High-Voltage Direct Current Corona Testing of Transmission Line Hardware and Insulator Assemblies

Development of Test Methodology

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Technical Update, December 2013

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ABSTRACT

When specifying hardware for new high-voltage direct current (HVDC) lines or replacement hardware for existing HVDC lines utilities generally require that the hardware meet specific corona performance requirements.

While standards and test methods exist for testing hardware used on HVAC systems, no such material is available for HVDC systems.

HVAC tests are sometimes conducted on the hardware and the results obtained are then related to HVDC by utilizing the peak HVAC line to ground voltage as the equivalent HVDC voltage. This practice is not optimal as the phenomena of dc and ac corona are, physically quite different due to the effects of space charge and ion cloud formation.

There is a need to develop specific guidelines for HVDC Hardware corona testing. For 2013, the focus of this work was the identification of the issues affecting HVDC hardware corona testing and the development of testing guidelines.

Keywords
Field effects
Hardware corona
HVDC
HVDC testing
Space charge

CONTENTS

LIST OF FIGURES

LIST OF TABLES

1 BACKGROUND

When specifying hardware for new high-voltage direct current (HVDC) lines or replacement hardware for existing HVDC lines, utilities generally require that the hardware meet specific corona performance requirements.

While standards and test methods exist for testing hardware used on high-voltage alternating current (HVAC) systems, no such material is available for HVDC systems.

HVAC tests are sometimes conducted on the hardware, and the results obtained are then related to HVDC by using the peak HVAC line-to-ground voltage as the equivalent HVDC voltage. This practice is not optimal, however, because the phenomena of dc and ac corona are physically quite different due to the effects of space charge and ion cloud formation.

Utilities and hardware manufacturers require guidance and best practices for HVDC hardware testing to ensure that they obtain accurate performance data from their tests. These guidelines to be developed under this contract are to be verified and further refined through corona testing.

The development of the hardware corona testing guideline will start with the identification of issues specific to HVDC. Once these issues have been identified, the guidelines will be developed based on the available literature.

Once the initial guidelines have been developed, full-scale testing will be carried out to verify these guidelines. Based on the testing results, these guidelines will be refined and updated.

For 2013, the focus of this work was the identification of the issues affecting HVDC hardware corona testing and the development of testing guidelines.

2
INTRODUCTION

Electrical power is generated as an alternating current (ac). It is also transmitted and distributed as ac and, apart from certain traction and industrial drives and processes, it is consumed as ac. However, in a growing number of circumstances, it is becoming economically feasible and technologically advantageous to introduce HVDC links into the bulk electrical supply system.

HVDC transmission applications fall into four broad categories, and any scheme usually involves a combination of two or more of these:

- Transmission of bulk power where ac would be uneconomical, impractical, or subject to environmental restrictions
- Interconnection between systems that operate at different frequencies or between non-synchronized or isolated systems that, although they have the same nominal frequency, cannot be reliably synchronized
- Addition of power in feed without significantly increasing the short-circuit level of the receiving ac system
- Improvement of ac system performance by the fast and accurate control of HVDC power

Historically, HVDC schemes have been expensive due to the cost of the terminal equipment. Today, with continuing development of power electronics, the terminal equipment is becoming less expensive and more reliable. For this reason, HVDC transmission is seeing a resurgence in its traditional long-distance applications and is also being implemented for shorter lines operating at lower voltages. Because of its historically limited applications, international standards that are clearly defined for HVAC transmission systems are absent for HVDC. Specifically, while standards and test methods exist for testing the corona and radio noise performance of hardware used on HVAC systems, no such material is available for HVDC applications.

For HVAC transmission systems, utilities generally require that line and station hardware meets specific corona performance requirements. With the growing use of HVDC, utilities require the development of standard methods for assessing corona performance in HVDC applications. Over the past few years, manufacturers, test engineers, and utilities have expressed a need for the development of standard practices that can be used for this.

In some situations, HVAC tests are being conducted on hardware intended for HVDC use, and the results obtained are related to HVDC performance by using the peak HVAC line-to-ground voltage as the equivalent HVDC voltage. However, this practice is not optimal because the phenomena of dc and ac corona are physically quite different due to the effects of space charge and ion cloud formation present on HDVC systems.

It is clear that utilities and hardware manufacturers require guidance and the development of best practices for HVDC hardware testing to ensure that they obtain accurate performance data from their tests. This report is intended to lay the groundwork for the development of an HVDC hardware corona testing guideline. It is expected that a follow-on project comprising experimental testing based on the information contained in this report will be carried out in 2014. The ultimate goal of the two projects is to develop a guideline for performing HVDC corona testing for line and station hardware used in HVDC applications.

Scope

This document presents a discussion of the background and potential methodologies that will be used as a basis for the development of laboratory corona and radio noise test procedures for hardware used on HVDC lines and stations.

Purpose

Corona discharges present on line and station hardware cause radio interference, damage to insulating material (polymer insulators), and unnecessary power losses. To ensure that corona discharges do not occur on HVDC systems over their in-service life, a test procedure that in essence mirrors the available standard test procedures for HVAC needs to be developed. The HVDC procedure must, however, take into account the different electrical effects present in HVDC systems. This document identifies differences between HVAC and HVDC that are potentially important in the development of HVDC corona test procedures and suggests test methodologies for the performance of HVDC tests.

Definitions

Connector: Device for joining one or more conductors or earth wires. It may be a tension or non-tension fitting.

Corona discharge: Electric discharge that partially breaks down gaseous insulation.

Corona extinction: Voltage or conductor voltage gradient at which corona discharges cease to occur during a decreasing test voltage sequence.

Corona inception: Voltage or conductor voltage gradient at which corona discharges initiate during an increasing test voltage sequence.

Specified minimum corona extinction: The minimum corona extinction voltage or conductor voltage gradient specified by the purchaser or declared by the supplier.

High-Voltage Transmission Line Hardware

The transmission line hardware referred to in this report comprises splices, spacers, dampers, and insulator assemblies.

3
CORONA EFFECTS

Corona is a luminous discharge in the air surrounding a conductor caused by an electric field (E) exceeding a certain critical value. Electrical breakdown is the abrupt transition of the gap resistance from a practically infinite value to a relatively low value [1]. Corona and breakdown are part of the same electrical response of air when its dielectric properties have been exceeded.

In ac systems, the visual appearance of corona depends on the polarity of the voltage applied to the electrode under study. Under the positive half-cycle, corona appears in the form of a uniform bluish-white sheath over the entire surface of the wire (see Figure 3-1). Under the negative half-cycle, corona appears as bluish-reddish glowing spots distributed along the wire. The number of spots increases with the corona current. Because of the different properties of corona under different voltage polarity, the following discussion treats positive and negative corona separately.

