Enhancement of Water Tree initiation due to residual and applied Mechanical Strain on XLPE Cables

Erling Ildstad and Simon Årdal Aarseth
Department of Electric Power Engineering
Norwegian University of Science and Technology
NTNU, Trondheim, Norway

Erling.Ildstad@elkraft.ntnu.no

Hallvard Faremo
Department of Power Technology
SINTEF Energy Research
Trondheim, Norway

Abstract- **This paper presents results from laboratory water tree experiments performed on samples of commercially available 6/10 kV XLPE insulated cables. The main purpose of the investigation was to examine possible water tree enhancement, due to mechanical tension of the insulation.**

During water tree ageing at 50 Hz AC voltage of 14 kV (E_{max}=5.2 kV/mm) the cable samples were mechanically stretched at 1%, using both static and dynamic mechanical load varying at 0.1 Hz. In addition thermal treatment indicated a total residual longitudinal mechanical strains of 6% , frozen in during the manufacturing process.

Both the density and growth rate of vented and bow-tie water trees was found to increase with increasing applied mechanical tension. During non-strained thermal treatment the axial length of cables was reduced by about 6%. The low density of vented trees originating from the outer insulation screen supports the assumption that frozen in compressive stresses at the outer insulation surface may balance the effect of the applied strain.

Keywords; XLPE cable, mechanical tension, water treeing

I. INTRODUCTION

The increased demand for exchange of electric power with floating off-shore installations has made it necessary to design so called “dynamic” high voltage power cables. The free hanging sections of such cables will be exposed to mechanical stresses due to its own weight and movements caused by ocean streams and waves. Thus the total mechanical stresses will be of both static and dynamic character and strongly depend upon the design of the cable system. To prevent ingress of water and premature water tree degradation XLPE cables are usually equipped with metallic barriers.

In case of dynamic sub-sea cables it is not recommended to use extruded lead barriers, due to their high susceptibility to fatigue damage [1]. An alternative approach is to use thin aluminum or copper foils wrapped or welded as corrugated tubes around the cable core. Nevertheless, it is sometimes considered economically favorable to use cables without any metallic barriers. Such, so called wet cable designs are for example used at system voltages below approximately 50 kV and in case of some special off-shore applications.

During such wet service conditions, water will diffuse into the insulation causing water tree formation. It has previously been shown that static tensile stress enhances water tree initiation and growth in the insulation, while static compressive stresses suppress water tree growth [2]. The main purpose of the work presented here has been to examine how and dynamic mechanical stress affect initiation and growth of water trees. The paper presents possible external and internal sources of mechanical tension and briefly reviews the mechanical damage theory of water treeing. Finally results from water tree degradation performed on 12 kV XLPE cable, exposed to combined mechanical and electrical stress are presented and discussed with respect to the proposed mechanisms.

II. MECHANICAL STRESSES ACTING ON THE INSULATION OF A FREE HANGING CABLE

In general the resulting tensile forces F_T acting on a cable hanging in a catenary loop between a floating construction and the sea-floor will be determined by contributions from gravity, acceleration and drag forces:

$$F_T = F_w + F_a + F_D$$

Where:

i) $F_w = \dfrac{m_w g d}{1 - \sin\alpha}$ is the stationary gravity force determined by the wet weight m_w (dry weight – buoyancy) per meter cable, the sea depth d, gravity g and the catenary angle α.

ii) $F_a = \dfrac{h}{2} m (2\pi / T)^2 \cos(2\pi t / T)$ is the vertical acceleration force, assuming a sinusoidal vertical wave movement with a peak to peak amplitude of h. The relation shows that this dynamic force is proportional to the square of the frequency, the total mass m of the hanging cable and the wave height h. The frequency is determined by the period time T between subsequent wave peaks. -A time which in many cases results in ocean wave frequencies around 0.1 Hz.

iii) F_D is the drag or friction force associated with moving the cable up and down in the water. The magnitude of this force is increasing with increasing outer diameter of the cable, but is usually considered to be small compared to that of the static and acceleration force.

