Abstract
The paper presents measurements on the electrical performance of polyethylene with respect to the inception voltage of a needle-plate arrangement as well as the breakdown voltage of PE films in a sphere-sphere arrangement and an extruded cable insulation. The tests were performed with dc and lightning impulse voltage at 20 °C and 90 °C. By measuring the electrical conductivity as a function of temperature and electrical field strength it was possible to calculate the field distribution in the PE insulation of cables. Breakdown voltages with different temperature differences across the PE-insulation were measured and the results are discussed.

1 Introduction
Polyethylene (PE) is widely used as insulating material for medium- and high voltage ac cables. Compared to conventional oil-paper or mass impregnated cables PE insulated cables are almost maintenance-free, have a lower weight and a smaller thermal resistance for a given voltage and conductor cross section [1, 2]. Because of these advantages much work had recently been done to develop PE insulated high voltage dc cables [2]. The breakdown voltage characteristic of different PE compounds is commonly measured with thin foils in model arrangements [3]. The influence of inhomogeneities on the electrical performance of PE insulations can be investigated with a needle-plate arrangement [4, 5, 6]. But in all cases of testing with model arrangements the question arises how the results can be transferred to real cable insulation.

2 Experimental Setup
For the needle-plate arrangements Ogura needles with a tip radius of 5 µm were used. The distance between the electrodes was 5 mm [6].
In the sphere-sphere arrangement both the high voltage and the earthed electrode were copper spheres plated with chromium. Both electrodes had a radius of 5 mm. In all breakdown experiments the thickness of the polyethylene foils were 100 µm. The complete electrode arrangement was immersed in silicone oil to avoid flashovers and discharges on the sample surface during the test [4].
The cable used for the test was manufactured under industrial conditions and had a 2.5 mm thick extruded polyethylene insulation with inner and outer semiconductive layer. The radius of the inner insulation was 6 mm. The active tested length of each cable sample was 10 m in addition to a length of about 3 m for each cable termination. High voltage was applied to the inner conductor whereas the outer conductor was grounded. For the tests at higher temperatures the cable insulation was heated by a 50 Hz ac current, flowing through the inner conductor. Different temperature gradients of the cable insulation had been realised by different thermal insulations of the cable.
In all three electrode arrangements the same uncrossed polyethylene compound was used. The inception voltages and the breakdown voltages were analysed by means of the Weibull-distribution with two parameters. The number of samples in each test was n = 10.

3 Experimental Results
3.1 Breakdown and inception voltages under dc and lightning impulse voltage at 20 °C
The inception and breakdown voltages under dc U_{dc} were based to their values under lightning impulse voltage U_{li}. The ratio of the inception voltages of the needle-plate arrangement \( U_{dc}/U_{li} \) is 2.15 [5, 6]. The ratio of the breakdown voltages \( U_{dc}/U_{li} \) of the sphere-sphere arrangement and the cable was measured as 1.66 and 1.71, respectively.
The higher dc inception and breakdown voltages can be explained by the accumulation of space charges in the insulating material [3]. Under a high electric dc field space charges have sufficient time to build up a homopolar charge area in the vicinity of the inhomogeneities, which reduces the macroscopic field strength locally. In contrast, under lightning impulse voltage the space charges have not sufficient time to build up which leads to lower inception or breakdown values under lightning impulse voltage.
The difference of the ratio \( U_{dc}/U_{li} \) between the different arrangements indicates that the degree of space charge accumulation depends on the electrode geometry. It can be assumed that the needle tip is a much greater imperfection than it appears on the surfaces of the semiconductive layers in the cable or the surfaces of the metallic spheres [7]. A comparison of the ratio \( U_{dc}/U_{li} \) between the cable and the sphere-sphere arrangement shows that the dc and lightning impulse voltage breakdown characteristic is almost similar. The higher number and the greater variety of inhomogeneities in the
extruded cable can explain the slightly higher ratio $U_{dc}/U_{li}$ of the cable.

3.2 Breakdown voltages under dc and lightning impulse voltage at higher temperatures

Under service conditions insulating materials often work at higher temperatures. Therefore, the breakdown behaviour of polyethylene foils and the PE cable insulation was investigated at different temperatures.

As Figure 1 shows, under both dc and lightning impulse voltage the breakdown voltage of PE foils decreases when temperature is increasing. Under lightning impulse voltage the breakdown voltage decreases only slightly whereas under dc the breakdown voltage decreases strongly for temperatures above 60 °C. For the lower breakdown voltages at higher temperatures two reasons can be assumed. Firstly, the degree of cristallinity in the PE decreases with increasing temperature, which leads to a reduced intrinsic strength of the material [8]. Secondly the mobility of space charges in the PE-insulation is much higher at higher temperatures [3]. Therefore, space charges are wider distributed in the PE and the screening effect is less pronounced. Under lightning impulse voltage the influence of space charges is much lower than under dc voltage (section 3.1). This can be seen as the reason for the relatively lower reduction of the breakdown voltage at higher temperatures in Figure 1.