Figure 3-1
Visual appearance of corona on positive (left) and negative (right) wires at ±70 kV [2]

Under dc voltages, stroboscopic studies show that dc corona on the positive pole has the same visual appearance as the ac corona on the positive half-cycle of the wave. Generally, dc corona starts at a value corresponding to the maximum (peak value) of the ac wave [3]. However, this is not always the case as shown in Reference [4]. The physics of positive and negative coronas are noticeably different. This asymmetry is the result of the great mass difference between electrons and positively charged ions. At very small spacing, the breakdown characteristics for the two polarities nearly coincide, and no corona-stabilized region is observed. However, in ac for large gaps, negative corona occurs at lower voltages than positive corona [4] while under corona of both polarities initiates at approximately the same voltage [5].

Positive Corona

Positive corona starts with an electron drifting from a zone near the conductor surface S_0 and develops as an avalanche toward the anode (+ electrode) in the direction of increasing field (Figure 3-2). Because the highest electric field is found close to the anode, the greatest ionization activity is found there. Due to the large mass difference between ions and electrons, positive ions are left behind along the path of the developing electron avalanche.

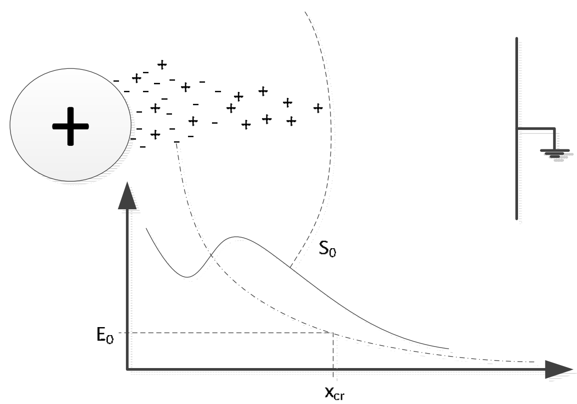


Figure 3-2
Positive corona: undisturbed original electric field (dash-dot line -•-); modified electric field due to space charge (continuous line –) [6]

In positive corona, the effect of negative ions is much lower than that of the other charged species at the anode region because negative ions are formed mainly in the lower field region far away from the positive electrode. Some negative oxygen ions (O_2-) are created far from the anode. Fast incoming electrons flowing through the anode cannot be readily absorbed by the electrode; as a result, free electrons tend to spread over the anode surface—enhancing subsequent discharges over the anode surface.

The positive ions left behind create a local electric field that attracts secondary electrons. Secondary electrons are assumed to be created as a result of photoionization and are responsible for the propagation of the discharge. If voltage is further increased, streamers develop and extend into the low field region beyond S_0. Positive ion space charge, while it travels toward the cathode, attracts secondary electrons that neutralize the primary space charge and in turn generate further positive ion space charge, letting ions travel to the cathode region.

Space charge formation modifies the local electric field as shown in Figure 3-2. The initial electric field (excluding the effect of space charge) is shown as the dash-dot line, and the modified electric field due to space charge is shown as the solid line. As can be seen from the figure, the effect of space charge for positive corona is a net reduction in the electric field in the region of the anode and a net increase in the electric field far from the anode.

As the voltage applied to a gap is increased, the electric field at the anode is increased. This leads to a significant increase in the concentration of ions and electrons, which in turn greatly affects the local field distribution. As the voltage applied to a gap is increased, four different modes of corona are generated:

- **Burst corona (BC)**. This discharge process is generated at the anode surface with high energetic electrons generating positive ions and being absorbed by the anode. Burst corona results in small, positive pulse currents corresponding to the spread of electrons in the small area on the anode and its suppression by the positive space charge created. It is the first mode of positive corona to appear as the voltage is increased.
- **Onset streamer (OS)**. This mode corresponds to a radial spread of the discharge caused by the positive ions left near the region S_0. They create a high electric field region, which attracts subsequent electrons—forming a streamer channel. The onset streamer current is of pulsating nature and of higher amplitude than that produced due to burst corona. Onset streamers appear as the voltage is raised past the point of burst corona.
- **Positive glow (PG)**. Positive glow is a luminous discharge of a spherical shape close to the anode surface. Its current nature is a dc superimposed on a high repetition rate current in the 102 kHz range. Positive glow occurs as the voltage is increased beyond the onset streamer stage.
- **Breakdown streamer (BS)**. On increasing the voltage still further, new and more vigorous streamers appear. The streamers ultimately lead to complete breakdown of the gap. These are termed *breakdown streamers*.

Figure 3-3 shows the various stages of positive corona as the electric field is increased for a positive corona discharge in atmospheric air using a point-to-plane gap.

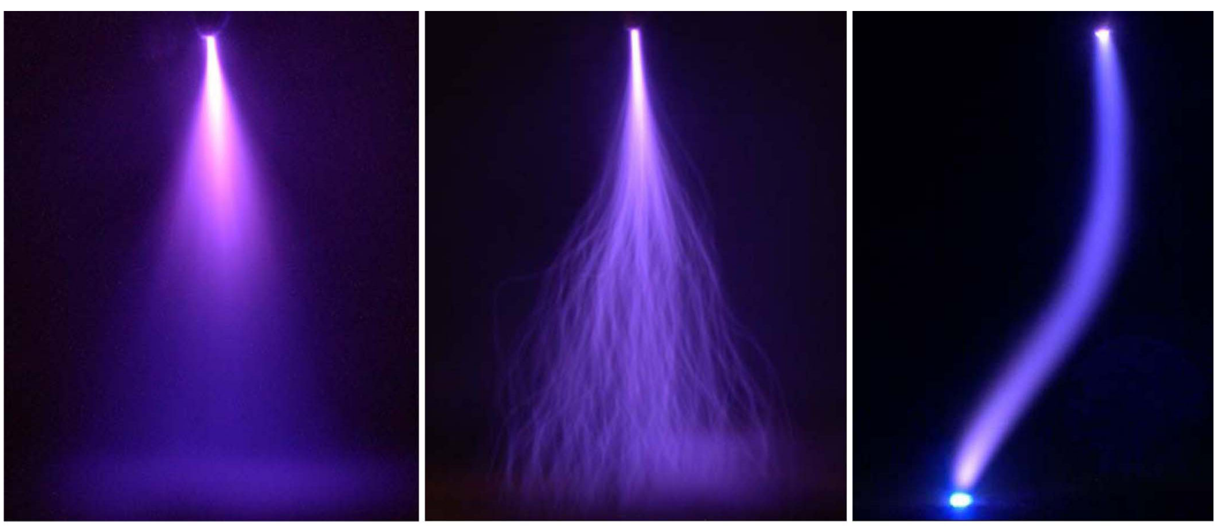


Figure 3-3
Positive dc corona transitions from BC to OS and PG discharge in atmospheric air

Negative Corona

Negative corona occurs when an electrode is subjected to a negative polarity voltage. Electrons are emitted from the cathode (- electrode) and move toward the anode (+ electrode). The electron avalanche stops at region S_0 where the electric field is too low to generate further ionization (Figure 3-4). Since the electrons travel much more quickly than ions due to their great mass difference, they are concentrated at the head of the avalanche—positive ions are left behind, travelling more slowly to the cathode.

