WATER TREEING IN POLYETHYLENE CABLES

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Abstract— This review discusses water tree growth in polyethylene cable insulations. The characteristics of water trees, the effect of aging parameters on water tree growth and the possible mechanisms of growth are considered, emphasizing vented tree development in polyethylene insulating materials. Moreover, test methods and measures to reduce water treeing are discussed...

Keywords— Water treeing detection; water treeing mechanism; underground polymeric cable; XLPE cable; modified leaf-like method; vented tree; bow-tie tree.

INTRODUCTION

The high voltage cables started making using polyethylene as insulation and became apparent that cables had been laid in wet environments such as under rivers, so their failure rates increased in late 1960's [20]. This phenomenon was found that water from the river was soaking through the outer protective sheaths and was absorbed by the insulation. Only a few percent (by weight) of water can be held by polyethylene. This kind of degradation was transformed and known as water treeing in early 1970's. A water tree is bush-like structure developing in an electrical treeing which is from points of stress enhancement and can Cause a reduction in the insulation's breakdown stress level which encourages the breakdown [20].Water trees can grow at lower electrical stresses and more diffuse than electrical stress. There are two types of water trees that have been recognized which are 'bow-tie "trees and 'vented' trees. They got their name from the pattern of the water trees [20]. The degradation of cables occurs during the long-term use under electric stress application. The degradation was divided into three which are outer damage distortion, void, contaminant and protrusion and moisture of the cable. The combination of outer damage distortion and void, contaminant and protrusion and moisture will produce electric stress and partial discharge distortion. Water treeing degradation was formed with the combination of these three Degradation which are outer damage distortion, void, Contaminant and protrusion, and moisture of the cable [21].Water trees were first discovered in Japan and growth in polymeric cable insulation [6, 15, 17-19, 22-24].Furthermore, the important factor that influence the lifetime of the cable is a water treeing process. The 'lifetime 'means the insulation performances of water treeing degraded polyethylene such as XLPE and LDPE, especially at the. Breakdown of 'penetrating water tree' that determines the lifetime of the cables. A penetrating tree is a kind of water tree that bridges across the insulation since the water tree is generally highly conductive compared to the non - tree region. Water treeing grows in an ac field but very rarely grows under dc field [25].According to Visata [26], water treeing is an important degradation phenomenon in the polymeric insulation of electrical cables under ac field and in the presence of moisture. In addition, ions play one of the important roles in the mechanism of water treeing process [26]. Acedo et. al. [27] stated that the water trees grow when the electric field is amplified during the service life of power cables. By using the needle method, the water tree growth was increased from 0.1μm to 1μm. It is because needle will increase the presence of electric field and favoring the initiation of water trees [28-30]. Although there are many ways to improve the growth of water trees and the cables have been improved to be retardant of water tree, the maintenance of the installed log is still a big problems and hot issue [31]. Using the Weibull function, the water tree length distribution can be obtained whereby the probability of finding a tree of length less than or equal to length L is given by

$$P\ (L) = 1 - \exp\ [-\ (\ (t))a]\ (1)$$

Where Lc (t) is the characteristic tree length with respect to the function of time, and α is the shape parameter of the distribution [36]. The average water tree length L (t) appears
to have a development of power nature during water tree growth, namely

$$L\ (t) = (\ )\ m\ (2)$$

Where t_0 and m are parameters.

m= range 0.2 – 0.9

WATER TREEING INITIATION AND GROWTH MECHANISM

The water trees grow is the most important revealing to understand and this phenomenon requires neither defects in the insulation nor direct liquid contact. Water tree phenomenon was formed under normal condition [33].Without causing failure of the cable, water tree may breach the entire insulation and as they grow the dielectric strength of the insulation getting lower that will cause electrical trees. As the electrical tree was formed, it will cause the failure of the cable within hours [34]. Water tree was formed and grow by the following mechanism [35]

:i) Electrochemical process such as oxidation and chain scission refer to an ageing process ii) Electro physical process that is diffusion of water and ions into degrading polyethylene. From the chemical and physical mechanism, the process that have been considered are oxidation, chain scission and ion diffusion. Oxidation is a possible step for the introduction of hydrophilic groups in water trees and the presence of caboxylate groups in water trees. Ion diffusion occurs in the presence of salts and water through the needle test steps. While the chain scission explains when there is electrons injection or mechanical failure that makes the polymer broken.

