Abstract: In order to cope with extremely-high direct voltage large screening electrodes are necessary. Aim is an optimal dimensioning of such electrodes. Experimental investigations on the discharge behaviour at high direct voltage have been carried out on different sphere-plane- and toroid-plane-arrangements. The results have been compared with experiments at alternating and switching voltage. The streamer inception voltage has been calculated for these investigated arrangements. Only a minor deviation was found between the calculated values and the measured breakdown voltage in weakly non-uniform electrical fields as well as the inception voltage in extremely non-uniform electrical fields.

The high voltage supply conductor between the test equipment and the test object has a great influence on the discharge behaviour at DC. If a thin wire was used instead of a PD-free flexible tube at DC – in opposite to AC or SI – significant larger inception voltages on the electrode were measured. The “parasitic” discharges on the wire generate space charges, which weak the electrical field next to the electrode. The inception voltage at disturbances on the screening electrode will be increased too. This effect must be taken into consideration if DC equipment will be tested.

1 INTRODUCTION

The trend in the last years is to transmit the electrical energy with high rated direct voltage (DC) up to 800 kV [1]. In order to cope with extremely-high direct voltage up to 800 kV screening electrodes are necessary with large radii of curvature R in the range of meters. Aim is an optimal dimensioning of screening electrodes for the HVDC equipment, to avoid undesired discharges at the rated voltage and to prevent breakdowns or flashovers at overvoltages with pass reliability. That causes the need of investigations on the discharge behaviour on large screening electrodes at high direct voltage.

Experimental investigations have been carried out on different sphere-plane-arrangements and a double-toroid-plane-arrangement without and with imperfection. Imperfections on screening electrodes can strongly influence the discharge behaviour of the electrode arrangements. They can be caused by a bad design or generated during transport and assembly of screening electrodes. In type tests and on site tests such imperfections on the screening electrodes should be found.

The electric field and streamer inception voltage were calculated for these investigated arrangements. The field-calculation-method is based on the charge simulation-method and applies the streamer criterion for the determination of the streamer inception voltage. The discharge behaviour at direct voltage has been compared to these calculations and to the discharge behaviour at alternating and switching voltage.

The standard for high voltage testing [2] gives no instruction for the connection between the high voltage equipment and the test sample. A possible influence of the kind of connection on the inception voltage by stress at direct voltage was tested by using the sphere – plane – arrangements with two kinds of supply connections – a thin wire and a flexible tube connection (Figure 1).

2 TEST SETUP AND PROCEDURE

The investigations were carried out in a high voltage laboratory with the size: 45 x 21 x 18 m. Different spheres (D = 20…500 mm) and a toroid (D_R = 250mm, D_T = 1500 mm) were tested. A metal plane (4 m x 4 m) was used as ground plane. The spheres and the toroid without and with imperfections were fixed at a 2 m long tube with 100 mm diameter and suspended on a composite insulator (Figures 1 and 2). A distance around the test sample of at least some times the largest gap separation under investigation was kept free from any grounded or non-grounded objects, in order to minimize any parasitic influences on the inception and breakdown voltage. The investigations were carried out at positive and negative direct voltage, at positive and negative switching impulse voltage, at positive and negative switching impulse voltage and at alternating voltage.

A three-stage Greinacher generator rated at 900 kV was used for generating DC voltage and a two-stage transformer rated at 1200 kV for generating AC voltage. A twelve-stage impulse
generator rated at 2.4 MV was used for generating the test impulses, whose time-to-crest was 250 µs. The test impulse was measured using a capacitive voltage divider and a measuring system.

The inception and breakdown voltage at DC and AC were determined in the voltage rising test. During the voltage rise the test sample was observed by a CoronaScope to determine the partial discharge. Partial discharge can be determined in daylight with Coronascope [5].

The contour of integration is the field line that starts on the surface of electrode \( x = 0 \). It will be integrated to the critical length \( x_c \), where the field strength \( E \) achieves the intrinsic strength of air that means the effective ionisation coefficient \( \alpha \) becomes zero. The streamer inception voltage and \( x_c \) can be determined by iteration procedures.

