Time Domain Dielectric Response of Field Grading Sleeves Subjected to High Humidity and Temperatures

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ABSTRACT

It is experienced that MV XLPE cable links including heat shrink cable joints can have a high electrical conductivity compared to the XLPE cable insulation. The field grading sleeve included in the joint design is proposed to be responsible for the reduced insulation resistance and is therefore studied in this paper. New field grading sleeves are aged in the laboratory at temperatures up to 150 °C in both dry and humid conditions. The degree of ageing is determined by DSC measurements, the mechanical properties are determined by tensile strength testing, and the electric properties are characterized by time domain dielectric response measurements. The results show that after only a few days above the melting point of 104 °C the tensile strength of the material is strongly reduced. The electrical conductivity is strongly dependent on the degree of thermal ageing of the sleeve material but also the water content. The combination of significant thermal degradation and a high water content results in particularly high conductivity values. It is shown that the increase of the conductivity after ageing at 150 °C for 15 days is five orders of magnitude for wetted field grading sleeves measured at 30 °C.

Index Terms — **dielectric measurements, stress control, thermal factors**

1 INTRODUCTION

MEDIUM voltage (12/24 kV) XLPE cable joints installed in the 1980s and 1990s were typically heat shrink types equipped with a field grading sleeve and a rubber type insulation body with an outer semi-conductive layer. During installation, this layer is centered over the aluminium cable conductor connector with contact to the insulation screen of the cable on both sides after heat shrinking. The field grading principle of the sleeve material is nonlinear resistive [1].

With respect to non-destructive diagnostic testing of medium voltage cable links, high dielectric loss tangent (tan δ) values have been associated with the presence of joints with field grading sleeves having a low insulation resistance [2]. When not knowing if any joints are present in the cable link, which is often the case, severe misinterpretation during cable condition assessment can occur. The high tan δ values can erroneously be taken as severe water tree degradation of the cable insulation when using the automated assessment provided by the

instrument [3]. Such misinterpretations can be very costly, as cables with long remaining life consequently will be replaced.

Medium voltage cable designs installed during 1980s and to some extent the 1990s, were of a so-called "wet" type allowing water vapor to permeate through the outer jacket and then into the cable core or the joint body. In addition, local overheating in medium voltage joints due to ageing metallic connectors has also been observed. The temperatures can likely become very high and well above 100 °C [4]. It has therefore been proposed that the strongly reduced insulation resistance, or correspondingly very high and voltage dependent tan δ values of medium voltage XLPE cable links, is due to the combined action of degradation by overheating and water vapor transport through the outer jacket, the polymeric joint body and finally to the field grading sleeve.

The surrounding soil of the direct buried cables in Norway is generally wet, and the low thermal conductivity also cause the temperature gradients across the cable to become low. Elevated temperatures caused by local heating of a metallic connector in a joint can then also heat the surrounding liquid or water vapor close to the cable surface. The water diffusion and solubility in polymeric materials are strongly temperature dependent and determined by the partial pressure of water [5]. Sorption of

water vapor at high temperatures can both change the thermal ageing mechanism of the materials involved, as well as the resulting conductivity of the field grading sleeve material [6].

The main purpose of this paper is therefore to test the hypothesis that the combined action of thermal ageing and water sorption is responsible for the strong increase of the measured $\tan \delta$ or correspondingly strong decrease of the insulation resistance of the field grading sleeve material in the joints. This has been performed by thermal ageing and characterization of a commercially available heat shrink sleeve with the same material composition as used during the 1980s and 1990s.

2 DIELECTRIC RESPONSE

Applying a step voltage across a dielectric material causes a current due to conductivity and dielectric displacement. This current is called the polarization current and can be expressed by:

$$I_p(t) = C_0 U\left(\frac{\sigma}{\epsilon_0} + f(t)\right) \qquad (1)$$

where C_0 is the geometric capacitance of the dielectric material, U is the applied voltage, σ is the conductivity, ϵ_0 is the vacuum permittivity, and $f(t)$ is the dielectric response function [7]. By applying the voltage for a sufficiently long time, the contribution from the dielectric response function will vanish leaving only a steady-state conductive current flowing through the material. Short-circuiting the material causes a depolarization current flowing in the opposite direction as the polarization current. The depolarization current is expressed as:

$$I_d(t) = C_0 U\big(f(t) - f(t + t_c)\big) \qquad (2)$$

where $f(t + t_c)$ describes the remaining charges from previous voltage applications. There is no contribution from the conductivity at this point as there is no voltage applied. Assuming $f(t + t_c)$ is small compared to $f(t)$, Equations (1) and (2) can be combined to give an approximation to the conductivity of the material expressed as:

$$\sigma \approx \frac{\epsilon_0}{C_0 U}\big(I_p(t) - I_d(t)\big) \qquad (3)$$

The loss tangent is defined as:

$$\tan \delta = \frac{C''(\omega)}{C'(\omega)} = \frac{\sigma + \omega\epsilon''}{\omega\epsilon'} \qquad (4)$$

where C' and C'' are the real and imaginary part of the complex capacitance of the test object, ω is the angular frequency, and ϵ' and ϵ'' are the real and imaginary parts of the permittivity, respectively [7]. If the test object is a long cable section with one or several joints, the resulting loss tangent can be expressed as:

$$\tan \delta = \frac{C''_{cable} + C''_{joint}}{C'_{cable} + C'_{joint}} \qquad (5)$$

