THE PERFORMANCE OF XLPE WATER TREE RESISTANT INSULATION SYSTEMS AGAINST THE REQUIREMENTS OF DIN VDE 0276-605/A3

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INTRODUCTION

Polyethylene was introduced as an insulation material for electric power cable more than 40 years ago. Polyethylene’s inherent characteristics of toughness, resistance to chemicals and moisture, low temperature flexibility, and excellent electrical properties, along with low cost and easy processability, make it a very desirable material for insulating low, medium and high voltage electric cables. Since its introduction, there have been a number of significant advances in materials technology that have contributed to polyethylene’s continued worldwide position as the material of choice for insulating cable.

While, in North America the use of water tree resistant insulation (WTR) is predominant, the European market has diverged into the use of so-called homo-polymer systems and co-polymer systems. The use of co-polymer systems in Europe has been governed especially by the two-year wet aging requirements of VDE. The use of homo-polymers is preferably used in “dry designs”, where the access of water to the cable core during the life time of the cable is prevented. The harmonized standard CENELEC HD605 S1 HD 605 S1:1994/A3:2002 “Electric cables - Additional test methods” is in place now. It contains the two-year aging test in water and may drive a more uniform approach to the use of insulation materials. The current study evaluates the performance of WTR insulation materials against critical European test requirements. The paper will also discuss the fundamental mechanism of the WTR technology in this material.

PEROXIDE CROSSLINKING OF POLYETHYLENE

The peroxide cross-linking of polyethylene will be reviewed briefly as by-products can play an important role in life time predictions of cables. The peroxide cross-linking process is a first order reaction that is initiated with the thermally driven homolytic cleavage of the peroxide bond.

After thermally induced cleavage of the peroxide, and hydrogen abstraction from the polymer backbone to initiate cross-linking, an alcohol by-product is formed. In the case of di-cumyl-peroxide, the alcohol that is formed is cumyl-alcohol. If traces of acid are present in the material, these alcohols can dehydrate to form water. By-products, water content, and the presence of voids can alter cable test results and cable life [1].

EXPERIMENTAL

Three medium voltage cables according to DIN VDE 0276-620 were extruded with a triple layer die for the conductor screen, insulation, and insulation screen and were cured under nitrogen atmosphere in a continuous vulcanization process. A homo-polymer, a co-polymer, and WTR XLPE insulation were used. In all cases, the semi-conductive screens were made from the same conventional material, fully bonded to the insulation with a stranded aluminum conductor of 25 mm². The thickness of the insulation was between 3.2 and 3.3 mm. These cores were conditioned, exposed to water and tested under field strength of 6 – 6.7 kV/mm, analogous to 20 kV medium voltage cables. Microscopy was used to identify the development of water trees with aging. The loss factors of the cables have been measured in the range up to 18 kV (3Uo) as a function of temperature up to 130 °C. They were measured in water, in hot air, and after additional dry conditioning.

Measurement of the thickness of the insulation and the semi-conductive screens

The measurements are carried out according to HD 605 S1:1994/A1; 1996/pt. 2.1.11.1 and also IEC 811-1-1, pt. 1. Six measurements per test piece and layer were made, starting where the insulation was thinnest. To evaluate the whole length of the core, test pieces were taken at 1, 90, 180, 272, 363, and 453 m. Measurements were made with a profile projector Mitutoyo PJ 3000.

Calculation of the AC breakdown field strength

The geometrical dimensions of model cables and cores,

A visual inspection was carried out by means of a strong lamp. The value of the profile projector. This piece was cut into slices, which were used to measure the thickness of the core and the breakdown field strength at the inner screen (effective value) is given below:

$$E_{eff,IS} = \frac{U}{r_i \cdot \ln \left( \frac{r_i + a}{r_i} \right)}$$

Where:
- $U$ is the breakdown value (effective value) [kV]
- $r_i$ is the radius above inner screen [mm]
- $a$ is the thickness of insulation [mm]
- $E_{eff,IS}$ is the AC-field strength at the inner screen [kV/mm].

Silicone oil bath test

A visual inspection was carried out by means of a strong lamp and a glass vessel of 400 mm depth with silicone oil at a temperature of 135 °C. Test pieces were taken at 0, 90, 180, and 362 m of the core length with a length of 450 mm each and the outer screen was removed. Subsequently, they were put in the bath until transparency of the insulation was achieved, which made possible an analysis of irregularities, like voids, ambers, black contaminants, etc. The presence of vented trees was detected and marked with a needle for subsequent optical analysis.

