown strength), processability, mechanical toughness and flexibility, good resistance to chemicals and moisture. [9]

XLPE is a material produced by the compounding of low density polyethylene (LDPE) with a crosslinking agent such as dicumyl peroxide.XLPE has good dielectric properties for high voltage applications. However, ageing of XLPE material can not avoidable after long time in operation under various stress conditions. XLPE insulated cables for high voltage applications have been studied and investigated in order to evaluate a function of service stresses and ageing time. Many researcher are studied improved XLPE properties in order to improve dielectric performance of XLPE material. [14, 15]

During the production of XLPE, this is molten and cooled serveral times. The material properties are influenced by the manufacturing process, heating and cooling temperatures and time. During the cable production the material is also heated and cooled several times during the different steps. The cooling process influences significantly the morphology and thus the electrical properties of XLPE cable.The electrical breakdown strength is depending on the density and it is also depending on the increase of the amorphous structures inside the polyethylene.[5]

Defects in XLPE may be introduced in the process of transporting or laying, although cable manufacturing is improved. In practical service condition, electric field deformation around these defects is very sharp and exert negative effects on the XLPE insulation breakdown. The breakdown of XLPE is closely related to electrical trees and partial discharges and it was found that the breakdown voltage decreased with an increase in frequency. [4]

Crosslinking Process

In this process, the long-chain PE molecules “crosslink” during a vulcanization process to form a material that has electrical characteristics that are similar to PE, but with better mechanical properties, particularly at high temperatures. The dominating process in the industry is the peroxide cross-linking process. Recent studies by

Smedberg et all. Haveshown that XLPE has different types of cross-linking points and there are beside chemical cross-linking also physical cross-links and both are nearly equally strong and influence the structure of XLPE.[14, 5]

The crosslinking of some polymersto form XLPE was first accomplishedin 1955 at the GE Research Laboratoryin New York, USA. Crosslinking increases maximumoperation temperature to 90 °C, the emergency temperatureto 130 °C, and short-circuit maximumtemperature to 250 °C. Crosslinking alsoincreases dimensional stability, impact strength, tensile strength, chemical resistance, thermal properties,and it improveselectrical properties, ageing, andsolvent resistance of polyethylene.[9]

Influence of Peroxide and Antioxidant [5]

XLPEis never used without peroxide and antioxidants. The choice of these additives will influence the morphology of the insulation.Additives like antioxidants can influence the crystallization temperature of a pure LDPE.

In commercial XLPE formulation, several different kinds of mixtures of antioxidants are used. The antioxidants are chosen for their long term protection, since cables are designed for a life time of 40 years. Several antioxidants are also used in combination and the influence of these antioxidants on the properties of XLPE are evaluated in many studies. The different antioxidants also influence the overall properties of the cable insulation and they will additionally influence the decomposition of the peroxide that is used for cross-linking of PE.

The decomposition products of peroxide are mainly acetophenone (AP), α-methyl-styrene (MS), cumylalcohol (CA), methane and water. For safety reasons, methane should be removed out of the cable. However also the other cross-linking by-products will influence the electrical properties under AC and DC conditions. It is known that acetophenone increases the AC tree inception voltage, decreases the insulation resistance and increases the space charge after a DC voltage application.

Ageing of XLPE insulation

In general, during the operation an insulation system is subjected to one or more stress that causes irreversible changes of insulating material properties with time.This process is called ageing and ends when the insulation is no more able to withstand the applied stress. The relevant time is the time-to-failure or time-to-breakdown, alternatively called insulation life time.In the case of electrical insulation, the stresses most commonly applied in operation are electric field (due to voltage) and temperature (due to loss), but also other stresses, such as mechanical stresses (vibration) and environmental stresses (pollution, humidity) can be present.[15]

Stability of microstructure and composition of the insulating material is changing due to degradation processes. These changes result to changing behaviour of insulation material from view of polarization processes. Ageing in a polymer changes the electrical, physical, mechanical and morphological properties of the insulation [19]. All these properties are influencing the dielectric parameters and characteristics of insulation [21].

