Influence of DC Stress Superimposed with High Frequency AC on Water Tree Growth in XLPE Insulation

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Abstract

Power electronics used for HVDC converters will stress cable insulation with a DC voltage with superimposed transients. The effect these transients have on the performance of the polymeric cable insulation is yet not clear. The main purpose of this work has been to investigate the effect of such transients on XLPE cable insulation when exposed to moisture.

Laboratory experiments were performed on Rogowski shaped test objects with an insulation thickness of 1.3 mm. At one of the semi-conductors, 20 sodium chloride (NaCl) particles were placed in order to facilitate initiation of vented water trees. The test objects were conditioned with water at 20 °C for two months ensuring saturation of water inside the insulation system before testing.

The test objects were aged with an AC voltage simulating the transients from a HVDC converter. Experiments were performed using the AC voltage with and without DC stress to investigate the influence of the DC level on the water tree growth.

The ageing was done at 30 °C.

Test objects were taken out and inspected for water tree growth regularly. The results show a rapid ageing caused by water treeing when exposed to the DC voltage overlaid AC voltage with a frequency of 5 kHz and a pure AC voltage stress.

1. Introduction

The production of electric power from floating wind turbines is a big upcoming challenge in Norway and internationally. Environmental requirements concerning noise pollution, the impact of visual image as well as conflicts of interests in the near shore areas lead to increasing distances between offshore wind farms and onshore distributions grids [1]. When the distance between the wind farm and shore is long, transmission by HVDC will be the preferable method. The alternating voltage produced by the wind mills are rectified either using Line Commutated Converters (LCC) or Voltage Source Converters (VSC), the latter being preferred due to its lower volume size and simple structure [2]. When using VSC (and LCC) the resulting DC voltage will also contain transients originating from the switching of the power electronic components. For DC/AC converters a Total Harmonic Distortion (THD) of 5 % is tolerated for AC voltages below 69 kV, while for higher AC voltages the maximum THD allowed is 2-3 % [3]. However, for HVDC cables there are currently no requirements for THD.

The THD from a VSC installation can be reduced installing a filter. In general, the lower THD the more space is required. As space is limited and costly for offshore wind farm parks, VSC installations are urged to be as space effective and small as possible.

The voltage stress on the HVDC cable will be unequal distributed along the cable length as the higher frequencies quickly are attenuated and dispersed. The insulation closest to the rectifiers will be subjected to the most severe share of harmonics. In floating offshore installations, this part of the cable will also be the flexible part and hence, the place most likely to experience damage in the metal based moisture barrier. In addition, to save weight, wet designed cables are also an. Both designs can, however, lead to water intrusion that might lead to water tree initiation and growth.

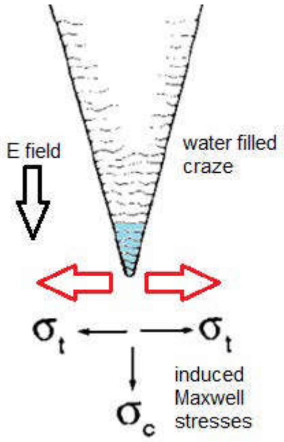

Fig. 1 - Scketch showing a mechanical model for initiation and growth of vented water trees

The mechanical damage theory assumes that water treeing is due to mechanical overstressing, caused by a combined effect of external mechanical stress and electric stress (see Fig. 1). Previous investigations have shown that initiation and growth of water trees in polymeric cable insulation will only take place when an AC voltage is applied and the relative humidity of the insulation and the semi-conductive screens are sufficiently high to allow formation of liquid water within micro cracks and crazes [4]. The alternating AC voltage and the strongly inhomogeneous field around the crack will induce high Maxwell stresses between the water and the polymeric insulation. These stresses will, if sufficiently high, lead to further crazing zones around the tip of the water filled craze. Electric forces will attract water into these crazes and the water tree growth is established. Investigations have also shown that increased frequency of the ageing voltage accelerates water tree growth [5, 6].

In this work the water tree growth in wet cable insulation stressed with DC (20 kV/mm) with a 10 % sinusoidal high frequency (5 kHz) has been studied. In addition, same studies have been performed for a test object subjected to DC voltage (20 kV/mm) and the same 5 kHz voltage stress.

2. Experimental

2.1. Test Objects

The Rogowski test objects, schematically illustrated in Fig.3, were manufactured using high quality cross-linkable cable grade materials of 1.3 mm thick low density polyethylene (LDPE) and 0.5 mm thick semi-conductive screen material. Before assembling the test objects, a microliter syringe was used to place 20 droplets of 0.2 µl 0.1 M sodium chloride solution on the surface of the lower semi-conductive screen. The droplets were then allowed to evaporate in a vacuum chamber at 30 °C for 4 hours before assembling the complete test object and cross-linking. The test object was pressurized and then cross-linked at 170 ºC for 12 minutes. Afterwards, the test objects were cooled down to room temperature under pressure. In order to remove mechanical stress, the test objects were heated to 130 ºC for about 5 minutes. After that, in order to remove any volatile by-products from the curing process, the test objects were kept in a ventilated oven at 90 ºC for 72 hours.