Harmonized long term aging test

Accelerated aging tests were carried out according to CENELEC HD 605 S1. All cable cores have been conditioned during 500 hours at (55 ± 5) °C in tap water before aging to remove remaining by-products of cross-linking and also allow the insulation and screens to absorb moisture. The electrical aging was performed in a thermally isolated water tank at an aging voltage of (18 ± 3) kV. In accordance with the new harmonized CENELEC long-term test procedure, an ageing voltage of 18 kV for 10 kV cable cores is specified. It follows that the aging field strength at the inner screen is in the range form 6.0 to 6.7 kV/mm for conductor sizes between 95 and 400 mm². As the dimensions of the model cable are smaller, the same aging field strength at the conductor screen is reached at 16 kV instead of 18 kV. Both ends of the coils were prepared with terminations.

Determination of the AC breakdown voltage

The active sample length was 10 m plus an additional 5 m for water terminations. Each of the samples had to be fitted with an additional copper wire screen. After preparation, the AC step test was carried out at room temperature (20 ± 15) °C, starting with 5 minutes at 18 kV and followed by 6 kV increases, each during 5 minutes, until breakdown. A small core length with the breakdown channel was cut out for further examinations. All of the AC breakdown data is reported by means of Weibull statistics and a maximum likelihood estimation of the 95% confidence intervals. The “Eta” parameter is the AC breakdown value at the 63 % confidence level. The “Beta” value is the shape parameter. Higher “Beta” values indicate a steeper slope of the failure curve. The latest draft of DIN VDE 0276-620/A3 of September 2003 contains a class model rather then the Weibull statistical model. The required values are summarized in Table 1.

<table>
<thead>
<tr>
<th>Breakdown Strength</th>
<th>Number of Samples</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Model 1</td>
</tr>
<tr>
<td>20 kV/mm</td>
<td>6</td>
</tr>
<tr>
<td>26 kV/mm</td>
<td>4</td>
</tr>
<tr>
<td>32 kV/mm</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Model 2</td>
</tr>
<tr>
<td>24 kV/mm</td>
<td>6</td>
</tr>
</tbody>
</table>

Table 1. Class models according to draft DIN VDE 0276-620/A3

For the evaluation of the step test results after 1 and 2 years the results with both models will be reported.

Measurement of the dissipation factor

The dissipation factor and the capacitance were measured as a function of temperature and voltage level. Both virgin samples as well as aged samples were tested. The samples were prepared by mounting a copper wire screen on to the outer screen which was fixed with non-conductive tape. The sample ends were prepared with slip-on terminations together with guard ring configurations. Samples of virgin cores and cores after wet conditioning (55 °C ± 5 °C, 500 h) and after wet aging were measured in different states. Virgin samples were measured as delivered and after conditioning during 180 hours at 90 °C in air. Samples after wet conditioning and wet aging were measured in water up to 90 °C and in an oven up to 130 °C and partly after conditioning during 180 hours at 90 °C in air. For the measurement in water the samples were electrically insulated from the water bath by means of a non-conducting flexible tube filled with de-mineralized water.

Determination of the water tree pattern

With the aim to look for trends and to differentiate between the insulation systems, the water tree examination was carried out in two different ways. First, the breakdown channel area of the core sample with the lowest break down strength was analyzed for water trees. A core piece containing the breakdown channel was taken and micromotomed in slices of 500 µm thickness, with the main part of the breakdown channel in some of the slices. These slices were stained in a...
methylene blue dye solution [2] for examination. Trees were investigated with an optical microscope with a magnification of 75. Secondly, more than 10 m per type of core were inspected in the silicone oil bath test to analyze a possible growing of vented trees at the interface between the inner semi-conductive layer and the insulation layer. Vented trees starting from the inner screen were marked with a needle and subsequently microtomed and microscopically inspected.

RESULTS OF THE EXAMINATION

The designation of the various produced cores is as follows:

- A) extra clean standard homopolymer XLPE
- B) extra clean standard co-polymer XLPE
- C) extra clean water tree resistant XLPE

In all cases the same type of a standard bonded semi-conductive screen was used for the inner and for the outer layer.