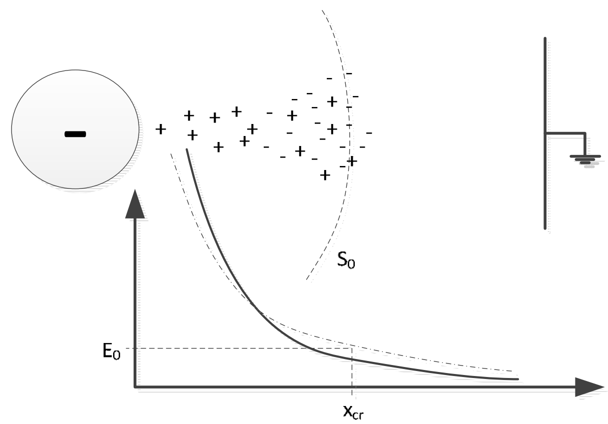


Figure 3-4
Negative corona: undisturbed original electric field (dash-dot line -•-); modified electric field due to space charge (continuous line −) [6]

Once electrons move beyond the ionization region, S_0, they are rapidly attached to oxygen molecules, forming negative oxygen ions (O_2-). Non-attached electrons drift out from the ionization region with insufficient energy to produce further ionization, leaving behind two space charge regions formed by positive ions close to the cathode and negative ions at region S_0.

Figure 3-4 shows the initial electric field that originates the negative corona process as a dash-dot line and the modified electric field due to space charge as a continuous line. As can be seen in the case of negative corona, the effect of space charge is to enhance the field in the cathode region and reduce the field away from the cathode toward the anode.

In this case, the electron avalanche initiates at a higher electric field but extends a smaller distance. The physics of this process create three different corona modes with different characteristics as the voltage is increased. These are named with increasing electric field intensity as follows:

- **Trichel streamers (TS)**. Regular pulsating pattern in which streamers are initiated and suppressed with a short dead time until next cycle is repeated. The duration of a single pulse is on the order of 100 ns, and the dead time varies from 10 μs to 10 ms.
- **Negative glow (NG)**. The main characteristic of this mode is its absence of pulses. It is characterized by a dark region followed by a glow region, a Faraday dark space, and a conical shaped column.
- **Negative streamers (NS)**. The natural evolution of the negative glow if the electric field is further increased. The conical shape is extended, forming streamers extending farther to the gap, and pulses are generated again.

Figure 3-5 shows the transition of the negative corona mode to spark. On the left side, the Trichel pulses can be observed. Then, in the middle image, the glow is formed. Finally, because the air gap is too small, spark occurs without showing the negative streamer's formation.

Figure 3-5
Negative dc corona transitions from TS to NG to NS in atmospheric air

Parameters Affecting Corona

It is well known that corona is affected by several parameters that lead to different voltage onsets and even breakdown in unexpected situations. These parameters can be grouped as atmospheric or electrical and are summarized in the following section.

Atmospheric Parameters

Several parameters related to atmospheric air conditions, such as temperature, pressure, humidity, ionizations, and wind, have an effect on corona:

- **Altitude**. Altitude has a significant effect on corona inception due to the lower air density present at higher altitudes. Corona onset voltage can decrease significantly as the altitude is increased.
- **Temperature and pressure**. Temperature and pressure have a significant effect on the corona onset field. It is well known that relative air density (δ) changes with pressure and temperature. Thus, electric field equations related to corona starting conditions are expressed as a function of relative air density [3]. It is well known that a temperature rise results in an increase of the velocity and frequency of the collisions. These effects lower the corona onset [7].
- **Humidity**. It is known that changes in absolute humidity affect corona onset. Research done in a corona cage for ultra-high voltage (UHV) dc transmission lines showed that the onset voltage gradient increases on positive wire as humidity increases [8].
- **Ionization degree**. Changes in initial air ionization have no appreciable effect on the corona onset field if the ionization degree is low. Initial ionization, regardless of the ionization degree, affects the discharge time [3]. Thus, a high initial ionization level produces a fast discharge. However, saline solutions in wetted insulators placed in coastal areas showed decreases up to 20% for short rod air gap [9].
- **Wind**. It has been demonstrated that wind removes electron and ion concentration, so ionization mechanism has to start again. Thus, wind tends to decrease corona formation [10].

Electrical Parameters

Unlike atmospheric conditions, which do not depend on human intervention, electrical and geometrical parameters are related to the design process and usually have a great influence on corona performance. The following are the main electrical and geometrical parameters:

- **Electrical current**. Circulating current can generate a magnetic field in the surroundings of the electrode that accelerates the charged particles existing near the electrodes, thus having an effect on corona. External crossed magnetic fields affect corona as reported by Reference [11].
- **Frequency**. Below 1 kHz, the influence of frequency on onset corona field, if any, is small—as observed in testing transformers. Therefore, it cannot be detected by an oscilloscope [3].
- **Electrode geometry**. For a given voltage, increasing the electrode radius decreases the electric field and can be used as a way to avoid corona formation. Conversely, reducing the electrode radius enhances the electric field and corona onset voltage [3].
- **Electrode surface**. For a given applied voltage between electrodes, dirt on the surface of the conductor increases the visual corona effect due to increased surface roughness, which causes local brush discharges as reported by Reference [3].
- **Electrode material**. Electrode material is considered part of the secondary ionization process in corona effect. *Materials work function* refers to the energy needed to extract an electron. Thus, materials with higher work function value would lower the secondary ionization process.

The atmospheric and electrical parameters discussed above and their effects on corona onset are summarized in Table 3-1.

Table 3-1
Parameters influencing corona inception

Corona Parameters		Corona Onset
Altitude	↑	↓
Pressure	↑	↑
Temperature	↑	↓
Absolute humidity	↑	↑
Wind	↑	↑
Current	↑	↓
Electrode surface cleanliness	↑	↑
Electrode surface smoothness	↑	↑
Electrode material (work function)	↑	↑

4
ELECTRIC FIELD CALCULATIONS

In the previous section, it was shown that corona can be affected by several parameters. However, in indoor corona testing, most of these parameters are maintained constant throughout the test. The major focus is on producing an electric field around the test object that is representative of the field present during in-service operation. The electric field can be either measured or calculated. Calculation of the electric field is based on electrostatic modeling.

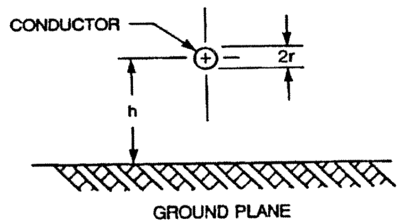
Electrostatics

Electrostatics is used for modeling corona and radio interference voltage (RIV) tests for hardware because currents present in corona tests are generally very small in magnitude (10^{-3} A). Given these low current values, the magnetic fields present can be disregarded compared to electric fields caused by high test voltages (10^{4} V). Furthermore, in the absence of corona, quasi-static approximation can be used to analyze the problem.

