Review of water treeing in polymeric insulated cables

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Abstract

Since discovering the water treeing phenomenon (WT) in polymeric cables in the early 1970s, water treeing has been extensively studied. Historically, different theories were proposed to describe this phenomenon's mechanism. The two most prominent theories link the initiation of WTs to (i) mechanical damage and (ii) Stress-induced electrochemical degradation (SIED). Additionally, different investigations in the past have shown that the water trees growth is correlated to different operation conditions e.g. voltage, frequency and mechanical stresses. This paper aims to review the two prominent water treeing initiation theories. Then, discusses the factors influencing the water tree growth.

1. Introduction

Since the 1960s, extruded cross-linked polyethylene (XLPE) has conventionally been used as insulation for HV cables laid in wet environments [1]. Only a few years after deployment, such cables were reported to have a high failure rate. Further investigation revealed water ingress into the insulation, which causes tree-like water structures that leads to insulation breakdown [2]. Fundamentally, there are two types of water trees depending on the shape, namely: bow-ties and vented water trees. Typically, vented water trees are observed to start growing from either the conductor or the insulation screen whilst bow-ties are scattered around within the insulation. Example of typical water tree observations are shown in fig. 1.
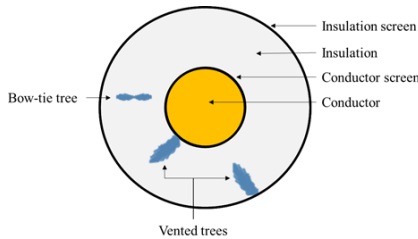

Fig. 1 – Illustration of bow-tie and vented water trees

Previous literature on water treeing proposed different theories to predict the mechanism of water tree initiation. These theories belong to different schools of thought i.e. i) mechanical damage, ii) electrochemical and iii) chemical potential [3]. Despite that it has been challenging to determine or agree upon particular water treeing initiation mechanism, it is generally accepted that during the cable lifetime, the insulation system is subjected to different aging factors that can contribute to the initiation and growth of water trees and eventually lead to the breakdown of the cable insulation system.

The mechanisms involved in water treeing initiation and growth are of complex nature. Thus, it is difficult to categorize different factors based on their contribution either on the water tree initiation or growth specially when different factors can coincide leading to presence of water trees. In this paper, the water treeing mechanisms are presented either as an initiation or growth mechanism based on the convention set by the authors of earlier work.

2. Water migration in polymers

Since polymers are inherently not watertight, the ingress of water into the insulation is inevitable. The water ingress into polymers can be characterized using Henry's law in conjunction with Fick's law for the diffusion of water in the bulk polymer [4]. First, Henry's law states that the water concentration $\rho_{(w,s)}$ at the polymer surface is proportional to the water vapor pressure above the surface $p_{(w,s)}$ i.e.

$$\rho_{(w,s)} = S \cdot p_{(w,s)} \tag{1}$$

where S is the solubility coefficient for water within the polymer.

Then, Fick's law states that the water mass flux by diffusion j to be proportional to the diffusing species concentration gradient $(\nabla\rho)$ i.e.

$$j = -D \cdot \nabla\rho \tag{2}$$

where D is the diffusion coefficient.

The temperature dependency can be taken into account by expressing the solubility and diffusion coefficient in the form of Arrhenius relationship as follows [5]:

$$S = S_0 \cdot \exp\left(\frac{-E_s}{RT}\right) \tag{3}$$

$$D = D_0 \cdot \exp\left(\frac{-E_d}{RT}\right) \tag{4}$$

where S_0 and D_0 are the pre-exponential factor for solubility and diffusion respectively. E_s and E_d is the activation energy for solubility and diffusion reaction respectively. R is the universal gas constant and T is the absolute temperature.

Moreover, the water within the polymer can be quantified by the relative humidity levels (RH) within cables, which can be expressed as [5]:

$$RH = \frac{\rho}{S \cdot p_{sat}} \tag{5}$$

where p_{sat} is the saturation water vapor pressure.

