Wet designs for HV submarine power cables

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ABSTRACT

This paper presents an evaluation and results from a water aging test performed at 10 kV/mm - 500 Hz of a HV 52 kV XLPE core. Water permeation tests and associated modelling have been performed on power cores with a PE-sheath only and a non-impervious water barrier to evaluate the effect of the "semi-wet" barrier. The cable is installed as part of an HV dynamic power umbilical in Åsgard Subsea Compression Project in Norwegian Sea. The estimated lifetime of high voltage (HV) XLPE cables having such a "semi-wet" design is discussed on basis of test results and diffusion models. It is shown that for example swelling tapes, overlapping Cu-tapes and PE-sheath in combination may increase the time to reach critical relative humidity levels significantly in cable insulation. Water treeing does occur but will terminate at a level which could be acceptable at voltage levels higher than traditionally limited to medium voltage (MV). HV cables for oil/gas industry, HV dynamic cables, HV array cables for wind farms, may be applications of interest for this design. However, even if results seem to be safe for many types of applications, caution has to be taken to the conditions needed to such a market introduction; i.e. good and robust material selection, material cleanliness and process technologies are vital.

KEYWORDS

XLPE HV cable, wet design, moisture barrier, 500 Hz, wet ageing

INTRODUCTION

Historically, HV cables have normally been applied with impervious moisture barriers in order to prevent any risk of degradation, e.g. water treeing. MV cables have on the other hand mostly been applied without moisture barriers. In the past, water treeing was a major factor for early breakdowns in MV cable networks but given considerable improvements in insulation material cleanliness, screening layer smoothness and cleanliness, processing, etc., the phenomenon of water treeing, though present in many cables today, cannot be considered to have the same detrimental consequences as it sometimes had 25 - 30 years ago.

There are three conditions that must be fulfilled simultaneously for a water tree to be initiated and/or grow:

1. Electrical field
2. Supply of water
3. An initiation point - impurities and lack of smoothness of screening layers

Item 1) is always valid for both MV and HV cables. Item 2) will be insignificant for dry designs but a wet design using some kind of "retardation" mechanism will decrease the supply of water significantly. Item 3) is the most pronounced improvement over the last decades and has therefore a positive effect for both dry, semi-wet and wet designs.

This paper presents results and analysis from water diffusion and 500 Hz long term ageing tests in water on HV cables using a "semi-wet" design, i.e. a design including swelling tapes, Cu-tapes and PE-sheath. The test is a modification of the test used for MV in ref [1]. It is shown that such a "semi-wet" design will increase the time to reach critical RH-levels [4] in the cable, significantly. Ross and Guerts have earlier shown that swelling tapes and PE-sheath reduce water migration properties, significantly [8]. The lifetime and possible arguments to introduce such cables for different HV applications is therefore discussed and outlined, in light of modern cable materials and processing techniques as well as modelling tools.

All materials used in this design have been characterized with regards to diffusion, saturation and permeability constants and activation energies. A model calibration check of the water permeability properties based on water diffusion measurements on reference cable samples at varying temperatures have been performed, giving good agreement.

The tests described herein are related to the Dynamic Power Umbilical as part of the Åsgard Sub Compression Project. The application of the power umbilical and power cable system is shown in Figure 1. The complete system was recently installed in Norwegian Sea.