S.NO	Ageing parameters	Ageing geometry	Material properties
1	Electric field strength	i. Cables	i. Density
2	Frequency	ii. Samples	ii. Additives
3	Temperature		iii.Cross-linking
4	Voltage stress		iv. Polymer structure
5	Availability of water		v. Cylindrical geometry of cable
6	Presence of contaminants		

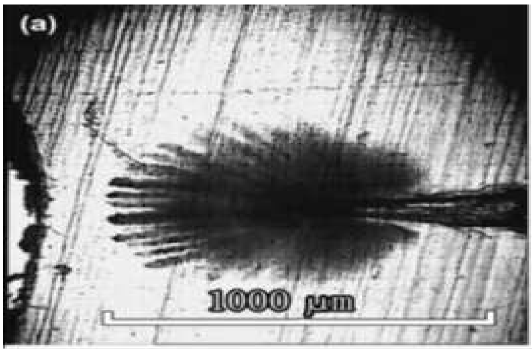

Fig 1.Typical vented trees observed in the water needle electrode of XLPE cable insulation

AGEING CONDITIONS

The ageing conditions can be categorized into three classes which are ageing parameters, ageing geometry and material properties. The classes are shown as Table 1.

CHEMICAL, MECHANICAL AND THERMAL ASPECTS

In mechanical process, mechanical stresses broke some molecular bonds which make result in micro cracks that fill with water and finally water trees were formed. According to the chemical process, it relies on the interactions between water and contaminants or oxygen or a combination of all these parameters and all the reactions are sensitive to the temperature. When conductivity increases, the electrochemical process increases [6, 38-39]. According to these papers [13, 40], electromechanical process is a theory of water treeing by electromechanical forces, that have stress cracking or electrically driven diffusion of water. Temperature and frequencies are neither chemical nor mechanical parameter. When the frequency increases, the water tree growth also increases

INVESTIGATION OF WATER TREEING USING FTIR, MICRO-PIXI, AND ELECTRON SPECTROSCOPY

A few studies have been reported in order to understand

the mechanism of water tree growth and propagation, dealing with trace electron microscopy can also be done [42].Scanning with the micro-PIXE technique was done to analyze the water trees in XLPE insulation of a field-aged underground high voltage cable and capable to measure the trace element concentrations at ppm levels and distribution Profiles with µm spatial resolution. The picture of X-ray spectra of bow-ties and vented water trees, the inner and outer semi conductive compounds, and an insulation spot free from any water tree were required. In this technique, various trace element impurities were identified in the analyzed spots and the differences in elemental distribution profiles in the scanned areas were observed [43].The scanning electron microscope (SEM) illustrates the range of water tree structures observed in medium voltage cable insulation and high resolution imaging system using transmission electron microscope (TEM) [44]. Using the micro-FTIR, the results show that the water content up to 2%was found in vented water tree structures and the majority to be free liquid water. At the tree branches, the water content was highest and at the tip of the radius is the lowest which is the length of the regions was about 200-300 µm [45].

FRACTAL BEHAVIOR AND ANALYSIS DURING WATER TREE

The calculation of the fractal dimension can help to confirm and identify the fractal character and understand the physical mechanisms that lead to water tree formation and growth. Water trees that have grown in different frequency have different visual shapes. There are several ways to define the fractal dimension. The values of fractal dimension can be affected by many factors such as resolution, fineness of sampling, quantization and rounding of sample values [46].When operating in a humid or wet environment, water trees arise from penetration of water into XLPE dielectric of medium and high voltage power cables. Under the AC electric field, the growth process and shape of water treeing in XLPE dielectric is random and cannot be described using Euclidean Geometry. Furthermore, in order to estimate the fractal dimension and the tendency of water treeing in XLPE dielectric, partial electrical breakdown and fractal theory can be the reference. Using an optical microscope, the shapes and structures of water trees were observed to proof the fractal characteristics. The fractal dimension of water treeing can be defined as able to describe its branching tendency [47]. Water trees are fractal objects and to prove the fractal characteristics of water trees, the shapes and structures of water trees were observed by optical microscope [48].

