Impact of Multistress Aging on the Dielectric Relaxation Behaviour of XLPE Cable Insulation

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Abstract: This contribution reports on experimental investigations dealing with the impact of different combined aging parameters like electrical field strength, conductor temperature, and test duration on the dielectric relaxation behaviour of full-sized model cables with cross-linked polyethylene insulation. The evaluation of time-domain isothermal depolarisation current measurements turns out that characteristic properties of a third order exponential decay function exhibit different trends depending on the nature of the various aging factors.

INTRODUCTION

Today cross-linked polyethylene (XLPE) is used commonly as insulating material for power cables in nearly all voltage levels of the power supply network mainly due to economical and ecological reasons. In particular good experiences in service as well as enhanced manufacturing procedures led to applications of XLPE as insulating material for high voltage cables. In this scope aging phenomena due to the impact of water could be avoided to a great extent under employment of longitudinal and transversal water tight constructions and the insert of metal sheaths. Therefore aging mechanisms resulting from multistress operating conditions which are mainly characterized by the simultaneous presence of electrical and thermal stress represent an important factor for the characterization of the insulation state.

Multistress aging constitute a complex process for the insulation characterization of XLPE insulated cables due to synergetic effects resulting from different aging factors [1]. Therefore approaches to expound the impact of interacting factors of influence on suitable measurable quantities represent an essential task to comprehend aging mechanisms. A differentiation of customary methods might be basically possible under consideration of results gained from destructive and non-destructive test procedures. Generally a complete state estimation of an insulating system requires both diagnostic measuring parameters of integral and local nature as well as appropriate evaluation tools. To register integral state variables the investigation of the dielectric relaxation behaviour represents a suitable procedure and might help to characterize the insulation condition. Dielectric relaxation of polymeric solids is basically caused by molecular movements within the solid. Therefore the original material structure, chemical manufacture processing units, and impacts resulting from operating and external conditions, resp., are essential quantities of influence on the molecular motion [2].

Taking account of the outlined problem area experimental investigations on the impact of different combined aging quantities on the dielectric relaxation of XLPE insulation material have been performed. In a first step a laboratory aging course on a full-sized XLPE-model cable with high voltage insulation quality and reduced insulation diameter was carried out varying the electric field strength, conductor temperatures, and test durations to provide different aging states of the insulation material. After the corresponding aging program in a second step the test samples were prepared for time-domain measurements of the isothermal depolarisation current. For further evaluation a modified simulated annealing algorithm with evasion of empirical starting values was implemented for receiving characteristic relaxation time constants. So the temporary gradient of the determined depolarisation currents and typical relaxation time constants were used to investigate both separate and combined impact of the respective aging factors on these quantities.

MATERIAL AND EXPERIMENTALS

Test Samples

The experimental investigations were performed on a full-sized XLPE-model cable (Tab. 1).

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Louter / Linner</td>
<td>9.15 / 6.40</td>
</tr>
<tr>
<td>wall thickness [mm]</td>
<td>2.80</td>
</tr>
<tr>
<td>Cspecimen [pF]</td>
<td>540</td>
</tr>
</tbody>
</table>

The raw material was a superclean low-density polyethylene which was dry cured under dicumyl peroxide. Strand shield and semiconducting screen were supersmooth and made of basic XLPE-material. The cable was manufactured according to [3] except the insulation thickness had been reduced below the
minimum requirement. The laboratory aging course was carried out with various field grading units according to the different adjusted electrical stresses and inductive heating was applied to generate several conductor temperatures (Tab. 2).

**Table 2: Applied range of aging parameters and corresponding field grading units (a: aging)**

<table>
<thead>
<tr>
<th>Aging quantity</th>
<th>Range</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>without field grading</td>
<td>silicon slip-on sealing end</td>
<td>water termination</td>
</tr>
<tr>
<td>$E_a$ [kV/mm]</td>
<td>0</td>
<td>13.1</td>
<td>max. 52.3</td>
</tr>
<tr>
<td>$\vartheta_a$ [K]</td>
<td>323...403</td>
<td>293...403</td>
<td>293...363</td>
</tr>
<tr>
<td>$t_a$ [h]</td>
<td>max. 2000</td>
<td>max. 5000</td>
<td>max. 100</td>
</tr>
</tbody>
</table>

**Measuring Procedure and Evaluation Method**

The measurements of the isothermal depolarisation current were carried out after mechanical preparation of the specimens in a shielded chamber to reduce environmental noise influences. Thus a minimum measuring resolution of approx. 1 pA was achieved. The depolarisation currents were recorded on cable samples at ambient temperature after a charging period of 30 minutes with a DC voltage of 1 and 3 kV, resp., and a subsequent short-circuit time of 5 seconds for the duration of 30 minutes (Fig. 1). A picoamperemeter was used to validate the accuracy of the measuring test setup.