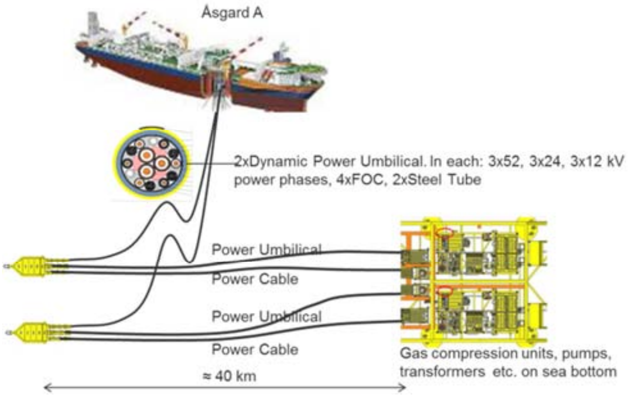


Figure 1. Åsgard Sub compression project installed in Norwegian Sea

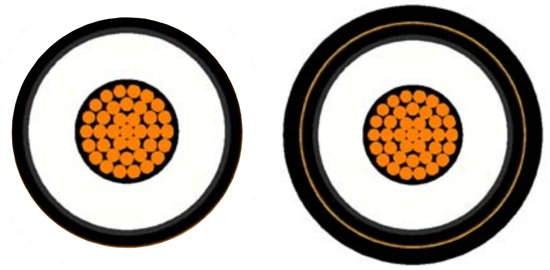
TEST AND MODELLING CONDITIONS

To evaluate the performance of HV wet and semi-wet cable designs, a test and modelling program was set up, containing tests and models on one reference cable (Design 1: Wet design including XLPE core and PE sheath) and one power core design (Design 2: Semi-wet design including swelling tapes and Cu-tapes in addition):

1. Water permeation tests on both Design 1 and 2
2. Water ageing test at 500 Hz of HV XLPE core
3. Modelling of different designs under different environmental conditions
4. Aging test data

The 52 kV XLPE core consists of a stranded/compacted 240 mm^2 watertight Cu conductor including a homo-polymer HV insulation system. The insulation thickness is 9 mm. The reference cable (Design 1) is applied with an inner PE-sheath (2.0 mm), only. Design 2 is applied with an inner PE-sheath (2.0 mm), swelling tapes + double Cu-tapes and an outer PE-sheath (3.2 mm). See cable designs in Figure 2.

The water permeation test has been conducted for both designs. Cable samples with sealed ends of about 0.5 m have been laid in water baths for different durations and the water concentration in each layer measured. The water bath temperatures were 40, 55 and 90 °C aiming at evaluating agreement with diffusion/saturation data from earlier material characterizations.



Reference: Design 1 Power Core: Design 2

Figure 2. Reference and power core designs.

CENELEC [1] has introduced a 500 Hz water ageing test for MV cables mainly based on work made in the Netherlands and Norway during the 90's [5][6].

Table 1. Modified water ageing test at 500 Hz for HV

Test item	MV (CENELEC HD 605)	HV (Modified Test)
Electrical evaluation before test	N.A.	#6 @ 10 m
Preconditioning	55℃/500 h	55℃/500 h
Water ageing test	$3U_0$/3000 h/500 Hz	10 kV/mm /3000 h / 500 Hz
Electrical evaluation after water ageing test	CENELEC: # 6 @ 10 m - ≥ 14 kV/mm, #6 - ≥ 18 kV/mm, #4 - ≥ 22 kV/mm, #2 - Water tree analysis (optional)	VDE: # 6 @ 10 m - ≥ 23 kV/mm, #6 - ≥ 29 kV/mm, #4 - ≥ 35 kV/mm, #2 - Water tree analysis
Continuation of water ageing test	N.A.	10 kV/mm /+3000 h /500 Hz
Electrical evaluation after water ageing test	N.A.	CENELEC: #6 @ 10 m - ≥ 14 kV/mm, #6 - ≥ 18 kV/mm, #4 - ≥ 22 kV/mm, #2 - Water tree analysis

The CENELEC-test has here been scaled up and modified slightly to align to HV testing in water. Table 1 summarizes the most important parameters used in the test.

The main modifications in the test regime are the duration of total 6000 hours and the voltage level, which is related to an inner electrical ageing stress of 10 kV/mm. Water tree analysis and AC breakdown tests have been performed after each 3000 h period. After 3000 hours, the more stringent VDE requirement was set.