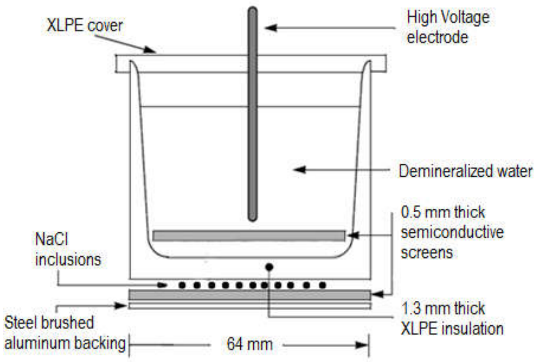

Fig. 2 - Test object. 20 NaCl particles were placed between the lower semi-conductor and the XLPE insulation in the homogeneous field region to facilitate water tree growth. The test object was filled with demineralized water and sealed off with a cover of XLPE to prevent any evaporation of water.

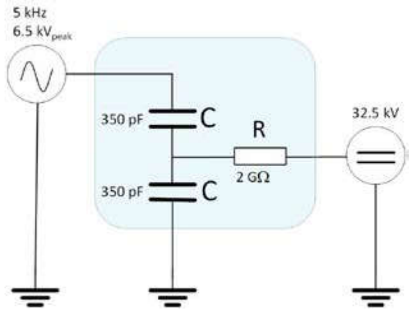

Fig. 3 - Experimental set-up. Principal drawing of the combined DC and AC stress ageing test set-up. The lower electrode of the test objects are connected to the DC source and the upper electrode is either connected to the high voltage amplifier or ground.

2.2. Ageing Conditions

The objects were screened at 20 kV/mm for 5 min to secure high quality of the test objects. Finally, before starting the ageing, the test objects were randomized. Prior to the ageing, all the samples were soaked in water for 2 months at 20 °C and then one week at 30 °C to saturate the insulation with water. This facilitates conditions for simultaneously water tree initiation at both electrodes due to the initial high relative humidity.

The DC ageing was performed using a stable high voltage source normally used for conduction current measurements. The combined high frequency and DC ageing was performed using a TREK high voltage amplifier and the same DC source. The same amplifier was also used during application of 5 kHz only. The high DC stress (25 kV/mm) was applied to the lower electrode as indicated in Fig. 2. Five objects were removed after 2, 4, and 8 weeks of ageing for measurements of breakdown voltage and degree of water treeing.

2.3. AC Breakdown Strength

All samples were kept wet prior to the AC breakdown strength testing. During testing the Rogowski samples were subjected to an AC ramp until breakdown increasing at a rate of 20 kV/minute. In order to prevent external flash-over, the objects were soaked in silicone oil. The observed breakdown values were fitted using Weibull statistics [8].

2.4. Water Tree Analysis

20 slices from each Rogowski type object were microtomed from the center of the sample including the breakdown channel (~ 0.52 cm^3). Measurements of water tree lengths and density was performed using an optical

stereo microscope with a magnification of 30 times. Before examination the 0.5 mm thick microtomed slices were stained in methylene blue dye solution. Only the longest bow-tie and vented water tree were measured in each slice, and extreme value statistics was used to characterize the distribution of the longest water trees [8]:

$$P(L_{\max} < l_{\max}) = W(x) = \exp\left[-\left(\frac{d-x}{d-\nu}\right)^{\beta}\right] \qquad (1)$$

where l_{max} is the length of the largest water tree, v is the expected largest tree (36.8 % - value), d is the insulation thickness and β is a parameter characterizing the dispersion. This distribution could be called the Weibull type distribution of the largest value because it's analogy with the Weibull distribution of the smallest value. In order to have sufficient number of observations, the longest tree in 10 consecutive slices was recorded.

3. Experimental Results and Discussion

3.1 AC Breakdown Strength

Fig. 4 shows the breakdown stress values up to 8 weeks of ageing. The breakdown stress of the unaged wet conditioned test objects including the NaCl particles is about 50 kV/mm. It can be seen that ageing for 8 weeks at a DC stress of 25 kV/mm only slightly reduced the AC breakdown values to 46 kV/mm. The effect of the high frequency is to strongly reduce the breakdown stress. After 2 weeks, the breakdown stress was reduced to 16 kV/mm. The same reduction was initially not observed for the combined DC and high frequency AC stress. However, after 8 weeks of ageing the reduction was in the same range.