Analytical Methods Used in International Standards

To perform accurate corona and RIV tests on hardware for HVAC systems, published national and international standards present equations for the calculation of in-service electric fields surrounding transmission line conductors where the hardware has to be installed and/or methods for building setups that simulate in-service operation have to be built. Examples of such standards are the ANSI/NEMA CC1 standard [12] for substation connectors and the IEC 61284 standard [13] for fittings installed in overhead lines.

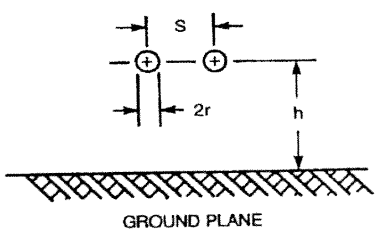
In the case of the ANSI/NEMA standard (Section 3.3.2 of that document), the electric field used during the test is based on calculation. Once the corona extinction voltage of the operating line is stipulated, the electric field on the in-service conductor is calculated. Then, the electric field present on the operating line is used to determine the height above ground and the test voltage at which the object should be tested. Figure 4-1 shows an example of calculation formulas used in the CC1 standard.



$$E_a = \frac{V_1}{r \ln\left[\frac{2h}{r}\right]}$$

$$E_m = \frac{h}{h - r} E_a$$

Figure 3-2
CONDUCTOR VOLTAGE GRADIENT
FOR SINGLE CONDUCTOR



$$r_e = r\left[\gamma \frac{s}{r}\right] \frac{n-1}{n}$$

$$E_a = \frac{V_1}{n\, r \ln\left[\frac{2h}{r_e}\right]}$$

Figure 4-1
ANSI/NEMA CC1 standard; electric field calculation for single and bundle conductor [12]

IEC 61284 uses a different approach that is based on the use of gradient calibration spheres. A *calibration sphere* is a small sphere that is mounted on a clip and can be attached to a conductor. Figure 4-2 shows the design details of the calibration sphere and how it is attached to the conductor under test.

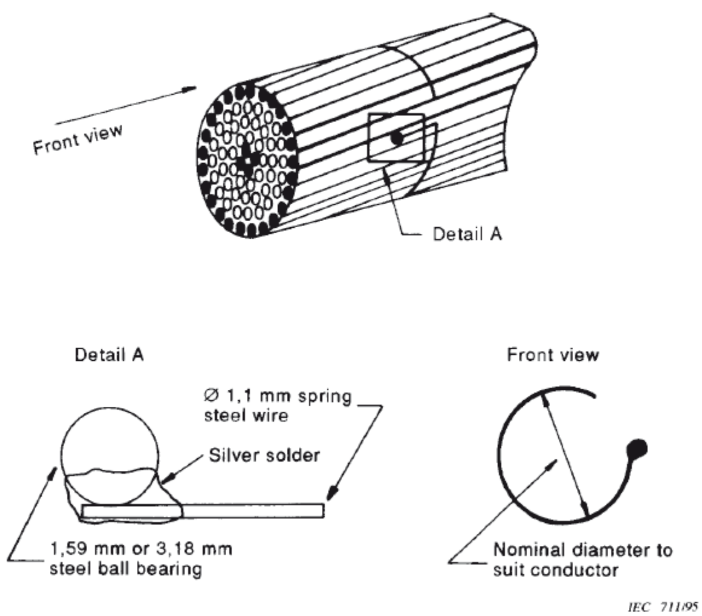


Figure 4-2
IEC 61284 voltage gradient calibrator

The spheres themselves are calibrated on various sizes of conductor to establish the relationship between the electric field gradient at which the particular sphere will go into positive corona and the conductor diameter. The details of the calibration technique for the calibration sphere are given in Appendix A.

When performing the laboratory corona test, the previously calibration sphere is mounted at the center of a length of conductor and is used as a calibration device to relate applied voltage to conductor gradient. After the applied voltage/conductor surface gradient calibration factor is established, the sphere is removed and the hardware under test installed. The applied voltage is then raised to the level required to produce the maximum conductor surface gradient as specified under operating conditions.

While these two standards differ in their approach to obtaining the representative in-service conductor surface field in laboratory tests, both require, as a base, the calculation of in-service operating fields that use equations based on simple geometries that have been solved using classical electric field theory. The procedures given in these and other similar standards have been and are being used in daily tests performed in high-voltage laboratories around the world. However, some questions are introduced when dealing with HVDC transmission systems. While in HVAC transmission systems, voltage changes polarities twice per cycle, in HVDC systems the same polarity is maintained for infinitely long periods. This results in the formation of space charge, which affects the electric field in the vicinity of the conductors (to a degree). The impact of this effect has not been quantified, but it may be of significance in the performance of HVDC corona tests. This concept is discussed in detail in Section 5.

The Finite-Element Method

In recent years, the finite-element method has proven to be a powerful technique to solve partial differential equations over complex domains. It works in limited meshed regions; therefore, fictitious boundaries have to be defined to solve each problem—and different boundary conditions can be settled [14]. Advantages of using finite element model (FEM) simulations include the applicability to both homogeneous and non-homogeneous systems; flexibility and adaptability for dealing with one, two, or three dimensional problems; the possibility of using different element sizes and shapes to adapt to any complex geometry; and the ability to give a numerical result to differential equations that cannot be solved analytically. The main drawbacks of FEM simulations are the limited accuracy, making it necessary to validate the results by means of experimental tests [4], and the requirement for using a large amount of space and elements around the model to solve open boundary problems [15].

A 765 kV ac substation connector model was carefully prepared and simplified to limit its complexity, while trying not to influence its accuracy. The model was used to calculate the electric field on the surface of the conductor; this in turn was used to predict the corona inception voltage. The computational results were compared to results from experimental corona testing on the actual fitting. The correlation between the model output and the test results was very good. The result demonstrates that 3-D FEM of hardware can give accurate results for HVAC applications. Given this, it can be expected that for HVDC tests, the finite-element method will also predict an accurate value for the electric field on the hardware surface with similar correspondence between the modeling and experimental results. However, the incorporation of space charge effects present on operating HVDC systems into the computational models will add significant complexity and is still a challenge that requires study. In essence, with regard to corona testing, the following open questions about HVDC space charge effects remain:

- How significant is the effect of space charge on the electric field surrounding line and station hardware?
- How well do laboratory tests compare with in-service conditions?
  - Do tests inside a closed laboratory give the same results present under in-service conditions?
  - Does a minimum laboratory size need to be specified?

5
SPACE CHARGE EFFECTS

In HVDC fields, as corona generates ions that drift along electric field lines created by high voltages on conductors or hardware, space charges are created that modify the local electric fields. In the past few years, several publications have indicated that modeling that takes into account the presence of space charge in nonuniform geometries is possible [19, 20, 21].