WATER TREE INITIATION AND GROWTH

Water tree initiation and growth is influenced by many factors such as type and size of water soluble contaminants, the frequency and magnitude of the applied voltage as well as the relative humidity in the insulation [2-4]. During service, the ageing in wet designed cable systems can essentially be split up in three phases as indicated in Figure 1 and Table 2:

Table 2. Description of ageing phases

Phase No.	Relative Humidity (RH) [%]	Comment
1	RH < 70	No initiation of water trees
2	70 < RH < 100	Initiation and reduced growth rate of water trees
3	100 < RH	Water available in the insulation for water tree growth

In Phase 1, the relative humidity is too low for water trees to initiate [2,3]. This has been explained by that the initiation of water trees at relative humidity values below 100% is associated to condensation of water vapour at water soluble contaminations such as salts. The classification of the service life of the wet designed cable in phases as in Table 2, it is assumed that sodium chloride particles are present in the insulation system acting as initiation site for water trees. Then condensation of water occurs at about 70 %. In case of Phase 2, the availability of water vapour is limited, impeding further growth of the trees after ageing. It has previously been found that the growth rate as well as the density in model cable (cup-shaped) insulation is strongly dependent on the relative humidity. In Phase 3, the insulation is completely saturated with water.

Dependent on the water transport characteristics of the outer sheath layers, the time dependence of the relative humidity at the interface between the XLPE insulation and the insulation screen could follow the curve presented in Figure . Initially this will be the position where water treeing will occur first. The different phases with typically time durations are included. As can be seen, the time to reach 70% RH (Phase 1) is much shorter than the time from 70% to 99% RH (or saturation). It is also less likely that critical ageing do occur during Phase 2 due to the reduced growth rate of both bow-tie and vented water trees [2].

The effect of acceleration of water treeing by frequency has been studied for a long time. Generally, the effect of frequency on water treeing is to accelerate both the initiation and growth.

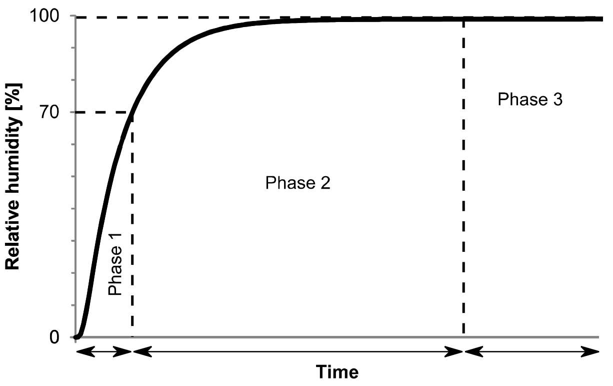


Figure 2 Typical humidity increase in the insulation of an XLPE cable, where water absorption occurs from the outside [2].

It has been found that the inception times are more or less continuously distributed, and that the accelerating factor of the growth is proportional to √*f* rather than *f* at least at frequencies less than 1 kHz [5]. It is important to note that the study on the effect of frequency on water tree acceleration in most cases includes bow-tie water trees. Mainly due to the limited contamination (water soluble) size such trees will terminate to grow independent of the test frequency. In case of vented water trees the acceleration factor is dependent on the ageing method used [5, 6].

MODEL AND CRITERIA

To model the diffusion properties across different cable layers, the partial pressure (p) is used as it is continuous across the layers. The concentration (C) in radial direction (r) is according to Henry's law proportional to the partial pressure (for constant temperature):

$$C = S \cdot p = S_0 e^{-\frac{E_S}{R\theta(r)}} p(r,t,\theta) \qquad (1)$$

where S is the solubility of the material in radial direction, E_s is the activation energy and R is the molar gas constant. The temperature in radial position is denoted by $\theta(r)$ in (1).

The concentration of water in ppm is measured at different times and temperatures. Results may then be compared to a FEM-model to see the delay in water diffusion, for reference and power cable samples.

Equation (2) has been used to estimate the change in partial pressure as function of time, radial direction and temperature:

$$\frac{\partial C}{\partial t} = \nabla \cdot \left(D \nabla C \right) = 0 \Rightarrow S\frac{\partial p}{\partial t} + \nabla \cdot \left(-DS\frac{\partial p}{\partial r} - D\frac{\partial S}{\partial r}p \right) = 0 \qquad (2)$$

Equation (2) is a modified Fick's second law in cylindrical coordinates in one dimension (r) but in place for the concentration (C), the partial pressure (p) is introduced. Parameter (D), is the diffusion coefficient normally seen in Fick's law but here also the solubility (S) is introduced to include the absorption properties of Design 2. The diffusion coefficient has the same Arrhenius character as the solubility but with different activation energies, though.