If the polymer is subjected to temperature cycling, which is typical during operation, this can lead to supersaturation of water in the polymer. In other word, the polymer will shift from equilibrium solubility state into supersaturation. This will result in condensation and the presence of liquid water within the polymer potentially at high local pressure that may damage the insulation. To sum up, the water ingress into the polymeric insulation is governed by: i) solubility and saturation level ii) diffusivity iii) temperature vi) vapor pressure.

3. Water tree initiation theories

From the presence of water within the insulation to the formation of tree-like structures, it is still unclear what mechanism dominates. Throughout the years, several theories have been proposed to explain how water tree growth starts. Currently, there are two predominant theories:

3.1. Mechanical damage theory

In this school of thought, the initiation of water trees are linked to mechanical overstressing on the polymer due to a possible combination of mechanical and electric stresses, which leads to damages on the insulation and the formation of micro cracks and voids. With the water present in the insulation, condensation of water into micro cracks and crazes is likely to occur. This condensation is further enhanced within areas with high electric field concentration i.e. the increased driving forces can lead to more diffusion of water and as a result increase the water content within crazing zones [6].

Since the water has a much higher permittivity than polymers, this will result in an inhomogeneous field around crazes. If the resulting electric field is sufficiently high, further crazing zones can be developed around the tip because of the induced Maxwell stresses as seen in Fig. 2.
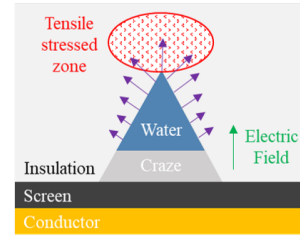

Fig. 2 – Illustration of mechanically stressed zones on the insulation

Moreover, the propagation of a water tree channel is presumed to be similar to a well-known mechanical phenomenon known as Environmental Stress-Cracking (ESC) [7].

3.2. Stress Induced Electrochemical Degradation theory (SIED)

This is currently the predominant theory in the electrochemical school of thought for Al conductors. The presence of water between the conductor strands is presumed to be responsible for the development of porous channel like structures in the semiconductor. This was first reported in the earlier work of [8] and [9], which showed some structural changes in the conductor screen neighboring vented water tree inception sites of some accelerated aged test samples.

Later work proposed that such structures are the results of the formation of a galvanic cell, which is constituted by the conductor as an anode, the semicon as a cathode and an electrolyte i.e. the water in addition to the ionic resultants from the corrosion site [10]. Such reaction was proposed to be a type of degradation and often referred to as "Stress Induced Electrochemical Degradation" (SIED) in the literature. An example of a SIED structure is shown in Fig. 3.
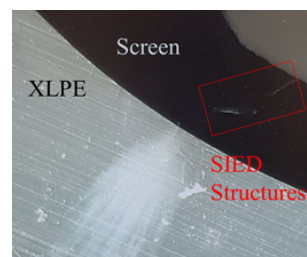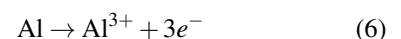

Fig. 3 – Example of SIED structures observed in service aged cables

The release of electrons initiates the buildup of chemical potential difference which lead to the oxidization and corrosion of the conductor. This can be chemically illustrated through the following example of a conductor in the presence of water [11]:

Aluminum conductor oxidization

$$Al \rightarrow Al^{3+} + 3e^- \tag{6}$$

Reaction between aluminum and water

$$Al^{3+} + 3e^- + 4H_2O \rightarrow Al(OH)_3 + H_2 + H_3O^+ + e^- \tag{7}$$
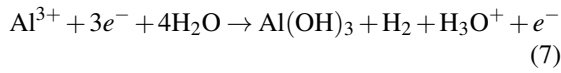
In order to characterize the nature of the impact such reaction has on a polymeric insulation; three different hypotheses were suggested in [11]:

1. Saponification: This hypothesis is based on ester groups present in the copolymers e.g. Ethylene Ethyl-Acrylate (EEA). It is presumed that ester groups interact with the carbon black particles and can be attacked by alkaline causing an ester hydrolysis reaction to take place, which results in weakening of the polymer interface. However, this hypothesis was found to be not applicable after lots of structures and vented trees were observed even after considering a polyethylene based semicon that did not contain ester groups [12].