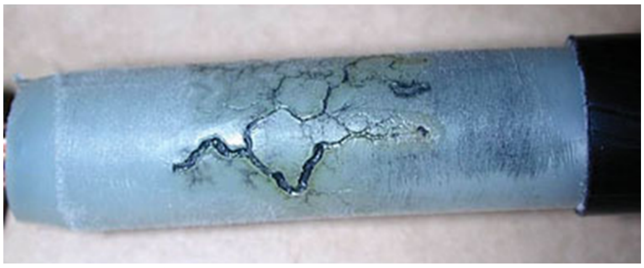

Fig. 1 Damage of XLPE insulation due to ageing

XLPE is composed of crystalline phase and amorphous phase. Defects such as submicrovoids and microvoids in XLPE may be formed and developed at the interface of crystalline and amorphous area, which can be regarded as weak point of insulation.[12].

Integral ageing of XLPE cables changes the morphological properties of the insulation. It is well known that the aged XLPE cable insulations have many microvoids whose number increases with the distance from the cable conductor. Their dimensions and number depend on the technology and the kind of cable insulation. It is generally assumed that during production, microvoids, impurities, water and residual products from crosslinking will be collected in amorphous regions of the insulation. Increasing of ageing temperature , the microvoids are of larger size. [7]

XLPE insulation is low-mobility material in which the mean free path length is quite small. However, the injected high energy electrons may easily cause bond dissociation in insulation. With the development of bond dissociation, some low density regions, low cohesive energy density regions and thus free volume can be generated. In these regions, impact ionization is more likely, and thus leading to avalanches, partial discharge and eventually breakdown of the XLPE insulation. Such a process can be accelerated when there are weak points on the interface of void and insulation. [4]

Ageing of XLPE cables is related to the temperature of the insulation. All XLPE cables contain antioxidants which protect the XLPE from oxidation during the extrusion and cross-linking process, and also during the service life of the cable. The rate at which the antioxidant is used up is dependent on temperature. The normal maximum operating temperature of XLPE cables is 90°C.

The rate of consumption of anti-oxidant has been calculated to provide a cable life of a minimum of 30 years at normal maximum operating temperature. Increasing the operating temperature of the cables will increase the rate at which the anti-oxidant is used up and hence reduce the service life.Small increase in temperature has a significant impact on the ageing of the XLPE. The XLPE will start to oxidize and become brittle, once the anti-oxidant in the cable is used up. This then leads to the cable will be subject to stress cracking and electrical failure at positions of mechanical stress. [20]

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. Under these conditions, the cables should be applied for a maximum of 4 hours at any one time, for a maximum of not more than 100 hours in any consecutive months, and for not more than 500 hours in the lifetime of the cable.At temperatures in excess of 105°C deformation of XLPE readily occurs, particularly at positions where the insulation is under mechanical stress. The maximum overload temperature of XLPE is limited to 105°C.[9, 20]

When the cables are ageing in hydrothermal condition for a period of time, the mechanical and electrical properties of the XLPE insulation may degrade, which may lead to an apparent deterioration in dielectric performances such as electric conductivity, permittivity and dielectric loss. The physical form and chemical structure of XLPE cables will be altered.An increase in humidity leads to an increase in the low frequency lossand it was found that the relative humidity had a statistically significant linear relationship with the loss values.During thermal ageing, several structural changes occur such as variation in crystalline, chain scission and variation in heat of fusion and in melting point. [12, 13]

Quantitativeassessment ofageingordamage of the XLPEinsulations can beseparatedassessment of therelaxationmechanisms.XLPE cable ageing has been studied for nearly 40 years and many methods have been proposed to evaluate the properties of XLPE. [12]

Accelerated ageing

It is degrading stresses of insulation material, such as electrical stress, thermal stress, mechanical stress, and environmental stress. The accelerated ageing process usually studies multi-stresses (double or triple stresses). Widely used multi-stresses are electrical - thermal stress and electrical – mechanical stress.

