Water Treeing of XLPE Cables under combined mechanical and electrical stress

Erling Ildstad, Ståle Nordås and Truls Amundsen Lindseth
Department of Electric Power Engineering
Norwegian University of Science and Technology
NTNU, Trondheim, Norway

Abstract

This paper gives a brief review of the mechanical damage theory for water treeing and present results from water tree tests performed on samples of mechanically stresses commercially available 12 kV XLPE cable. In addition the insulation was characterized with respect to mechanical properties. At 30°C the tensile elastic modulus of XLPE was measured to be 80MPa, with a yield strength of 12MPa. Creep relaxation measurements showed a relatively rapid decay of static mechanical stress with a time constant of about 150 s.

During ageing in tap water at 30 °C the XLPE cable was bent around pipes with diameters of 5, 10, 20 and 30 cm and energized at 14 kV (2 U_0). Thus samples were subjected to both tensile and compressive strains in the range of 0-18 %.

Both the density and growth rate of vented and bow-tie water trees increased significantly with increased applied axial tensile strain, and a corresponding reduction was observed for compressive strain. The results are in good agreement with the mechanical damage theory.

1. Introduction

Forty years have passed since it was first discovered that water treeing cause premature service failure of extruded XLPE power cables. It is generally accepted that initiation and growth of water trees in the cable insulation requires application of an ac voltage, a relative humidity of water higher than about 70% and an initiation site. The initiation site can be either embedded contaminations inside the insulation, resulting in so-called bow-tie trees, or defects at the insulation/semiconductor interface resulting in vented water trees.

Studies of cables aged during service or in long term laboratory ageing tests, have shown that vented trees typically need longer initiation time than bow-tie trees. However, when a condition for growth is established, they seem to grow at a nearly constant rate. In XLPE cables which have failed during service, vented trees have been found to cross the insulation wall. Such trees are therefore considered to be a more frequent cause of cable failure than bow-tie trees, which seem to saturate in length rather rapidly [1].

Over the years the problems associated with water treeing have largely been reduced by the introduction of more water tree retardant insulation material and improved cable manufacturing processes. Such as using cleaner insulations, semiconductors and smoother insulation/semiconductor interfaces. In addition metallic sheaths are introduced in order to prevent ingress and absorption of water into the insulation. Nevertheless, in case of medium voltage cables it is common to use regular XLPE insulation without metallic sheath barriers. For these reasons, water treeing continues to be a subject of some interest.

Initiation and growth of water trees have been found to depend on the mechanical properties of the electric insulation. While compressive stresses are assumed to retard the water treeing, tensile stresses have been found to accelerate it [2, 3]. It is believed that a tensile stress reduces the amount of energy required to cause bond breaking of the polymer chains, thus increasing the probability of initiating a water tree. In addition to internal stresses, frozen in during the manufacturing process, the power cables are subjected to various mechanical stresses during installation and service. This is particularly true for modern dynamic cables intended for offshore installations.

The mechanical damage theory assumes that water treeing is due to mechanical overstressing, caused by the combined effect of external mechanical stress and electric stress. The aim of the work presented here has been to review the basis of this theory and to report results from water treeing experiments performed on mechanically bent XLPE cables.

2. Mechanical Damage Theory

Polymer crazing and environmental stress-cracking are considered important precursors to water tree initiation and growth. From fracture behavior of polymers it is known that crazing can initiate cracks at stresses below what is needed to cause bulk shear yield . From mechanical fracture theory crazes are known to be localized regions of plastically deformed polymer, consisting of voids and polymer fibrils. They are initiated when mechanical stress cause micro voids to nucleate at points of high mechanical stress concentration. Examinations of the microstructure of crazes i n polyethylene have shown that typical craze thickness is in the range of 0.1 - 0.5 µm, which tapers off to less than 2.5 nm at the tip of the craze [4]. -Measures known to reduce stress cracking are: introduction of compressive stresses, increasing the molecular weight, annealing and addition of copolymers. It is known that some liquid environments may promote crazing and crack formation, causing so-called environmental stress-cracking (ESC).

Due to the large thermal expansion of XLPE compared to that of the Aluminum or Copper conductor combined with cooling of the cable form the outside, rather high internal stresses may be introduced in the cable insulation during the manufacturing process. Typical magnitudes of frozen in longitudinal tension stresses have been measured to be in the range of 10-37 MPa [5]. These values are comparable to the yield strength of polyethylene. - It is therefore likely that, crazes and micro cracks are present in the insulation particularly close to the semiconducting interfaces. The effect of sharply bending a cable is to introduce both tension and compression stresses. It is likely that formation of micro voids will be eased in the elongated sections.

