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TECHNICAL REPORT

colour
inside

Electromagnetic performance of high voltage direct current (HVDC) overhead transmission lines

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

ELECTROMAGNETIC PERFORMANCE OF HIGH VOLTAGE DIRECT CURRENT (HVDC) OVERHEAD TRANSMISSION LINES

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IEC TR 62681, which is a technical report, has been prepared by IEC technical committee 115: High Voltage Direct Current (HVDC) transmission for d.c. voltages above 100 kV.

The text of this technical report is based on the following documents:

Enquiry draft	Report on voting
115/71/DTR	115/84/RVC

Full information on the voting for the approval of this technical report can be found in the report on voting indicated in the above table.

This publication has been drafted in accordance with the ISO/IEC Directives, Part 2.

The committee has decided that the contents of this publication will remain unchanged until the stability date indicated on the IEC web site under "http://webstore.iec.ch" in the data related to the specific publication. At this date, the publication will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

A bilingual version of this publication may be issued at a later date.

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INTRODUCTION

Electric fields and magnetic fields are produced in the vicinity of an HVDC transmission line. When the electric field at the conductor surface exceeds a critical value, known as the corona onset gradient, positive or negative free charges leave the conductor and interact with the surrounding air and ionization takes place in the layer of surrounding air, leading to the formation of corona discharges. The corona discharge will not only bring out corona loss but also produce electromagnetic environment problems.

The parameters used to describe the electromagnetic environment of an HVDC transmission line mainly include the:

1) electric field,
2) ion current,
3) magnetic field,
4) radio interference,
5) audible noise.

To control these parameters in a reasonable and acceptable range, for years, a great deal of theoretical and experimental research was conducted in many countries, and relevant national standards or enterprise standards were developed. This Technical Report collects and records the status of study and progress of electric fields, ion current, magnetic fields, radio interference, and audible noise of HVDC transmission lines.

ELECTROMAGNETIC PERFORMANCE OF HIGH VOLTAGE DIRECT CURRENT (HVDC) OVERHEAD TRANSMISSION LINES

1 Scope

This Technical Report provides general guidance on the electromagnetic environment issues of HVDC transmission lines. It concerns the major parameters adopted to describe the electromagnetic environment of a High-Voltage Direct Current (HVDC) transmission line, including electric fields, ion current, magnetic fields radio interference, and audible noise generated as a consequence of such effects. Engineers in different countries can refer to this Technical Report to:

- ensure the safe operation of HVDC transmission lines,
- limit the influence on the environment within acceptable ranges, and
- optimize engineering costs.

2 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

2.1
corona
set of partial discharges in a gas, immediately adjacent to an uninsulated or lightly insulated conductor which creates a highly divergent field remote from other conductors

[SOURCE: IEC 60050-212:2010, 212-11-44, modified – Note 1 has been deleted.]

2.2
electric field
constituent of an electromagnetic field which is characterized by the electric field strength E together with the electric flux density D

Note 1 to entry: In the context of HVDC transmission lines, the electric field is affected not only by the geometry of the line and the potential of the conductor, but also by the space charge generated as a result of corona; consequently, electric field distribution may vary non-linearly with the line potential.

[SOURCE: IEC 60050-121:1998, 121-11-67, modified – Note 1 to entry has been added.]

2.3
space-charge-free electric field
electric field due to a system of energized electrodes, excluding the effect of space charge present in the inter-electrode space

2.4
ion current
flow of electric charge resulting from the motion of ions

2.5
magnetic field
constituent of an electromagnetic field which is characterized by the magnetic field strength H together with the magnetic flux density B

[SOURCE: IEC 60050-121:1998, 121-11-69, modified – Note 1 has been deleted.]

2.6
radio interference
degradation of the reception of a wanted signal caused by RF disturbance

2.7
audible noise
unwanted sound with frequency range from 20 Hz to 20 kHz

[SOURCE: IEC 61973:2012, 3.1.14]

3 Electric field and ion current

3.1 Description of the physical phenomena

Electric fields are produced in the vicinity of a HVDC transmission line, with the highest electric fields existing at the surface of the conductor. When the electric field at the conductor surface exceeds a critical value, the air in the vicinity of the conductor becomes ionized, forming a corona discharge. Ions of both polarities are formed, but ions of opposite polarity to the conductor potential are attracted back towards the conductor, while ions of the same polarity as the conductor are repelled away from the conductor. Space charges include air ions and charged aerosols. Under the action of an electric field, space charge will move directionally and ion current will be formed. The physical phenomena of electric field and ion current are described in this clause.

The electric field and ion current in the vicinity of an HVDC transmission line are defined mainly by the operating voltage and line configuration. The voltage applied to line conductors produces an electric field distribution. Unlike High-voltage Alternating Current (HVAC) transmission lines, the electric field produced by HVDC transmission lines does not vary with time and, consequently, does not produce any significant currents in humans or objects immersed in these fields.