Thus, all the above mentioned forces strongly depend upon the design of the cable. In case of a practical subsea cable with a wet weight of for example 30 kg per meter, the total tensional design force at a sea depth of 250 m will typically be in the range of 100 kN. This means that strong reinforcement is needed, usually facilitated by means of armor in the form of round, galvanized steel strands applied as a spiral with a certain pitch length around the cable. This tensile armor is designed such that insulation damage is prevented, provided the following criteria are fulfilled:

a) *The relative elongation of the conductor and the armor must be equal, to avoid shear forces in the insulation.*
b) *The maximum strain/elongation must be lower than that of the mechanical yield point of the conductor, to prevent permanent elongation of the conductor.*

Yielding in copper occurs at strains lower than 0.1 %, while cross-linked polyethylene is much more flexible, yielding at about 9% at 30 °C . This means that in a practical cable installation the externally applied longitudinal strain in the insulation will be limited to values far below the yield point of the polymer. When sharply bending a cable, the outer parts of the insulation may, however, be stressed to values close to the yield stress [2].

III. Mechanical Stresses Frozen in during Cable Manufacturing

Water tree ageing of extruded cable insulation may also be affected by mechanical stresses frozen-in during the manufacturing process. After the extrusion and curing processes, at a maximum temperature of above about 170 °C, the cable is rapidly cooled from the outside. This means that the outer parts of the insulation become cold and solid at a time when the inner insulation parts still are melted and expanded at a higher temperature. During further cooling the shrinkage of the inner insulation region will be prevented by the more solid and colder outer parts. This introduces internal tension forces close to the conductor, and circumferential and axial compression of the outer insulation regions.

In addition large axial or longitudinal tension stresses will be introduced due to the high thermal expansion of the polymers compared to that of the metallic conductor. High adhesion between the conductor and the extruded semiconducting conductor screen, however, prevents the insulation from shrinking to its equilibrium dimension. Thus a rather complex distribution of frozen-in mechanical stresses will be distributed within the insulation, including both longitudinal and radial residual stress components [3]. Typical magnitudes of such longitudinal tension stresses have been measured to be in the range of 10-30 MPa, values which are comparable to or higher than the yield strength of polyethylene [4].

IV. Mechanical Damage Theory of Water Treeing

The mechanical damage theory assumes that water tree ageing is due to mechanical overstressing, caused by a combined effect of external mechanical stress and electric stress. Previous investigations have shown that initiation and growth of water trees in polymeric cable insulation will be enhanced by tensile mechanical tension and retarded by compressive stresses [2, 5, 6]. It is assumed that mechanical tensile stresses reduce the amount of electric energy needed to cause bond scission of the polymer chains. Thus, facilitating craze formation and initiating of water trees partly filled with liquid water.

During AC voltage application, tensile Maxwell stress will be generated perpendicular to the interface between the water filled zone and the insulating material. It is therefore likely that the effect of applying mechanical tension to cable insulation is to ease micro voids and subsequently water tree formation, while compressive forces are expected to have an opposite effect.

Based upon the above description of frozen in mechanical stresses of an XLPE cable, it is reasonable to assume that after manufacturing the magnitude of the tensile stress will be highest close to the conductor. Thus it is reasonable to assume a higher number of crazes, acting as initiation sites for water trees, close to the conductor than in the outer parts close to the insulation screen.

V. Experimental

All experiments were performed using samples taken from a commercially available 6/10 kV triple extruded XLPE cable, with 95 mm^2 copper conductor and the same semiconducting conductor and insulation screen materials. The effect of both static and dynamic mechanical tension was examined using the water tree ageing setup schematically shown in Fig. 1. The 3m long samples were clamped to the test-rig and the cable insulation was simultaneously exposed to AC voltage, tap-water and oscillating mechanical tension.

Prior to ageing the copper conductors were removed from the examined cable sections, allowing only the insulation to be uniformly stretched during the ageing. This was done by first filling silicone oil in-between the conductor strands. Thus providing sufficiently low friction for the conductor to be pulled out of half the cable length, using a force lower than about 10^4 N. Sufficient mechanical support for mechanical clamping was provided, at one end, by the remaining conductor, while a short steel tube was inserted into the cable core at the end without copper conductor. This tube also made it easy to keep the conductor filled with water during ageing.

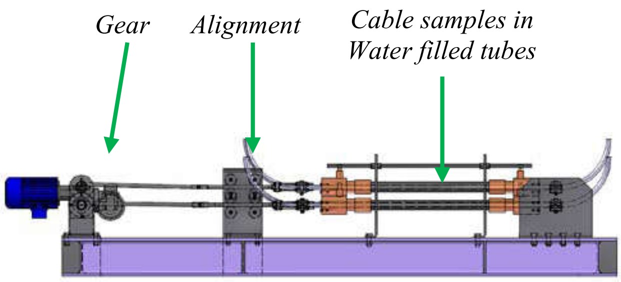


Figure 1: Sketch of the experimental set-up for water tree ageing of cables simultaneously applied to dynamic mechanical tension and 14-25 kV 50 Hz voltages.

