Electrical Effects of HVDC Transmission Lines

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EPRI Project Manager

B. Clairmont

ELECTRIC POWER RESEARCH INSTITUTE
3420 Hillview Avenue, Palo Alto, California 94304-1338 • PO Box 10412, Palo Alto, California 94303-0813 • USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com

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Engelbrecht Consulting
Catharinadaal 84
6715 KD Ede, The Netherlands

Principal Investigator
L. Zaffanella

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ABSTRACT

Electrical effects can constrain the design of prospective high-voltage direct current (HVDC) lines operating either alone or sharing the same rights of way structures with high-voltage alternate current (HVAC) lines. In 2013, the Electric Power Research Institute (EPRI) research on HVDC electrical effects focused on electric field and ion density at ground level. The ultimate goal of the project is to calculate with confidence these electrical effects. The algorithms on which the software currently used by EPRI to calculate these effects are based on, and extensively validated for, bipolar lines with horizontal configurations. Research performed in 2012 sought to verify the validity of these algorithms for other types of possible HVDC line configurations: bipolar vertical, multipolar, and HVDC line configurations derived by converting three-phase HVAC lines into HVDC lines. Results of tests on these configurations showed several differences from those obtained with the existing algorithms. Needed improvements in the software algorithms were indicated, and an appropriate test plan was developed for work in 2013.

All tests described in this report were conducted in the ultra-high voltage building of EPRI's laboratory in Lenox, Massachusetts, using the modeling technique previously developed and successfully validated. Electric field and ion current densities were measured on bipolar vertical configurations and on bipolar horizontal configurations with small pole spacing-to-height ratios. Extremely small diameter conductors would be used for the tests so that all the configurations tested were in maximum (saturated) levels of corona. The test results were used to develop algorithms that allow more reliable calculation of electrical effects for any type of line configuration.

A study of electrical effects of individual corona sources was started in 2011, was continued in 2012, and was completed in 2013. Model tests were performed on bipolar horizontal lines with an individual corona source in the worst location on one of the two HVDC poles. The peak electric field and the peak ion current density at the center of the ion plume and the lateral and longitudinal widths of the plume were measured. The tests were performed varying the ratio between the corona inception voltage of the source and the applied voltage and the polarity of the pole where the source was placed.

In addition, ion emission of an insect as a corona source was studied specifically. The change in ion emission with time was studied by applying voltage much higher than corona inception and periodically measuring the corona inception voltage. The study of individual sources was concluded with a performance assessment of HVDC lines in practical conditions, which are quite different from the commonly assumed uniform corona along the conductor's length.

Keywords
Corona
Electric field
High-voltage transmission
HVDC
Hybrid
Ions

CONTENTS

LIST OF FIGURES

LIST OF TABLES

1 REVISIONS OF EMPIRICAL EQUATIONS USED BY ACDCLINE SOFTWARE

The Concept of Corona Saturation and ACDCLINE Algorithms

The calculation method incorporated in the Electric Power Research Institute's (EPRI's) ACDCLINE software (which is a module within the Transmission Line Workstation) is based on a theoretical approach, on the results of reduced-scale model tests with conductors in maximum (saturated) corona, and on the results of full-scale long-term tests performed at EPRI's Laboratory in Lenox, Massachusetts. The highlights of the calculation method are the following:

In calm wind the electric field at ground (*E*) and the ion current density (*J*) are assumed[1] to be bounded by "electrostatic" and "saturated" values. "Electrostatic" conditions occur when corona is not present. Charge resides on the conductors and there is no charge in the space between conductors and ground. The electric field in electrostatic conditions (E_0) can be calculated using simple algorithms; ion current density in electrostatic conditions is zero. "Saturated" conditions occur when corona is so severe that the conductors cannot hold any charge. The space between conductors and between conductors and ground is saturated with charges. Saturated *E* and *J* are determined with tests using conductors that go in corona at extremely low voltage. Based on these tests, empirical equations were developed to calculate saturated E (E_s) and saturated J (J_s). Actual conditions are defined by the "degree of corona saturation", α.

$$E = E_0 + a\cdot(E_s - E_0) \qquad J = a\cdot E_s \qquad \textbf{(Eq. 1-1)}$$

Empirical values of α were determined by analyzing the results of a large number of full scale line tests performed with different bipolar line geometry, with different voltages, in different seasons, and in different weather conditions. It is assumed that the degree of corona saturation depends only on conductor surface conditions, weather, and conductor surface gradient, *G*.

$$\alpha = 1 - e^{-k\cdot(G-G_0)} \qquad \textbf{(Eq. 1-2)}$$

k and G_0 depend on surface conditions, season, and weather

Values of *k* and G_0 were derived from full scale test [4] and, for sake of completeness, are reported in Table 1-1.

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[1] The assumption is correct for monopolar lines and it may practically apply to any other configuration. However, it was found that bipolar lines with corona on one pole only could produce ground level electric fields and ion current densities exceeding saturated values.

Table 1-1
Degree of corona saturation for different weather conditions

(Northeast U.S. climate) $\alpha = 1 - e^{-k\cdot(G-G_0)}$

Season and Weather	Polarity	Percentile (%)	G_0 (kV/cm)	k
Summer Fair Weather	Positive	50	9	0.037
		95	3	0.067
	Negative	50	9	0.015
		95	3	0.032
Rain	Positive and Negative	50	6	0.058
		95	6	0.032
Snow	Positive and Negative	50	12	0.030
		95	11	0.045
Summer High Humidity or Fog	Positive	50	7.5	0.060
		95	3	0.086
	Negative	50	8.5	0.045
		95	3	0.063
Spring Fair Weather	Positive	50	14.5	0.041
		95	11	0.086
	Negative	50	14.5	0.021
		95	11	0.065
Fall Fair Weather	Positive	50	12	0.039
		95	10	0.092
	Negative	50	12	0.017
		95	11	0.070
Winter Fair Weather	Positive and Negative	50	20.5	0.029
		95	20	0.055

ACDCLINE is a computer program developed by EPRI to calculate all the parameters characterizing the electrical performance of HVDC lines. One of the subroutines ("EISAT") of the software is for the calculation of dc electric field and ion current density at ground. Calculations are performed accounting for the presence of all the conductors in the corridor: those energized with dc voltages, those energized with ac voltages, and those at ground potential. The algorithms of ACDCLINE are described in [1]. The brief review reported below is limited to HVDC lines and does not cover the hybrid case.

Electric fields can be calculated accurately, using a well known method, when the charges are only on the surfaces of conductors and ground and there is no charge in space (electrostatic case). Calculations start with this step. ACDCLINE makes a simplification by substituting each bundle with its equivalent single conductor. This simplification leads to an accurate calculation of the electric field at ground in the electrostatic case. In the saturated case, conductors do not hold any charge and, therefore, the geometry of the conductors is not important.