The electric field is another aspect of the electrical environment around an overhead HVDC transmission line. An electric field is present around any charged conductor, irrespective of whether corona discharge is taking place. However, the space charge created by corona discharge under d.c. conditions modifies the distribution of an electric field. The effect of space charge on electric fields is significant.

For the same HVDC transmission lines, the corona onset gradients of positive or negative polarities are different and the intensity and characteristics of corona discharges on positive or negative conductors are also different. Consequently, during the design of HVDC transmission lines, special consideration should be paid to the allowable values of the maximum ground-level electric field and ion current density [1][1].

Corona on a conductor of either positive or negative polarity produces ions of either the positive or negative polarities in a thin layer of air surrounding each conductor [1]. However, ions with a polarity opposite to that of the conductor are drawn to it and are neutralized on contact. Thus, a positive conductor in corona acts as a source of positive ions and vice-versa. For a unipolar d.c. transmission line, ions having the same polarity as the conductor voltage fill the entire inter-electrode space between the conductors and ground. For a bipolar d.c. transmission line, the ions generated on the conductors of each polarity are subject to an electric field driven drift motion either towards the conductor of opposite polarity or towards the ground plane, as shown in Figure 1. The influence of wind or the formation of charged aerosols are not considered at this stage. Three general space charge regions are created in this case:

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[1] Numbers in square brackets refer to the bibliography.

a) a positive unipolar region between the positive conductor and ground,

b) a negative unipolar region between the negative conductor and ground,

c) a bipolar region between the positive and negative conductors.

For practical bipolar HVDC lines, most of the ions are directed toward the opposite polarity conductor, but a significant fraction is also directed toward the ground. The ion drift velocity is such that it will take at least a few seconds for them to reach ground. Actually, the molecules traveling along ion paths are not always the same ions. In fact, collisions between ions and air molecules occur during the travel at a rate of billions per second and cause charge transfer and reactions between ions and neutral molecules, so the ions reaching the ground are quite different from those that were originally formed by corona near the conductor surface. The exact chemical identity of the ions, after a few seconds, will depend on the chemical composition and trace gases at the location.

Electric field is another component of the electrical environment around an overhead HVDC transmission line. Electric field is caused by electrical charges, both those residing on conductive surfaces (the transmission line conductors, the ground, and conducting objects) and the space charges. The effect of space charge on electric field is significant.

A nonlinear interaction takes place between electric field and space charge distributions in all three general space regions identified above in a), b), c).. The nonlinearity arises because ions flow from each conductor to ground or to the conductor of opposite polarity along the flux lines of the electric field distribution: while at the same time, the electric field distribution is influenced by the ionic space charge distribution. In addition to the nonlinear interaction described above, the space charge field in the bipolar region is affected by other factors. Mixing of ions of both polarities in the bipolar region leads firstly, to a reduction in the net space charge density and secondly, to recombination and neutralization of ions of both polarities.

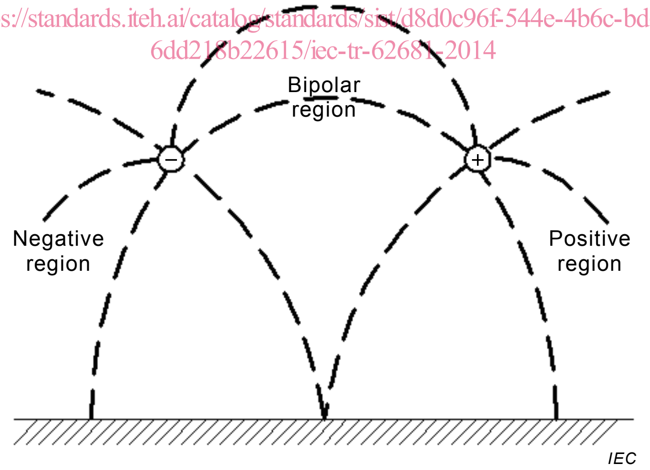

Figure 1 – Unipolar and bipolar space charge regions of a HVDC transmission line [1]

The corona-generated space charge, being of the same polarity as the conductor, produces a screening effect on the conductor by lowering the electric field in the vicinity of the conductor surface and consequently reducing the intensity of corona discharges occurring on the conductor. In the unipolar regions, the space charge enhances the electric field at the ground surface. The extent of electric field reduction at the conductor surface and field enhancement at the ground surface depend on the conductor voltage as well as on the corona intensity at the conductor surface. In the case of the bipolar region, however, the mixture of ions of opposite polarity and ion recombination tend to reduce the screening effect on the conductor surface. This leads to a smaller reduction in the intensity of corona activity near the conductors than in the unipolar regions.

The electrical environment at ground level under a bipolar HVDC transmission line is, therefore defined mainly by three quantities:

a) electric field, E,

b) ion current density, J,

c) space charge density, ρ.

The electric field produced by HVDC overhead transmission lines is a vector defined by its components along three orthogonal axes. The space charge density is a scalar. The ion current density is also a vector, and it is determined by the electric field and space charge density.