4 INFLUENCE OF VOLTAGE SUPPLY

4.1 PD free connection

To verify the calculation method with the streamer criterion at direct voltage investigations on sphere-plane-arrangements were carried out. At first spheres with small diameters were selected to study the discharge behaviour at large electrode gaps, although the limit of direct voltage was 900 kV.

Besides investigations at positive and negative direct voltage the discharge behaviour was investigated at alternating voltage too, in order to determine differences. The empirical distribution function of the inception voltage was evaluated and approximated through a normal distribution. The measured inception voltage of these arrangements showed a small standard deviation. Therefore the number of tests per gap was fixed of 30. The measured values were compared direct with the calculated values of inception voltage.

First the discharge behaviour at direct voltage was investigated on a discharge free test arrangement. The connection between the test equipment and test sample was realised with a flexible tube. Parasitic discharges at the electrodes can be excluded because of the visual observation of the test objects during the voltage rise.

The contour of integration is the field line that starts on the surface of electrode \( x = 0 \). It will be integrated to the critical length \( x_c \), where the field strength \( E \) achieves the intrinsic strength of air that means the effective ionisation coefficient \( \alpha \) becomes zero. The streamer inception voltage and \( x_c \) can be determined by iteration procedures.

3 CALCULATION OF THE STREAMER INCEPTION VOLTAGE

As experimental investigations are time-consuming, it was tried to calculate the field distribution and the streamer inception voltage. The field distribution is calculated with the charge-simulation-method. For the estimation of streamer inception voltage the maximum field intensity on the surface of screening electrode and the field distribution near the electrodes are required. The streamer inception voltage is the voltage, at which the field strength is so high, that following equation is achieved direct.

\[
\int_{x=0}^{x=x_c} \alpha(E(x)) \, dx = \ln 10^8
\]  

Figure 3: measured and calculated inception voltage \( U_s \) of two sphere–plane-arrangements at direct voltage with flexible tube as supply conductor
The measured inception voltage at positive and negative direct voltage correlated well. That means there is no influence of the polarity on the inception voltage (Figure 3). The measured inception voltage has a minimal greater increase than the calculated inception voltage for electrode gaps up to 6 m. Due to the fact that the measured values are slightly higher than the calculated values, it is allowed to use the estimation of the inception voltage with the streamer criterion to dimension screening electrodes.

4.2 Wire connection

The standard IEC 60060 gives no regulations concerning the connection between the high voltage equipment and the test sample. It is known that wire electrodes can withstand high voltages at AC. Therefore a wire connection is often used as supply connection between test sample and test equipment [3].

At this thin wire an intensive glow discharge – sometime named ultracorona - is generated which causes a stabilised space discharge near the wire. The space charge changes the field distribution near the wire that the process of discharges is not stopped. Hence a balance between generated and migrated particles is generated. Beside the avalanche can not achieve its critical amplification to initiate a streamer. Only if the voltage is significantly raised the space charge is not able to stop the generation of a steamer discharge [3].

To find out whether there is an influence of the supply connection between the sphere-plane-arrangement and the test setup on streamer inception voltage investigations were carried out with wire connection at DC and AC. For different diameters of spheres the inception voltage at alternating voltage (Figure 4) and direct voltage (Figure 5) was determined.

The investigations at alternating voltage show a good correlation between measured and calculated inception voltage for spheres with diameter $d \leq 50$ mm and electrodes gaps up to 6 m (Figure 4). For small electrodes and moderate electrode gaps a good correlation between calculated and measured (10 %-quantile) voltage was determined in dissertation Digmayer [4] too.

The investigations at positive and negative direct voltage show that the measured and calculated values of inception voltage correlate well only for electrode gaps up to 0.5 m (Figure 5). At large electrode gaps the measured inception voltage is clearly higher than the calculated one. It was determined again no influence of polarity at direct voltage on inception voltage (Figure 5). The relation between measured and calculated inception voltage is approximately the same for all test arrangements and both polarities of direct voltage.