EFFECTS OF WATER TREEING ON ELECTRICAL PROPERTIES

The effect of water treeing on electrical properties such as dielectric loss, breakdown strength, conductivity, and space charge distribution of insulating materials, the large area specimen on which the water treeing is grown has been investigated. The growth length of water tree increased as the breakdown strength of the specimen reduced. Using pulsed electro acoustic (PEA) method, the space charge distributions in the virgin and aged specimens have been measured in order to study the correlation between ac breakdown strengths and space charge distributions in XLPE water tree degraded. As the result, it has been found that treeing which is heavily concentrated at the tip of water treeing path is known as homo-charge while treeing that is gathered in front of electrode is known as hetero-charge. The local field enhancement at the tip of water tree path has been verified using the space charge distribution by electric field calculation [48].When the length and permittivity of water treeing Increase, the electric field in front of degraded area is amplified. It is because of the homo-charge concentration at the tip of water tree path causing the reduction of electrical breakdown [48-49]. The method that allows to accurately calculating the electric field in a polymer in the presence of water treeing is the finite element method. The calculations performed in the needle-plane geometry will confirm the maximum of amplification of the field had reached at the front of water tree [50].

Types of water treeing

Water trees are hydrophilic dendrite, tree-like Features (specifically, it's appear initially to be chains of water filled cavities that later become bushes) of microscopic channel and grows under wet and electrical operating. It may reach the lengths of order 1mm within several years [30].There are two types of water trees which are bow-tie tree and vented tree

Bow-tie tree

Bow-tie trees are the initiated in the bulk ofInsulating material that grows towards the conducting screens from a void [20]. Bow-tie tree can grow symmetrically outwards from the electrode within the dielectric insulation-tie tree consists of divergent straight branches radiating in opposite directions from a central point [52]. It can also define as initiating in the insulation volume and can grow in opposite directions, along the electrical field lines. Usually the growth of bow-tie trees is reduced after at ascertains time and the total length is restricted so that this kind of water tree is rarely the origin of cable breakdown. The length of bow-tie trees is related to the size of the location that containing the impurities [53]. Fig. 2 shows a typical shape of bow-tie tree.

Vented Tree

Vented trees grow into the insulating bulk from one of the conducting screens and the trunk of the tree is vented to the surface of the insulation [20, 51, and 53]. The branches are generally away from the insulation surface that oriented in the direction of the electric field [51-52]. The important factor for the growth of vented tree is having access to free air and these trees are able to grow continuously until they are long enough to bridge the electrode that will cause failure in the insulation [51].The vented tree is more dangerous under service ageing conditions compared to the bow-tie tree and the study of vented tree is more difficult than bow-tie tree. Furthermore, vented tree has low concentration and propagation rate rather than bow-tie tree [53].

Diagnostic and testing of water treeing

There are several techniques to diagnose the water treeing in cable insulation. When the degree of water treeing in XLPE cables rated at 36 kV and above, it depends on the cable design and the system voltage. It is possible to detect water treeing in old high voltage cables and developed medium voltage cables [54].

Capacitance and Loss Tangent

The differential variation of loss tangent is a temperature dependent. Starting at room temperature, the loss tangent decreases first when the temperature increases, passes through a minimum and the loss tangent increases. The absolute values of loss tangent are different for different cable insulation but have same basic behavior. Furthermore, the solubility of water in the surrounding polymer also depends with temperature. The loss tangent will have different changes when the temperature increases [24, 55-56].