The insulation thickness for all cores was in the range between 3.2 and 3.3 mm, i.e. it was slightly below the standard requirement of 3.4 mm for 6/10 kV cables. The thickness of the semi-conductive screens complied exactly with the standard requirements. The difference between the maximum and minimum values of the insulation thickness sometimes exceeded 0.5 mm.

The requirements for the hot set tests as specified in DIN VDE 0276-620 S1 Tab. 2A were passed at all times.

<table>
<thead>
<tr>
<th>Type</th>
<th>Elongation under load [%]</th>
<th>Permanent elongation [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>TYPE A</td>
<td>82</td>
<td>-5</td>
</tr>
<tr>
<td>TYPE B</td>
<td>74</td>
<td>-5</td>
</tr>
<tr>
<td>TYPE C</td>
<td>82</td>
<td>-4</td>
</tr>
</tbody>
</table>

Table 2. Hot set test results of the tested cable cores.

During the oil bath test no irregularities larger than 50 µm and no protrusion larger than 80 µm were found in any of the cable systems under investigation. Samples had been taken approximately every 90 m on a total of 500 m. The cores were found to be manufactured free of significant irregularities and the cleanliness was similar to standard MV cables. The quality was sufficient for further investigations.

### Breakdown strength with homo-polymer system

All samples have passed the aging up to one year without breakdown during the aging. The breakdown value was slightly higher then after 0.5 years (28.2 kV/mm).

<table>
<thead>
<tr>
<th>Minimum [kV/mm]</th>
<th>Nominal [kV/mm]</th>
<th>Maximum [kV/mm]</th>
<th>Eta</th>
<th>Beta</th>
<th>r²</th>
</tr>
</thead>
<tbody>
<tr>
<td>31.0</td>
<td>33.4</td>
<td>35.9</td>
<td>33.4</td>
<td>12.8</td>
<td>0.858</td>
</tr>
</tbody>
</table>

Table 3. Weibull analysis after 1 year aging for the homo-polymer system.

The breakdown strength fulfills the requirements of DIN VDE 0276-620/A3 as shown in Figure 1 below.

Based on the direction of the branches in the electrical trees adjacent to the actual break down channel, the initiation site in four out of five samples was at the conductor screen. Channel width was between 430 and 560 µm. No visible origin of the breakdown cause could be detected.

### Breakdown strength with co-polymer system

All samples have passed the aging up to one year without breakdown during the aging. The breakdown value was higher then after 0.5 years (30.8 kV/mm).

<table>
<thead>
<tr>
<th>Minimum [kV/mm]</th>
<th>Nominal [kV/mm]</th>
<th>Maximum [kV/mm]</th>
<th>Eta</th>
<th>Beta</th>
<th>r²</th>
</tr>
</thead>
<tbody>
<tr>
<td>30.1</td>
<td>36.3</td>
<td>43.7</td>
<td>36.3</td>
<td>4.96</td>
<td>0.890</td>
</tr>
</tbody>
</table>

Table 4. Weibull analysis after 1 year aging for the co-polymer system.

The breakdown strength fulfills the requirements of DIN VDE 0276-620/A3 as shown in Figure 2 below.

Based on the direction of the branches in the electrical trees adjacent to the actual break down channel, the initiation site in four out of five samples was at the conductor screen.

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Figure 2. Class model values after 1 year aging for the copolymer system.

Channel width was between 400 and 560 µm, with one channel being 800 µm wide. No visible origin of the breakdown cause could be detected.

**Breakdown strength with WTR-polymer system**

All samples have passed the aging up to one year without break down during the aging. The breakdown value was slightly higher then after 0.5 years (28.2 kV/mm).

<table>
<thead>
<tr>
<th>Minimum [kV/mm]</th>
<th>Nominal [kV/mm]</th>
<th>Maximum [kV/mm]</th>
<th>Eta</th>
<th>Beta</th>
<th>r²</th>
</tr>
</thead>
<tbody>
<tr>
<td>46.6</td>
<td>51.3</td>
<td>56.6</td>
<td>51.3</td>
<td>9.64</td>
<td>0.922</td>
</tr>
</tbody>
</table>

Table 5. Weibull analysis after 1 year aging for the WTR-polymer system.

The breakdown strength fulfils the requirements of DIN VDE 0276-620/A3 as shown in Figure 3 below.

Figure 3. Class model values after 1 year aging for the WTR-polymer system.