After calculating the charges on the conductors, ACDCLINE calculates the geometry of the flux lines that go from the conductors to ground. This geometry is defined as a series of successive segments lined up in the direction of the electrostatic field, and along which the electrostatic field is known.

At this point ACDCLINE, similar to many other calculation methods reported in the literature, makes a key assumption, first made by W. Deutsch [2] and commonly referred as "the Deutsch assumption", which states that *in the presence of corona generated space charge, the electric field magnitude changes but its direction may be assumed constant*. In other words, a flux lines remain unchanged in shape with or without corona. This is true only for uniform corona and for very particular geometries (concentric cylinders, concentric sphere) but not for transmission line conductors. The assumption, however, is so attractive that it is widely used, save applying corrective algorithms to compensate for its basic flaw, which consists in neglecting the contribution of the space charge in defining the geometry of the flux lines. ACDCLINE follows the same philosophy, which is: (1) calculate electric field and ion currents using Deutsch assumption and the knowledge that, in saturated corona conditions, the electric field at the conductor surface is zero and then (2) apply correction factors in order to match the results obtained by tests with saturated corona [4].

After calculating the saturated electric field and ion current density using Deutsch assumption and zero electric field at the conductor surface, ACDCLINE applies two empirically derived correction factors, one to account for the degree of bipolarity and one to account for the length of flux lines.

The correction factors to account for length of flux lines are:

$$FFE = e^{-(L/H-1)/22.5} \qquad \textbf{(Eq. 1-3)}$$

$$FFJ = (FFE)^{\wedge}2 \qquad \textbf{(Eq. 1-4)}$$

FFE is the correction factor to apply to saturated fields at ground

FFJ is the correction factor to apply to saturated ion current densities at ground

L is the length of the flux lines

H is the height of the conductor above ground

It should be noted that *FFE* and *FFJ* corresponding to the highest values of *E* and *J* in the monopolar case are equal to 1, because the flux line that goes straight to ground has a length equal to the conductor height. For other flux lines, however, electric field and ion currents are less than what would be calculated using Deutsch assumption alone. For instance, if the flux line length were twice the conductor height, the field calculated using Deutsch assumption should be multiplied by 0.96 and the ion current density should be multiplied by 0.91 to match experimental results.

The degree of bipolarity, *DB*, is a measure of deviation from the monopolar mode of energization. For a monopolar line, *DB* = 1. For a line with several poles, the degree of bipolarity of pole *i* is defined as:

$$DB_i = \frac{V_i / H_i + \sum_{j \neq i} (V_i - V_j) / P_{ij}}{V_i / H_i} \qquad \textbf{(Eq. 1-5)}$$

V_i is the voltage of pole *i*

V_j is the voltage of pole *j*

H_i is the height above ground of pole *i*

P_{ij} is the distance between pole *i* and pole *j*

For instance, for each pole of a bipolar horizontal line with pole spacing equal to its height, *DB* = 3.

The correction factors applied by ACDCLINE to account for the degree of bipolarity are:

$$FFFE = 0.45 + 1.1 \cdot e^{-0.294 \cdot (DB-1)} - 0.53 \cdot e^{-0.712 \cdot (DB-1)} \qquad \textbf{(Eq. 1-6)}$$

$$FFFJ = 0.4 + 0.87 \cdot e^{-0.39 \cdot (DB-1)} \qquad \textbf{(Eq. 1-7)}$$

FFFE is the correction factor to apply to saturated fields at ground

FFFJ is the correction factor to apply to saturated ion current densities at ground

DB is the degree of bipolarity defined by equation (1-5)

For bipolar horizontal lines the correction factor to apply to electric field is generally close to 1. In fact, for monopolar lines and for bipolar lines with pole spacing, P, greater than 1.25 times the height above ground, H, the value of *FFFE* is: 0.97 < *FFFE* < 1.03. Only when P/H is less than 0.85 is FFFE less than 0.9. On the other hand, the correction factor for ion current density may be significantly different from 1. In fact, *FFFJ* < 0.9 when P/H < 1.4. When P/H is 0.2, DB = 11 and FFFJ = 0.42.

The correction factors to account for flux line length and degree of bipolarity were developed in order to match experimental results obtained primarily with bipolar horizontal lines with P/H in the range between 1 and 2. In this range the correction factor FFFJ is between 0.85 and 1.04. ACDCLINE applies the same correction factor equations for bipolar horizontal lines with values of P/H outside the tested range and to other line geometries. While this was expected to be a reasonable assumption, there was no experimental evidence to support it. Tests performed in 2012 and in 2013 were designed to shed some light on this issue.

Test Results

The 2012 tests were described in a previous report [3]. The results were re-analyzed to determine whether correction factors could be developed to obtain a better match between calculations and tests. It was not possible to determine accurate correction factors because the conductors used for these tests were covered with corona sources, but were not in saturated corona conditions, and the degree of corona saturation could not be accurately assessed. In 2013 tests were performed on horizontal and vertical bipolar configuration in saturated corona using a very small wire (trademark: Bekinox) which produced corona at very small voltages. The complete list of tests performed in 2013 is reported in Appendix 1. The list includes tests of conductors in saturated corona, and tests of conductors with single corona sources. The results of the tests with saturated corona are shown in Appendix 2.

The peak values of measured electric fields and ion current densities at ground are reported in Table 1 of Appendix 2. The table also reports the values calculated using three different methods: (1) ACDCLINE without correction factors, (2) ACDCLINE with correction factors, and (3) the empirical equations described in Reference [4] which were used to develop the correction factors for bipolarity used by ACDCLINE.

The voltage and height above ground varied from test to test. In order to better compare the results, the normalized electric field and the normalized ion current density were calculated. The normalized electric field was calculated by multiplying the electric field by H/V. The normalized positive ion current density was obtained by multiplying the ion current density by H^3/V^2. The normalized negative ion current density was obtained multiplying the ion current density by $0.76 \cdot H^3/V^2$, where 0.76 is the estimated [4] ratio between positive and negative ion mobility. In this way positive and negative ion current density calculated by ACDCLINE and by the empirical equations will coincide. The normalized electric field and ion current densities for the tests performed are shown in Table 2 of Appendix 2.

Measured values are compared with those calculated by the three different methods in Figure 1-1 for the electric field and in Figure 1-2 for the ion current density. The data are reported as a function of the degree of bipolarity, DB. These figures show that the ACDCLINE calculations without corrections gives results that match the measured values better than the other two methods. Figures 1-3 and 1-4 report measured values and ACDCLINE results without corrections. In these figures, positive and negative measured values are marked with a different symbol. It can be seen that normalized measured values for positive polarity are consistently lower than those for negative polarity. There are two potential explanations for this phenomenon: (1) when a positive voltage was applied to the small Bekinox wire, the wire was vibrating in a clearly visible way, while no visible vibration was observed when a negative voltage was applied, and (2) the ratio of positive to negative ion mobility may have been different from the value (0.76) estimated by ACDCLINE. Because of the uncertainty associated with positive values, only the negative results were considered in subsequent analyses.