Generally a crack cannot propagate unless there is some tensile stress component at the crack tip, providing the driving force for the creation of new craze regions. -In case of voltage application this will be realized by the Maxwell forces and the highly inhomogeneous electric field generated adjacent to the thin tip of conducting water filled cracks or crazes. The force is directed perpendicular to the interface between the water filled zone and the insulating material 1 and has a magnitude per unit area of:

$$\sigma = \frac{F}{A} = 1/2(\varepsilon_1 - \varepsilon_2)(E_{t1}^2 + \frac{\varepsilon_1}{\varepsilon_2}E_{n1}) \qquad (1)$$

where ε_1 and ε_2 are the permittivities of the two regions and E_{n1} and E_{t1} are the normal and tangential components of the electric field at the boundary. If the water filled tree channel is considered conductive, the local boundary force per unit area becomes:

$$\sigma = 1/2(\varepsilon_0 \varepsilon_r E^2) \qquad (2)$$

Thus in the near vicinity of the tip, tensile Maxwell stresses will appear resulting in a pulsating 100Hz compressive stress acting perpendicular to the crack surface. As schematically illustrated in Fig.1 this will result in local tensile stresses at the tip of the craze. In case of high local field enhancement these forces may become higher than 10 MPa, a force sufficiently high to create new crazes into which water are pulled [6]. Thus a situation for further growth of vented and bowtie water trees are established.

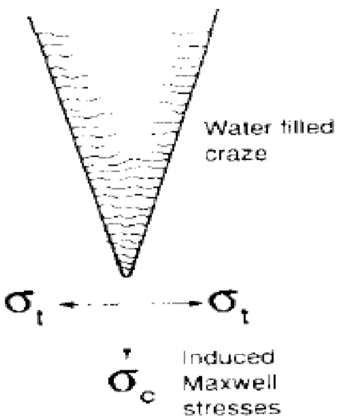


Figure 1: Sketch showing a mechanical model for initiation and growth of vented water trees.

3. Stresses within the insulation of a bent cable

After extrusion and curing the cable is cooled from the outside. This means that the outer parts of the insulation become cold and solid at a time when the inner parts of the insulation still is melted at a higher temperature. Cooling then result in formation of a rather complex stress distributions within the insulation, including both longitudinal and radial residual stresses [7]. It is, however, reasonable to assume that after manufacturing the magnitude of the frozen-in tensile stress will be higher close to the conductor than at the outer insulation surface, due to on one hand the differences in thermal expansion coefficient of solid and molten polymer and the effect of the conductor with low thermal coefficient of expansion.

In the following the additional stresses introduced by bending a cable is considered. It is assumed that the cable is elastically elongation or compressed around a central neutral plane. This assumption is valid only if the magnitudes of the elasticity modulus for tension and compression are equal. The axial strain at a given point in the insulation then becomes:

$$\epsilon_z(r,\theta) = \frac{\Delta l}{l} = \frac{2r\sin\theta}{D_p + 2r_O} \qquad (3)$$

Where, r and θ refer to the cable radial and angular position, r_O is the outer diameter of the cable and D_p is the pipe diameter.

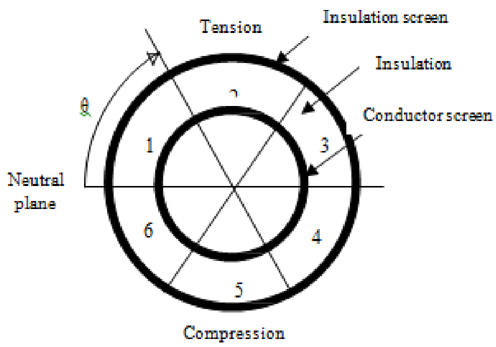


Figure 2. Illustration of the cable cross section showing the division into six e qual sectors.

The region of the cable cross-section at the outer circumference (sectors 1,2 and 3) will experience an axial tensile strain, while sectors 4,5 and 6 will experience a compressive axial strain, as illustrated in Figure .

4. Experimental

All experiments were performed using samples of a 12 kV triple extruded XLPE cable with copper conductor with inner and outer insulation radius of 4.5 and 10.5 mm, respectively.