Loss current waveform and its non-linearity with voltage

A current-comparator technique is used to accurately Measure the total harmonic distortion of the loss current in high voltage cable including test results obtained on laboratory-aged specimens [57]. In the loss current reflect water treeing degradation, the harmonic components occur and the superposition phase is related to water treeing lengths, breakdown strengths and other aspects of degradation. As a result of the nonlinear voltage-current characteristic of water tree insulation, the harmonic components arise. A degradation signal occurs at characteristic frequency when a voltage at a frequency differing from commercial frequencies [58].Water tree causes the decrease in residual a breakdown strength and high and non-linearly increasing low frequency dielectric loss. The reduction in residual breakdown strength is related to the length of the longest vented water treeing rather than the density of water treeing [59].

Space Charge

Space charge behavior is also affected by the degradation of insulating materials such as water treeing and can be measured using pulsed-electro acoustic (PEA) method [60, 61]. The space charges accumulate not inside the tree butat the interface of the tree and the space charges quantity is directly proportional to applied voltage. Furthermore, the space charge only exists at the tip of the tree and the PEA method can be used as a non-destructive method to find the length and direction of water trees [62, 63].It means that the water conductivity is high [63].Space charge distribution can be used to differentiate between un-degraded and degraded water treeing films. Carrier injection from water tree degraded can form space charge rather than the impurity ions in the non-degraded region. The distortion of the high field ac dissipation current waveforms in water tree is considered to have some relation to the space charge
Formation [64]

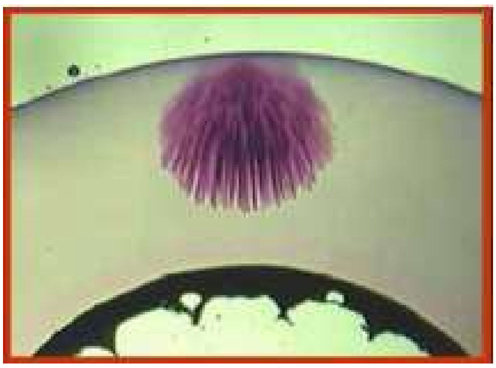

Fig. 2 Vented trees

Broadband Dielectric Spectroscopy

The broadband dielectric spectroscopy can be used as a diagnostic technique for water treeing growth in cables and can determine the degree of water treeing damage in polymer insulated cables. During the growth of water trees, the dielectric response of a 50 meter length of XLPE cable has been measured at different time. The cable was acting as a laboratory model of a service distribution cable and changes can be observed in the dielectric response of the system at low and high frequencies [65]

DC Leakage, Depolarization and Polarization Current Response

The polarization and depolarization current response is a method that can find the depolarization current after Poling the insulation with dc voltage. This method is used to detect the operating state of polar dielectrics such as transformer oil or paper insulation systems and analyze the depolarization current for cable insulation. The polarization current alone can be used to find the operating state of insulation and the advantages of this polarization current have provided consistent results and eliminate the need to analyze the depolarization currents as a function of poling time. The length of water trees increases when the area under the curve of the polarization curves [66].According to [67], polarization current is obtained from two different brands of cross-linked polyethylene subjected to water tree ageing and showed that the RC time constant and the area under the polarization current curve change with time. The depolarization current did not produce consistent results and used in some diagnostic cable insulation assessment tests [67]. The dc leakage current method and dc conductivity method applied to predict the condition of extruded underground power cables. The results show the relation between the dc leakage current and conductivity testing and the presence of water trees in insulation cables. Using microscope testing, the samples suspected to have water tree are examined [68].

Current Pulses during Water Treeing

This method is to find the electrical current signals and its characteristics during water treeing. The sensitivity, characteristics and noise effects were assessed carefully in order to get the signals. The methods of identifying and eliminating noise artifacts are described for resolving the high voltage (HV) phase existing when a fast event occurs.

Four types of pulsed current are studied which have two noises (1-channel and 2-channel noise) and two signals (fast and slow pulses) and have unique characteristics to the channels which occurs in amplitude, shape and phase of the 60 Hz [69].

Time Domain Dielectric Spectroscopy

Dielectric spectroscopy was used to assess the degradation state of field-aged extruded cables from underground network and as a diagnostic tool. A high voltage time-domain spectrometer was used to measure the time domain electric response of un aged and field-aged cables up to 25 kV and the high voltage frequency domain dielectric spectroscopy was performed for the sake of comparison. Furthermore, cables were characterized into two which are water content and water tree density and ac breakdown strength measurement were performed to estimate the state of degradation [70].