To perform space charge effect calculations, the system of Poisson equation (Equation 5-1) and convection-diffusion equations (Equations 5-2 to 5-4) need to be solved together. The resulting system has special characteristics that have to be dealt with to achieve the most accurate results possible.

The fundamental equations used in space charge calculations are as follows:

$$-\nabla^2 V = \rho_p - \rho_e - \rho_n \qquad \textbf{Eq. 5-1}$$

$$\frac{\partial \rho_e}{\partial t} - \left(\mu_e \vec{E}\right)\nabla \cdot \rho_e - D_e \nabla^2 \rho_e = S_e \qquad \textbf{Eq. 5-2}$$

$$\frac{\partial \rho_p}{\partial t} + \left(\mu_p \vec{E}\right)\nabla \cdot \rho_p - D_p \nabla^2 \rho_p = S_p \qquad \textbf{Eq. 5-3}$$

$$\frac{\partial \rho_n}{\partial t} - \left(\mu_n \vec{E}\right)\nabla \cdot \rho_n - D_n \nabla^2 \rho_n = S_n \qquad \textbf{Eq. 5-4}$$

Where sub-indices e, p, and n are used for electrons, positive ions, and negative ions; μ is the mobility of charged specie in $m^2 \cdot V^{-1} \cdot s^{-1}$; D is the diffusion coefficient in $m^2 \cdot s^{-1}$; E is the electric field; and S is the source term in $C \cdot m^{-3} \cdot s^{-1}$ involving ionization, attachment, and recombination processes.

Space Charge Effects in HVDC Transmission Lines

In HVAC systems, as conductors change polarity every cycle, ions produced by corona tend to stay close to the conductor because they are repelled and attracted as voltage on the conductors alternates between positive and negative polarity.

Conversely, the voltage present on an HVDC system conductor remains constant at one polarity. Thus, when corona occurs on an HVDC electrode of either positive or negative polarity, both positive and negative ions are generated in the vicinity of the electrodes. Ions of opposite polarity to that of the conductor are neutralized on contact with the conductor. Thus, a positive conductor in corona acts as a source of positive ions and vice versa.

For a unipolar positive or negative dc transmission line in corona, ionic space charge having the same polarity as the line fills the space between the line conductor and ground. The ions drift in the electric field created by the voltage applied to the line, while at the same time the ionic space charge modifies the electric field distribution.

In bipolar dc transmission consisting of two conductors of opposite polarity located above ground, when the line goes into corona, both positive and negative ions are generated by the conductors. The ions generated by each conductor drift to either the conductor of opposite polarity or to ground. Thus, three distinct space charge regions exist in the vicinity of a bipolar dc line: two unipolar regions between each conductor and ground and a bipolar region between the two conductors of opposite polarity. While ions of either positive or negative polarity fill the unipolar regions, ions of both polarities mix in the bipolar region, which results in space charge neutralization and ionic recombination (see Figure 5-1).

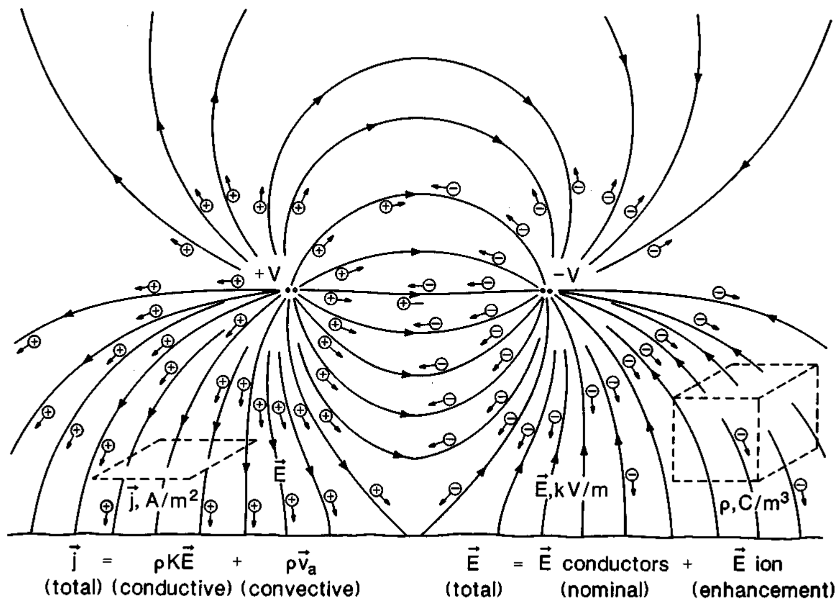


Figure 5-1
Diagram description of air ions and electric field in HVDC transmission line [22]

The regions in which ion flow and electric field interact with one another, as described for HVDC transmission lines, are characterized as ionized fields. Depending on whether ions of only one or both polarities exist, the regions are described in terms of unipolar or bipolar ionized fields.

Studies in HVDC and measurements performed in the 1980s by Bonneville Power Administration give some fundamental insight into the effects of space charges due to HVDC transmission lines. The studies were performed to determine proper parameters to ensure safe dc transmission systems and to protect humans, animals, and the environment. Because of this, most measurements were performed at ground level. Even if measurements of ion distribution next to the conductor had been attempted, the meter would have influenced the electric field distribution and, as a consequence, the ion measurement would not have been representative of the unperturbed fields present under normal operating conditions.

Calculation of Space Charges

Taking into account space charge is computationally far more complex than the case of a purely electrostatic system because Equations 5-1 to 5-4 are coupled. This system of equations can be solved only by making several assumptions. Work is currently underway on using the finite-element method to solve, in a coupled manner, the equations involved in space charge calculation. The main objectives of this are to investigate the characteristics of the space charge present near HVDC conductors and to quantify the significance and importance of the space charge on the electric field on HVDC hardware surfaces when operating under normal in-service conditions. This is certainly an area that requires further study both computationally and experimentally.

Analytical Methods Applied to an HVDC Bipolar Transmission Line

Following on the work presented in Reference [23], the ionic space charge was computationally calculated for the main ion species described earlier in this section. Because the positive conductor acts as a source of positive ions and the negative conductor as a source of negative ions, both species were considered.

Based on several assumptions, the equations were solved and the results are presented in Reference 23. Figure 5-2 shows the calculated and measured values at ground level for the electric field and the ion current density. At the time these data were generated, no measurements were feasible above ground level; even today, there is no specific mechanism for measuring the electric field next to the line without affecting the measured values.