There are several methods to accelerate the ageing process. The most popular are experimental performed on insulation material at voltages and temperatures higher than normal operating conditions.There are also two methods of apply voltage stress to insulation material. In the first method, the voltage is held constant until sample aged and breakdown. In the second method, the voltage stress is increased in steps until sample aged and breakdown. For both methods, when breakdown occurred are noted experimental data of lifetimes for calculation life models.[7, 15]

Water treeing in XLPE insulation

Well known ageing phenomenon of cables with polyethylene insulation is water treeing. This phenomenon can reduce the service life of XLPE cables and it leads to degradation of the insulation.In the last decade, many theoretical investigations and experiments were made to describe the effect of water absorption in XLPE cable insulation [7].

The cables having water trees exhibit reduced value of the retained AC breakdown strength. The parameters to assess the extent of insulation deterioration caused by water treeing are the retained AC breakdown strength and water tree characteristics of the cable. For water tree formation in XLPE cable insulation is required existence of water in insulations. Water can be absorbed into the insulation at the time of cable manufacturing, stocking and installation,or in practical service condition from the end or terminal of the cables. The most important process is that water enters through the cable insulation from outside environment during service of installed cables. [6, 12]

Typical water trees are shown in Figure 2. Water trees grow relatively slowly over a period of months or years and they can grow from both the outside inwards and from the conductor outwards toward the outer semiconducting layer through the insulation.The electrical stress can increase to the point that an electrical tree is generated at the tip of the water tree. Electrical trees then grow rapidly and the insulation is so weak that it can no longer withstand the applied voltage. Then an electrical fault occurs at the water/electrical tree location.Water treeing phenomenon is also the main reason causing the ageing of XLPE cables, especially the middle and low voltage cables.[14, 8]

Water treeing or electrochemical in solid dielectric cable has been recognized since 1969. Water trees are generally observed as a dendritic pattern of water-filled microcavities in the polymer. These microcavities are connected by oxidized “tracks,” probably about 10 nm wide.The length of these microscopic structures increases with operation time.

Water treeing is best described as a self-propagating pattern of electrooxidation, which results from electro-oxidation of the hydrophobic polymer to a substantially more hydrophilic state. This causes condensation of moisture from the surrounding hydrophobic polymer into the hydrophilic electro-oxidized region, resulting in self-propagation of the electrochemical “water” tree.Such self-propagation (water treeing) is likely to occur in any polymer that can be oxidized to a substantially more hydrophilic state, which includes a wide range of organic polymers.[9]

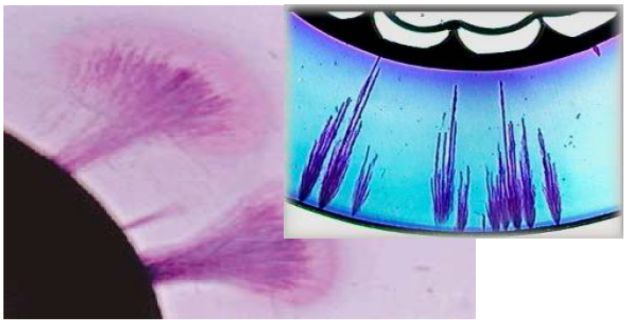

Fig. 2Water trees growing from the inner (bottom) and outer (top) semiconductive screens[14]

Tree-retardant XLPE

Many actions can be taken to reduce water tree growth. The approach that has been most widely adopted is the use of specially engineered insulating materials designed to limit water tree growth. These insulation materials are called TRXLPE. In North America, additive-based TRXLPE was introduced in the early 1980s and has shown excellent field service performance. [9]

Many extensive studies have been made to improve the resistance of XLPE to water treeing. Work in this respect can be categorized into three general methods:

1) Use of additives in the conventional XLPE. They are usually of low molecular weight organic species to incorporate water retardancy.
2) Blending XLPE with polar polymers, which forces XLPE to make it slightly hydrophilic and reduces the condensation of water and thus water treeing.
3) Use of very low density polyethylene (VLDPE), which represents a newer and more effective method for increasing the tree resistance of XLPE and improving the properties of the PE base.