Figure 1-5 reports measured (positive and negative) normalized electric field calculated by ACDCLINE without correction, versus the relative length of the flux line that reaches the point where these parameters are at their peak value. Figure 1-6 shows the same type of comparison for normalized ion current densities.

Figures 1-3 to 1-6 show the need to apply correction factors to ACDCLINE. However, selecting the correction factors that best match the measured values is not a simple task.

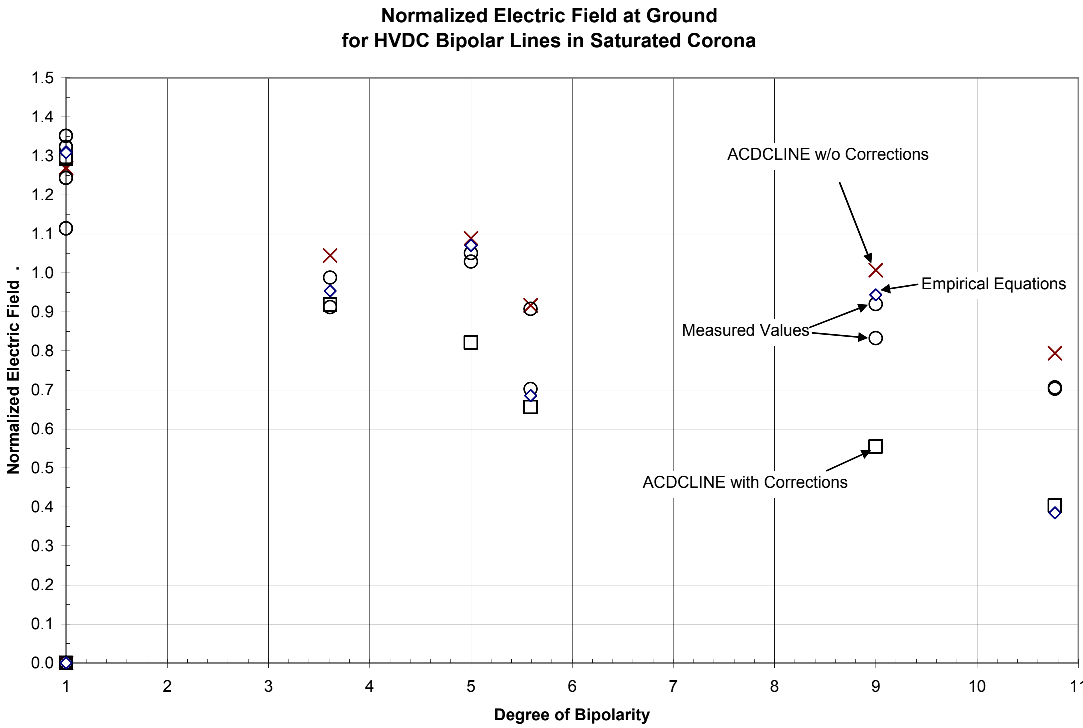

Figure 1-1
Measured and calculated normalized electric field

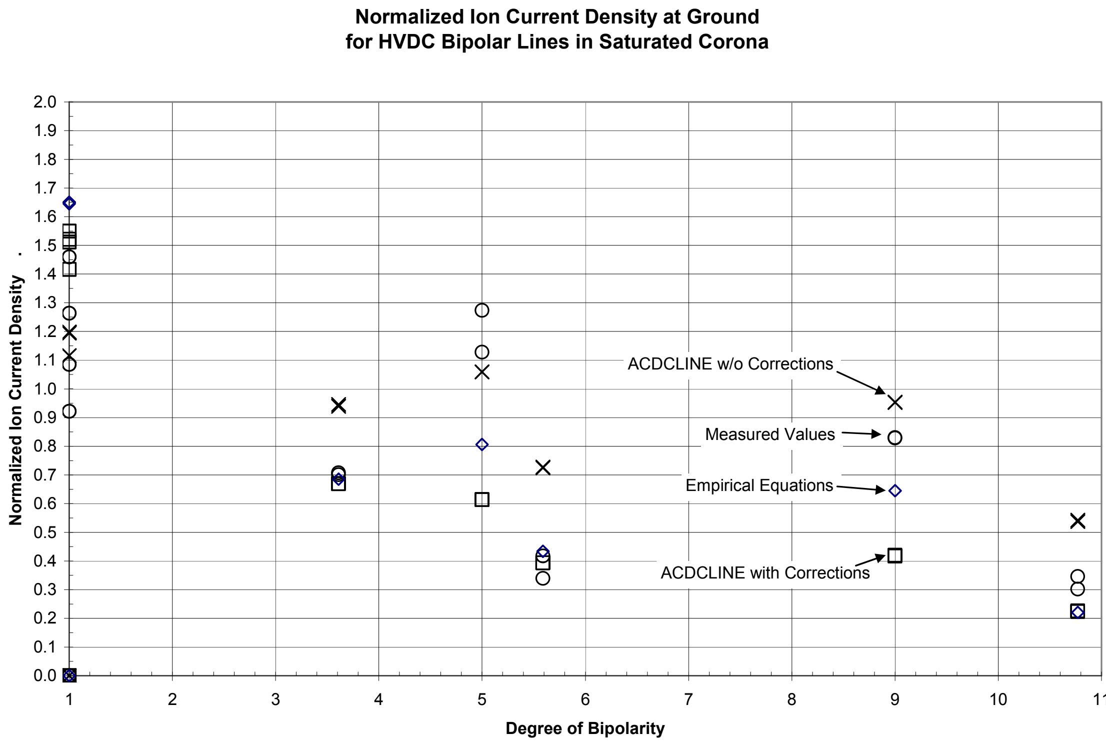