Noticing that the diffusion and solubility are functions of $\theta(r)$ - (temperature), a zero temperature drop across the cable will make S constant in Equation (2). Thus, for a zero temperature drop across the cable (no load), Equation (2) is transformed to the Fick's second law without any temperature dependence *(dS/dr=0):*

$$\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial r^2} \qquad (3)$$

It should be noted, that the critical relative humidity (RH)-levels are chosen to be 70 and 99%, respectively for the outer semi-conducting screen (OSC), because of the following:

- >70% - water trees may be initiated [4]
- 70 - 99% - water trees may continue to grow

The choice to measure the RH-level at the OSC will give worst conditions for the evaluation of the aging parameters since a temperature drop will make the RH-level less towards the conductor. Similarly, with zero temperature drop the saturation level of the inner layers are reached later in time.

To make comparisons of Design 1 and 2 possible, Design 1 has been used to calibrate/validate the model at RH=70%, i.e. to make a check and possible adjustment to measured data from Design 1. The water permeation parameters for the moisture barrier in Design 2 are not known but can be estimated by means of measurement results. Since only the water barrier layer is unique compared to Design 1, the water permeation parameters for the water barrier have been estimated by tuning these parameters aiming to fit the calibration point at RH=70% for Design 2, as well. These comparisons are performed at constant temperatures in the samples, i.e. 40, 55 and 90 °C. Furthermore, the effect of varying temperature drops across the complete core has then been investigated. However, the PE-sheath in Design 1 has been adjusted to the same total thickness as in Design 2, to evaluate the effect of the same temperature drop across the outer PE-sheath.

PERMEATION TESTS

Cable samples with sealed ends from Design 1 and 2 have been laid in an oven containing water baths at constant temperatures (40, 55 and 90°C). The samples have been taken out at different times and the water concentration level has been measured. Furthermore, saturation data for the different layers have been measured and correlated to data from material characterization tests. Good agreement between material characterization tests and permeation measurements on complete cable samples has been noticed. The results from the permeation measurements of cable samples from Design 1 and 2 are seen in Figure 3 and 4.

From Figure 3 and 4 it is clear that the "semi-wet" design (Design 2) will delay the permeation of water significantly, at least for 40 and 55°C. The effect is not that pronounced at 90°C, however. It may be due to uncertainties in measuring water content at high temperatures and/or non-linearity phenomena at higher temperatures. Since a higher conductor temperature normally implies a relatively higher temperature drop across the outer PE-sheath, the cable is partially "protected" by this temperature drop, meaning the critical RH-level of 99% is never reached. This is shown in next section.

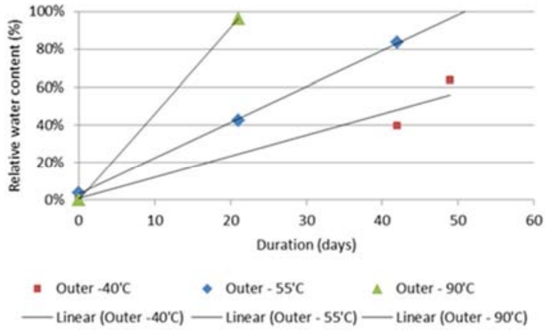


Figure 3. RH for Design 1 at OSC.

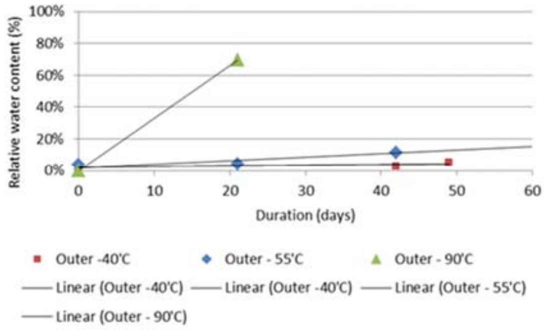


Figure 4. RH for Design 2 at OSC.