TRXLPE insulation consists of XLPE with a tree-retardant additive. This insulation does not stop water tree growth, it impedes water tree growth, i.e., the number and size of water trees is reduced.Tree length comparison between TRXLPE and XLPE is shown in Figure 3. Some varieties of TRXLPE dielectric contain a dispersion of hydrophilic molecular clusters in the hydrophobic matrix. It islogicalto assume that the hydrophilic clusters “stop” water tree channels, i.e., when a water tree channel “hits” a tree-retardant cluster, it stops propagating. It is probably because the hydrophilic cluster impedes condensation of water into any electro-oxidized region near it, so that the water tree cannot propagate. [9]

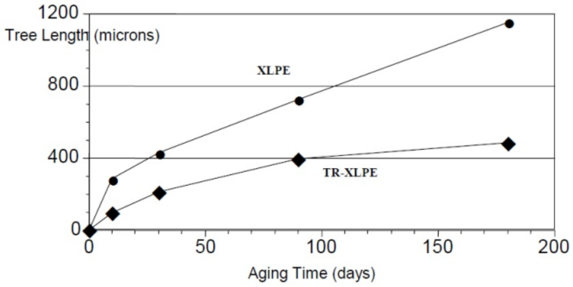

Fig. 3Tree length comparison between TRXLPE and XLPE[17]

A tree-retardant grade has shown improved performance in accelerated ageing tests. This leads to superior longterm reliability. Projected useful life of TRXLPE cables is more than 40 years and they can operate under emergency conditions with a conductor temperature of 130 °C for periods of up to 36 h, not more than three times per year.[9]

TR-XPLE insulations were commercialized in the early 1980's and have now been performing reliably in service for over 20 years.[14]

Water tight cables

The water tight cables have better long term performance when operated in wet environment.The relative life of the partially water tight cable will be more than 1.57 times the life of a conventional cable and life of a completely water tight cable will be more than 2.76 times the life of a conventional cable. The completely water tight cable sheathis bonded to the radial moisture barrier which makes the sheath more robust. Since the cable is mechanically stronger there is less damage in installation and this feature will therefore increase its reliability preventing premature failures resulting from damage of core of cable. In addition, several other technical and economic benefits such as reduced outage rates and revenue losses and increased system reliability are also achieved when these cables are used.[6]

However, such cables are more expensive to produce than the conventional cables. An increase in cost has to be justified by the added benefits of selecting the water tight construction. The added life expectancy and other benefitsmore than offset the added cost.

Although the completely water tight cableshavehigh dielectric strength during ageing, it are not free of water trees. During the ageing process some of the filler in the conductor may be absorbed by the plastic materials in the cable. This in turn allowed water paths to form in the strand and the pressure pushes water into the core of the cable. This small amount of water result in the formation of some small bow-tie trees. [6]

Experiment

Experimental measurement was performed on one cable sample by the method of dielectric relaxation spectroscopy (DRS) in frequency domain. DRS is a one of the non-destructive measurement methods. This method evaluates the dielectric response function in the frequency domain using the dielectric dissipation loss factor tan δ and complex capacitance C(ω). Using DRS in frequency domain can be evaluated the effect of temperature and thermal ageing on dielectric parameters and change of properties of investigated insulation material after ageing and degradation processes.

The sample was aged and degraded cable of operationally unknown technical condition. It was a power cable with an aluminium core and XLPE insulation. Sample of cable was approximately 25 cm long and protective cable jacket and semiconducting layer have been removed (2 cm at both ends) and shielding taken out. Using the precision LCR meter Agilent E4980A were recorded changes of capacitance and dielectric dissipation loss factor depending on frequency. The frequency range of measurement was 20 Hz to 2 MHz. The Increase of frequency was decimal. The measurement was repeated after an accelerated thermal ageing of sample at 90 °C for 72 hours in an air oven.Aim measuring has been comparison of measured frequency dependence of capacitance and dissipation factor of cable sample before and after ageing process.