The real capacitance of the cable is generally much higher than the sum of the real capacitance of the installed joints. If one or more joints have a relatively high conductivity, the overall dielectric losses are dominated by the joints. Consequently, Equation (5) can be rewritten to:

$$\tan \delta \approx \frac{C''_{joint}}{C'_{cable}} \qquad (6)$$

Equation (6) shows that when joints with low resistivity are present in a cable link, the dielectric loss tangent will be dominated by the conductive losses of the joints. Note that the resulting dielectric loss tangent is dependent on the length of the cable section as C' is proportional to the cable length.

3 EXPERIMENTAL WORK

3.1 TEST OBJECT

The test object is a commercially available heat shrink field grading sleeve. Such sleeves are commonly used as the inner layer of a medium voltage heat shrink cable joint. In this work, sleeves were installed by heat shrinking them onto polytetrafluoroethylene (PTFE) rods equipped with metallic electrodes at both sides as illustrated in Figure 1. It is important that the sleeve is sufficiently long to cover both metallic electrodes completely. PTFE was used due to the material's excellent resistance to elevated temperatures as well as the low bulk and surface conductivity. The diameter of the rod is 25 mm, and the outer diameter increased to 29 mm after installation of the sleeve. The dimensions were kept in the same range as for a typical medium voltage cable joint designed for 24 kV XLPE cables with an aluminium conductor cross section of 240 mm^2. The length of the PTFE rods was either 20 or 100 mm. The latter was selected as being typical for medium voltage joints. The samples with a 20 mm long PTFE rod were used to study the effect of higher electric field strength magnitudes. The 100 and 20 mm long rods with unaged field grading sleeves installed are referred to as test object A and test object B, respectively.
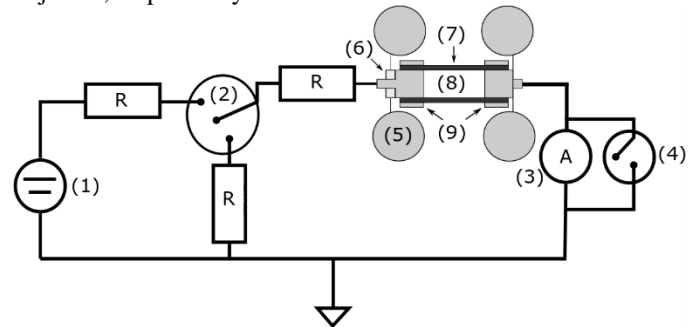
Figure 1. Illustration of the test object with connections to HVDC source and electrometer for time domain dielectric response measurements; (1) FUG 65 kV HVDC source, (2) 70 kV HV switch, (3) Keithley 6485 picoammeter, (4) 6 kV HV switch, (5) corona rings, (6) PTFE ring insulating the measuring electrode from ground, (7) field grading sleeve, (8) PTFE rod, and (9) metallic clamps to secure good electrical contact between the metallic electrodes and the field grading sleeve. The resistors, R, are 50 MΩ each.

Prior to time domain dielectric response measurements, one of the electrodes was connected to high voltage DC through a 50 MΩ resistor relay for short circuit protection, whereas the other was connected to a picoammeter. Corona rings were attached at both ends to avoid corona discharges from sharp edges in the set-up. To ensure good electric contact between the sleeve and the electrode, metallic clamps were used at both ends of the test object. Figure 1 illustrates the final assembly.

3.2 VACUUM TREATMENT

Before being subjected to any measurements, the test objects were pre-conditioned in a vacuum chamber for three days at 70 °C, and then lowering the temperature to 25 °C for one day maintaining the vacuum pressure. This was done to remove any volatiles and humidity that could influence the resulting reference conductivity measurements.

3.3 AGEING PROCEDURE

Unaged, but vacuum treated, test objects of type A, were placed in heat chambers for thermal ageing. The ageing was performed both in dry air and in humid water vapor conditions at 98 °C. The purpose of including ageing in a humid environment was to examine if water vapor likely present in such materials during service, could accelerate any ageing in this temperature range by e.g. hydrolysis of stabilizers [8]. The relative humidity was close to 100% as the test object was placed just above the water surface in a sealed polyethylene box partially filled with deionized water. In addition, dry air ageing was also performed at 150 °C as such a high temperature may occur close to bad metallic cable connectors in service (135 °C is reported in [4]). In the following, the aged samples are referred to as test object C, D, and E, respectively (see Table 1). To prevent any cracking of the edge of the sleeves during ageing at 150 °C, the edges were covered with a heat resistant heat shrink tube. This fluoropolymer (Viton) tube had a minimum shrink temperature of 300 °C. Only a limited length of the sleeve was covered to secure that the presence of this tube did not limit the access of circulating air in the electrically active area (section between the electrodes) of the test object. The Viton tube was removed before performing any measurements. Table 1 shows the ageing times and other treatments used on the different test objects. The water treatment test objects F and G received is described in Section 3.7. The ageing of test object B is also described there.