Figure 1-2
Measured and calculated normalized ion current density

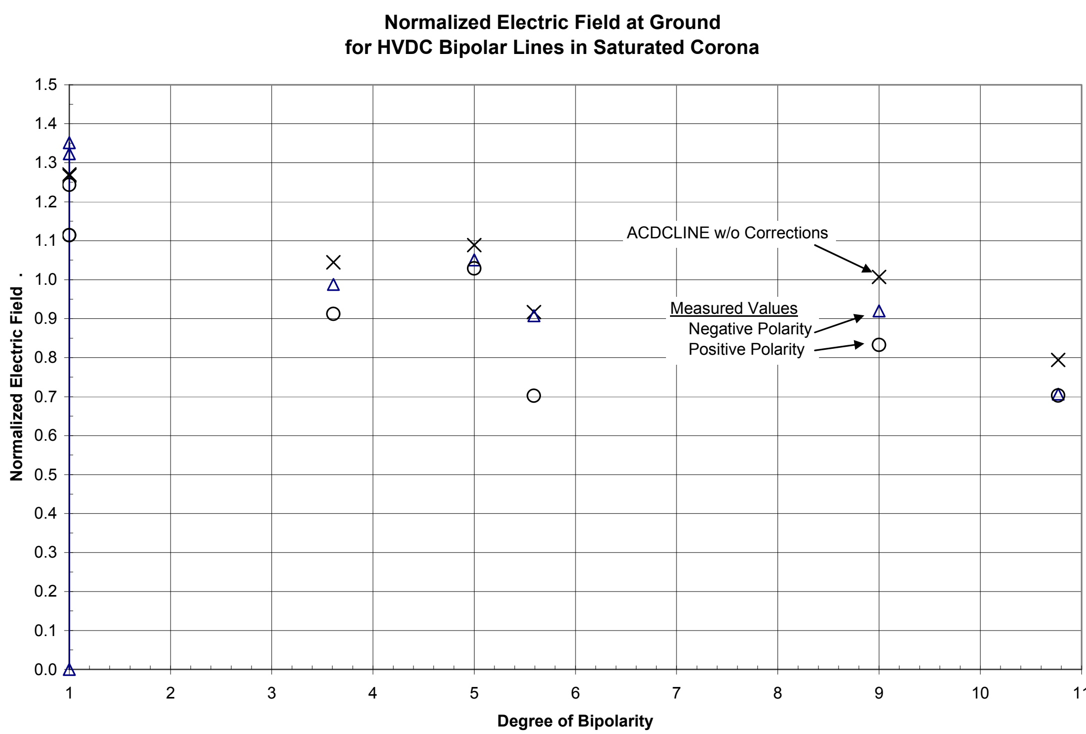

Figure 1-3
Measured positive and negative normalized electric field compared with values calculated by ACDCLINE without corrections versus DB

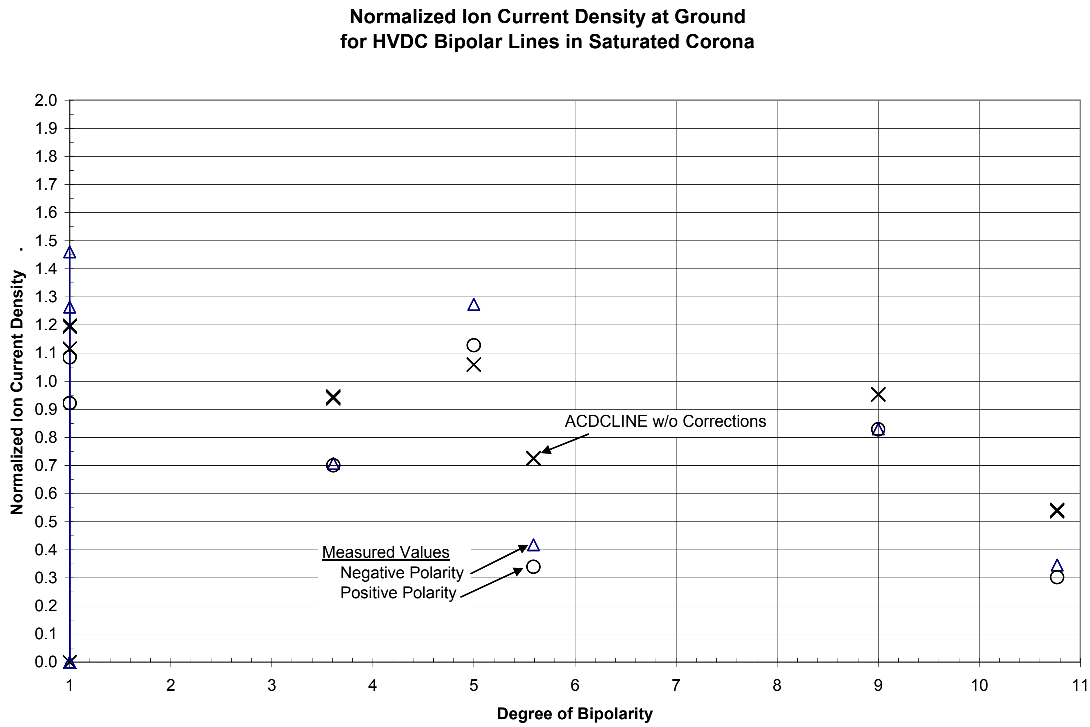

Figure 1-4
Measured positive and negative normalized ion current density compared with values calculated by ACDCLINE without corrections, versus DB

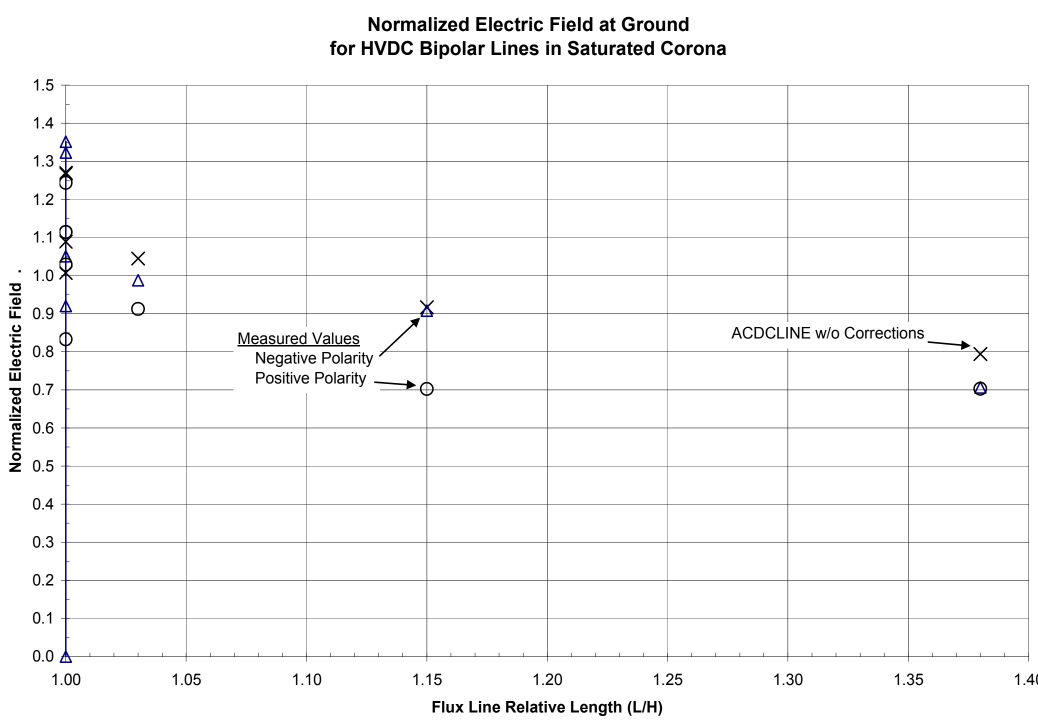

Figure 1-5
Measured positive and negative normalized electric field compared with values calculated by ACDCLINE without corrections, versus L/H