Very small currents in some cases may flow through an object or person located under the line because of exposure to the electric field and ion space charge. From the point of view of environmental impact on persons and objects located under the line, the main consideration is the combined exposure to the electric fields and ion currents. The scientific literature indicates that exposure to the levels of d.c. electric field and ion current density existing under operating HVDC transmission lines pose no risk to public health, but may cause some induced current and annoyance effects to humans. Consequently, during designing of HVDC transmission lines, special consideration should be paid for the allowable values of the maximum ground-level electric field and ion current density [1].

Design of HVDC transmission lines requires the ability to predict ground-level electric field and ion current distribution as functions of line design parameters such as the number and diameter of sub-conductors in the bundle, height above ground of conductors and pole spacing. Prediction methods are based on a combination of analytical techniques to calculate the space charge fields and accurate long-term measurements under experimental as well as operating HVDC transmission lines.

As described and illustrated in Figure 1, the ground-level electric field and ion current environment under a bipolar HVDC transmission line can be thought primarily as a unipolar space charge field under each pole. The bipolar space charge field between the positive and negative conductors, however, has no significant impact on the ground-level electrical environment. For the purpose of calculating the ground-level electric field and ion current distributions, therefore, analytical treatment of the unipolar space charge field between each of the positive and negative conductors and the ground plane is adequate.

Unipolar d.c. space charge fields are defined by the following equations:

$$\nabla \cdot E = \frac{\rho}{\varepsilon_0} \qquad (1)$$

$$J = \mu \rho E \qquad (2)$$

$$\nabla \cdot J = 0 \qquad (3)$$

where

E and J are the electric field and ion current density vectors at any point in space,

ρ is the space charge density,

μ is the ionic mobility,

ε_0 is the permittivity of free space.

The first Equation (1) is Poisson's equation, the second Equation (2) defines the relationship between the current density and electric field vectors, and the third Equation (3) is the continuity equation for ions. The solution of these equations, along with appropriate boundary conditions, for the conductor-ground-plane geometry of the HVDC transmission line, determines the ground-level electric field and ion current distributions [1].

Corona activity on conductors and the resulting space charge field are influenced, in addition to the line voltage and geometry, by ambient weather conditions such as temperature, pressure, humidity, precipitation and wind velocity as well as by the presence of any aerosols and atmospheric pollution. It is difficult, if not impossible, to take all these factors into account in any analytical treatment of space charge fields. Information on the corona onset gradients of conductors, which is an essential input in the analytical determination of electric field and ion current environment, is also difficult to obtain under practical operating conditions. For these reasons, it is necessary to use analytical methods in combination with accurate long-term measurements of ground-level electric field and ion current distributions under experimental as well as operating HVDC transmission lines, in order to develop prediction methods. Some of the information required in the analytical treatment, such as corona onset gradients of conductors, can be obtained only through experimental studies. Reliable experimental data is also essential in validating the accuracy of analytical or semi-analytical methods for predicting the ground-level electric field and ion current distributions under HVDC transmission lines.

NOTE 1 Industry consensus and standards have not been reached on appropriate analytical methods to capture all effects of weather in the calculation of enhanced fields due to space charge.

NOTE 2 As described in reference [2] the conditions most conducive to enhanced fields due to space charge (wet conductor conditions in fog, with zero wind) occur for a very small percentage of time over a given year.

NOTE 3 As further pointed out in reference [2], to attempt to address very rare conditions in the design of an HVDC transmission line may not be fully justifiable, given the lack of clear standards, analytical methods, and consensus on the subject.

3.2 Calculation methods

3.2.1 General

Ground-level electric field and ion current distribution under HVDC transmission lines depends primarily on the conductor bundle and on the minimum height above ground of conductors. Pole spacing has a secondary influence on the electric field and ion current distributions, and is selected mainly on the basis of air gap clearances required to withstand the maximum values of overvoltage that may appear on the conductors.

Corona performance criteria, particularly for radio interference (RI) and audible noise (AN), are used to select the number and diameter of conductors in the bundle required on each pole. Conductor height and pole spacing have a secondary influence on the RI and AN performance.

Following the selection of the conductor bundle based on RI and AN design criteria, the minimum conductor height is selected on the basis of design criteria for ground-level electric field and ion current density. The conductor heights selected using these criteria are generally significantly higher than would be required from insulation and safety considerations.

Calculation of the desired ground-level electric field and ion current distribution for proposed HVDC transmission line configurations is, therefore, an essential step in selecting the minimum conductor height. Methods of calculation that are presently available for this purpose are described below.

Calculation methods for determining electric field and ion current distributions involve the solution of the boundary value problem described by the set of Equations (1) to (3) along with appropriate boundary conditions. The first rigorous analytical solution to the unipolar space charge modified field problem was obtained by Townsend [3] for the concentric cylindrical configuration. The main interest in this solution was to obtain the voltage-current characteristic for a thin wire at high voltage and in corona, placed concentrically inside a large metallic cylinder at ground potential.