Table 1. Ageing times for the different ageing conditions.

Test object	Ageing conditions	Ageing time [days]	Water treatment
A	None	0	-
B	None	0	-
C	Dry air at 98°C	12, 17, 24, 39, 50, 75	-
D	Wet air at 98°C	12, 17, 24, 39, 50, 75	-
E	Dry air at 150°C	5, 10, 15, 50	-
F	None	0	30 days at 90°C
G	Dry air at 150°C	15	30 days at 90°C

3.4 WATER SORPTION

After installing an unaged field grading sleeve on a PTFE rod, it was cut into small rectangular plates weighing approximately 1.5 g and subjected to the vacuum treatment described in Section 3.2. Immediately after removal from the vacuum chamber, 16 plates were weighed before being immersed in deionized water at 30, 60, and 90 °C. Prior to weighing and immediately after removal from the heated water, the sample was placed in deionized water kept at 4 °C. This was done to limit the desorption of water. After cooling, the surface of the sample was dried using lint free paper towels to remove excess water. Before weighing the sample, it was moved through an electrostatic precipitator to remove any surface charges. Finally, immediately after weighing, the sample was placed back in the heated water.

3.5 DIFFERENTIAL SCANNING CALORIMETRY

Differential scanning calorimetry (DSC) was used to determine any phase transitions in the unaged sleeve material, and later to assess the consumption of stabilizers in the material during the wet and dry thermal ageing. First, to determine phase transitions, the temperature was increased from 20 to 200 °C at a rate of 10 °C/min. These measurements were performed twice on samples taken from an unaged sleeve installed on the PTFE rods. Second, the oxidation induction temperature (OIT), T_{ind} method was used to determine any consumption of stabilizers during ageing. After 10 minutes at 25 °C, a continuous heating with a rate of 10 °C/min was performed up to 400 °C. The test objects C, D, and E were included in these measurements being subjected to heat shrinking at the same degree as that during installation of sleeves on PTFE rods in advance of the calorimetric measurements.

3.6 TENSILE TESTING

The tensile testing was performed according to IEC 60811-1-1. Five "dog bone" shaped samples with dimensions in accordance with the standard were used for each ageing type. The strain rate was 25 mm/min, and the length extension was continuously measured using a laser meter.

3.7 TIME DOMAIN DIELECTRIC RESPONSE

The unaged test object B was placed in a heating cabinet, and polarization and depolarization currents were measured at different temperatures from 40 to 140 °C. For each temperature, the currents were measured for 10 hours each at the electric fields listed in Table 2. A current sensitive experimental setup, including a stable high voltage DC source and a picoammeter was used to measure the currents, see Figure 1. After each voltage cycle, the temperature was increased to the next level. New measurements were started one hour after the temperature had reached the desired level.

The polarization and depolarization currents of test objects A, C, D, and E with different ageing durations were measured for 3 hours each at temperatures 30, 90, and 150 °C. Details are listed in Table 2.

Table 2. Electric fields applied to the different test objects and their ageing level.

| Test objects	Ageing time [days]	Electric field [V/mm]							
A	0	10	50	100	200				
B	0	25	50	125	250	500	750	1000	50
C, D	50	10	50	100	200				
E	15	10	50	100	200				
C, D	75	10	50	100					
E	50	10	15	20					

After the dielectric response measurement had been completed, test object A and test object E aged for 15 days were placed in water vapor saturated air at 90 °C for 30 days. The resulting test objects are called F and G, respectively (see Table 1). This was done to examine the effect of water sorption on both unaged and thermally aged sleeves as this is relevant to real service conditions. The water sorption set-up was the same as that used during the ageing at high humidity. At the end of

the water sorption period, the samples were immediately transferred to a climate chamber keeping 30 °C and 95% relative humidity. The samples were then subjected to another round of dielectric response measurements.

4 RESULTS AND DISCUSSION

4.1 WATER SORPTION

Figure 2 shows the water uptake for an unaged sleeve at 30, 60, and 90 °C. Prior to sorption measurements, the sleeve was installed on the PTFE rod. The water uptake has a significant temperature dependence. A higher temperature implies a larger water uptake rate. It is also observed a "two-stage" sorption which is a non-Fickian type becoming more pronounced at higher temperatures [9]. Such absorption is characterized by a rapid initial uptake to a quasi-equilibrium, followed by a slower absorption rate to a final, true equilibrium. It is likely that the fillers in the sleeve are responsible for the non-Fickian feature. Even after 80 days, the sleeve has not reached saturation, with water concentrations higher than 6% at 90 °C increasing linearly with time.
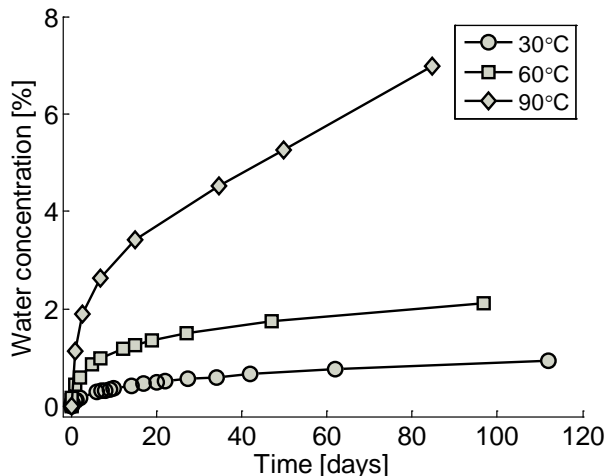

Figure 2. Water sorption at 30, 60, and 90 °C as a function of time for an unaged sleeve.