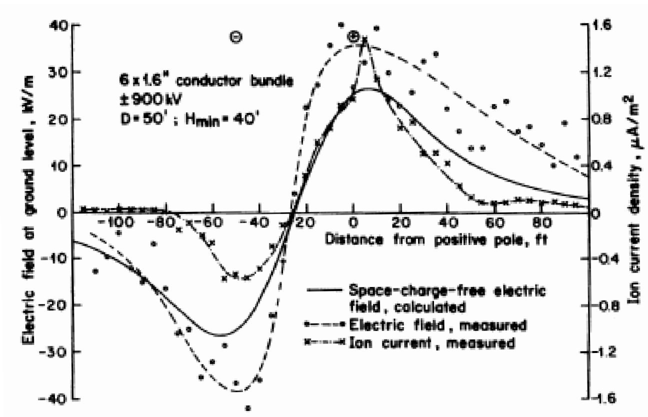


Figure 5-2
Electric field and ion current density for a ±900 kV HVDC transmission line [23]

From the measurements and calculations presented in References [23] and [24], it can be concluded that it is correct to assume that the electric field between the two conductors of the HVDC line is close to zero. Therefore, it can be assumed that the introduction of a virtual ground plane inserted parallel to the conductors—perpendicular to ground and halfway between the two operating poles—would reproduce the same results as those given in Figure 5-2.

Results given in Reference [23] show that calculation of space charge at ground level—taking into account positive and negative ions and neglecting electrons—gives sufficient accuracy when compared to measured data.

However, these calculated and measured results do not quantify how the electric field surrounding the HVDC hardware is influenced by space charge under normal operating conditions. This is an issue that needs to be examined with regard to the performance of laboratory corona testing of HVDC hardware. Because it is still not possible to physically measure the field at the hardware surface, finite-element computational techniques and measurement methods to obtain these data require development.

6
HVDC CORONA TESTING

This section presents a methodology that can be used as a basis for the development of HVDC corona tests.

Historically Reported Corona Tests [5]

The pioneering research on HVDC visual corona and RIV testing on insulators and conductor samples was published in 1971 [21]. Different conductor configurations and insulator strings were studied under dc voltage. The researchers found that the repetition rate of the corona pulses was extremely low at the corona onset level. Up to 5 minutes was required to determine whether a corona pulse existed at a given voltage level. Based on their findings, the authors of the study recommended the use of a 5-minute time interval at each voltage step to minimize the uncertainty in the determination of the visual corona or RIV inception voltage.

If at least one visible corona pulse were detected during the 5-minute period at a given voltage level, this voltage was defined as the *corona inception voltage*. The RIV level was taken as the maximum value recorded during the same period of time. There was substantial voltage difference, roughly 25% between the voltage level as defined above and the voltage level at which the corona phenomenon appears practically permanent—that is, with a pulse repetition rate higher than one pulse per second.

An important conclusion drawn from the research data under dc voltage is that for all conductor configurations studied, the positive corona inception voltage was lower than the negative corona inception voltage. The measured RIV at the positive corona inception voltage was also significantly higher than the measured RIV at the negative corona inception voltage. Similar conclusions can be drawn from the data for insulator strings. These conclusions were supported by a later EPRI study on the corona measured on an experimental ±600 kV bipolar dc line between July 1973 and December 1974 [22]. The bipolar line studied used a quad conductor bundle with 30.5 mm conductor diameter. The pole spacing was 11.2 m, and the average height of the bundle above the ground was 15.2 m. EPRI found that the maximum RIV measured at 0.5 m from the ground was directly under the positive-polarity bundle conductor. This conclusion was further supported by more recent measurements by Chinese researchers on a ±800 kV bipolar line [23]. In that case, the bipolar line used a bundle made of six 33.6 mm conductors. The pole spacing was 22.0 m, and the minimum height of the bundle above ground was 18.0 m. The Chinese researchers also found that the maximum RIV measured at 1.5 m from the ground was directly under the positive-polarity bundle conductor. They also concluded that the main source of RIV is positive corona.

General Test Conditions

Tests are conducted under the ambient atmospheric conditions prevalent at the laboratory during testing. It is recommended that these ambient conditions (temperature, pressure, and absolute humidity) be recorded and included in the test report. Correction factors for atmospheric conditions given in IEC 60060 can be considered for application, but it is important to recognize that these corrections have been formulated for application to disruptive discharge tests rather than for corona testing. Therefore, one area that requires further study is the refinement of the atmospheric correction factors in view of corona testing as opposed to breakdown testing.

As with HVAC corona testing, the test samples and auxiliary equipment should be clean and dry [13].

Test Arrangement

Most common dc overhead systems use bipolar dc lines. The positive and negative pole conductors are usually positioned symmetrically at the transmission towers. With this arrangement, and neglecting the effect of the overhead ground wires, all points on the virtual ground plane shown in Figure 6-1 are at ground potential.

As mentioned earlier, space charges created at each conductor are neutralized at the virtual ground plane as shown by the previously discussed ground-based measurements that indicate negligible electric field at half pole distance (see Figure 5-2).

Figure 6-1 shows the virtual ground plane in a ±800 kV transmission line. The virtual ground plane is perpendicular to ground, parallel to the pole conductors, and located at the mid-point between the positive and negative poles. The virtual ground plane separates the positive and negative poles. Therefore, the positive or negative poles can be tested separately if a vertical ground plane is placed at the location of this virtual ground plane.

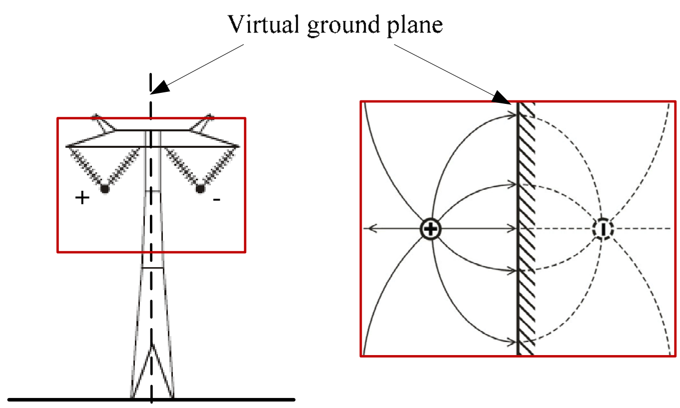
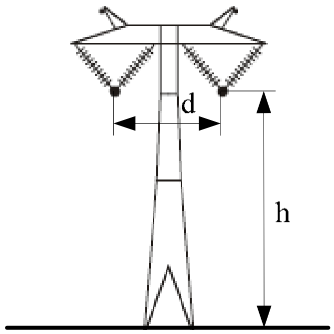


Figure 6-1
Virtual ground plane between bipolar dc transmission lines

Due to the construction details of bipolar transmission lines, the virtual ground plane introduces a zero-potential plane much closer to the line than the actual ground plane beneath the line. It is expected that higher electric fields arise in the direction perpendicular to this ground plane than to the actual ground. Table 6-1 gives the construction characteristics of a typical ±600 kV dc transmission line.