CALCULATIONS

Validation of Design 1

The results from permeation test of Design 1 in Figure 3 may be used to validate/calibrate the model, by using the inclination of the trend-lines. The model and measurement results gave similar results so the model was validated only with very small adjustments of parameters (< 1 %). The trend-line for 40°C is here inserted into Figure 5. Measurements at OSC are located close to the modelled curve, showing acceptable agreement with measurements.

The same type of verification process has been performed for 55 and 90°C as well. Both temperature verifications were giving good agreement, however the lower the temperature the better relative tolerance is achieved.

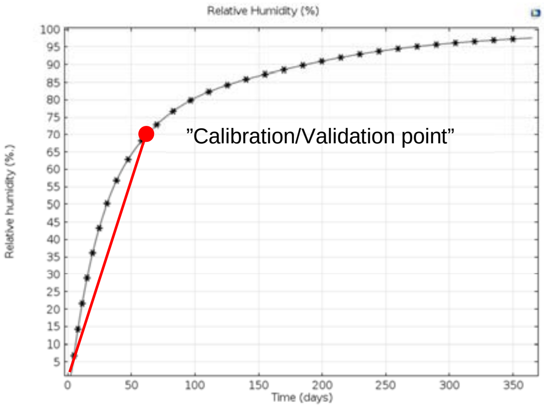


Figure 5. Validation of RH at 40°C for Design 1 at OSC. Red line shows inclination from Figure 3.

The reason for using the inclination is that the RH-curve is relatively linear up to about 70% and if good agreement is achieved for this part, the curve may be extrapolated to evaluate the approximate time needed to reach an RH-level of 99% (or 70%).

Correlation to Design 2

Accepting the agreement seen in Figure 5 for Design 1, the diffusion/saturation parameters for the ”moisture barrier” in Design 2 consisting of swelling tapes and Cu-tapes, have been tuned to align with measurement data according to Figure 4.

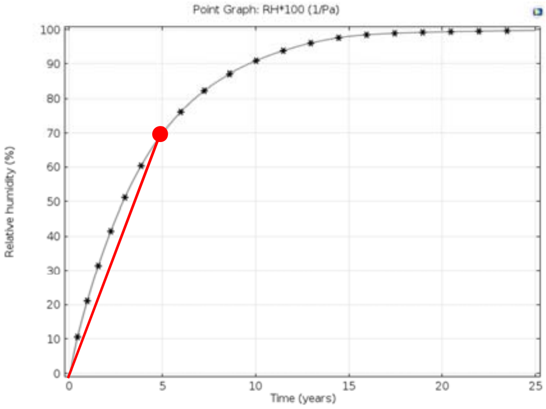


Figure 6. RH for Design 2 vs time at 40 °C (tuned parameters to align to model)

Measurement data from Figure 4 are located close to the curve in Figure 6, when parameters for Design 2 (water barrier) are tuned to attain good agreement for RH=70%. The same acceptable agreement was seen for 55 and 90°C.

As seen, when comparing Figure 5 and 6, the difference in time to reach 40°C is significant when a ”semi-wet” barrier is applied onto the cable. Notice that the temperature here is 40°C across the complete core, i.e. there is no improvement from any temperature drop across the cable. The effect of temperature drop is seen next.

Effect of temperature drop across cable

A temperature drop across the cable core will slow down the time to reach critical RH-levels even more. Figure 7 and 8 show the time needed to reach 70 and 99% RH-levels for Design 2.

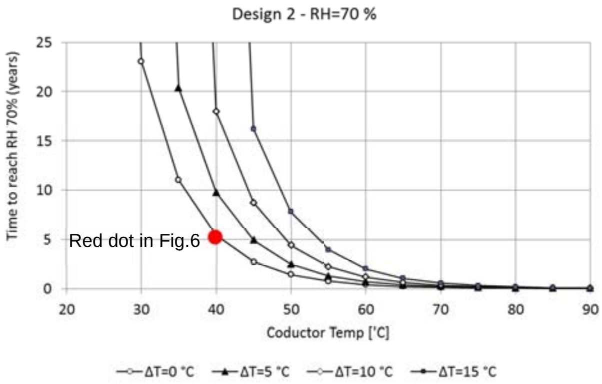


Figure 7. Time to reach RH=70% at OSC for Design 2.