**Figure 1:** Principle course of isothermal depolarisation currents vs. measuring time with the DC charging voltage $U_{\text{charge}}$ as parameter (samples were thermally stressed at 363 K for 500 h)

For the investigation of the impact of different combined aging parameters on the dielectric relaxation behaviour the depolarisation current curves were evaluated by application of a modified simulated annealing algorithm with evasion of empirical starting values. The formal basis of the evaluation procedure constitutes an exponential decay of third order with the extracted characteristic relaxation time constants $\tau_{1...3}$. After smoothing the raw data by Nalimov runaway method multiple start variant with random values and commitment to an acceptance function lead to an iterative procedure with local variation search for finding a global optimum for the determination of the based equation parameters. This procedure represents a combinatorial optimization problem which was regarding to the running algorithm time not optimized by the use of heuristics owing to the exactness of the evaluation method. In the following diagrams the depicted results represent arithmetic mean values resulting from five times running the evaluation algorithm. The truncation term was set to the total calculation time of four hours for one run.

**RESULTS AND DISCUSSION**

**Relaxation Time Constants of Thermally Aged XLPE-Model Cable Samples**

In Fig. 2 the influence of different thermal aging times on the amplitude of the relaxation time constants $\tau_{1...3}$ is shown in an aging temperature range between 323 and 403 K.

**Figure 2:** Relaxation time constants $\tau_{1...3}$ of cable samples vs. aging temperature with the aging time as parameter ($U_{\text{charge}} = 1$ kV)

It can be taken from Fig. 2 that in case of the relaxation
time constant $\tau_{1}$ for the three different aging durations the curves exhibit a local maximum. Moreover, it becomes obvious that as far as the local maximum amplitude is considered prolonged aging is entailed by a shift of the maximum relaxation times towards higher values and lower temperatures. This observation could be explained by two superimposed effects. Principally, the origin of depolarisation currents in XLPE is attributed to relaxing molecules, charge as well as orientational and interfacial polarization, and trapping phenomena [4-6]. So, first an increasing aging temperature will lower the degree of internal mechanical strains resulting from manufacturing processes and therefore an enhancement of the time amplitudes appears. The rate of this relaxation in general depends on the temperature level and the affecting time of the thermal stress. Second, due to larger stress impact times coupled with rising aging temperatures the level of cross-linking along long polymer chains increases and the number of fast polarizable molecules per free volume unit will be reduced. So a decrease of the relaxation time amplitudes can be observed.

For the relaxation time constant $\tau_{2}$ (Fig. 2) increasing aging temperatures cause for all investigated aging times lower relaxation time amplitudes. This appearance could be mainly attributed to volatile cross-linking residues exhibiting a more polar character [6]. The different courses of the time constant in the aging temperature range up to approx. 363 K might be resulting from several amounts of cross-linking by-products with various elapsing behaviour.

Further, it can be observed from Fig. 2 for the relaxation time constant $\tau_{3}$ that with rising aging temperatures the time amplitudes tendentiously increase. These relatively slow relaxation processes could be induced by a raised probability of a temperature supported release of trapped charge carriers. Additionally, in this time constant range contributions to the total relaxation time amplitudes elicited by the non-permanent cross-linking agents seem to appear. Therefore, an enhancement of the aging duration from 500 to 1000 h leads at first to an increase of the time amplitudes while a further extension of the aging time to 2000 h results in a decline of the relaxation time amplitudes.

**Relaxation Time Constants of Electrically and Thermally Aged XLPE-Model Cable Samples**

Fig. 3 shows an overview concerning the combined impact of thermal and electrical aging stress on the amplitudes of characteristic relaxation time constants. In this case the relaxation time amplitude $\tau_{3}$ seems to be not markedly influenced by the additional acting electrical stress compared to the results gained after exclusively thermal aging. Apparently, the thermally enforced release of trapped charge carriers will not be supported by electrically activated processes at the adjusted energetic level.