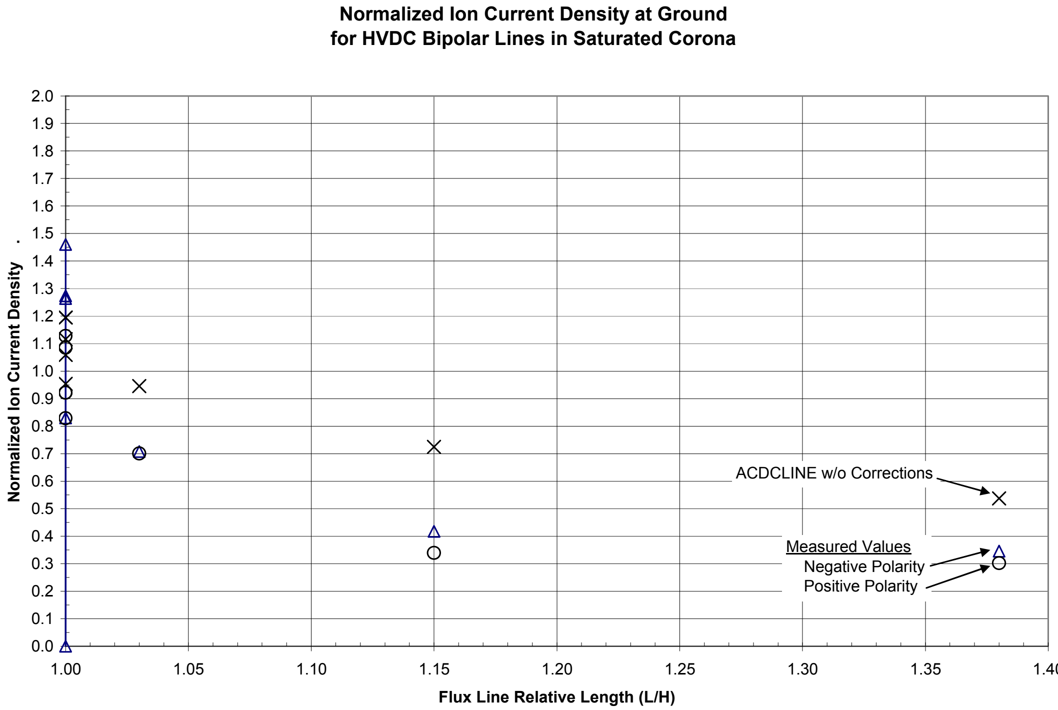

Figure 1-6
Measured positive and negative normalized ion current density compared with values calculated by ACDCLINE without corrections, versus L/H

Review of Corrections for Electric Field

The current version of ACDCLINE applies a negligible correction to account for L/H, so that the actual correction is practically a function of DB only. This is confirmed by the current data, which show no need to correct the peak values of E for L/H, as long as the best possible correction for DB is applied. The deviation between measured and calculated (ACDCLINE without correction) electric field values expressed in percent of the calculated values is shown in Figure 1-7 versus the degree of bipolarity, DB. The figure includes also data from previous results of bipolar horizontal lines with P/H between 1 and 2. The data are reasonably well matched by the empirical equation (1-8).

$$\delta = a - b \cdot (1 - e^{-(DB-1)/c})$$

$$a = 2.6,\ b = 15,\ c = 6 \qquad \textbf{(Eq. 1-8)}$$

The correction factor for E to account for DB is then:

$$FFFE = 1 + \delta / 100 = 1.026 - 0.015 \cdot (1 - e^{-(DB-1)/6}) \qquad \textbf{(Eq. 1-9)}$$

Using this correction factor, the standard deviation of the error is about 2.4%. This means that 95% of the errors are likely to fall between -4.8% and +4.8%.

For comparison, Figure 1-7 reports also the correction currently used by ACDCLINE:

$$FFFE = 0.45 + 1.1 \cdot e^{-0.294(DB-1)} - 0.53 \cdot e^{-0.712(DB-1)} \qquad \textbf{(Eq. 1-10)}$$

The correction factor expressed by Equation (1-10) is obviously not appropriate for values of DB greater than 3.5.

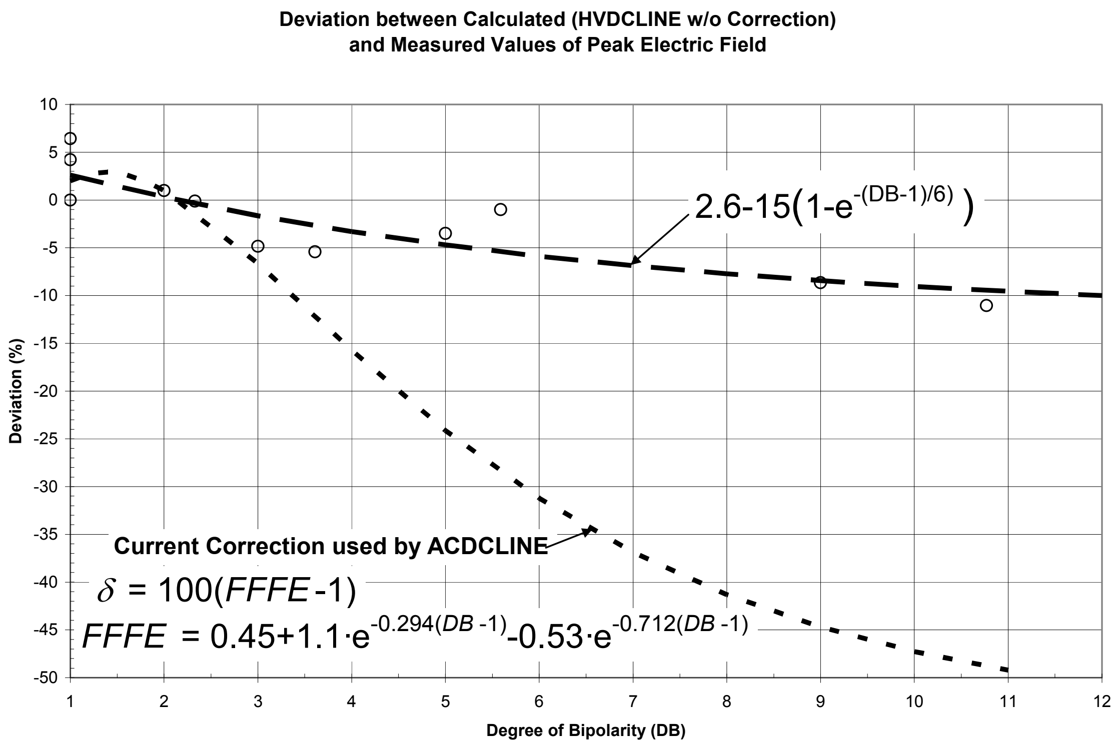

Figure 1-7
Percentage deviation between peak electric field values calculated by ACDDCLINE without correction and measured values versus degree of bipolarity