An electric motor provided longitudinal dynamic sinusoidal oscillating mechanical strain at a maximum elongation strain of 1 % and a mechanical frequency of 0.1 Hz. Due to the non-constrained cable samples it was not possible to apply external compressive forces during this test. In parallel 3 test objects were aged as references; two with conductor and without external mechanical strain and one sample without conductor which was statically strained at 1 %.

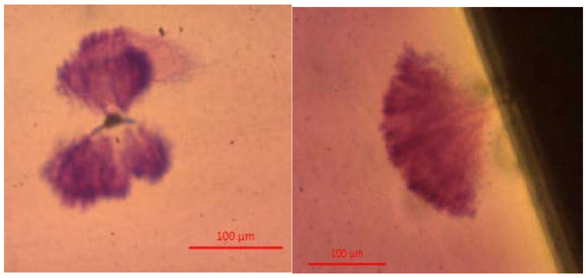
During ageing the cable conductors were filled with tap water and all cable samples were kept in a tube filled with tap water at 20 °C. An effective 50 Hz ac voltage of 14 kV (E_{max} = 5.2 kV/mm) was applied across the cable insulation, during the ageing period of 3 weeks. One of the no strained reference cable samples was energized at 25 kV, providing an effective stress at the insulation screen interface of 5.2 kV/mm.

After 3 weeks of ageing each 20 cm long cable sections were helically cut into 0.40 mm thick slices using a lathe. The helicoids were then dyed according to the standard CIGRE methylene blue procedure, and investigated with an optical microscope at 25-100 times of magnification. The number and maximum length of bow-tie and vented water trees from the conductor and insulation screens were examined in each slice. The 3.5 mm thick insulation wall was divided in 3 equally wide sectors, inner, middle and outer, allowing the radial distribution of bowtie trees to be measured.

The amounts of frozen in longitudinal strains were measured as the change in length of 0.5 and 1 m long cable samples. All lengths before and after removal of the conductor as well as after thermal treatment at 120 °C for 2 days were measured at room temperature.

VI. Experimental Results and Discussion

Micrographs of typical bow-ties and vented water trees are shown below in Fig. 2. This implies that the initiation takes place relatively quickly, as 3 weeks of ageing was sufficient for water trees to grow to lengths longer than the detection limit of ~50 µm.



a) Bowtie tree b) Vented tree

Figure 2: Micrograph showing examples of typical water treeing after 3 weeks of ageing at 14 kV (50 Hz) dynamic 1 Hz testing at 1 % strain

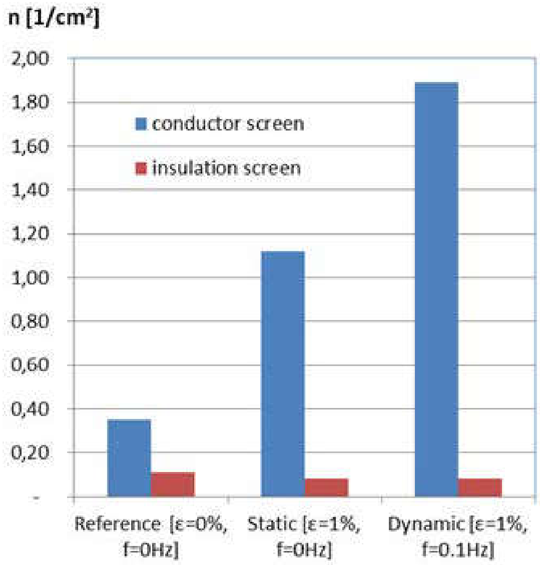


Figure 3: Observed density of vented water trees after 3 weeks of ageing at the indicated test conditions at 14 kV rms. Cable samples without conductor.