4.2 DIFFERENTIAL SCANNING CALORIMETRY

Figure 3 shows the two heating runs for an unaged installed test sample. The endothermic peaks indicate that the cross-linked field grading sleeve has a melting point at about 104 °C. The onset of this peak is close to 90 °C which is the maximum allowed service temperature of XLPE insulated power cables.

During the first heating run, the sample will undergo a dimensional change due to additional shrinking. This is likely what is observed close to 80 °C where another endothermic peak is observed. This peak is not present during the second run, where the shrinking of the sample is complete.

Figure 4 shows the oxidation induction temperature (OIT) as a function of ageing time for the three different ageing conditions. The difference between ageing at 98 °C in dry or humid conditions is small for short times. Still, humid conditions seem to have a negative effect for longer ageing times, as the OIT steadily decreases at humid conditions, but seem to stabilize for dry conditions.
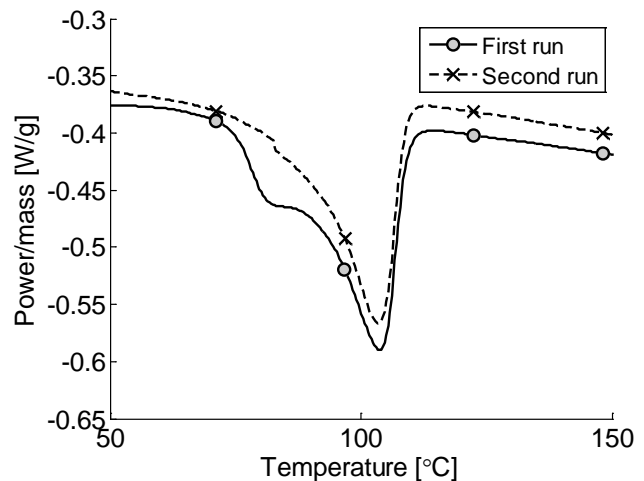
Figure 3. DSC measurements on an unaged installed field grading sleeve.

Dependent on the stabilizer type used, the high water vapor content during ageing could degrade the antioxidant by hydrolysis increasing the degradation rate of the material as observed for the sleeve studied in this work [8]. Also, the interactions between the filler used for field control and the polymer matrix are complex and involve many phenomena that can have an effect of the thermo-oxidative ageing [10]. Ageing at higher temperatures causes a larger loss of antioxidants, shown by the much lower OIT for the ageing at 150 °C even at short ageing times. Moreover, the OIT barely changes after 15 days of ageing, which indicates that almost all antioxidants are consumed at that ageing time. It is important to keep in mind that the availability of the oxygen is large compared to that in a real power cable joint. The oxygen must diffuse from outside through several layers of stabilized polymers including the insulating joint body. Therefore, the reactions will be diffusion-limited in the sleeve at service conditions.
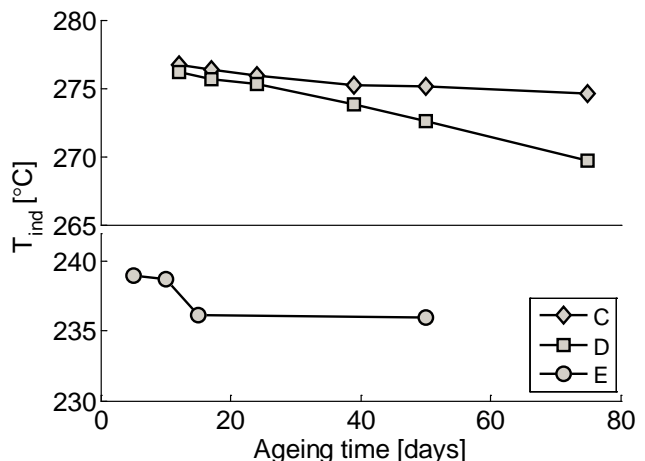

Figure 4. Oxidation induction temperature as a function of ageing time for the three ageing conditions.

4.3 TENSILE STRENGTH TESTING

The percentage strain at break for the three ageing conditions is shown in Figure 5. As the field grading sleeve thickness is not completely uniform, the graphs show the mean value of five samples for each ageing condition. For C and D, there is a gradual decrease in the strain-at-break. After 75 days, the

reduction in strain-at-break is still less than 50% of the reference. No visible discoloration or micro-cracks was observed. Water vapor has a slight impact on the degradation rate compared to that in dry conditions, which supports the results from the OIT measurements. As seen in Figure 2, the sorption of water vapor is large at 90 °C, and a dual mode type is observed. This means that the sorption of water is not at equilibrium even after 80 days. The continuous almost linear uptake with time could accelerate the degradation rate for longer times. This is not studied in this work.