3.2 Water Tree Analysis

Pictures of the longest observed vented and bow-tie water trees are shown in Fig. 5. The longest trees observed were vented trees growing from the sodium chloride particles from the lower electrode. Only after 2 weeks at 5 kHz AC, long vented water trees bridged the insulation as shown in Fig. 5 a). The darker vented trees growing from the particles indicated a much higher density of voids and channels than for the water trees not growing from such particles. The trees growing from the particles were also wider. Long vented water trees were also found to initiate at the upper electrode at

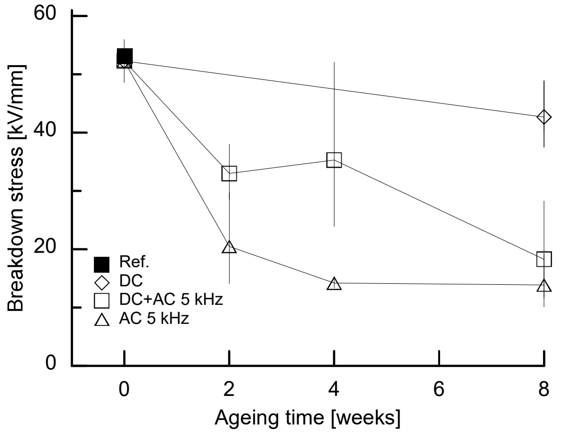

Fig. 4 - Breakdown stress (Weibull 63.2 % values) for the different ageing conditions as function of time, including the 95 % confidence interval.

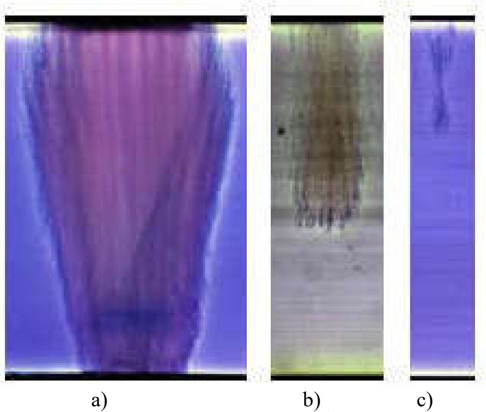

Fig. 5 – Longest observed water trees: $^{a)}$ Vented tree growing from a NaCl particle bridging the insulation (2.5 kV/mm AC 5 kHz, 4 weeks). AC 5 kHz, 4 weeks). b) Longest observed tree from upper electrode (2.5 kV/mm at 5 kHz, 2 weeks). c) Longest observed bow-tie tree (25 kV/mm DC/ 2.5 kV/mm 5 kHz, 8 weeks).

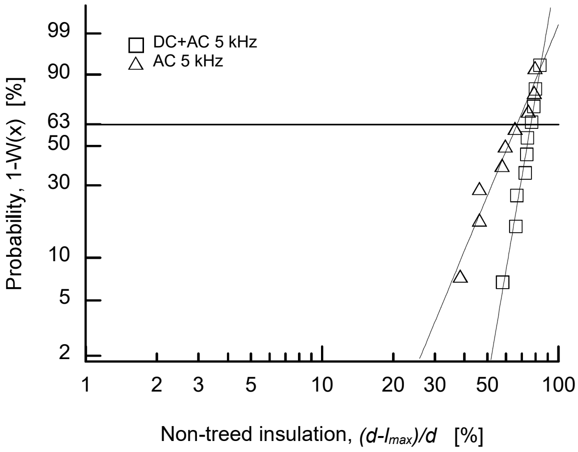

Fig. 6 - Distribution of vented water trees (according to (1)) after two weeks of ageing from the upper electrode.

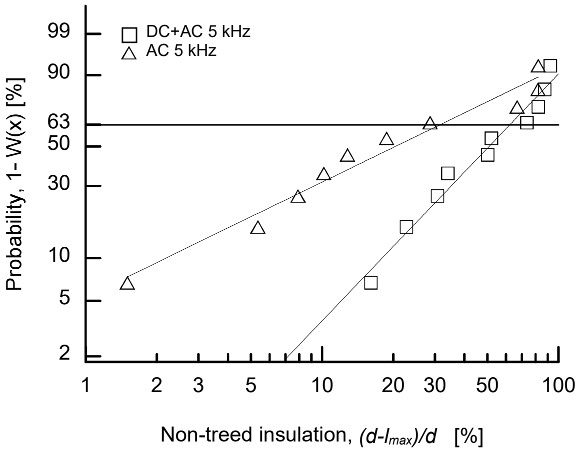

Fig. 7 - Distribution of vented water trees (according to (1)) after two weeks of ageing from the lower electrode.

5 kHz AC. These trees had a more diffuse shape and were narrow. Many small (< 50 µm) bow-tie trees were detected. The longest observed bow-tie is shown in Fig. 5c.

