Dielectric and electric parameters used for insulation characterization of multistress aged XLPE-cables

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Abstract: This contribution reports on investigations dealing with the influence of different combined electric field strengths, temperatures and test durations on the residual electrical strength and the distribution of relaxation time constants of high-polymeric insulation. The results reveal that the destructive residual strength determination and the non-destructive evaluation of isothermal depolarisation current measurements for receiving relaxation time constants seem to be suitable procedures to gain knowledge about the insulation state. Especially the comparison of relaxation time constants of different combined aged polymeric cable samples constitutes a sensitive method for insulation characterization.

1. Introduction

The insulation state as well as the prediction of the time-to-failure of polymeric insulated cables might be influenced by aging owing to service conditions. In particular aging of cross-linked polyethylene (XLPE)-cables for high voltage applications 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 [1]. Therefore special significance can be ascribed to aging mechanisms of XLPE-cables resulting from multistress conditions which are essentially characterized by the simultaneous presence of electrical and thermal stress [2].

The combined impact of electrical and thermal stress on the aging behaviour of the insulation causes synergetic effects due to the interaction between the different factors of influence. This synergism will be basically characterized by the modification of the aging process entailed by the combination of several aging factors relative to the sum of their aging effects if acting separately on different objects [3].

Therefore knowledge concerning the irreversible change of the serviceability of an electrical insulation system like for instance high-polymeric insulated power cables caused by multifactor aging is still in the focus of interest. Particular approaches to transform findings obtained from accelerated life tests at elevated stress levels to the aging behaviour under service conditions constitute an essential step to comprehend aging mechanisms. A differentiation of these methods with regard to integral and differential modes might be basically possible under consideration of results gained from destructive and non-destructive electrical test procedures.

An accepted destructive test procedure is the residual breakdown voltage test. This method is characterized by a gradual increase of the voltage level after a fixed time until breakdown. A non-destructive test procedure is the determination of the dielectric response function by for instance measurements of the depolarisation / relaxation current. This method might be qualified for the detection of integral aging of insulating materials [4].

2. Experimental course

To examine the impact of temperature, electrical field strength, and time on the electric withstand and dielectric relaxation behaviour of full-size cables with XLPE-insulation the aging course was studied after accelerated tests at elevated stress levels (Tab. 1).

Table 1: Applied range of aging parameters

<table>
<thead>
<tr>
<th>Aging parameter</th>
<th>Range</th>
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<tbody>
<tr>
<td>Electrical field strength [kV/mm]</td>
<td>0...48.8</td>
</tr>
<tr>
<td>Temperature [°C]</td>
<td>20...130</td>
</tr>
<tr>
<td>Time [h]</td>
<td>max. 5000</td>
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The long-term aging course was performed under use of standard slip-on sealing ends. Therefore several test collectives were stressed with a maximum electrical field strength of 13.1 kV/mm which corresponds to 5 times of the service field strength E₀ and different conductor temperatures between 20 and 110 °C for a max. test duration of 5000 h. Additionally the aging scope was also carried out at high electrical stress in the range of 36.4 to 48.8 kV/mm by application of a water termination system for field grading.

Test specimen

The experimental investigations were performed under use of an XLPE-model cable (Fig. 1). The cable was manufactured according to [5] except the insulation thickness had been reduced below the minimum requirement.

The raw material was 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 sample length was adjusted to 3.5 m.
Figure 1: Schematic cross-section of the used model cable (dimensions in mm)

Measurement procedure

For the determination of the residual breakdown voltage the laboratory aged cable samples were stressed in a step test with AC voltage. This procedure started at a low stress level of $6 \cdot E_0$ for the duration of one hour. Following the stress level was increased in steps of $E_0$ every five minutes. The residual breakdown voltage is represented by the last full withstand level. This step test was performed at room temperature.

The measurements of the depolarisation current were carried out in a shielded chamber with a noise current of approx. 4 pA at ambient temperature. The current was recorded at cable samples with a total capacitance of 540 pF after a charging period of 30 minutes with a DC voltage of 1 kV and a short-circuit time of 5 seconds for the duration of 30 minutes via a current amplifier with a resolution of 1.2 pA (Fig. 2). A picoamperemeter was used to verify the accuracy of the entire circuit.

For the measurements of the depolarisation current different aged cable specimens were removed from aging collectives. Additionally also samples after step test stress were subjected to the above described measuring procedure. For receiving relaxation time constants depolarisation current curves have been evaluated by the application of a modified simulated annealing algorithm with evasion of empirical starting values. The formal basis (1) was used to determine the unknown coefficients $I_0$, $a_i$ and $\tau_i$ by this evaluation method [6]. After smoothing by Nalimov runaway test multiple start variants with random values and commitment to an acceptance function lead to an iterative procedure with local variation search for reaching a global optimum for the determination of the equation parameters.

$$i_{\text{depol}}(t) = I_0 + \sum_{i=1}^{\infty} a_i \cdot e^{-\frac{t}{\tau_i}}$$

This procedure constitutes a combinatorial optimization problem which was regarding to practical application not optimised with reference to the running time of the algorithm. The use of heuristics to reduce the running time was avoided with regard to the exactness of this evaluation method [7].

3. Results and discussion

Residual electrical strength

In Fig. 3 the impact of different conductor temperatures on the residual electrical strength of XLPE-insulated model cables is shown after an accelerated aging course at $5 \cdot E_0$ for the duration of 5000 h.