4.1 Tensile Testing of XLPE Cable Insulation

From the insulation section of 10 cm long cable samples 2 mm thick dumbbell shaped XLPE samples were cut using a microtome. The length of the 4 mm wide parallel portion of the dumbbells was 25 mm.

The dumbbell samples were tested in a Tensile-strain (LLOYD LR5K) testing machine equipped with a heat cabinet. Measurements were performed at 30, 40 and 50°C, using a constant elongation rate of 5 mm/s. The tensile elasticity modulus was calculated from the initial slope of the stress-strain-curve. In addition creep measurements were done at 30°C. In this case the samples were elongated until 4, 8, 12, 16 and 20 % of strain and then the resulting load was measured for 1 hour.

4.2 Water tree Aging of XLPE Cable

The 12 kV XLPE cable was cut into two 8 meter long samples, and each length was bent around pipes with diameters 5, 10, 20 and 30 cm, as shown in Fig.3. In order to ensure that the insulation was saturated with water the conductor was filled with water, and the cables were submerged in a water filled tank at 30°C for 2 weeks prior to aging. Then a voltage of 14 kV ($2U_0$) at 50 Hz was applied across the cable insulation

Figure 3. A cable bent around pipes of four different diameters.

4.3 Microscopy examination of Aged Cables

Cable samples were removed for water tree analysis after 3 and 9 weeks of ageing, respectively. Prior to removing the cable sample a longitudinal notch was made in the outer surface of the cable. This was done in order to determine in which sector the trees were formed.

Then 20 cm long sections were helically cut into 0.40 mm thick slices using a lathe. The helicoids were dyed according to the standard CIGRE methylene blue procedure, and investigated with an optical microscope at 25-100 times of magnification. The number and length of water trees were examined in the 6 equal angular sectors shown in Figure 2. In addition, the length of the longest tree was measured in the tensile and compressive zones for each 4 cm long cable sample.

The distribution of bow-tie trees was investigated in a 30 mm long cable segment of the most sharply bent cable only.

5. Experimental Results and Discussion

5.1 Tensile Testing of XLPE Cable Insulation

Results from measurements of stress-strain relations of XLPE cable insulation are shown in Figure 4. The apparent elasticity modulus was determined from the initial slope to be 80, 53 and 20 MPa at 30, 40 and 50°C, respectively. At 30 °C the stress was found to be proportional to the strain up to approximately 0,9% and the yield limit was determined to be about 12MPa.

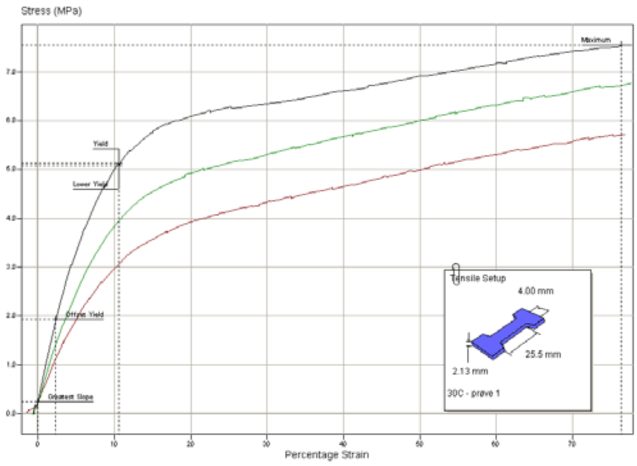


Figure 4. Tensile stress-strain curve for XLPE cable insulation at 30, 40 and 50°C.

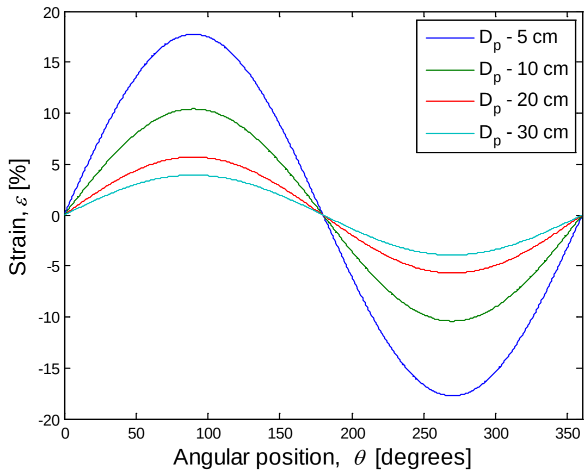


Figure 5. Estimated strain versus angular position within the insulation of the XLPE cable bent around pipes of indicated diameter, according to eq.3.