2. Radical degradation: This hypothesis assumes an oxidization of water leading to the formation of hydrogenperoxide (H_2O_2) at the semicon. The resultant radical reaction is suspected to be the reason behind the formation of the structures in the semicon.

$$2e^- + 2H_2O + O_2 \rightarrow H_2O_2 + 2OH^- \tag{8}$$
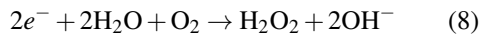
To investigate this hypothesis, an experiment was conducted where hydrogenperoxide and sodium hydroxide were forced to diffuse into semicon through a 5000 h aging process [12]. However, no vented trees were observed. Since the formation structures is assumed to be mainly due to radicals, further experiments were done considering different antioxidants with different concentrations. The work showed that even with the highest antioxidant concentration, the formation of structures could not be prevented. This suggests that the initiation of the structures and vented tree is not via radical resultants.

3. Hydrogen gas: hydrogen gas (H_2) from the reaction above starts to build up and causes a mechanical damage on the semicon. The source of the resulting hydrogen gas was illustrated in eq. 3 earlier. Since it is difficult to detect hydrogen gas in the semicon, a strong reducing agent i.e. $LiAlH_2$ was forced to diffuse into cable core in order to facilitate the generation of hydrogen gas within the semicon [11]. After 1000 h of aging, numerous SIED structures were observed using SEM. As a result, it was concluded that, the hydrogen gas accumulation is the most probable cause of the formation of SIED structures [12]. However, the nature of the damage to the polymer due to hydrogen gas is still unclear due to the difficulties associated with hydrogen detections. Three different theories were proposed [11]:

(a) Chemical theory: Hydrogen chemically reduces the surface groups on the carbon black particles impacting the adhesion of the carbon black to the polymer matrix. With the adhesion forces being weaken, the mechanical forces can become more prominent.

(b) Physical theory: Hydrogen absorption by the semicon occupies the bonding sites for the polymer causing it to be weakened facilitating the formation of porous like channels in the polymer.

(c) Mechanical theory: Hydrogen gas pressure accumulation can mechanically break the adhesion forces in the interface between the carbon black and the matrix, which results in the formation of porous structures.

These early SIED theories were proposed while considering labratory aged samples. However, SIED on service aged cables was first reported in [13]. It was suggested that there is a strong correlation between the inception of vented water trees initating from the inner screen and the corrosion of the aluminum conductor. Also, it was suggested that the inception of SIED structures is mainly caused by environmental stress cracking (ESC). Further investigations in [14] supported the earlier claims in [13] when it was shown that SIED or porous structures can be reproduced in the lab without applying voltage or load current and the only prerequisite for such structures is the corrosion of the conductor. Additionally, it supported the claim that the formation mechanism of these structures constitutes of microcracks initiated by ESC (see fig. 4).
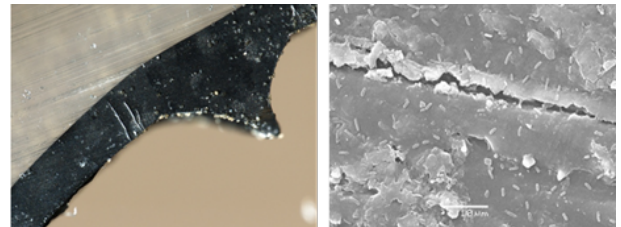

Fig. 4 – Example of Microfracture due to SIED [14]

This result can be seen to oppose SIED theory in term of porous structures being a result of an stress induced electrochemical degradation as these structures were seen to grow in the lab under no electrical stresses.