Thermally Simulated Currents

The Thermally Stimulated Current (TSC) technique has been used to detect the dry state water trees in field-aged cables. In medium voltage extruded cable samples of XLPE, the measurement has been taken. Around -30°c (β) and 110°c(α) for field-aged and unaged insulation, the TSC peaks were observed. Low temperature peak intensity variations were assumed to be related and observed to the cable insulation characteristics. Between the total integrated charge from β peak and the dry state water-tree surface density samples, there is no correlation was observed [71].

Non-Standard Test Voltages

It is found that the characteristic signals of Deterioration in the insulation appear in the ground circuit of cable screen when the two voltages with different wave shapes of frequencies are applied to the insulation which has been degraded by water trees in XLPE cable [72]. Voltage withstand test is used to investigate a new method for life estimation for service-aged, and water treeing deteriorated 22-77 kV XLPE cables. The suitable waveform for testing voltage from damped oscillating wave (OSW) and very low frequency wave (VLF) voltage as instead of ac and dc were selected. The advantages of VLF voltage is can detect the water treeing and this method is less harmful to water treeing deteriorated cables, have smaller test facility, excellent water tree detection capability and the least detrimental effect on the test cables [73].

Return/Recovery Voltage Measurements

The return voltage measurement method is a Technique to determine the condition of insulation systems such as transformers, mass impregnated cables or XLPE cables. Compared to other diagnostic techniques, a return voltage measurement technique is less noise sensitive which is good for on-site The recovery voltage measurement was presented to allow the detection of water trees at low dc test voltage without the need for reference measurement and this method was used to call division spectrum which is obtained from the results of two separate recordings of the polarization spectrum. Thirsted the polarization processes in an Insulating material and a recovery voltage is obtained by charging, discharging and measuring recovery voltage [74].The return voltage measurement (RVM) method was used to determine the condition of the paper insulation of the transformer windings and as a diagnostic method for oilpaper insulating systems. The influence of temperature was recorded in this method. RVM method also used for detection of water trees in polyethylene and XLPE cables without the need for a reference measurement [75, 76].

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Dielectric response measurements

The diagnostic tests based on the dielectric response (DR) measurement in time and frequency domain also used in order to identify the water treeing degraded XLPE cables with high moisture content. Based on a review of individual measurement techniques, a combination of several DR parameters can improve diagnostic results with respect to water trees in XLPE cables because one parameter may not be sufficient to detect the status of cable insulation. DR measurement is a very useful tool to reveal the average condition of a cable system which is can detect few but long water trees. Furthermore, to improve the diagnostic results with respect to both global and local defects, the combination of DR and partial discharge (PD) measurements will be used[77]. The different types of responses related to the ageing status and the breakdown strength can be recognized and classified the dielectric response of water tree deteriorated cables [78]. Moreover, the non-linear behavior of the dielectric response was found to be different at the time and frequency domain and through threshold voltage value, a transition from nonlinear to linear of the dielectric response Can be observed [79-80].

Time Domain Reflectometry

Time domain reflectometry (TDR) has also been used for localization of transmission line discontinuities indifferent applications. There are many obstacles when applying TDR and one of them is to obtain knowledge of the high frequency characteristics of both the degraded andundegraded sections of the cable. In this technique, the wave propagation characteristics of water-treed XLPE cables can be investigated. The frequency that has been used is higher which is ranging from 300 kHz to 300 MHz The cable samples are differentiating at different temperature and different water content of the water trees. High frequency characteristics are influenced by the extended application of
High voltages [81].