The ageing at 98 °C is close to the transition tempeature at 104 °C where crystalline regions in the cross-linked sleeve material are melted. At 150 °C the material is in its amorphous state strongly increasing the free volume and susceptibility for oxidative degradation. Already at five days of ageing, the reduction in mechanical strength is significant. After 50 days, only one sample could be tested as the material was very fragile, indicating auto-oxidation. Even short periods of high temperature leads to irreversible physical changes of the material at these oxygen rich conditions. As mentioned, during service these reactions will be diffusion-limited causing a longer service time at high temperature conditions.
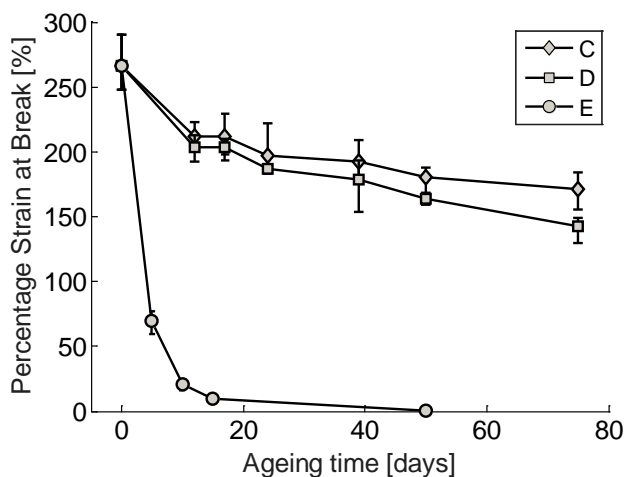

Figure 5. Percentage strain at break as a function of ageing time for the different ageing conditions.

### 4.4 TIME DOMAIN DIELECTRIC RESPONSE

Figure 6 shows examples of the measured polarization and depolarization currents for test object A at 0.2 kV/mm and temperatures from 30 to 150 °C. There is a significant temperature dependence of the current magnitudes. Increasing the temperature from 30 to 150 °C increases the polarization current by four decades. This increase is also shown in Figure 7, where the relation between the conductivity and electrical field is presented. It is observed that the conductivity is only slightly dependent on the electric field up to 0.2 kV/mm, whereas the temperature dependence is about the same even for the lowest field strength (0.01 kV/mm). In addition, the conductivity for the second measurement at 30 °C (after being subjected to 150 °C) is one decade larger than the first measurement. The exposure of the sleeve material to high temperatures, can change the molecular structure of the sleeve resulting in a change of the electrical properties, but also cause a material degradation during the dielectric response measurements (>30 h at each temperature). As seen in Figure 4 and Figure 5,

only short durations are needed to reduce the mechanical properties or OIT significantly. This is further discussed for measurements on aged samples.

The depolarization current shows a large increase from 30 to 90 °C. This is most likely due to the melting phase transition from semi-crystalline to amorphous morphology starting somewhere below 90 °C (see Figure 3). In the amorphous state, the polymer chains are freer to move, thus likely increasing the polarization of the material.
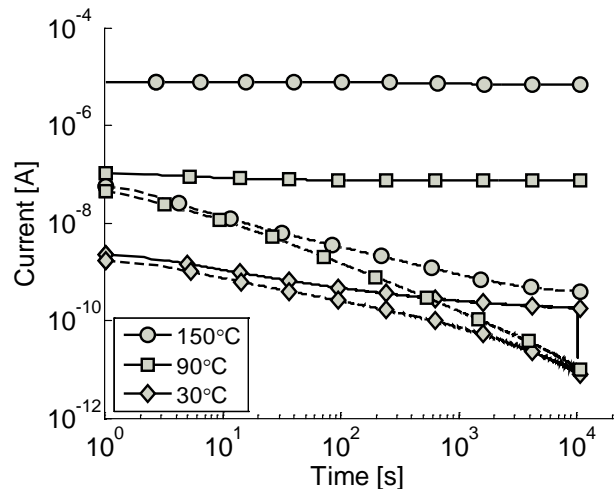
Figure 6. Polarization (solid lines) and depolarization (dashed lines) currents for test object A as a function of time for different temperatures. The electric field strength is 0.2 kV/mm.
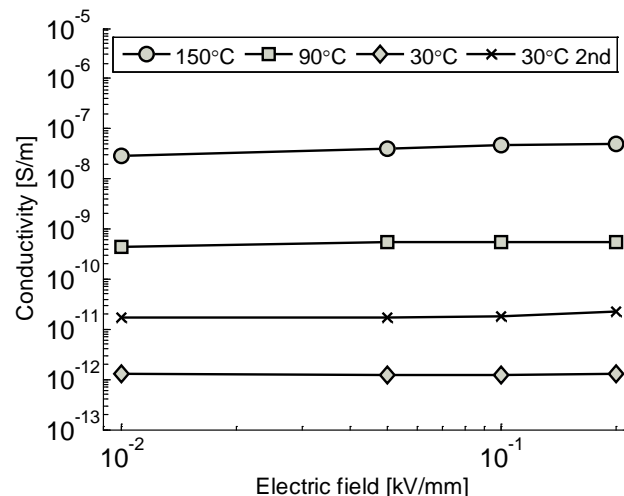
Figure 7. Conductivity as a function of applied electric field for test object A for different temperatures. The second 30 °C measurement is performed after 150 °C.