The reason for the clearly higher inception voltage at the sphere electrode is the space charge generated by ultra corona at the wire. With rising voltage the space charges growth to the earth electrode. Thereby the electrical field near the test electrode will be minimized although the distance between wire and electrode are more then 2 m. The steamer ignition can be generated first at clearly higher voltages than the calculated inception voltage. This influence of space charges can’t be considered in the calculation of inception voltage with streamer criterion (Equation (1)) at the moment. This effect had to be taken into consideration at high voltage test. Otherwise to high levels for the streamer inception will be determined.
5 SPHERE – PLANE – ARRANGEMENTS WITH IMPERFECTION

To understand the influence of imperfection at the screening electrode on the discharge behaviour at DC, investigations were carried out up to gap distances of 6 m. For the investigations sphere electrodes with small diameter (≤ 250 mm) were used. As imperfection spheres with diameter of 2.5 mm and 6 mm as well as a needle with a length of 6 mm, a diameter of 1 mm and a tip angle of 30° were used (Figure 3). The imperfection was placed on the electrode in the area of the highest electrical field. The streamer inception voltage at the imperfection was calculated too. The measured values were compared with these values as well as with the measured and calculated inception voltage of the same test sample without imperfection. The influence of an imperfection at the electrode on the discharge behaviour dependent on electrode gap should be explained at the example sphere electrode with diameter of 100 mm (Figure 6).

The relation between measured and calculated inception voltage (regarding to imperfections) of the test samples with wire connection was calculated too. The relation with as well as without imperfections is for all test arrangements and both polarities of direct voltage approximately the same. The relation increases linear from 1 at an electrode gap of 0.5 m up to 2 till 3 at 6 m distances (Figure 7).

6 TOROID – PLANE – ARRANGEMENTS WITH IMPERFECTION

The investigations were carried out with a spherical imperfection with a diameter of 6 mm at the toroid (Figure 2). The inception voltage was measured at positive and negative DC, at AC and at positive and negative SI. The experiments were carried out in voltage rising tests in order to determine the distribution function of inception voltage. The achieved results were compared with the calculated inception voltages.

For the test arrangements with imperfections the relation between 50-%-measured and calculated inception voltage scatter a lot more. It can be assumed that the wide scatter are caused by the low probability of existence of the start electrons in the small volume with highest electrical field in front of the imperfection and the observation method of discharge ignition on the imperfection.

The space charges generated on the wire connection influence the discharge behaviour at longer distances (d > 0.5 m) again. The imperfection was not completely screened by the space charges. The discharge always ignites on the imperfection but at significant higher values. Sometimes higher values than the calculated values for undisturbed electrodes were reached. Using a wire connection at type tests some imperfections may not be found.
At the spherical imperfection with diameter of 6 mm the measured inception voltage correlated well with the calculated streamer inception voltage up to an electrode gap of 0.5 m (Figure 8). For larger gaps the measured inception voltages rise stronger than the calculated one. The relation between the measured and the calculated inception voltage was in the same range like for the sphere-plane-arrangements with and without imperfection (Figure 7). The difference is caused again by the influence of space charges which are generated on the wire connection.

Also at negative polarity the streamer always starts at the imperfections. In all cases a stable streamer exists before the breakdown, because of the higher voltage demand of the negative streamer. The distribution of the inception voltage could be described with normal distribution again. The inception voltage at negative polarity is approximately the same as at positive polarity (Figure 8). There is no influence of polarity.

At negative DC a second kind of discharges were observed - glow discharges at dust particles near the electrode. These discharges occur at the whole electrode independent of imperfections. The inception voltages of these discharges are significantly lower than the streamer inception voltage of the imperfection (Figure 8). For gap distances greater 2 m the inception voltage is nearly constant because the change of the field strength is very low. These discharges do not convert to streamers.