Table 6-1
Geometric parameters of a ±600 kV dc transmission line [5]



Conductor height at tower	40 m
Conductor height at mid-span	24 m
Ground wire height at tower	49.2 m
Ground wire separation	12.6 m
Pole spacing	15.14 m

As can be seen from Table 6-1, the virtual ground plane for this configuration represents a zero-potential ground plane at a horizontal distance of 7.57 m from each of the poles, while the actual ground beneath the line would, at the mid-span location, be 24 m below the conductors. In view of this, if corona appears on hardware installed on an in-service line, it would be the result of the virtual ground plane or the tower body and cross-arm rather than the height of the conductors above ground. IEC 61284, Overhead Lines: Requirements and Tests for Fittings, describes the voltage method and the gradient method for performing corona and RIV tests for ac systems. Ideally, testing for HVDC systems should follow the general intent of these methods. However, space constraints within most high-voltage laboratories prohibit the direct use of the voltage method; therefore, the gradient method appears best suited for use in most testing laboratories.

Hardware such as spacers, dampers, and splices installed at mid-span locations is not influenced by the tower structures. In these applications, the electric field distribution on the hardware is governed by the distance to the virtual ground plane and the height of the hardware above ground.

Corona performance of hardware such as insulator assemblies, corona rings, and acing horns installed at tower locations is affected not only by the distance to the virtual ground plane and the height of the hardware above ground, but also by the tower body and cross-arm.

In both these applications, the height of the conductors above ground is much greater than the distance between the conductors and the virtual ground plane or the tower body. Therefore, the electric field at the hardware is affected primarily by the distance from the conductors to the virtual ground plane (in the case of hardware installed far from towers) and by the distance between the conductors and the virtual ground plane, the tower body, and the tower cross-arm for hardware installed at tower locations.

As previously mentioned, it is impossible to use a full-scale transmission line/tower setup in most high-voltage laboratories because of space constraints. However, based on the factors described above, advantage can be taken of the fact that the virtual ground plane and the towers are much closer to the conductors than is the actual ground plane. This allows the test setup dimensions to be minimized by reducing the height of the setup above ground.

When constructing the setup to be used for corona testing according to the gradient method, the virtual ground plane can be simulated by one of the laboratory walls parallel to the conductor. The distance between the wall and the conductor should be set to one-half of the pole spacing. Based on testing performed at Kinectrics to date, it appears reasonable to set up the conductor at a height above the laboratory floor that is, at a minimum, also equal to one-half of the pole spacing. Using this setup is equivalent to moving the ground from a distance equal to the minimum mid-span conductor height to a distance equal to one-half of the pole spacing. To simplify the installation of the test setup, the conductors used for the test can be smooth aluminum tubes with a diameter nominally equal (within 5%) to that of the stranded conductor used for the in-service application.

For testing mid-span hardware, this setup is sufficient. When testing hardware such as insulator assemblies that are to be installed at tower locations, a simulated tower arm should also be included in the setup.

To determine the test voltage, it is necessary to know the in-service conductor surface voltage gradient at the location where the hardware is to be installed. For applications far from towers, the calculation should be done using the mid-span line geometry at the point of minimum conductor height above ground and should take into account the presence of the shield wires and the ground plane. For applications at towers, the tower and the cross-arm should be included in the calculation, with the conductors sitting in free space at the location where they would be suspended by the insulator assembly under service conditions. Today, commercially available field plotting programs can be used to perform the calculation. Once the in-service conductor surface electric field is established, the gradient method can be used to establish the required test voltage.

When setting up transmission line insulator assemblies for testing in a laboratory environment, a simulated tower arm should be used. The full test setup is made up of the conductor installed in a test setup comprising a simulated cross-arm located at a distance above the conductors approximately equal to that in service, with the conductor installed at a horizontal distance equal to one-half of the pole spacing from a vertical ground plane (or laboratory wall). The height of the conductor above the grounded laboratory floor should be equal to at least one-half of the pole spacing. Under these conditions, when the correct test voltage is applied, the conductor surface is subjected to approximately the same electrical stress as that present on the operating transmission line.

Once the setup is complete, the test voltage is determined through the use of the previously described calibration sphere. The determination of the voltage is carried out before the hardware or insulator assembly is added to the test setup.

To determine the test voltage, the calibration sphere is mounted on the conductor at the location where the hardware under test will be installed (usually at the mid-point of the conductor free length). For a single conductor, it should be positioned toward the closest ground plane. For bundle conductors, the sphere should be located at the point of maximum conductor surface gradient. If stranded conductors are used in the setup, the calibration sphere should be located on the tip of an outer strand.

Before the calibration sphere is attached to the test conductor, it should be wiped clean with a lint-free cloth. Voltage should then be applied to the conductor and slowly but steadily increased to the minimum value at which positive polarity corona occurs on the calibration sphere. Corona inception is taken as the lowest voltage level at which at least one visible corona onset streamer occurs per second. The voltage at which positive polarity corona inception is observed should be noted.

When using the calibration sphere under dc voltages, it is important to ensure that the corona inception voltage is taken as the voltage at which positive onset streamers appear and that the onset streamers are not confused with positive breakdown streamers. The repetitive sparking associated with onset streamers occurs suddenly and within a relatively narrow band of voltage. As the voltage is increased beyond this band, they transition to positive glow. As the voltage is further increased, the positive glow makes the transition to breakdown streamers. Confusing the onset streamers with the breakdown streamers can cause large errors in the test results.

The positive polarity corona inception voltage is used to determine the test voltage using the following formula:

$$V_R = \frac{E_S}{E_C} V_C$$

where:

V_R = Calculated test voltage

V_C = Positive corona inception voltage observed on calibration sphere

E_C = Positive corona inception voltage gradient obtained through the initial calibration of the calibration sphere

E_S = Specified conductor surface gradient for positive corona extinction

The specified conductor surface gradient for positive corona extinction (E_S) is derived from the in-service operating conductor surface gradient calculated for the particular hardware location. It takes into account factors such as the altitude of the in-service location, expected surface aging of installed hardware, and the maximum system in-service operating voltage.

Visual dc Corona Test Procedure

Visual corona inception is taken as the lowest voltage level at which at least one visible corona onset streamer occurs per second. The visual corona extinction voltage of the assembly or hardware under test is defined as the highest voltage level at which no corona streamers occur over a 90-second time period [5]. Observation of the corona can be carried out in a fully lit laboratory with the aid of a specialized corona camera that detects ultraviolet (UV) light emitted by corona. Image intensifiers can also be used in a darkened laboratory. To measure corona onset, it is highly desirable to perform corona and RIV testing at the same time.

To ensure proper visual corona measurements on hardware for HVDC transmission lines, the following procedure is recommended:

1. Perform an initial pre-test to check the setup.
2. Perform a pre-conditioning test.
3. Perform the corona inception and extinction voltage test.

The initial pre-test should be carried out to ensure that the hardware or insulator assembly is appropriately set up after the installation. This includes ensuring that there is no corona activity on the conductors, conductor terminations, and other parts of the setup that do not make up parts of the hardware to be tested.

The pre-conditioning test is performed by applying the voltage and increasing it gradually and smoothly to the specified test voltage or the corona inception voltage. The applied voltage should be raised to a level approximately 3% above the inception voltage and maintained at that level for 5 minutes. The pre-conditioning test is run once to ensure that no corona activity is present on the hardware, conductors, and terminations that may lead to misleading results.