4. WATER TREES GROWTH

The rate growth of water trees has been found to follow the power law:

$$\frac{\partial L}{\partial t} = kE^n \tag{9}$$

However, there are several factors involved in this process that should be highlighted:

4.1. Temperature

The temperature can impact the migration of water into the polymer. This can be seen in temperature dependency of the solubility and diffusion discussed earlier. Additionally, supersaturation can occur due to temperature cycling and rapid cooling. This will result in condensation and the build-up of hydrostatic pressure, which can lead to additional mechanical stresses.

4.2. Mechanical stress

There are various sources of static and dynamic mechanical stresses on the cable insulation during service. This can induce more microcracks since the propagation of WTs is presumed to follow an ESC nature. This claim was supported in [15], where a strong correlation between static tensile stress and the initiation and growth of water trees was observed. As for dynamic stresses, the impact of dynamic strain on water trees was observed to be insignificant up to 1% [16]. During the cable lifetime, the typical amount of mechanical strains is below 0.2% [16].

Sever mechanical stresses might not only occur during the cable installations or laying but can also occur during the cable manufacturing. In fact, it was shown in [17], that the stresses due to the rapid cooling post cable extrusion and curing can in magnitude exceed the operation stresses in case of a subsea cable.

During the operation, if water filled channels are formed, then there will be electrostrictive forces due to electric field enhancement at the tip of the channels acting on the polymeric dielectric [18]. This is considered as one of the predominant mechanical stress sources. The other predominant on-site mechanical stress is due to the buildup of hydrostatic pressure from condensation. This was discussed in detail in [19]. Basically, the water condensation within voids can yield hydrostatic forces acting on the regions surrounding the void. Therefore, these forces mainly depend on relative humidity and in-turn the degree of supersaturation (see Fig. 5).
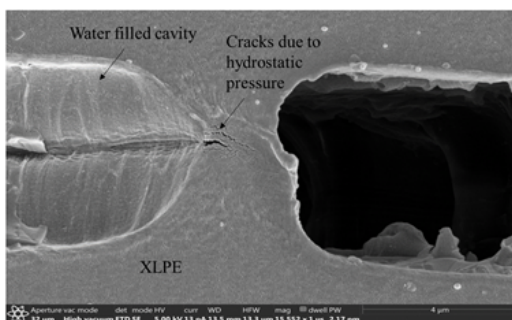
4.3. Operation conditions

The operation conditions e.g. voltage, electric field and frequency can enhance the water tree growth rate. The increase of the operation voltage is expected to increase the number and length of water trees. This can easily be explained in light of the concepts discussed earlier e.g. higher voltage will induce higher electric field at the tip of water trees leading to more electrostrictive forces, which facilitate the expansion of water trees.

Stressing the polymer with an increased frequency results in higher number of cycles during energization. Due to this, increasing the frequency has been used to accelerate the aging tests. Results from [21] supports that the frequency dependency is due to the polymer being subjected to more mechanical stresses.