Arrhenius plots of the calculated conductivities from polarization and depolarization current measurements on test object B is shown in Figure 8 for three field strengths. Linear fitting is used to calculate the Arrhenius activation energies, and the values are listed in Table 3. The curves do not differ much supporting the conclusion that the electric field dependence of the conductivity is relatively small. However, at 1 kV/mm and 140 °C, a slightly higher field dependence is observed. It is likely different activation energies involved as the slope in the ln σ vs 1/T slightly changes at a critical temperature. This is especially evident at 1 kV/mm. It is likely that the phase

transition or melting temperature at 104 °C is responsible for the activation energy change.

Electric field [kV/mm]	E_a [eV] below 100°C	E_a [eV] above 100°C	Single E_a [eV]
0.025	0.84	1.07	0.90
0.25	0.88	1.09	0.93
1.0	0.64	1.71	0.88

This change is from about 0.85 eV at temperature below the melting temperature and close to 1.1 eV above. The activation energies for the lowest field strengths are similar, whereas for the conductivity determined at 1 kV/mm, the difference is bigger, i.e. a lower activation energy below the phase transition and higher above it. The melting of the crystalline region at higher temperatures, increases the free volume of the system. This increase in free volume can likely facilitate an increase in motion of charge carriers and then higher electrical conductivity [11].
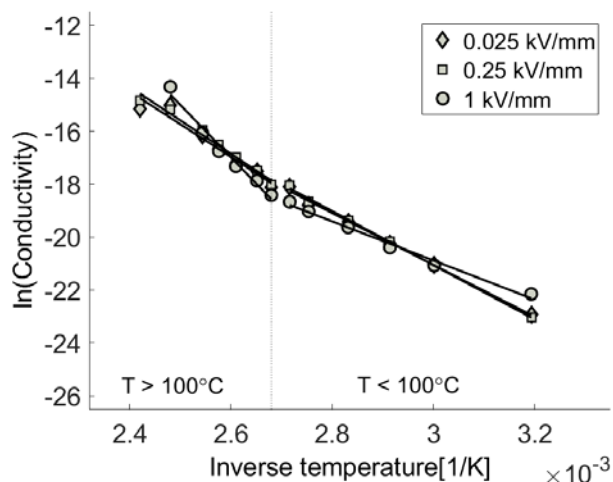

Figure 8. Natural logarithm of the conductivity for test object B as a function of inverse temperature for increasing electric field strengths. The measured values are denoted with symbols, and the straight lines are linear fits to the data points. The vertical dashed line is at 100 °C.
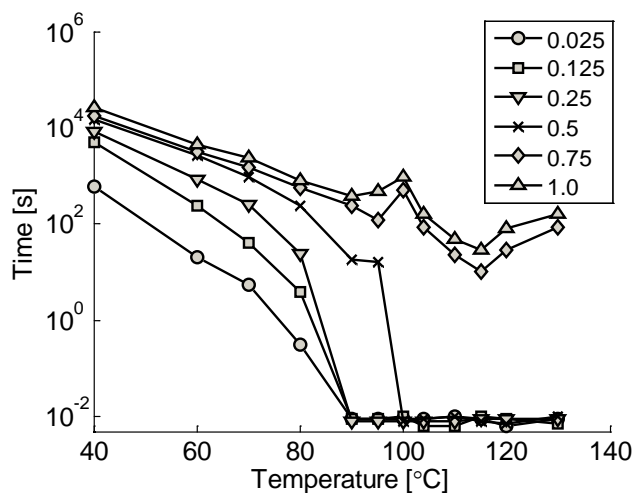
The depolarization currents of the field grading sleeve show anomalous behavior. Here, the depolarization current experiences a polarity change after some time depending on the temperature and the electric field. In Figure 9, the absolute value of the depolarization current at 60 °C for three different applied electric fields is shown. The sharp peaks indicate the polarity change. To the left of the peaks, the current is negative (normal behavior), whereas it is positive (anomalous behavior) to the right. Such an anomalous behavior has been observed earlier in both high- and low-density polyethylene films exposed to high temperatures and high electric fields [12, 13]. Theoretically, this effect can be caused by, for instance, space charge relaxation. Another cause may be the experimental hardware. A recent study has found that both the measuring cable and the use of a diode protection circuit contribute to the anomalous depolarization current [14]. The reported current contribution from the diode protection circuit is of the order of 1 pA. This contribution is negligible compared to the currents measured in the present experiments. In this work, the cable transferring the measured signal from the test object is a PTFE insulated coaxial cable with melting point well above the temperatures included in this study. Hence, pyroelectric current contribution from frozen-in polarization should not affect our measurements as the temperature is too low to have any morphology-changing effect.