Moreover, the graph of the relaxation time constant $\tau_{2}$ shows no discernible dependence on the applied aging temperature. This appearance can be probably traced back to the enhanced likelihood of a cross-linking by-product diffusion from the insulation material due to the longer aging duration compared with the observations after single thermal aging stress (Fig. 2). For the relaxation time constant $\tau_{1}$, the electrical field aging has an observable influence on the relaxation time amplitude. Field activated amounts of the total relaxation current could result from a higher occupation probability of shallow energetic traps during the aging course. Therefore, no explicit detectable local maximum of the time amplitude curve appears.

**Figure 3:** Relaxation time constants $\tau_{1-3}$ of cable samples vs. aging temperature ($U_{\text{charge}} = 1 \text{ kV}$, $E_{\text{aging}} = 13.1 \text{ kV/mm}$, $t_{\text{aging, max}} = 5000 \text{ h}$)

The influence of different aging field strengths on the relaxation time constants without thermal based superimposed effects is summarized in Fig. 4. The cable specimens were electrically aged with AC voltage at $13.1 \text{ kV/mm}$, $36.4 \text{ kV/mm}$, and $45.5 \text{ kV/mm}$.
ambient temperature until the maximum aging time of 100 and 5000 h, resp., was reached. It can be observed for the relaxation time constant \( \tau_1 \) that, as already seen in Fig. 3, the impact of an electrical field strength during an AC aging course can enhance the relaxation time amplitude. This effect becomes obvious since an increase of the aging field strength is followed by a rise of the time constant \( \tau_1 \) (Fig. 4). Shallow energetic trap levels can be more relieved populated by applying an electrical field and the comparatively fast relaxation processes might be influenced by this effect. The relaxation time amplitudes of the time constants \( \tau_1 \) and \( \tau_2 \) show no clear dependence on the applied aging field strength since these characteristic parameters exhibit a more pronounced thermally affected behaviour. In case of combined thermal and electrical aging the impact of the aging field strength on the relaxation time amplitudes is shown in Fig. 5.

![Figure 5: Relaxation time constants \( \tau_1, \tau_2, \tau_3 \) of cable samples vs. aging field strength (\( U_{\text{prez}} = 1 \text{kV}, t_{\text{aging, max}} = 100 \) and \( 5000 \text{ h}, \vartheta_{\text{aging}} = 363 \text{ K} \))](image)

It can be deduced from Fig. 5 that an interaction between electrical and thermal aging impacts leads to another trend of all relaxation time amplitudes compared with the case of separate stress applications (Fig. 4). The time constant \( \tau_1 \) exhibits a slightly decreasing trend with increasing aging field strength probably owing to more pronounced effects resulting from the removal of inner mechanical strains. This becomes especially obvious for the long aging duration of 5000 h compared to the shorter aging time of 100 h at an elevated field level. For the relaxation time constant \( \tau_2 \), the longer aging course results in a decline of the time amplitude due to an enhanced release of cross-linking residues caused by the manufacturing process. In addition to that, the relaxation time constant \( \tau_3 \) shows an increase of the amplitude with higher electrical aging stress which is compared with the corresponding values in Fig. 4 on a higher level. So the growth of the amplitude might be mainly caused by a thermally activated charge carrier release. The increased occupation probability of affected trap levels due to elevated field strengths acts as an additional effect.

CONCLUSIONS

The experimental investigations concerning the separation of factors of influence on characteristic relaxation time constants obtained by the analysis of isothermal depolarisation currents have revealed the following results:

The behaviour of the relaxation time constant \( \tau_1 \) shows a sensitive dependence on the applied thermal aging stress. Additionally acting electrical aging stress yields to further components of the time amplitude but a strict separation of the corresponding amount related to the individual factors of influence is difficult. The relaxation time constant \( \tau_1 \) seems to be a parameter to analyse the leakage behaviour of cross-linking residues from the manufacturing process. This time amplitude tends to decrease with the aging temperature and the aging time until a steady state is reached. With regard to the examination of the kind of interacting effects resulting from the combination of applied electrical and thermal aging stress the relaxation time constant \( \tau_3 \) could be a suitable parameter. But these phenomenological tendencies should be verified with further data evaluation.

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REFERENCES