4.4. Ionic contaminations

The presence of ions is necessary for water treeing. If the water surrounding the conductor is perfectly deionized, no water trees can grow. The diffusion of an ionic solution can be governed by the Fickan/Arrhenius relations discussed earlier. Thus, the temperature dependency on the diffusion of different ions is well justified. This was experimentally confirmed in [22], where it was found that ions present in the solution will also diffuse into polyethylene films. Additionally, it was found that the increase of the crosslinking amount can 'slow' the diffusion of ions. Typically, the increase of ionic concentration can be seen as a conductivity increase for the water within the polymer. As for the impact of this on water tree growth, the results from [23] suggests an increase in the length of the water tree in proportion to the concentration of NaCl solution. One can argue that the experiment used water needle method i.e. it is difficult to confirm that increase in propagation rate is mainly due to the ionic concentration only and not in conjunction with the micro cracks generated during sample preparation (drilling). Alternative work done in a full-length cable has confirmed that the increase of ionic concentration plays a role on enhancing the length of vented trees [24]. The cables were aged for one year under 50 Hz frequency. A typical example of the impact of voltage, temperature and ionic solution is demonstrated in fig. 6 [25].
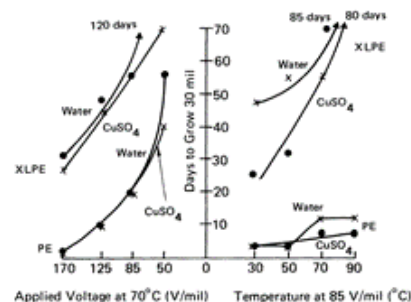

Fig. 5 – An example of cavities and hydrostatic pressure induced microcracks caused by supersaturation after thermal cycling and rapid cooling [20]

Fig. 6 – Typical impact of different factors on water tree growth [25]

In this study, the time taken for water trees to reach a certain length was considered. Furthermore, the effect of different ions can be justified by presuming that having ions subjected to an electric field can lead to electrophoresis forces acting on the insulation i.e. ions are forced to move due to electric field. Alternatively, one can also presume that the presence of different ions 'might' play a role in altering the chemical potential in favor of an electrochemical degradation to take place.

4.5. Morphology

With polymers known to be semi-crystalline, voids are expected to be formed within the amorphous regions. The degree crystallinity can dictate the polymer tensile strength i.e. higher degrees of crystallinity yields a 'harder' polymer. With the growth of water trees strong link to mechanical stresses, larger mechanical resistance can limit the growth of water trees. Thus, water trees will have a higher rate of growth in low density polyethylene (LDPE) compared to high density polyethylene since LDPE has lower degree of crystallinity (see Fig. 7) [26].
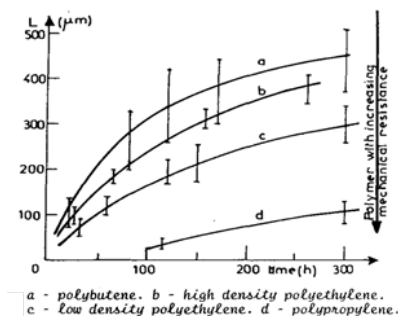

a - polybutene. b - high density polyethylene.
c - low density polyethylene. d - polypropylene.

Fig. 7 – Water treeing in polymers with different mechanical resistances [26]

Furthermore, recent results in [27] have shown that the presence of water trees can cause crystalline destruction in PE, which can make it 'easier' for further trees to grow.

5. Summary

The summary of the factors involved in the initiation and growth of water trees is presented in TABLE 1.

6. Conclusion

This paper presented a review on the initiation and growth mechanism of water trees in polymeric cables through a selection of papers. The limitations of this work arise from the complexity of categorizing initiation mechanisms from growth. However, for illustration purposes the paper discussed two predominant initiation theories in regard to water treeing namely: i) Mechanical theory ii) Stress Induced Electrochemical Degradation (SIED). Moreover, a brief overview was given on the factors influencing the growth of water trees e.g. operation conditions, ionic contaminations, ionic contaminations and morphology.

Acknowledgment

References

[1] E. Steennis and F. Kreuger, "Water treeing in polyethylene cables," IEEE Transactions on Electrical Insulation, vol. 25, no. 5, pp. 989-1028, 1990.

[2] T. Miyashita, "Deterioration of Water-immersed Polyethylene Coated Wire by Treeing," in Proceedings 1969 IEEE-NEMA Electrical Insulation Conference, Boston, 1969.

[3] S. L. Nunes and M. T. Shaw, "Water Treeing in Polyethylene - A Review of Mechanisms," IEEE Transactions on Electrical Insulation, Vols. EI-15, no. 6, pp. 437-450, 1980.