The corona inception and extinction test is then performed. The applied voltage is increased slowly and smoothly to the specified test voltage or the corona inception voltage as defined earlier. The applied voltage corresponding to the corona inception level is noted, increased to about 3% above the inception voltage, and maintained at that level for 5 minutes. The applied voltage is then reduced in steps from the corona inception voltage; each step is approximately 2% of the corona inception voltage. At each step, the voltage is maintained for 90 seconds to allow for observation to determine whether corona extinction on the assembly has taken place. The voltage at which corona extinction occurs is noted as the corona extinction voltage. The corona inception and extinction test procedure is repeated five times, and the corona inception and extinction levels are calculated as the averages of the respective five readings.

The results of the test can be expressed as voltage values corresponding to corona inception or extinction or as values of the conductor surface voltage gradient corresponding to corona inception or extinction using the following formula:

$$E_M = \frac{V_M}{V_C} E_C$$

where:

E_M = The conductor surface gradient corresponding to the measured corona inception or extinction

V_M = The applied voltage at corona inception or extinction

V_C = Positive corona inception voltage obtained through the initial calibration of the calibration sphere

E_C = Positive corona inception voltage gradient obtained through the initial calibration of the calibration sphere

Acceptance Criteria

For the hardware under test, the corona extinction voltage (V_M) or conductor surface voltage gradient (E_M) determined during testing should exceed the minimum specified corona extinction voltage or conductor surface voltage gradient.

7
CONCLUSIONS

The test methodology described in this report defines a test procedure for HVDC corona testing. This procedure is based on standard corona test methods used for HVAC system components. The difference between it and the standard HVAC test procedures is based on the physical differences between ac and dc corona.

Ideally, to identify potential improvements, the proposed procedure should be 1) carried out as part of a controlled round-robin test in different high-voltage laboratories and 2) assessed through experimental comparisons with operating HVDC lines.

Further studies—both experimental and computational—will serve to refine the procedure through the development of a better understanding of the characteristics and localized effects of space charge on the corona phenomenon on HVDC lines.

The reproducibility of the procedure would be improved by formulating atmospheric correction factors for the atmospheric parameters discussed in this report.

8
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A
PROCEDURE FOR THE CALIBRATION OF CORONA CALIBRATION SPHERES

Calibration of Corona Calibration Spheres

Corona calibration spheres are available in several different diameters for use on different diameter conductors [13]. Calibration of the calibration sphere is performed using a conductor of the same diameter as that of the bundled sub-conductors on which the corona test is to be performed.

The calibration procedure is based on the use of a geometry characterized by a known and easily calculable electric field distribution. Typically, the geometries used are either a single conductor positioned above a ground plane or a coaxial geometry with the conductor placed in the central axis of a metal cylinder. Both of these geometries allow for accurate and simple calculation of the electric field at the conductor surface. The calibration sphere is mounted on a conductor at its mid-point. If the calibration is being done in a coaxial corona cage, the orientation of the sphere is not important. If the calibration is being done using a ground plane, the sphere should be oriented toward the ground plane. The length of the conductor used must be sufficient to ensure that the electric field at the center of the conductor (where the sphere is located) is not subject to end effects. In addition, the distance between the conductor and the grounded cylindrical corona cage or the ground plane should be sufficient to ensure that positive corona appears well before there is any possibility of breakdown.

The nominal conductor surface electric field in a concentric cylinder geometry is:

$$E = \frac{V}{r \ln \frac{R}{r}}$$

where:

V = Voltage applied to the conductor

R = Radius of the test concentric cylinder

r = Radius of the conductor

The nominal conductor surface electric field when the calibration of the sphere is made using a single ground plane is:

$$E = \frac{V}{r \ln \frac{2h}{r}}$$

where:

h = The distance from the test conductor to the ground plane, which is usually the height of the conductor above the laboratory floor

r = Radius of the conductor

The calibration is performed by raising the voltage applied to the conductor and determining the applied voltage at which the corona calibration sphere goes into positive corona (that is, positive corona inception). Corona inception is taken as the lowest voltage level at which at least one visible corona onset streamer occurs per second. Observation of the corona can be carried out in full lighting with the aid of a specialized corona camera that detects UV light emitted by corona. Image intensifiers can also be used in a darkened laboratory. When using the calibration sphere, it is important to ensure that the corona inception voltage is taken as the voltage at which positive onset streamers appear and that the onset streamers are not confused with positive breakdown streamers. The repetitive sparking associated with onset streamers occurs suddenly. Onset streamers occur within a relatively narrow band of voltage and transition to positive glow as the voltage is increased. As the voltage is further increased, the positive glow transitions to breakdown streamers. Confusing the onset streamers with the breakdown streamers can cause large errors in the test results.

The voltage should then be slowly lowered to a level some 30% below the positive corona inception voltage and then increased again until positive corona inception occurs. Using this method, the voltage should be raised five times to obtain five voltage levels corresponding to corona inception. These five positive corona inception levels should be averaged to obtain the calibrated positive corona inception voltage value for the sphere. This value should then be used in the applicable equation above to determine *E*, the electric field required at the conductor surface to give positive corona inception on the calibration sphere.

Figure A-1 shows a typical setup used for calibration of a corona calibration sphere using the conductor above a ground plane geometry. Figure A-2 shows the details in attaching the calibration sphere to the conductor.

Figure A-1
Setup for calibration of the corona calibration sphere using a conductor above a ground plane geometry

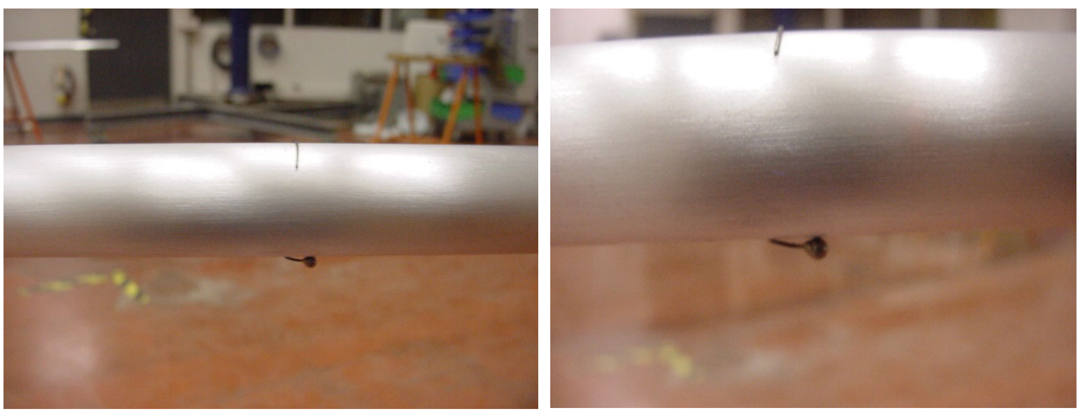

Figure A-2
Details showing installation of the corona calibration spheres

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