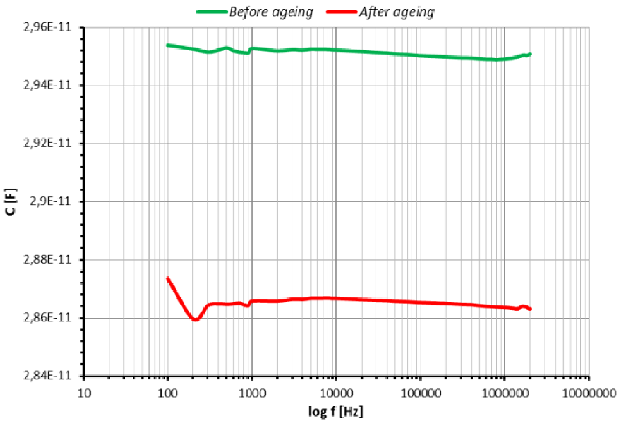

Fig. 4Frequency dependence of capacitance before and after ageing process

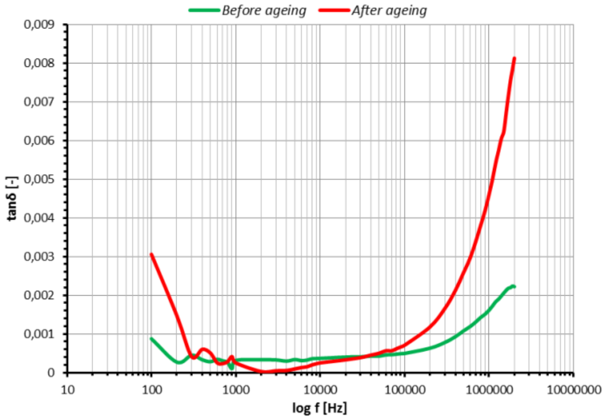

Fig. 5Frequency dependence of dissipation factor before and after ageing process

Figure 4 shows a decrease of the values of capacitance after ageing process. The change of capacitance is very small, order of 10^{-11} farad. From frequency circa 7 kHz occurs a slight decrease of capacitance in both measurements.The resulting dependence of capacitance could be affected by disturbances and surroundings, since the sample size was small with a very small capacitance. Such measurement is sensitive to disturbances and parasitic capacitance.

Figure 5 shows a change of the values of dissipation factor after ageing process. The change of dissipation factor is significant at low frequency up to 200 Hz and at high frequency from 100 kHz where there was a significant and steeper increase of measured values. In frequency range between 1 kHz and 10 kHz was decrease of measured values. The accelerated thermal ageing process caused a change of frequency dependence of dissipation factor.

Conclusion

The purpose of this paper was a short review aboutXLPE cable insulation and the effects of ageing and water treeing on XLPE.

Many studies, extensive tests and many years of practical experiences show that ageing and water treeing have a significant influence on the XLPE insulation.Crosslinking process, peroxide and antioxidants also affect to the quality of XLPE insulation. In the case of ageing of XLPE insulation, there are changes of electrical, physical, mechanical and morphological properties of the insulation. Water treeing is a well known ageing phenomenon of cables with polyethylene insulation, which reduce the service life of XLPE cables and reduce the value of retained AC breakdown strength. It can leads to degradation and damage of the insulation.Today there are TRXLPE insulation that is designed to inhibit the growth of water trees, allowing for even greater reliability for high voltage distribution cables.

The evaluation of measured frequency dependencies of capacitance and dissipation factor of operationally aged sample of XLPE cable before and after the additional degradationshow that ageing process change dielectric properties of XLPE cable sample. Such changes can be related to structural changes in the polyethylene morphology due to thermal ageing. The measurement confirmed the influence of thermal ageing to dielectric parameters of XLPE insulation. It is not possible exclude the surrounding of a disturbance during the measurement, which could affect the measured results. It is important to continue to investigate the process of ageing and their impact on the insulation system with use modern and suitable diagnostic methods and measuring equipment.

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