![Image](Fig. 1: Breakdown voltage of PE foils at different temperatures in the sphere-sphere arrangement)

Fig. 1: Breakdown voltage of PE foils at different temperatures in the sphere-sphere arrangement

In the cable the breakdown voltage decreases with increasing temperature. At room temperature the cable was tested with dc voltages up to the capacity of the available dc voltage generator of 600 kV with no breakdown. So, it can be concluded that at a temperature 90 °C the breakdown voltage of the cable decreases to less than 42 % of that at room temperature. In the sphere-sphere arrangement the breakdown voltage at 90 °C decreases to 58 % of that at room temperature (Figure 1). The influence of temperature on the breakdown voltage of the cable is stronger than of the PE foils.

In both arrangements no statistically significant difference between positive and negative polarity was observed [5], (Figure 2).

The electric field distribution in the sphere-sphere arrangement and the cable is supposed to be similar. The reason for the different temperature influence on the breakdown field strength is therefore supposed to be due to the different kind of interfaces between PE and semiconductive layer in the cable and between PE and chromium in the sphere-sphere arrangement. The semiconductive layers that cover the conductors of the cable show a higher surface roughness at 90 °C than at room temperature [7]. The higher roughness of the semiconductive layers in the cable may lead to local field elevations and to a higher degree of electron emission. Furthermore it can be assumed that at higher temperature the greater variety of impurities that occur at the semiconductive layers of the cable will be screened less by space charges.

3.3 Influence of temperature difference on breakdown voltage at the cable

With respect to service conditions of power cables the effect of different temperature differences across the insulation on the breakdown voltage was investigated. In the experiments the conductor temperature was always kept at 90 °C. The temperature difference of $\Delta \theta = 2$ K was achieved with a thermal insulation while the cable in free air had a temperature difference of $\Delta \theta = 12$ K.

![Image](Fig. 3: dc breakdown voltage of the cable at different temperature differences)

Fig. 3: dc breakdown voltage of the cable at different temperature differences

Figure 3 shows that at a higher temperature difference a lower breakdown voltage occurred. The difference is statistically significant for the 63%-values. The reason for this is supposed to be the field dependent electrical conductivity of the polyethylene. The effect of temperature and electric field on the conductivity can be approximated by the following equation [9, 10]:

$$ F_{\text{eq}} = \frac{1}{2} \left( \frac{\text{average breakdown field strength}}{\text{average breakdown field strength at } 20^\circ C} \right) $$
\[ \kappa = \kappa_0 \cdot \exp(\alpha \vartheta) \cdot \exp(\beta E) \] /1/

Where \( \vartheta \) is the temperature, \( E \) the electric field, \( \kappa \) the electrical conductivity at \( \vartheta = 0 \, ^\circ\text{C} \) and \( \kappa_0 \) the electrical conductivity at \( \vartheta = 0 \, ^\circ\text{C} \) and \( E = 0 \, \text{kV/mm} \).
\( \alpha \) and \( \beta \) are material depending coefficients. In Figure 4a the field- and temperature dependent conductivity of polyethylene is shown as it has been measured with 50 \( \mu \text{m} \) PE foils. The measurement was carried out with guarded electrodes in 5 consecutive current measuring sequences with the pA-meter “Keithley 6517”. The measurement value had been taken as steady state value after 5 minutes. Figure 4b shows the electrical conductivity according to Equation /1/.

![Figure 4: Effect of temperature and electric field on electrical conductivity of PE, above measured (a) and below approximated (b)](image)

The values \( \alpha \) and \( \beta \), shown in the Table, are measured and calculated with the best approximation to Equation /1/. As seen in the Table the values \( \alpha \) and \( \beta \) are quite similar to those given in the literature [10, 11].

<table>
<thead>
<tr>
<th>coefficient</th>
<th>( \alpha [1/\text{K}] )</th>
<th>( \beta [\text{mm/kV}] )</th>
</tr>
</thead>
<tbody>
<tr>
<td>PE as measured</td>
<td>0,094</td>
<td>0,121</td>
</tr>
<tr>
<td>Thermoplastic [10]</td>
<td>0.040-0.115</td>
<td>0.034-0.128</td>
</tr>
<tr>
<td>PE [11]</td>
<td>0.050-0.01</td>
<td>0,15</td>
</tr>
</tbody>
</table>

\textbf{Table: Measured and given conductivity coefficients}

For a constant electrical conductivity \( \kappa \), the electrical field strength in the cable \( E(r) \) is given as follows:

\[ E(r) = \frac{U}{r \ln \frac{r_{i}}{r_{a}}} \] /2/

Whereas \( r \) is the radius of the cable and \( r_{i} \) and \( r_{a} \) is the inner and the outer radius of the cable, respectively. As both the electrical and thermal conductivity vary with temperature the temperature distribution in the insulation has to be known.