Factors affecting the growth and initiation of water treeing

Water tree length was measured according to the Weibull statistical distribution and parameters [12]. There are many varieties of factors that affected the initiation of water treeing growth. The rate of growth of water treeing depends on the factors that stated below [33]

i) Application time of voltage the effect of application time of voltage on the amount and Size of water treeing depends and related to test conditions such as electrode configurations, applied voltage and water [33]

ii) Electric field an electric field is one of the factors that strongly influence the growth of water trees [49, 82]. The electric field is a function of radius of curvature, r and depends on the r of the needle tip that have been used as an electrode. When $d$ecreases, electric field increases. When electric field increases, the growth of electric field will also increase [19,31, 33, 49-50, 82-83]. In the presence of water tree, the electric field is amplified [50]

$.Ep = 2Ur$ ln $(1+4dr)$ (3)

Where Ep = Electric field in V/μm

U = Voltage applied

r = radius of curvature of needle tip

d = distance between tip of needle and

Sample [37]

iii) Applied voltage

The increasing of applied voltage will increase the water treeing length of water tree and growth of water tree [6, 19,31, 33, 53, 82, 84-85]. Fig. 4 shows the relation between the applied voltage and water treeing length.

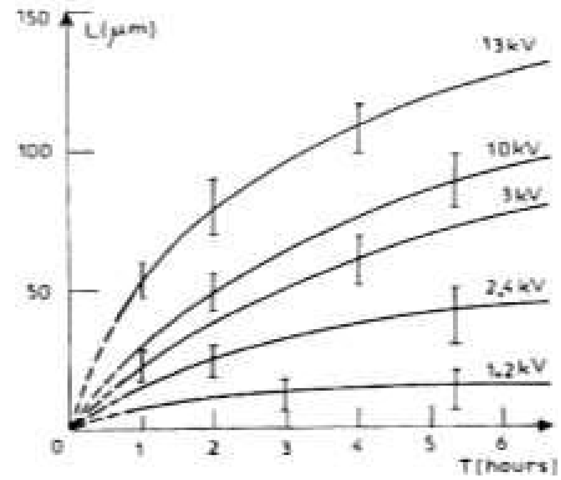

Fig. 3 Relation between the applied voltage and water treeing length

iv) Frequency

When the frequency was increased during the experiment, the growth of water treeing length also will increase [6, 19, 31,33, 53, 86-87]. The higher the frequency will make the growth of water tree faster [28].

v) Temperature

When the temperature increases, the water tree growth also will increase. The water tree degradation with high temperature will lead to the growth of water three [6, 19, 33, 38, 53, 85]. Contrary with the result, the paper [88] shows that when temperature increase, the growth of water tree will

Reduce in the case of wet grounding environment. The parameters that can only influence the effect of temperature on water tree growth are molding techniques either injection or compression, annealing process and the present of NaCl at the HV electrode (dry grounding) or on both sides which is wet grounding [89].

vi) Concentration of solution

If water is perfectly demonized, there is no water tree appears in specimens so the presence of ions in solution is a necessary

Condition to create a water tree [26]. A different solution will give different result and value. When the conductivities are high, the growth of water tree also will increase. By making the water conductive, which is use salt will allows the application of the voltage on the solution and acts as Impurities favoring the water tree development [28]. The concentration of ions in the solution depends on the conductivities of the solution. Therefore, the on contraptions

Also increase and the water tree growth will increase [7, 27, 33, 37, 53, 89-92].

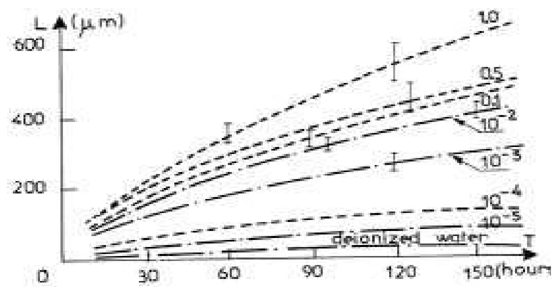

Fig.4. Relationship between concentration of NaCl and water treeing length

The electrode will also affect the water treeing growth. When the tip radius of electrode is small, the electric field that produces is large. Furthermore, when the needle immersed into the solution, the material of the needle also is a major effect in order to avoid corrosion process. A material that is very good to avoid corrosion process is Platinum (PT) and Copper (Cu) followed by Aluminum (Al), Ferum (Fe) and Plum bum (Pb) [27, 33, 53, 89]. Tungsten needle is the best electrode because tungsten cannot corrode during water tree test. Fig. 6 shows the relationship between types of electrodes and water tree length. Saniyyati et al [93] utilize tungsten.