Studying the polarity change of the depolarization current reveals that the change is dependent on both temperature and applied electric field. Figure 10 shows the time before the polarity change occurs for different applied electric fields as a function of temperature. Note that the field grading sleeve broke down at 15 kV at 140 °C, hence the absence of this temperature in the figure. The general behavior is that the polarity change time decreases with increasing temperature as well as with decreasing electric field. However, at fields 0.75 and 1.0 kV/mm, there is an increase in this time around 95-100°C, just like the change in conductivity activation energy seen in Figure 8. This temperature interval is just above the onset of the melting peak seen in Figure 3. Another increase is observed at temperatures at 120 °C and above.
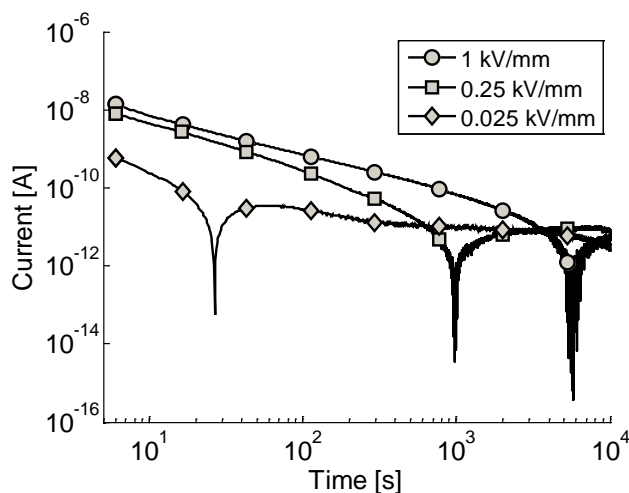

Figure 9. Absolute value of the depolarization current for test object B at 60 °C for different applied electric fields. The currents are negative (normal) to the left of the peaks and positive (anomalous) to the right.

Figure 10. Time to polarity change of the depolarization current from negative to positive as a function of temperature for different applied electric fields (values in legend are in kV/mm).

The effect of ageing on the conductivity of the field grading sleeve material is shown in Figure 11. Ageing for 15 days at 150 °C increases the conductivity by almost two decades

compared to an unaged sleeve. In case of ageing at 98 °C in both dry and wet conditions, the conductivity increase is closer to one decade when measuring at 30 °C. When measuring at 150 °C, the conductivity increase is smaller, especially for dry conditions. However, between 0.05 and 0.1 kV/mm, a conductivity increase for the sleeve aged in wet conditions is observed.
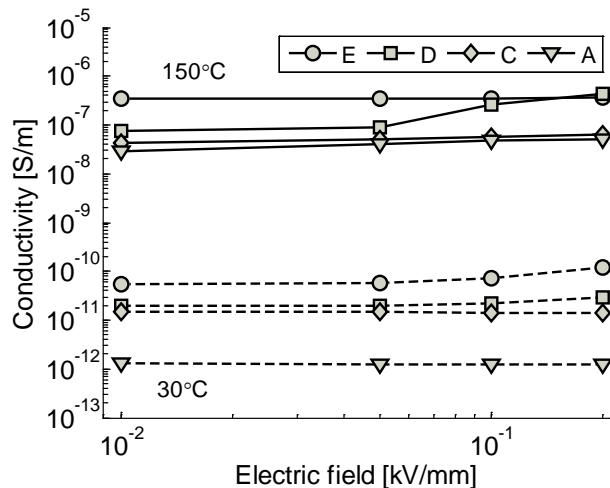
Figure 11. Conductivity as a function of electric field at different levels of ageing. A is an unaged sleeve. C and D are aged for 50 days at 98 °C in dry and wet conditions, respectively. E is aged for 15 days at 150 °C in dry conditions. Dashed and solid lines show the conductivity calculated from measurements performed at 30 and 150 °C, respectively.

The natural logarithm of the conductivity as a function of inverse temperature for different ageing conditions is shown in Figure 12.
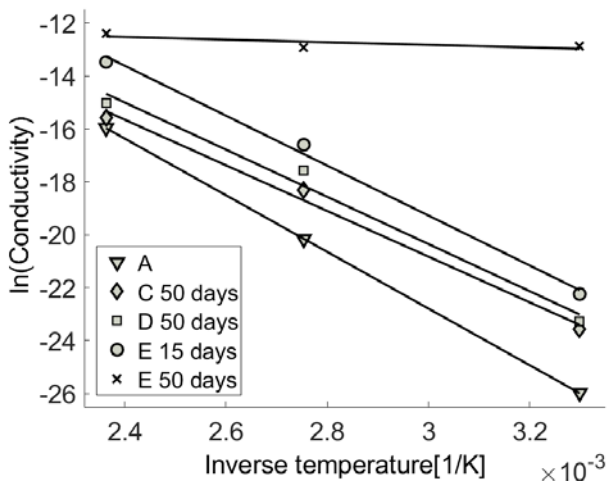
Figure 12. The conductivity for different ageing conditions as a function of inverse temperature. The applied electric field is 0.01 kV/mm.

The corresponding activation energies are shown in Table 4. Ageing above the melt transition temperature of the field grading sleeve material strongly reduces the activation energy. In this case the conductivity is high, and after 50 days of ageing at 150 °C, the conductivity is almost independent of applied test temperature. The oxygen rich environment during the high temperature laboratory ageing of the sleeve material, will most

Table 4. Activation energies for the different ageing conditions.