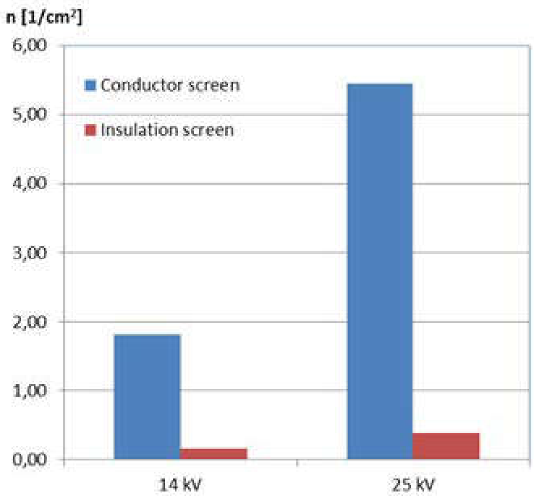


Figure 4: Density of vented water trees observed after 3 weeks of ageing reference cable samples at the indicated rms voltages. Cable samples with conductor.

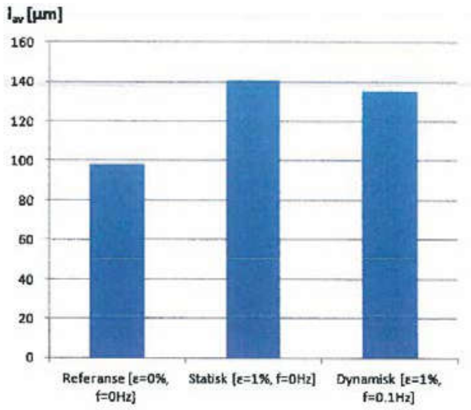


Figure 5 Average lenth of vented water trees after 3 weeks of ageing at the indicated test conditions at 14 kV rms.

The results presented in Fig. 3 and 4 shows that most of the vented trees were found to initiate at the conductor screen. In total, typically less than 5 vented trees and more than 400 bowtie trees were found per cm cable. The average length of the bow-tie trees was found to be around 100 µm and to be nearly independent of the applied stress. The results presented in Fig. 3 and 5 show that the effect of applying a mechanical elongation of 1 % was to enhance both the number and the average length of the vented trees initiated at the conductor screen. Oscillating 0.1 Hz mechanical strain seems to have nearly the same effect as static strain.

A very interesting observation was that the vented tree densities observed in the reference cable sample aged without conductor and a static strain of 1 % was comparable to that of a reference cable with conductor, aged at the same voltage. This is a result in good agreement with the results presented in Table I, which indicate that the effect of removing the conductor is to reduce the frozen in longitudinal strain by 0.7 %. Due to the viscoelastic properties of XLPE the residual longitudinal tension in the cable insulation is probably lower than the total strain of 6% released during thermal treatment.

Table I: Measured cable length before and after the indicated treatments

Condition	Removal of conductor	Thermal treatment at 120 °C
Start length 1m	0.994 m	0.945 m
Start length 0.5 m	0.496 m	0.47 m
Average total strain removed	0.7 %	5.8 %

The very low density of vented trees from the insulation screen supports the assumption that frozen-in compressive stresses may balance the effect of the applied strain at the outer insulation surface. On the other hand one may argue that the 1.8 times electric stress enhancement at the conductor screen may contribute to the difference. The results presented in Fig 4 strongly indicate that this is not a dominating effect. Here it is, as expected, shown that the tree density increases with increasing voltage. In case of applying 25 kV the applied electric stress at the insulation screen was the same as that applied at the conductor during ageing at 14 kV. Thus, at an applied electric field stress of 5.2 kV/mm, the density of vented trees initiated from the conductor screen was found to be 4.5 times higher than that from the insulation screen.

Results presented in Fig. 6 shows that also the number of bowtie trees was highest close to the conductor screen, indicating a 3.6 times higher density of bowties in the inner region than in the outer more compressed parts of the insulation.

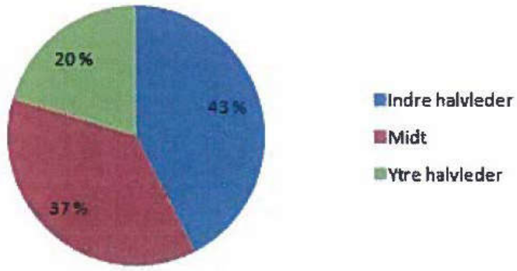


Figure 6: Relative number of bow-tie trees of reference cable with conductor, no external strain. After 3 weeks of ageing at the at 14 kV rms

VII. Conclusions

Static and dynamic tensile mechanical strain enhances water tree formation in XLPE cable insulation.

The magnitudes of remnant compression and tension stresses, frozen-in during the production process of a cable, are higher than what may be applied during service of a dynamic subsea cable.

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