The estimated values presented in Figure 5 indicate that the most sharply bent cable sample (D_p = 5 cm) were subjected to strains well above the yield or elasticity limit of around 10%.

The results of the 1 hour creep measurements are presented in Figure 6. The large stress relaxation, due to the viscoelastic properties of XLPE, was clearly demonstrated. It was shown that when a static strain is applied the stress in the insulation will be rapidly decayed, apparently according to a time constant of about 150s. Due to considerable yielding increasing the strain above about 16 % had minor effect on the resulting stress.

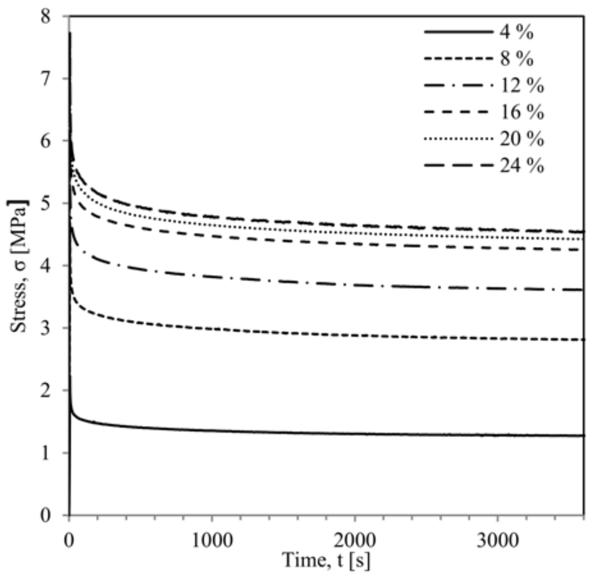
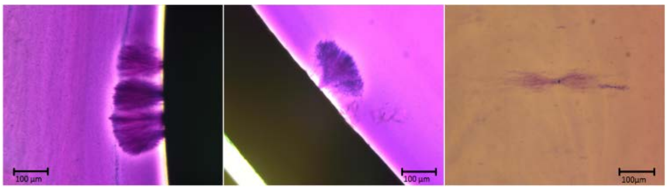


Figure 6. Measured stress relaxation as a function of time for XLPE dumbbell shaped test objects initially subjected to tensile strains at 30 °C in the range from 4 % to 24 %.

5.2 Examination of Water Trees

Some examples of water trees observed in the examined cables are shown in Figure 7, while the number of vented trees initiated from the conductor screen in each sector of the cables are shown in Table 1.



a) *b)* *c)*

Figure 7. a) Several vented trees initiated close together at the conductor screen. b) A vented tree initiated at the insulation screen. c) A large bow-tie .

TABLE 1. OBSERVED NUMBER OF VENTED TREES AT CONDUCTOR SCREEN

Pipe diameter [mm]	Aging time [weeks]	Total number of vented water trees in each sector					
		Tension			Compression		
		1	2	3	4	5	6
50	3	27	26	22	9	3	11
	9	33	18	20	6	2	13
90	3	34	15	32	12	8	10
	9	29	31	30	15	7	10
180	3	29	41	32	14	11	11
	9	25	31	37	23	17	15
300	3	19	19	18	13	11	15
	9	25	21	27	15	15	17
∞	3	23	13	16	17	18	16
	9	18	23	25	31	26	18

TABLE 2. OBSERVED DENSITY AND AVERAGE MAXIMUM LENGTH OF BOWTIE TREES

Pipe diameter [mm]	Aging time [weeks]	Density and average maximum length of bowtie trees			
		Tension		Compression	
		n [cm^{-1}]	$l_{av,max}$	n [cm^{-1}]	$l_{av,max}$
50	3	84,8	109,7	41,0	71,8
	28	121,7	111,1	90,8	98,7
300	28	86,7	112,5	41,7	109,0
∞	3	52,1	69,1	67,9	74,0

Results presented in Fig. 8 show that the fraction of vented water trees in the compression zone was approximately 20% for the most sharply bent cable sections, while as expected it was approximately 50 % in the straight cable sections.