Based on the direction of the branches in the electrical trees adjacent to the actual break down channel, the initiation site in all samples was at the conductor screen. Channel width was between 600 and 700 µm. No visible origin of the breakdown cause could be detected.

**Water tree levels near break down channels**

In order to evaluate the water treeing tendency 20 wafers of 500 µm thickness were taken following the procedure described before. No bow tie trees or vented trees were found in the WTR-polymer based system. In the homo- and co-polymer system the bow tie tree density remained below 3/cm². Only the homo-polymer system showed an increased level of 11/cm² bow tie trees with a length between 50 and 100 µm. No vented trees were found in the homo-polymer system, whereas the density in the co-polymer system stayed below 2/cm².

**Water tree levels of aged cables after silicone bath inspection.**

After aging, 10 m of each cable system has been inspected by means of a silicone oil bath test as described before. The level of vented trees, thus identified is summarized in Table 6.

<table>
<thead>
<tr>
<th>Vented trees/m</th>
<th>After 6 months</th>
<th>After 12 months</th>
</tr>
</thead>
<tbody>
<tr>
<td>TYPE A</td>
<td>0.5</td>
<td>1.3</td>
</tr>
<tr>
<td>TYPE B</td>
<td>0.3</td>
<td>4.2</td>
</tr>
<tr>
<td>TYPE C</td>
<td>0.2</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Table 6. Identified vented trees per meter after silicone oil bath inspection.

The tree size remained below 500 µm. Some trees after 12 months aging of TYPE B were larger. This may be explained by some statistical effects inherent to the test procedure, caused by the relatively low number of trees that can be practically detected in a length of 10 m.

**Dissipation factor of the various systems**

The dissipation factor has been measured as a function of temperature and voltage level for all investigated systems. A comparison at 90 °C and at 18 kV is given in Figure 4 for new cores after production, after 500 hours conditioning in water, and after 1 year conditioning in water at 40°C (CENELEC conditions).

![Dissipation factor at 18 kV and 90°C temperature for new cores after production, after 500 hours conditioning in water, and after 1 year water aging.](image)

The new cores were measured in a dry air oven, the samples after conditioning and wet ageing were measured in water.
It is evident that the performance of the WTR-polymer SYSTEM C is very similar to that of the homo-polymer SYSTEM A. The co-polymer SYSTEM C generally shows somewhat higher numbers after contact with water, due to the higher polar polymer system.

Figure 5. Dissipation factor of new cores at 18 kV and 130 °C in air.

**DISCUSSION OF THE RESULTS**

The dissipation factor of all three insulation systems meets the requirements of DIN VDE 0276-620, valid for new insulation systems under all measured conditions. The difference between system A and C are probably more of a statistical nature, as typically the latter is measured to be somewhat higher. The wet aging up to 1 year so far does not raise the dissipation factor compared to unaged samples. The high retention of AC breakdown strength and the low level of tree growth for the WTR XLPE material are consistent with results from similar test programs [3]. Defects in the cable insulation may lead to trees and premature failure. The unique dissipation factor behaviour of the additive in the WTR XLPE insulation material makes it able to neutralize defects in the cable. This mechanism is based on the observation that trees initiate at points of high and divergent electrical stress such as imperfections at the semi-conductive shield-insulation interface. Sharp protrusions at the conductor shield-insulation interface can increase electrical stress by more than 200 times. At these stress points WTR XLPE will dissipate the electrical stress as heat, due to the increase of power factor as a function of electrical stress. The local increase in temperature will cause a further increase in power factor and more energy is dissipated until equilibrium is achieved. Not affecting the over-all dissipation factor of the cable core, the power factor response of the tree-retardant additive contributes to tree retardance and longer life by locally dissipating electrical stress only at defects in the cable.

**SUMMARY**

It has been found that the retention of the electrical breakdown strength of the WTR material shows the best performance after 1 year aging, when compared to homo-polymer and co-polymer systems. No obvious causes for the initiation of the electrical breakdown could be visually identified. The WTR-system shows the lowest level of identified water trees both in the breakdown channel vicinity, as well randomly distributed in an investigated 10 m core length. This indicates a better performance in long term wet aging conditions. These results suggest that the use of WTR materials can be an excellent choice to pass the European two-year wet aging test. Such materials profit from more than 20 years experience in North America, both with strippable and fully bonded insulation screens.

**ACKNOWLEDGEMENT**

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