Wire as an electrode and modified of leaf-like model for electrical tree observation to be implemented in water treeing observation

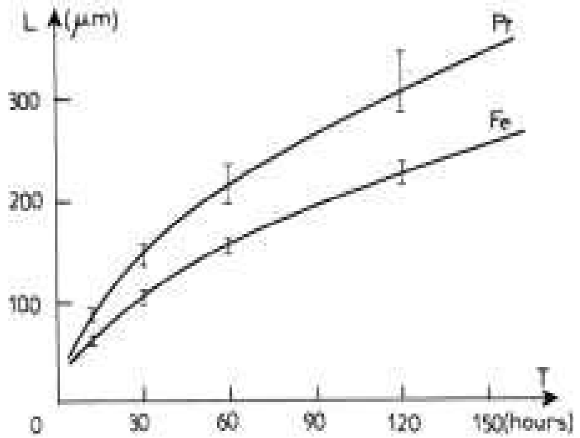

Fig.5.Relationship between types of electrodes and water tree length

Measures to reduce water treeing

Two different methods can be applied to obtain a better aging performance of cables under wet conditions. On the one hand it is possible to make water-tight cable Constructions. On the other hand it is possible to accept water in contact with the insulation and to apply so called water tree retardant insulating materials.

Water tight constructions

In many countries today the utilities install cables with Water-tight constructions having longitudinal water blockings or a combination of longitudinal and radial water

Blockings. To avoid any radial water ingress by diffusion utilities often apply cables having radial water barriers. Such a radial water barrier for medium voltage cables is usually a metal foil under the plastic outer sheath. Water vapor is not able to permeate through the metal. Examples of such constructions are given in many publications, for instance by Bourjot [22], Nagabasami [lo81 and Bow [23].To avoid axial water ingress under the outer sheath after a damage of this sheath; longitudinal water barriers can be applied. These barriers are situated in between the outer sheath and the cable core and mostly consist of swelling tapes or swelling powders [135]. Cable damage can be expected also when liquid water from the soil can reach the conductor, but this conductor can be made water

Tight for instance by means of a solid conductor or by the application of swelling powders between the strands. Concerning the swelling material under the outer sheath,

These materials have the ability to absorb water vapor diffusing through the plastic outer sheath into the cable. In this way, by absorption, the swelling material is able to

keep the relative humidity low for a long period of time for cables having a HDPE outer sheath (with a relatively low water diffusion coefficient). For example, assuming dry swelling materials right after production, it is expected that this period will be a few decades at least. It is the authors' opinion that it would be of interest to prove that with a MDPE outer sheath (having a much higher diffusion coefficient) this period is long enough to avoid to much water in the cable. Such a situation would be reached when in and near the cable insulation the relative humidity level exceeds a level of *x* 70%

Water tree retardants

Compound manufacturers and cable manufacturers, often in close cooperation, put much effort in the development of water tree retardant insulating materials. Publications show that developments are based on different philosophies concerning the mechanism of water tree growth. As will be shown, the water tree retardant materials

Presented are modified polymers, polymers in which chemical additives are incorporated or both. In many cases a modification of the polymer is required to prevent that these additives become fugitive. The test results as

Described in the various publications give the impression that tree retardants can be effective at least over the limited time period of the tests. Already in 1980 Soma *et* al. [141] formulated a bow-tie tree inhibiting material. Soma assumed that bow-tie trees are initiated by condensation of water in a void under the action of an electric field. Further condensation will lead to **a** pressure build up and creep of the void surface. The

Mechanically damaged surface contains polar groups and water will enter the polymer. The water tree retardant material (intended to suppress bow-tie tree development)is based on additives having hydrophilic groups absorbing the water in the polymer structure around the voids. The publication describes different additives and presents their effectiveness in a 3000 h test on a full-scale cable. In 1984 Nagasaki ***et al.*** [log] presented a water-tree retardant insulating material containing an ethylene copolymer (EVA) that acts as a barrier against water tree growth. The cause of this retardant effect has not been clarified. Life tests up to 30000 h were carried out on medium voltage cables showing that the material suppresses the growth of both bow-tie trees and vented trees.