The temperature distribution in the PE-insulation of the cable at 90 \( ^\circ\text{C} \) conductor temperature and 20 \( ^\circ\text{C} \) ambient temperature has been calculated for both with and without thermal insulation. For the calculation, the insulation is segmented into thin hollow cylinder elements whereby the electrical and thermal conductivity is assumed to be constant in each element. Then, the temperature difference across the PE-insulation is given as follows:

\[ \Delta \vartheta = \frac{P_{V} \cdot R_{th}}{2\pi} = \frac{P_{V} \cdot r}{2\pi} \sum_{j=1}^{n} \left( \frac{1}{\beta_{j}} \ln \frac{r_{j+1}}{r_{j}} \right) \] /3/

\(-\text{with} \ r_{1}=r_{i} \text{ and } r_{n+1}=r_{a}\)

Whereas \( P_{V} \) is the dissipated power per unit cable length and \( R_{th} \) is the radial thermal resistance of the PE insulation per unit cable length. The electrical field in the elements is given as follows:

\[ E_{j}(r) = \frac{U}{r \cdot \kappa_{j} \sum_{j=1}^{n} \left( \frac{1}{\beta_{j}} \ln \frac{r_{j+1}}{r_{j}} \right)} \] /4/

Whereas \( \kappa_{j} \) is the electrical resistance of one element and \( n \) is the number of elements.

As the coefficients \( \alpha \) and \( \beta \) (Figure 4) can be assumed to be valid up to an electric field strength of 100 \( \text{kV/mm} \) [3, 7] they can be used to calculate the field distribution in the cable. The current flow under dc voltage had been calculated for different temperature differences and is plotted in Figure 5 for the dimensions of the cable. The electrostatic field at ac is additionally shown in Figure 5.

![Figure 5: Field distribution in the cable at different temperature differences \( \Delta \vartheta \)](image)

Compared to the field distribution without temperature differences a field inversion emerges with \( \Delta \vartheta = 12 \, K \). With increasing temperature gradient the point of maximum electric field changes from the inner semiconductive layer \( (r_{i}) \) to the outer semiconductive layer \( (r_{a}) \). The maximum electric field with \( \Delta \vartheta = 12 \, K \) is higher than with \( \Delta \vartheta = 2 \, K \) (Figure 5). Both facts, the higher maximum value of the electric field and the place of the maximum
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electric field lead to a decrease of the breakdown voltage (Figure 3).

With respect to different working conditions the degree of field uniformity of the cable was calculated for a wider range of temperature differences (Figure 6).

Fig. 6: Effect of temperature difference on the degree of field uniformity in the cable

The field distribution in the cable is almost uniform when the cable insulation has the same temperature. With higher temperature differences the electric field becomes more uniform up to $\Delta \vartheta = 3$ K where the degree of field uniformity in the cable is $\eta = 1$. At a temperature difference of more than 3 K the field distribution in the cable becomes less uniform with increasing temperature gradient. At $\Delta \vartheta = 3$ K the point of the highest electric field inverses and changes to the outer semiconductive layer.

This calculation shows that the temperature difference across the insulation has a strong effect on the field distribution. So it can be concluded that testing of the cables should consider this effect.

4 Conclusion

Measurements of the electric strength of polyethylene (PE) in a needle-plate and in a sphere-sphere arrangement, measurements of electrical conductivity of PE, as well as breakdown voltage tests of a PE insulated cable were carried out and lead to the following conclusions:

1. The electrical strength under dc voltage is higher than under lightning impulse voltage. This effect is stronger for the needle-plate arrangement than for the sphere-sphere arrangement.
2. With increasing temperature the breakdown voltage decreases for both the sphere-sphere arrangement and the cable. The reduction of the dc breakdown voltage at higher temperature is stronger than under lightning impulse voltage. With increasing temperature the reduction of the breakdown voltage of the cable is stronger than of the sphere-sphere arrangement.
3. For cables with extruded insulation both the temperature of the insulation and the temperature difference across the insulation have a significant influence on the breakdown voltage. At higher temperature differences a field inversion occurs in the cable which can lead to a reduced breakdown voltage.

5 References