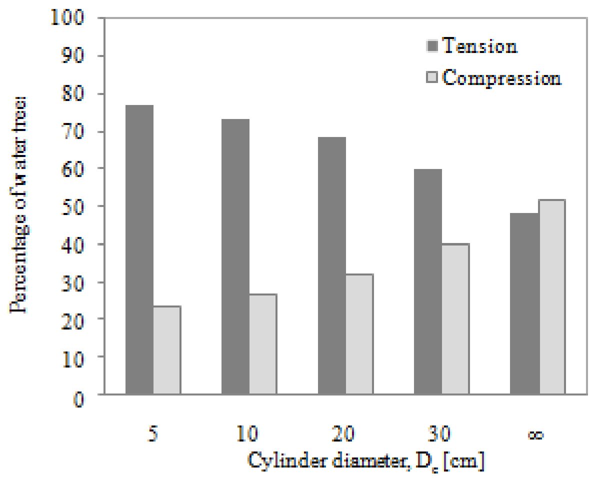


Figure 8. The percentage of vented water trees in the tension zone and in the compression zone after 3 week of ageing at each pipe diameter.

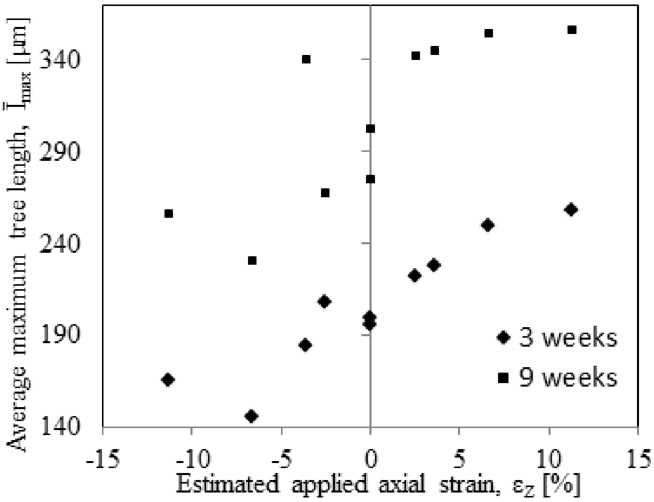


Figure 9. Average maximum lengths of vented water trees from the conductor screen versus estimated strain.

The total number of vented trees was approximately equal after 3 weeks and 9 weeks of aging. The results presented in Figure 9 show, however, that the average maximum tree lengths increase with ageing time. This result implies that the initiation takes place relatively quickly, and that 3 weeks of ageing are sufficient for the water trees to grow to lengths above the detection limit (~50µm).

Approximately 98 % of the vented trees were found to originate from the conductor screen. This was somehow unexpected as the applied mechanical strains were highest close to the insulation screen of sector 2. This could probably be caused by higher frozen in compressive stresses at the outer screen, balancing the effect of tension due to bending. The difference in tree density is much higher than what may be caused by the approximately 60 % higher applied electric field at the conductor screen.

The data presented in table 2 show that the angular distribution of bow-tie trees was similar to the distribution of vented trees.

The obtained results thus provide very strong evidence that the water tree initiation rate is reduced by compressive stresses, while it is increased by tensile stresses, in accordance with earlier studies.

6 Conclusion

- Tensile mechanical stress enhances water tree formation, while compressive stress will retard water tree degradation.

References

[l] E.Ildstad , J.Sletbak and H.Faremo: "Water Treeing and Breakdown Strength Reduction of XLPE insulation" . ICSD-89. Trondheim. Norway, July 2-6.1989.

[2] E. Ildstad, et al: "Influence of Mechanical Stress and Frequency on Water Treeing in XLPE Cable Insulation," Conference Record of the 1990 IEEE International Symposium on Electrical Insulation, pp.165-168.

[3] B.R. Varlow:" Electrical treeing as a mechanically driven Phenomenon", Proc. 1998 Int. Symp. On Electrical Ins. Materials, Japan Sept. 27-30, 1998.

[4] H.H. Kausch: "Polymer Fracture". 2. ed. Springer Verlag, 1987.

[5] J.W.Billing : "Examination of Mechanical Stress in Extruded Polymer Cable Insulation using Thermal Mechanical Analysis". ERA Report 89-0678R, Jan. 1990.

[6] J.Sletbak, "The Mechanical Damage Theory of Water Treeing - A Status Report," Proc.of the 3rd ICPADM, 1991, Tokyo, Japan: pp.208-213.

[7] L. Olasz , P. Gudmundson, "Prediction of Residual Stresses in Cross-linked Polyethylene Cable Insulation," Polymer Engineering & Science, 2005. 45(8): pp.1132-1139.