Review of Corrections for Ion Current Density

The current version of ACDCLINE applies a negligible correction to account for L/H, so that the actual correction is practically a function of DB only. The current data, however, show that the correction factor to apply to ACDCLINE is a complex function of both DB and L/H and probably other parameters that could not be identified. The deviation between measured and calculated (ACDCLINE without correction) peak ion current density values expressed in percent of the calculated values is shown in Figure 1-8. The figure includes also data from previous results of bipolar horizontal lines with P/H between 1 and 2. The best match is obtained by the empirical equation (1-12).

$$\delta = a - b \cdot (1 - e^{-(DB-1)/c})$$

$$a = 19.8,\ b = 40.5,\ c = 1.04 \qquad \textbf{(Eq. 1-12)}$$

The correction factor for E to account for DB is then:

$$FFFJ = 1 + \delta / 100 = 1.198 - 0.405 \cdot (1 - e^{-(DB-1)/1.04}) \qquad \textbf{(Eq. 1-13)}$$

Using this correction factor, the standard deviation of the error is about 16%. This means that 95% of the errors are likely to fall between -32% and +32%.

For comparison, Figure 1-7 reports also the correction currently used by ACDCLINE:

$$FFFJ = 0.4 + 0.87 \cdot (1 - e^{-0.39(DB-1)}) \qquad \textbf{(Eq. 1-14)}$$

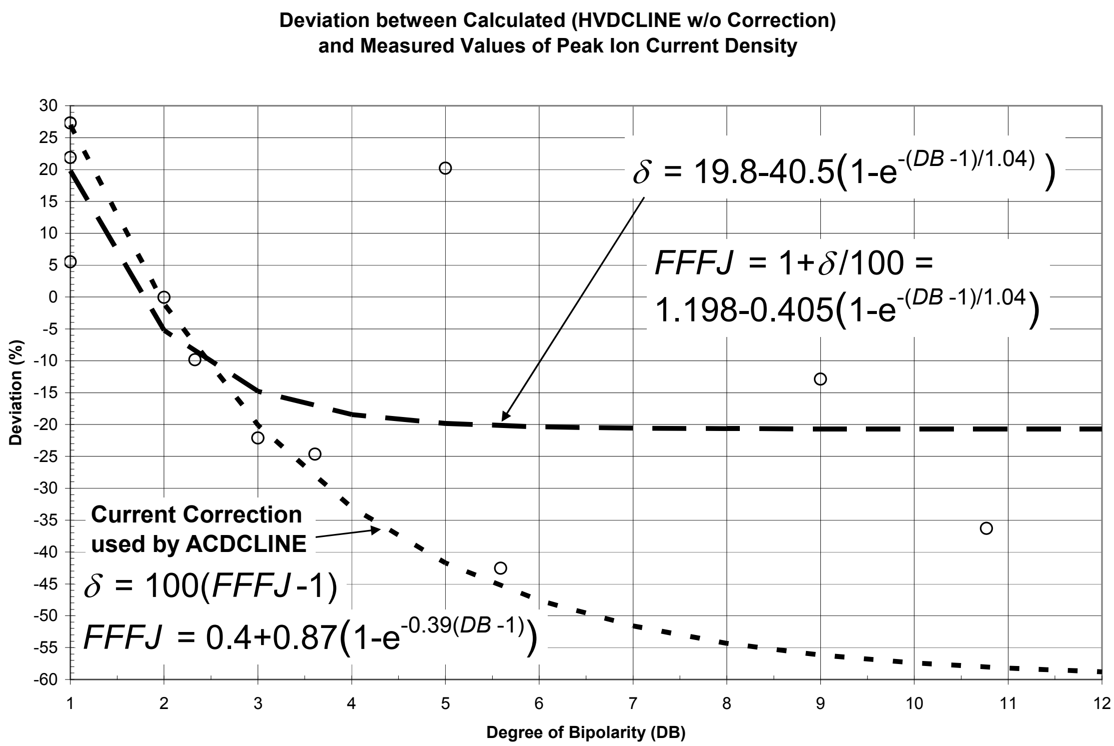

Figure 1-8
Percentage deviation between peak ion current density values calculated by ACDCLINE without correction and measured values versus degree of bipolarity

Search for Better Correction Factors

The correction factors currently applied by ACDCLINE are not appropriate for DB > 3.5. This is obvious from observation of Figures 1-7 and 1-8. In addition, Figure 1-8 shows that the correction to apply to peak ion current density is not a simple function of the degree of bipolarity, DB, as it is currently defined. The effect of degree of bipolarity on bipolar vertical lines is small. It appears that the vertical pole spacing should not be taken into account to the same degree as the horizontal pole spacing. This consideration led to define a new value of the degree of bipolarity, DBN, to be used to correct ion current density values.

For a line with several poles, the degree of bipolarity of pole i, DBN_i, is defined as:

$$DBN_i = \frac{V_i / H_i + \sum_{j \neq i} (V_i - V_j) \cdot (PH_{ij} / P_{ij}^2 + 0.003 \cdot \frac{PV_{ij}}{P_{ij}^2} \cdot (H_i / PV_{ij})^3)}{V_i / H_i} \quad \text{(Eq. 1-15)}$$

V_i and V_j are the voltages of pole i and of pole j, respectively.

H_i and H_j is the heights above ground of pole i, and of pole j, respectively.

P_{ij} is the distance between pole i and of pole j.

PH_{ij} is the horizontal component of P_{ij}.

PV_{ij} is the vertical component of P_{ij}.

The deviation between measured and calculated (ACDCLINE without correction) peak ion current density values reported as a function of the newly defined degree of bipolarity, DBN, is shown in Figure 1-9. The data are reasonably well matched by the empirical equation (1-16).

$$\delta = a - b \cdot (1 - e^{-(DBN-1)/c})$$
$$a = 18.8,\ b = 59.8,\ c = 1.94 \quad \text{(Eq. 1-16)}$$

The correction factor for J to account for DBN is then:

$$FFFJ = 1 + \delta / 100 = 1.188 - 0.598 \cdot (1 - e^{-(DBN-1)/1.94}) \quad \text{(Eq. 1-17)}$$

Using this correction factor, the standard deviation of the error is about 6%. This means that 95% of the errors are likely to fall between -12% and +12%.