An influence of dust particles on the discharge behaviour was not observed. The spherical imperfection on the toroid strongly decreases the inception voltage (Figure 9). The measured values for the undisturbed arrangement coincide very good with the calculated ones. With imperfections they are slightly greater. This can be explained by a statistical effect. Because the volume in which the discharge had to start is very small the probability of a starting electron is low.

The same arrangement was investigated at alternating voltage for electrode gaps from 1 m to 5.5 m. At all investigated electrode gaps long streamer discharges start at the imperfection. An influence of dust particles on the discharge behaviour was not observed. The spherical imperfection on the toroid strongly decreases the inception voltage (Figure 9). The measured values for the undisturbed arrangement coincide very good with the calculated ones. With imperfections they are slightly greater. This can be explained by a statistical effect. Because the volume in which the discharge had to start is very small the probability of a starting electron is low.

![Figure 8: measured and calculated inception voltage on a toroid-plane-arrangement with spherical imperfection (d = 6 mm) at positive and negative direct voltage compared to calculated streamer inception voltage](image1)

![Figure 9: inception voltage on the toroid-plane-arrangement with and without spherical imperfection (d = 6 mm) at alternating current compared to calculated streamer inception voltage](image2)

In Figure 8 the measured and calculated inception voltages at positive and negative switching impulse voltages for electrode gaps from 1 m up to 5.5 m are shown in Figure 10. Beside the 50 %-inception voltage as well as the range from 1 % to 99 % for the electrode with and without imperfection are shown.

![Figure 10: comparison of inception voltage between double toroid-plane-arrangement with and without spherical imperfection (d = 6 mm) at switching impulse voltage compared to calculated streamer inception voltage](image3)
At negative polarity a small scatter of the inception voltage was observed. The inception voltages agree with the values at AC and are slightly greater for the disturbed arrangement then the calculated one. At positive polarity of SI the values of inception voltage scatter a lot compared to negative polarity of SI for both test arrangements with and without imperfection.

This large scatter of the inception voltage is typically for positive polarity of switching impulse voltage because the first electron avalanche starts in the room in front of the electrode and not direct at the surface of the electrode like at negative polarity. The probability for creating a start electron and reaching the critical amplification of charge carrier is lower compared to negative polarity of switching impulse voltage [6].

7 CONCLUSIONS

1. The inception voltage at direct voltage can be calculated with streamer criterion if the test arrangement and electrode are free of parasitic partial discharges. The investigations show only a small difference between the measured breakdown voltage in weakly non-uniform as well as inception voltage in extremely non-uniform electrical fields and the calculated inception voltage. By using the calculated inception voltage with help of the streamer criterion for dimension the screening electrodes the engineer is on the safety side, because the measured values in the investigations were always slightly higher compared to the calculated one.

2. Parasitic discharges on the supply wire connection between test sample and test arrangement cause for large gaps significant higher measured inception voltages at DC than calculated. The relation between measured and calculated values increase from 1 at gap distance 0.5 m up to 2 till 3 at 6 m. The generated space charges on the wire reduce the electric field and lead to an increase of the inception voltage. This effect may lead to wrong results at high voltage tests.

3. Dust particles strongly influence the inception and breakdown voltage at direct voltage under dry condition. Glow discharges have been observed on the surface of screening electrodes at negative polarity in weakly non-uniform electrical fields. The inception voltage at dust particles is very low.

4. Imperfections on electrodes clearly reduce the streamer inception voltage. The calculated streamer inception voltage under consideration of imperfections correlated well with the measured inception voltages. The danger of imperfections can be estimated with help of the streamer criterion.

5. With parasitic discharges at the voltage supply the inception voltage at imperfections is increased too. The relation to the expected values is in the same range like undisturbed arrangements but with larger scatter. Sometimes higher values then the calculated inception voltages of undisturbed electrodes were reached. Through this effect imperfections may not be found at high voltage tests.

8 REFERENCES