The extreme value distribution of the longest vented water trees after two weeks of ageing from the upper and lower electrodes are shown in Fig. 6 and 7 respectively, where the 10 longest trees are included for each ageing condition and time. Fig. 6 shows the distribution of the trees growing from the upper electrode were no NaCl particles were present. It can be seen that the longest trees appeared at 5 kHz, and that the superposition of a 25 kV/mm DC field reduced the length of the longest trees. However, the expected longest tree (v) was not significant different. The same observations were made for the vented water trees growing from the NaCl particles at the lower electrode as shown in Fig. 7, but the difference were clearer as the trees were much longer. This is in contradiction to a previous study where no effect was found when a high DC voltage was super positioned to a high frequency AC voltage [9].

The longest observed water tree for each ageing condition is initiated and growing from one of the NaCl particles at the lower electrode. However, it was observed that not all of the NaCl particles initiated vented water trees. This might be caused by the surface being sufficiently smooth even with the inclusion present. The relatively large scatter in the tree lengths in Fig. 7 is due to that shorter trees initiated from other defects or contaminations are included in the distribution.

There were no observations of water trees at high DC stress using a stabilized voltage source, contrary to previous observations [9].

4. Conclusions

The acceleration of water tree growth by frequency is strongly dependent on the size of the contamination at the initiation site.

No water trees were observed under high DC field stress, even when large NaCl particles acting as initiation sites are present at the interface between the insulation and the semi-conductive electrodes.

The results show that the combined DC and high frequency AC stress generates long vented water trees. The initiation and growth rates are mainly determined by the AC part of the stress. Electrical fields less than 1.8 kV/mm (5 kHz) are sufficient to cause severe water tree degradation of the insulation.

5. Acknowledgement

This work is part of the Norwegian Renergi R&D project “High Voltage AC and DC Subsea Cables for Offshore WindFarms and Transmission Grids” funded by the Research Council of Norway and the industrial partners Nexans Norway AS, EDF R&D (France), Statoil ASA, Statnett SF, Statkraft SF and Borealis.

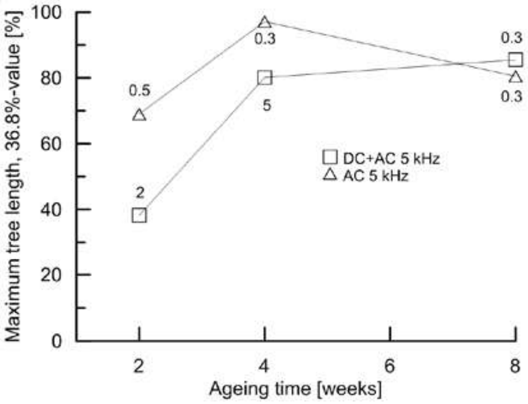

Fig. 8 - Tree lengths (most likely maximum length, 36.8 % - value) from the lower electrode. The numbers in the figure are the β values from (1).

6. References

[1] S. Meier, S. Norrga and H.P. Nee, *“New voltage source converter topology for HVDC grid connection of offshore wind farms”,* 4th Nordic Workshop on Power and Industrial Electronics, Nordpie ’04, Trondheim, Norway, 2004.

[2] E. Koldby and M. Hyttinen, *“Challenges on the Road to an Offshore HVDC Grid”,* Nordic Wind Power Conference 2009, Bornholm, Denmark, 2009.

[3] T. M. Blooming and D.J. Carnovale, “*Application of IEE STD 519-1992 Harmoinic Limits*”

[4] E. Ildstad, *“High Voltage AC and DC Aging of an XLPE Distribution Cable in Wet Environment”*, Nord-IS 1988, Trondheim, Norway.

[5] E. Ildstad, H. Bårdsen, H. Faremo, B. Knutsen, *“Influence of Mechanical and Frequency on Water Treeing in XLPE Cable Insulation”*, IEEE International Symposium on Electrical Insulation, 1990, Toronto, Canada

[6] J. Sletbak, A. Botne, *“A Study on Inception and Growth of Water Trees and Electrochemical Trees in Polyehtylene and Cross Linked Polyethylene Insulations”,* IEEE Trans. Electrc. Insul, Vol. EI-12 No.6, December 1977.

[7] S. Hvidsten, "*Nonlinear dielectric response of water treed xlpe cable insulation*", doctoral thesis, NTNU, Trondheim, Norway, ISBN 82-471-. 0433-4, 1999

[8] E. Ildstad, J. Sletbak and A. Bruaset, "*Estimating the maximum length of water trees using extreme value statistics*", 3rd ICPADM, July 8-12, Tokyo, Japan. 1991.

[9] E. A. Franke et.al., "*Water tree growth in polyethylene under DC voltage stress*", IEEE Trans. Electrc. Insul, Vol. EI-12, No. 3, pp. 218-223, June, 1977.