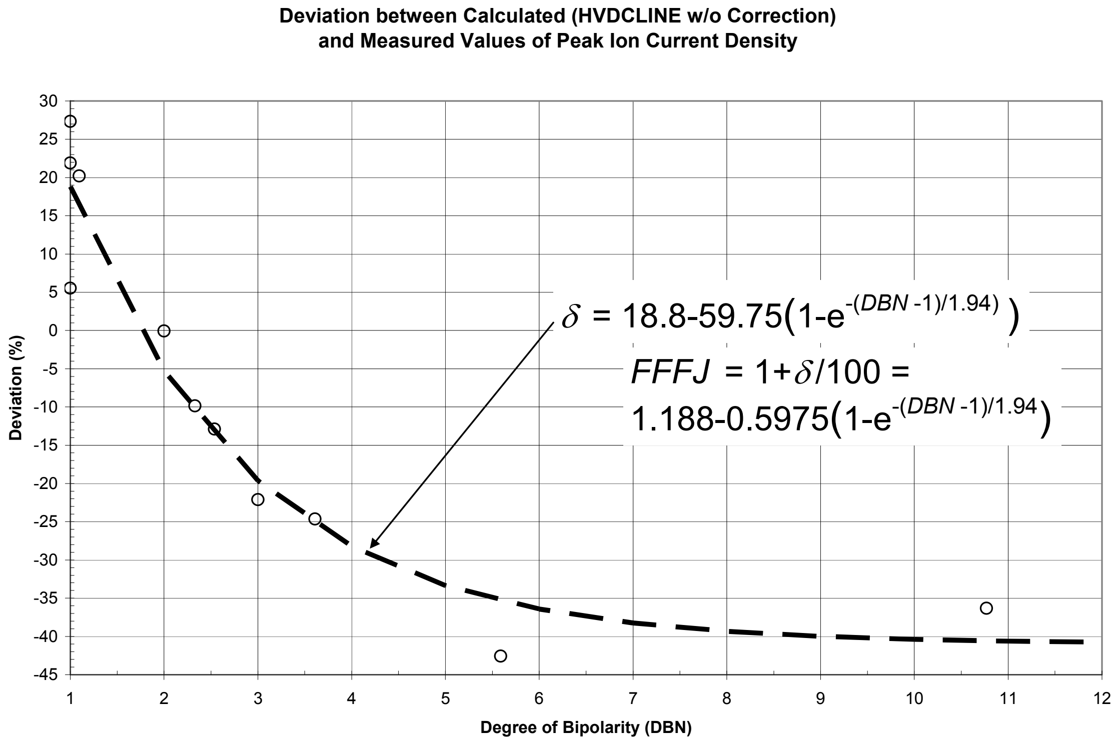

Figure 1-9
Percentage deviation between peak ion current density calculated by ACDCLINE without correction and measured values versus the newly defined degree of bipolarity, DBN

Conclusions

Calculations of electric field and ion current density at ground level should be made using the Deutsch assumption and the following correction factors:

Correction factors to account for flux line length should be the same as those used by the current version of ACDCLINE. There is no reason to modify them. They are:

$$FFE = e^{-(L/H-1)/22.5} \qquad \textbf{(Eq. 1-18)}$$

$$FFJ = (FFE)^{\wedge}2 \qquad \textbf{(Eq. 1-19)}$$

FFE is the correction factor to apply to saturated electric fields at ground

FFJ is the correction factor to apply to saturated ion current densities at ground

L is the length of the flux lines

H is the height of the conductor above ground

Correction factors to account for the proximity between poles at different voltages should be modified. The proximity to other poles is defined by the degree of bipolarity. The degree of bipolarity is a measure of deviation from the monopolar mode of energization. Two different degrees of bipolarity are defined, one (*DB*) to be used for correcting electric field, and the other (*DBN*) to be used for correcting ion current density. For a monopolar line, *DB* = 1 and *DBN* = 1.

For a line with several poles, the degree of bipolarity, *DB*, of pole *i* is:

$$DB_i = \frac{V_i / H_i + \sum_{j \neq i} (V_i - V_j) / P_{ij}}{V_i / H_i} \qquad \textbf{(Eq. 1-20)}$$

V_i is the voltage of pole *i*

V_j is the voltage of pole *j*

H_i is the height above ground of pole *i*

P_{ij} is the distance between pole *i* and pole *j*

For a line with several poles, the degree of bipolarity, *DBN*, of pole *i* is:

$$DBN_i = \frac{V_i / H_i + \sum_{j \neq i} (V_i - V_j) \cdot (PH_{ij} / P_{ij}^2 + 0.003 \cdot \frac{PV_{ij}}{P_{ij}^2} \cdot (H_i / PV_{ij})^3)}{V_i / H_i} \qquad \textbf{(Eq. 1-21)}$$

PH_{ij} is the horizontal component of P_{ij}.

PV_{ij} is the vertical component of P_{ij}.

The correction factor for the electric field to account for the degree of bipolarity is:

$$FFFE = 1.026 - 0.015 \cdot (1 - e^{-(DB-1)/6}) \qquad \textbf{(Eq. 1-22)}$$

The correction factor for the ion current density to account for the degree of bipolarity is:

$$FFFJ = 1.188 - 0.598 \cdot (1 - e^{-(DBN-1)/1.94}) \qquad \textbf{(Eq. 1-23)}$$

References

1. *Electrical Effects of HVDC Transmission Lines: 2011 Tests and Results from the EPRI High Voltage Laboratory*. EPRI, Palo Alto, CA: 2011. 1021958.
2. W.Deutsch, Ann. Phys. (Leipzig) Vol. 16, 588 (1933).
3. *Electrical Effects of HVDC Transmission Lines - 2012*. EPRI, Palo Alto, CA: 2012. 1024328.
4. *HVDC Transmission Line Reference Book*. EPRI, Palo Alto, CA: 1993. TR-102764.

2
CORONA SOURCE STUDY

Prediction of the magnitude of electric field and ion current density at ground level near overhead HVDC transmission lines is based on the results of long term testing and on theoretical models. Corona is assumed to be generated uniformly along the line and the results obtained at one location are assumed representative of the entire line. Even though it is known that corona is generated by individual sources, corona sources are usually considered in their totality by defining an equivalent conductor surface roughness to which corresponds a given corona inception surface gradient.