The displayed values represent Weibull nominal values established by maximum-likelihood parameter estimation of the two-parametric function scaled by $E_0$ along with 95-%-confidence intervals. The collective size was at least 5 samples. It can be seen from the figure that an increase of the conductor temperature during accelerated aging course is entailed by a slight decrease of the residual strength. This behaviour can apparently be caused by two superimposed effects.

First the applied electrical stress of 13.1 kV/mm is in the range of a critical field strength which has generally to be exceeded to initiate the formation of submicrocavities which is associated with the onset of aging mechanisms pursuant to the thermodynamic approach given in [8]. Appropriate high electrical fields cause with increasing time a rising number of submicrocavities so that the activation volume will be changed in comparison with the initial size. Therefore energetic relations will be varied whereby under the action of the electrical field thermal fluctuations could...
be induced in the amorphous area of XLPE connected with a change in the polymer morphology. This can result in an enlargement of the amorphous phase and thus in a reduction of the degree of crystallinity [9].

Second an increasing temperature can also lead to a lowering of the degree of crystallinity so that the formation of submicrocavities resulting from the influence of the electrical field will be supported.

**Distribution of relaxation time constants**

The influence of different conductor temperatures under the continuous action of an electrical field on the distribution of the relaxation time constants is displayed in Fig. 4.

![Figure 4: Relaxation time constants of cable samples after aging at 5-E₀ for 5000 h and at different temperatures](image)

The shown values are arithmetic means and standard deviations of the obtained results. It can be taken from Fig. 4 that in case of the time constants \( \tau_1 \) and \( \tau_2 \) an increase of the aging temperature is entailed by a growing amplitude of these time constants under the impact of an electrical field of 13.1 kV/mm for 5000 h. This phenomenon seems to be attributed to changes in the polymer morphology.

Due to the charging process with a sufficient low electrical field strength of approx. 0.4 kV/mm the charge carriers detected by the relaxation current measurements neither result in all probability from charge carrier injection at the electrodes nor from a generation in the insulation bulk. Thus the increase of the polarisation of a dielectric which is exposed to a time restricted low field is predominantly traced back on interfacial effects which can occur for instance in semi-crystalline polymers at amorphous-crystalline interfaces and molecular chain deformations. Also hopping of charge carriers resulting from the applied aging field between localised sites of charges can lead to polarisation. Consequently the depolarisation behaviour of the dielectric is attributed to these effects, too [4, 10].

Owing to the aging course the impact of a corresponding electrical field for a sufficient long time can induce changes in the amorphous phase. This effect may result in a modification of a retardation mode which can be represented by time constant \( \tau_1 \) [11]. Moreover the increasing aging temperature is also resulting in changes in the amorphous-crystalline region and can therefore lead to a modified \( \tau_1 \)-relaxation behaviour supported by the electrical field. Additionally also the shape of the amorphous-crystalline interfaces is influenced due to the applied temperature during the aging field stress. Changes in this domain may affect a retardation mode described by time constant \( \tau_2 \). Further it can be depicted from Fig. 4 that the amplitude of time constant \( \tau_3 \) shows a non-uniform trend with respect to the applied aging temperature. This occurrence may be attributed to changes of the slow polarisation which are also affected by the temperature-sensitive hopping behaviour of charge carriers between localised sites [10, 11].

In Fig. 5 the impact of different aging times on the distribution of the relaxation time constants is illustrated for separate thermal aging in a temperature range between 50 and 130 °C.

![Figure 5: Relaxation time constants of cable samples vs. aging temperature with the aging duration as parameter](image)

It can be borrowed from Fig. 5 that a separate applied thermal stress leads to a broadly non-uniform trend for the time constants depending on the aging duration in the investigated temperature range. However, for all time constants a similar behaviour can be deduced from Fig. 5 for the 500 h aging course. The amplitudes decrease for rising temperatures between 50 and 90 °C. Then at a temperature of 110 °C all time constants show an increasing tendency.
following by a marked decline at 130 °C. The relaxation behaviour after this aging time seems to be affected by different thermal expansion coefficients in the amorphous and crystalline domains [12]. Distinct changes in the polymer structure can be observed at a temperature of 110 °C which is in the range of the crystalline melting point of the polymer.

Further the influence of different high electrical field strengths on the distribution of relaxation time constants is illustrated in Fig. 6 in dependence on the withstand time of the solid insulation.

![Figure 6](image_url)

**Figure 6**: Relaxation time constants of cable samples at a temperature of 20 °C vs. aging field strength with the stressing time as parameter (b. d.: breakdown)

In case of a separate field aging at 20 °C for the time constants $\tau_1$ and $\tau_2$ an interesting phenomenon can be observed. Cable samples which resisted the applied aging stress indicate lower time constants over a wide area of the investigated field strength region in comparison with specimens which failed during the corresponding stressing time. For instance, a sample which do not failed during an aging time of 100 h at approx. 45 kV/mm exhibits a $\tau_2$-value of about 20 whereas a destroyed specimen with a withstand time of 81.5 h shows a $\tau_2$-amplitude of approx. 45 under the same aging conditions. Finally the investigations pointed out that both separate field resp. temperature aging and combined field and thermal stress influence the distribution of relaxation time constants in a different way. Certainly the impact of the electrical field on the relaxation behaviour of XLPE seems to be more pronounced and can apparently be supported by the applied temperature. This behaviour indicates an overlapping of multiple relaxation mechanisms having different temperature dependencies as it was also observed at other sites [13].

4. Acknowledgement

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5. References

[5] DIN VDE 0276-620 Part 5C "Distribution cables with extruded insulation for rated voltages from 3.6/6 (7.2) to 20.8/36 (42) kV", 1996