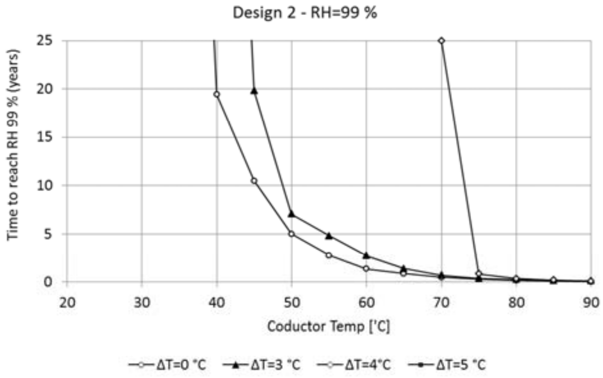


Figure 8. Time to rach RH=99% at OSC for Design 2.

Some observations can be made:

- For conductor temperatures < 60°C, the effect of temperature drop is significant for reaching RH=70%
- At conductor temperatures > 60 °C, only a small temperature drop (> 3°C) is needed to prevent the OSC to attain a RH-level of 99%. This means, already a centigrade temperature drop across the outer PE-sheath may "protect" the cable, significantly
- For low conductor temperatures (typically < 30°C) the diffusion rate is very low so the cable is "protected" by the low temperature itself
- For high conductor temperatures, the temperature drop across the core may "protect" the cable, despite the diffusion rate is higher

The RH at ISC is not shown in Figure 7 and 8 but is naturally lower than at OSC. In practice an RH-level of 70%/99% will take very long time to reach if reached at all, provided a temperature drop exists across the cable.

Though water treeing is very likely to appear for any load case, degradation will occur, but cable life may still be acceptable and good enough, maybe even for HV applications. Next section deals with the water ageing test for these types of cables.

WATER AGEING TESTS AT 500 HZ

As earlier described, the CENELEC 500 Hz test [1] has been slightly modified to HV cables. The most important Weibull parameters from the long term water ageing test are summarized in Table 3.

Table 3. Weibull statistical data from ACBD.

Weibull parameter	**0 h (Dry)**	**3000 h**	**6000 h**
η – Weibull average [kV/mm]	66	45 (-31 %)	35 (-47%)
β – Shape parameter	14)*	8	8
B1% - 95% confidence)** [kV/mm]	33-69	16-39	12-29

)* The shape parameter is most likely too high, since 4 out of 6 samples did not break down due to limitation in equipment. Either these values are therefore treated as suspended data or as having breakdown values to the next higher level. Most likely the spread in ACBD data will therefore be wider than here depicted.

)** The B1%-parameter is showing, though coarsely, the expected 1%-probability of breakdown, using a statistical confidence bound of 95%, i.e. after 3000/6000 hours there is a confidence of 95% that there is a breakdown in 1% of all cases within the stress window of 16–39 kV/mm and 12-29 kV/mm, respectively. By using more samples, this electrical stress window will most likely decrease.

Vented trees are considered being the most critical types of trees when growing from the semicon shields. However, they need continuous supply of water and impurities to continue growing. If impurities/ions are "consumed" the growth will stop [10].

A volume close to 30 cm^2 was investigated for water tree analysis close to breakdown area.

3000 hours: The density of bow-tie tress is moderate but no tree greater than 200 µm could be observed. The density of vented trees is low and no vented tree longer than approximately 100 µm could be observed.

6000 hours: The density of bow-tie tress is still moderate but no tree greater than 240 µm could be observed. The density of vented trees is low and no vented tree longer than approximately 100 µm could be observed.

In summary, the longest vented trees were about 1% of the insulation thickness, which is not likely to cause any premature breakdown, since the growth seems to have stopped after 3000 hours or earlier.