Water Treeing

One year later Matey et al. [92] presented a modified base polymer which should intrinsically be more resistant to water tree degradation. Matey assumes that mechanical Fatigue plays an important role in the process of water treeing. The modified polymer system should offer an enhanced Resistance to crack propagation. In addition the resistance is enhanced by water treeing inhibitor, being an organ metallic compound. With respect to this material, it is assumed by Saure et al. [132] that by migration the polar additives have the ability to reduce the electric field stress on places of field enhancement. In this publication Saure emphasized that the basic polymer is a PE copolymer stabilizing the presence of the additives. Short duration tests show that both vented trees and bow-tie trees are reduced in number and length. Long-term aging tests up to 10000 h reveal the good performance of the material both with respect to the breakdown strength and the bow-tie tree development. However, no data are presented concerning the growth behavior of the vented trees. In 1986 Fisher et al. [49] described the development of a water-tree retardant insulating material called HFDA4202. The development program was intended to find a material without filler and with additives being

no fugitive. From [119] it is known that the additive is an organo-metallic compound. Short-term water needle tests show the retardant characteristics of this material.

No more information about test results of long-term tests has been found. One year later Fischer et al. [48] described water--tree retardant material which is based on a modified base polymer with no fugitive additives. The additives are known to stabilize hydro peroxides by deactivation of the catalytically active metal ions via adsorption and by a deactivation of the initiating sites at which the assumed electrochemical reactions occur. The background of this electrochemical process during tree growth was published two years earlier by Henkel and Muller [63]. Fischer performed aging tests up to 6000 h and observed a reduction of both densities and lengths of bow-tie and vented trees.

Recently, Field et al. [43] described the results of 3000 h tests on full-scale cables. Assuming the water tree growth is related to free water, to ionic contaminants and to oxidation products, different water tree retardant materials were tested among which successfully a homo polymer with an additive and two different modified polymers. Indication of tree size reduction of both bow-tie trees and vented trees was obtained. Further testing to demonstrate long-term benefits are in progress. Apart from water-tree retardant insulating materials it is generally assumed that smooth semiconducting layers and a reduction of the amount of impurities in these layers would be helpful in retarding the water tree growth, especially the vented tree growth. A study of types and amounts of impurities is given by Belhadfa Impurities diffusing from the layers into the insulation are described by Crine et al. [31] and Johnson et al. [67]. Development of semiconducting layers with lower contaminants levels have been reported for instance by Nitta [115] and Umpleby [161].Unfortunately, the above described developments and test results are not informative about the actual degradation Mechanism, since modified polymers as well as additives can be considered as polar material. For all mechanisms discussed above, polar groups have water tree retardant consequences since polar groups are able to reduce the electric stress locally (effective for all mechanisms)or to reduce the interfacial energy of polar interfaces which reduces the absorption of water in general (effective especially considering electrochemical degradation).It is concluded that water-tree retardant insulating materials or a combination of these materials with smooth and clean semiconducting layers can be considered as serious candidates for solving the water treeing problem. However, in many cases long duration tests at least up to two years have not yet been performed; such tests are required to come to better evaluations of the characteristics of these materials on the long term. These tests should emphasize material stability and fugitivity of the additives. Moreover, tree growth of especially the vented trees should be taken into account

CONCLUSIONS

In polymeric cables, one of the main causes of insulation breakdown is aging caused by water-treeing. In this paper, the background and types of water treeing have been reviewed. Factors affecting the initiation and growth of water trees have also been discussed. In addition, the detection of water treeing mechanisms using methods such as the voltage breakdown test, the voltage return test and the RF technique have also been looked into. This enables preventive.

Measures to be taken, which will help in reducing the effort and cost associated with the replacement of the faulty cables caused by water treeing

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