Ageing type and time [days]	A	C 50	D 50	E 15	E 50
Activation energy [eV]	0.92	0.74	0.77	0.81	0.04

likely induce a severe oxidation of the sections close to the inorganic fillers. By time the oxidized areas close to the neighboring filler particles will likely increase and finally overlap. Severe oxidation of this area will induce a high electrical conductivity and likely also almost constant with temperature. A similar temperature independent electrical conductivity in polymers has been reported for polyvinylchloride (PVC) loaded with carbon nanotubes [15].

Figure 13 shows the conductivity as a function of applied electric field measured at 30 °C for field grading sleeves subjected to water sorption for 30 days at 90 °C. The conductivity of an unaged sleeve (test object F) increases by two decades, whereas for a sleeve aged for 15 days at 150 °C (test object G) a strong increase of the conductivity is observed and is in the range of six decades.
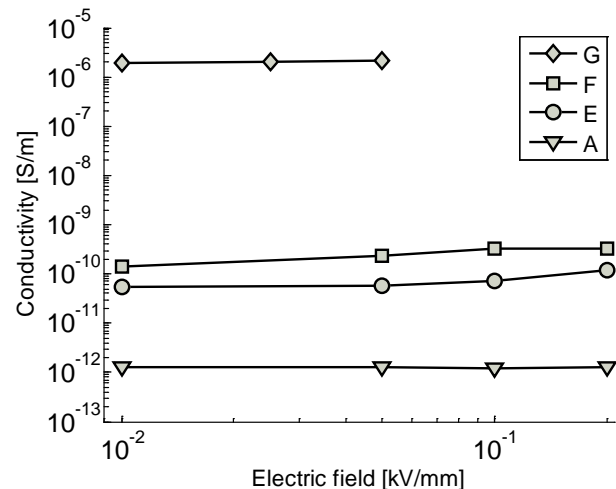
Figure 13. Conductivity as a function of electric field at 30 °C. A is an unaged sleeve, whereas E is aged for 15 days at 150 °C in dry conditions. F (unaged) and G (aged) are the same sleeves measured after being subjected to water absorption at 90 °C for 30 days.

4.5 IMPACT ON CABLE DIAGNOSTICS

Figure 14 shows the dielectric loss tangent at 0.1 Hz for a commercially available 240 mm^2 12/24 kV XLPE cable as a function of cable length.
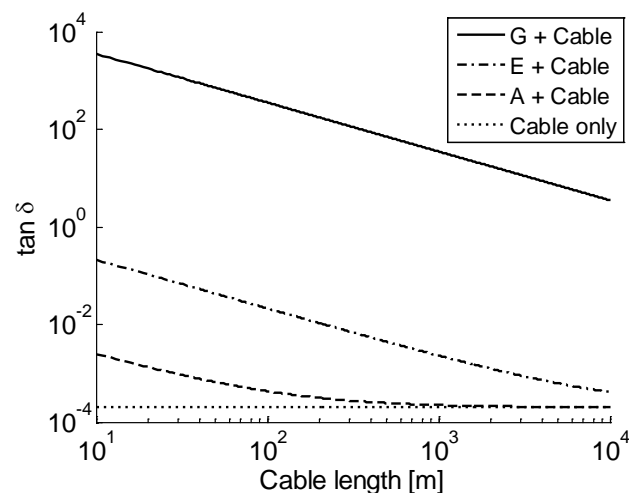
Figure 14. Total loss factor at 0.1 Hz for cables with different joints as a function of cable length.

The cable is equipped with joints where different ageing and humidity conditions are considered for the field grading

sleeves. Equation (6) and the measured conductivity values are used to calculate the resulting dielectric loss tangent. An unaged XLPE cable insulation is assumed to have dielectric loss tangent in the range of 0.0002 independent of the cable length [3]. The figure shows that an unaged joint (equivalent to test object A in this study) will not significantly affect the dielectric loss tangent for lengths longer than about 100 meters. When including a thermally aged joint (test object E) in the cable link, the impact on the dielectric loss tangent will be significant (>10 times) even up to cable lengths of 1000 m. Wet cable designs with no outer metallic sheaths allows water to enter the joint body and the field grading sleeve during service. When including a thermally aged joint that has been subjected to water in the cable link (test object G), the dielectric loss tangent is strongly increasing to above unity even at cable lengths of 10 km.

5 CONCLUSION

Medium voltage XLPE cable joints can be subjected to local high temperatures due to bad metallic connectors with a higher transition resistance. The resulting increased local service temperature can cause oxidative thermal ageing of the joint materials and in particular the field grading sleeve that is included in the design. This work has shown that thermal ageing of the field grading sleeve increases significantly the electrical conductivity of the sleeve by several decades. Also, water vapor is likely to diffuse into the field grading material from outside during service at a rate dependent on the local temperature. The water diffusion measurements of the field grading sleeve have shown that the water uptake in the material is high and well above 5% at 90 °C. Water uptake in a severely aged field grading sleeve causes the electrical conductivity to increase by more than six decades compared to an unaged field grading sleeve. The results obtained in this paper can explain why cable links with joints having no radial water barrier can have a very low insulation resistance. In addition, it is of crucial importance to distinguish the contribution from such joints to the VLF tan δ from severe water treeing.

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