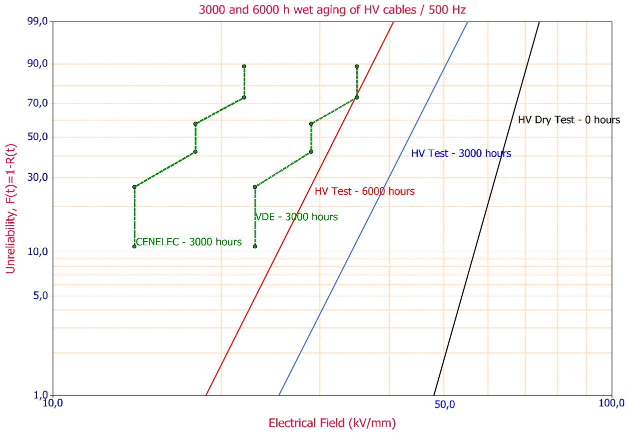


Figure 9. ACBD data for XLPE core at 40°C/500 Hz.

As seen in Figure 9, the HV water aging test showed a considerable margin to the Cenelec requirement for both 3000 and 6000 hours of aging. Similarly, the aging test showed ACBD data well above the VDE requirement after 3000 hours and was in parity with VDE after 6000 hours.

EVALUATION OF HV WET DESIGNS

When the water ageing test starts, the complete XLPE core is saturated with water, i.e. the RH-level is 100%. As here shown, an RH-level of 100 % will in practise never be attained but may be reached at high temperatures. When such a transition period from dry to wet aging is reaching several years, it may be difficult to evaluate this in relation to verification testing, since this period may, if long, include some aging as well. CENELEC HD 605 [1], specifies both dry and wet aging of MV cables. For example, the EDF 5000 h long term test in dry conditions [1], performed at 2U$_0$, with thermal cycles has more in common to the ordinary PQ-test in IEC 60840 (HV) and IEC 62067 (EHV) than the test here performed. However, one aim of dry long term aging tests is to show long term performance, normally 40 years maximum by applying an increased electrical stress on the cable system. The dry aging is considered relevant due to mainly possible impurities and voids in insulation/semi-conductive screen, eventually leading to failure.

The aging of HV (and MV) XLPE wet designs seems to consist of two aging mechanisms; one water tree aging mechanism (high degree of aging) and one other type of aging mechanism (slower long term aging after water tree degradation). However, using high quality cable materials and processing techniques, impurities are consumed due to the electro-chemical reactions [10]. Similarly ACBD data for ”good cables” seems after some time to remain unchanged [6] when impurities are consumed and the second aging period commences. Today, life time estimation (n-values) for dry aging may be as high as 15 for HV insulation systems. For conservative reasons, using an n-value of 7 (as used in PQ-tests in IEC 60840 and 62067) and a test stress of 10 kV/mm (which is lower than the lower bound of 12 kV/mm for the B1%-value) after 6000 hours in Table 2, a 40-year operating electrical stress of approximately 5.5 kV/mm may be possible for wet designs, taking no consideration to improvements achieved for the semi-wet designs as well as temperature drops.

Here, the time needed to reach an RH-level of 70% or 99%, should be added to the total lifetime. This may be questioned but seems plausible. If right, semi-wet designs seem to be good candidates for maximum electrical stress of at least 6 kV/mm, provided good experience from the field and not at least requirements of high quality insulation material systems and processing techniques. If the processing experience and conditions are not that pronounced, caution must be taken going in this direction as here outlined.

Another factor which further will “protect” the cable is the temperature drop. Critical RH-levels will sometimes never be reached and at ISC, the RH-level will most likely be considerably lower than at OSC.

CONCLUSION

The tests and analysis performed in this work gives confidence in using HV semi-wet designs in special HV submarine applications if experience and usage of high quality in materials and processes show high credibility. A full picture of test and operational conditions must be taken into account to select a reliable design for the intended application.

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GLOSSARY

ACBD: AC Break-Down
Dry design: Cables with an impervious moisture barrier, e.g. lead sheath
HV: High Voltage (> 36 – 170 kV)
ISC: Inner Semi-Conductor
MV: Medium Voltage (7.2 – 36 kV)
OSC: Outer Semi-Conductor
RH: Relative Humidity
Semi-wet design: Cables with major decrease of radial water penetration, e.g. swelling tapes+ PE-sheath
Wet design: Cables with minor decrease of radial water penetration, e.g. naked XLPE core (+PE-sheath)