[4] G. S. Park and J. Crank, Diffusion in polymers, London: Academic Press, 1968.

[5] S. Hellesø, S. Hvidsten, K. Furuheim and G. Håkonseth, "Water Treeing in Subsea XLPE Cables with Thermal Gradient," in 2013 IEEE Electrical Insulation Conference (EIC), Ottawa, 2013.

[6] J. Sletbak, "The mechanical damage theory of water treeing - A status report," in Proceedings of the 3rd International Conference on Properties and Applications of Dielectric Materials, Tokyo, 1991.

[7] C. Meyer and J. Filippini, "Water-treeing seen as an environmental stress cracking phenomenon of electric origin," Polymer, vol. 20, no. 10, pp. 1186-1187, 1979.

[8] W. Kalkner, U. Müller, E. F. Peschke, H.-J. Henkel and R. v. Olshausen, "Water treeing in PE- und VPE-isolierten," Mittel- und Hochspannungskabeln Elektrizitätswirtschaft, no. 26, pp. 911-922, 1982.

[9] D. Meurer, D. Kaubisch and W. Gölz, "Zum Langzeitverhalten von Isoliersystemen für VPE-isolierte," Mittelspannungskabel Elektrizitätswirtschaft, vol. 89, no. 26, pp. 911-922, 1990.

[10] K. Steinfeld and W. Kalkner, "Stress Induced Electrochemical Degradation of the inner Semicon Layer of extruded Cable Insulation," in I.C.D.I., Budapest, 1997.

[11] M. Bruggerman, W. Kalkner, A. Campus and A. Smedberg, "Electrochemical effects at the conductor/dielectric interface - a description of the mechanism," in Proceedings of the 2004 IEEE International Conference on Solid Dielectrics, Toulouse, 2004.

Table 1 – Summary of water tree initiation and growth factors

Factor	Prerequisite to cause consequences	Consequences
1. Water ingress	Sufficient solubility, diffusion and supersaturation (temperature cycling)	Condensation of water and the build-up of hydrostatic pressure that can result in a growth of water tree
2. Hydrostatic pressure	Water ingress in the polymer and supersaturation (temperature cycling)	Condensation of water within microvoids and the initiation or expansion of WTs
3. Mechanical stress	Sufficient tensile stresses on crazes tip	Formation of microcracks which can initiate trees or influence the growth of existing trees
4. SIED	Al conductors and water ingress to the conductor initating corrosion	SIED structures on the semicon and vented water trees can grow from the conductor screen
5. Static strain	Sufficient tensile stresses	Formation of microcracks which can initiate trees or influence the growth of existing trees
6. Dynamic strain	Above 1% dynamic strain	Formation of microcracks which can initiate trees or influence the growth of existing trees
7. Voltage/EF	Microvoids and sufficient water diffusion into the polymer	Sufficient maxwell stresses at the crazes tip that can induce further growth of water trees
8. Frequency	Sufficient resulting mechanical stresses	Accelerating the aging process of the polymer causing the initiation and growth of water trees
9. Ionic contaminations	Ions diffusion	Accelerating the chemical degradation, which can lead to the growth of longer trees
10. Morphology	Significant amorphous regions	Lowering the mechanical resistance, which can yield the presence of more water trees

[12] M. Brüggemann, W. Kalkner, C. Broman and A. Smedberg, "Influence of electrochemical effects on vented tree initiation in accelerated tests," in JICABLE '03 - International Conference on Insulated Power Cables, PARIS, 2003.

[13] S. Hvidsten, S. Kvande, A. Ryen and P. B. Larsen, "Severe degradation of the conductor screen of service and laboratory aged medium voltage XLPE insulated cables," in IEEE Transactions on Dielectrics and Electrical Insulation, vol. 16, no. 1, pp. 155-161, February 2009, doi: 10.1109/TDEI.2009.4784563.

[14] H. Faremo, M. Selsjord, S. Hvidsten, K. Bengtsson and A. Ryen, "Initiation of vented water trees from the conductor screen of MV XLPE insulated cables," in 2012 IEEE International Symposium on Electrical Insulation, San Juan, 2012.

[15] E. Ildstad, S. Nordås and T. A. Lindseth, "Water Treeing of XLPE Cables under combined mechanical and electrical stresses," in Nord-Is 11 Nordic Insulation Symposium, Tampere, 2011.

[16] E. Ildstad, S. M. Hellesø, S. Hvidsten, H. Faremo, P. Egrot, B. J-O, S. Nilsson, J. Eek, J. Matallana and H. M. Wølneberg, "Water Tree Ageing of High Voltage XLPE Cable Insulation System under Combined Dynamic Mechanical and AC Eletrical Stress," in Session Proceedings 2014. CIGRE (International Council on Large Electric Systems), Paris, 2014.

[17] E. Ildstad, S. Å. Aarseth and H. Faremo, "Enhancement of Water Tree initiation due to residual and applied Mechanical Strain on XLPE Cables," in Nord-IS 13 Nordic Insulation Symposium, Trondheim, 2013.

[18] J. Sletbak, "A Theory of water tree initiation and growth," IEEE Transactions on Power Apparatus and Systems, Vols. PAS-98, no. 4, pp. 1358 - 1365, 1979.

[19] E. Ildstad, Water Migration and Water Treeing in Cross-Linked Polyethylene Cables, Trondheim: NTNU, 1982.

[20] J. Henry, "Next Generation High Voltage Subsea Transmission Cables: Influence of electric field, NaCl impurities and thermal cycing rate on insulation lifetime," NTNU, Trondheim, 2019.

[21] C. T. Meyer and J. C. Filippini, "Effect of Frequency on the Growth of Water Trees in Polyethylene," IEEE Transactions on Electrical Insulation, Vols. EI-17, no. 6, pp. 554-559, 1982.

[22] T. Bao and J. Tanaka, "The diffusion of ions in polyethylene," in Proceedings of the 3rd International Conference on Properties and Applications of Dielectric Materials, Tokyo, 1991.

[23] J. Y. Koo and J. C. Filippini, "Effect of Physico-Chemical Factors on the Propagation of Water Trees in Polyethylene," IEEE Transactions on Electrical Insulation, Vols. EI-19, no. 3, pp. 217-219, 1984.

[24] H. Nagai, T. Fukuda, T. Tabata and Z. Iwata, "Sulfide Attack and Treeing of Polyethylene Insulated Cables - Cause and Prevention," IEEE Transactions on Power Apparatus and Systems, Vols. PAS-91, no. 4, pp. 1354 - 1360, 1972.

[25] B. S. Bernstein, N. Srinivas and P. N. Lee, "Electro-chemical treeing studies: Voltage stress, temperature, cmd solution penetration effects under accelerated test conditions," in Conference on Electrical Insulation & Dielectric Phenomena - Annual Report 1975, Gaithersburg, 1975.

[26] Y. Poggi, J. Filippin, V. Raharimalala, J. J. de Bellet and G. Matey, "Water treeing as a mechanical damage: influence of process parameters," in Proceedings of the second International Conference on Properties and Applications of Dielectric Materials, Beijing, 1988.

[27] X. Tao, H. Li and F. Lin, "Crystalline Destruction Caused by Water Tree Growth in Low-density Polyethylene," IEEE Transactions on Dielectrics and Electrical Insulation, vol. 28, no. 1, pp. 167-174, 2021.

[28] K. Abdolall, H. E. Orton and M. W. Reynolds, "An investigation into water trees: Existence of channels and the influence of crosslinking," in Conference on Electrical Insulation & Dielectric Phenomena - Annual Report 1985, Amherst, 1985.