To go beyond this simplification a systematic study of electrical effects of individual corona sources was initiated in 2011 [1], was continued in 2012 [2], and was completed in 2013. The study was conducted with scale model tests in which voltages and dimensions were appropriately scaled. Scale model tests were validated with full scale tests performed in 2011 [1]. Several tests were made in 2012 [2] to measure ion plume size, ion current density and electric field either at different lateral distances from the source (lateral profiles) or on a grid of points (contour lines) at ground, maximum ion current density, maximum electric field, and total ion plume current as a function of polarity of the pole where the source was placed, inception surface gradient of the source, and location of the source on the conductor surface. Most of the tests were performed on monopolar configurations. The characteristics of the ion plume generated by a single source on a monopolar line were obtained. Only a few tests were performed on bipolar lines. In 2013, tests were performed to complete the investigation about corona plumes from a single source on a bipolar configuration. The tests performed are listed in Appendix 1. The detailed test results are shown in Appendix 3.

Review of Results with a Single Source on a Monopolar Line

A typical representation of results obtained with a single source on a monopolar line is shown in Figures 2-1 and 2-2. The values of J and E at the center of the plume are compared with the saturated values and may be expressed as a percentage of the saturated values. The degree of corona saturation depends on the corona inception voltage of the source, which also may be expressed in percentage of the line voltage. Peak electric field and peak ion current density in an ion plume from an individual source are shown as a function of corona inception voltage in Figure 2-3. The highest peak values occur when the corona inception voltage of the source is zero, but are always lower than the values which occur when the conductor is in corona with zero inception voltage over its entire length. We will show in this report that the situation is quite different for bipolar configurations with a single source on one of the two poles. In these cases peak values of electric field and ion current density in the corona plume may exceed the values that occur when both poles are in uniform corona with zero corona inception voltage.

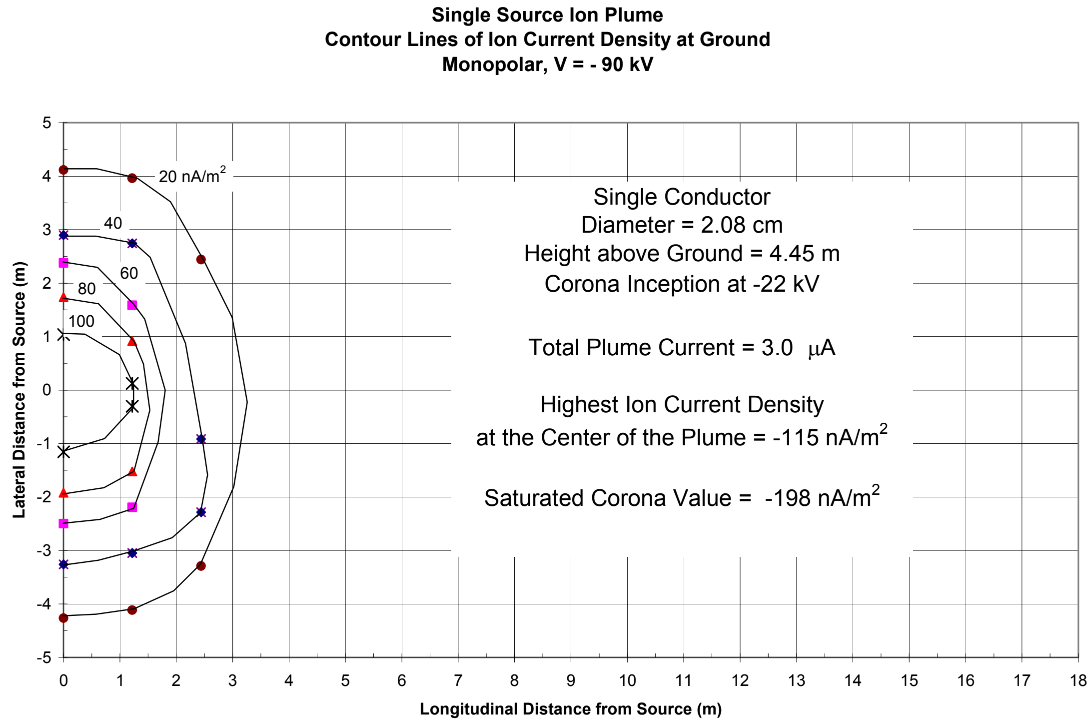

Figure 2-1
Contour lines of ion current density at -90 kV for the ion plume of a single source with corona inception at -22 kV

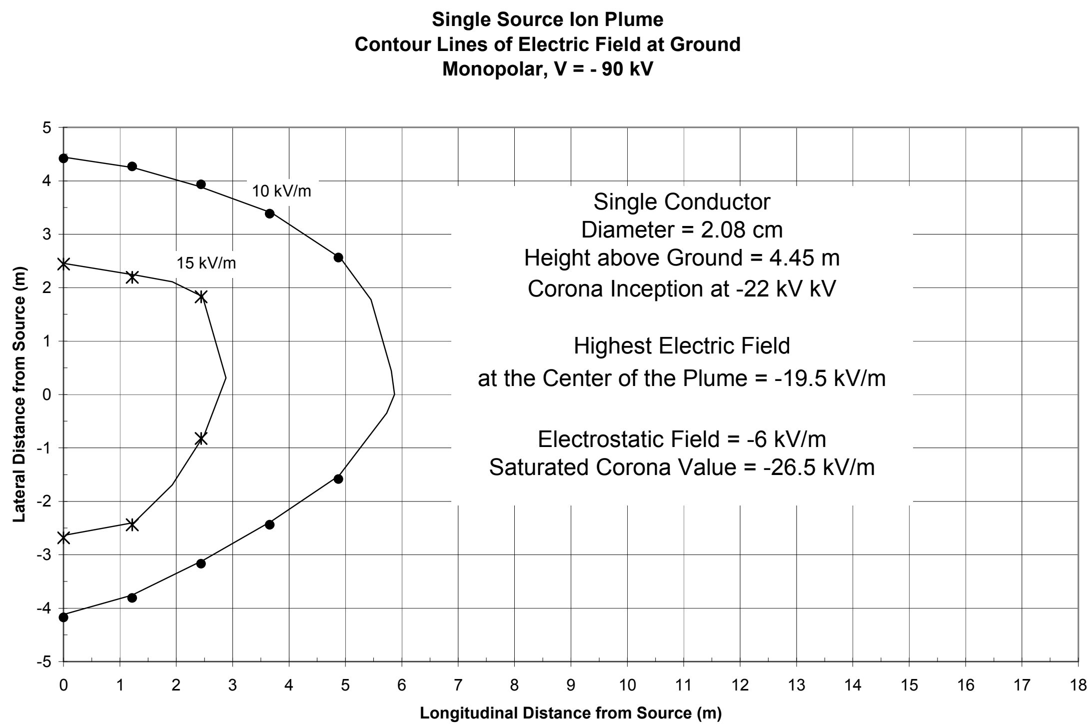

Figure 2-2
Contour lines of electric field at -90 kV for the ion plume of a single source with corona inception at -22 kV

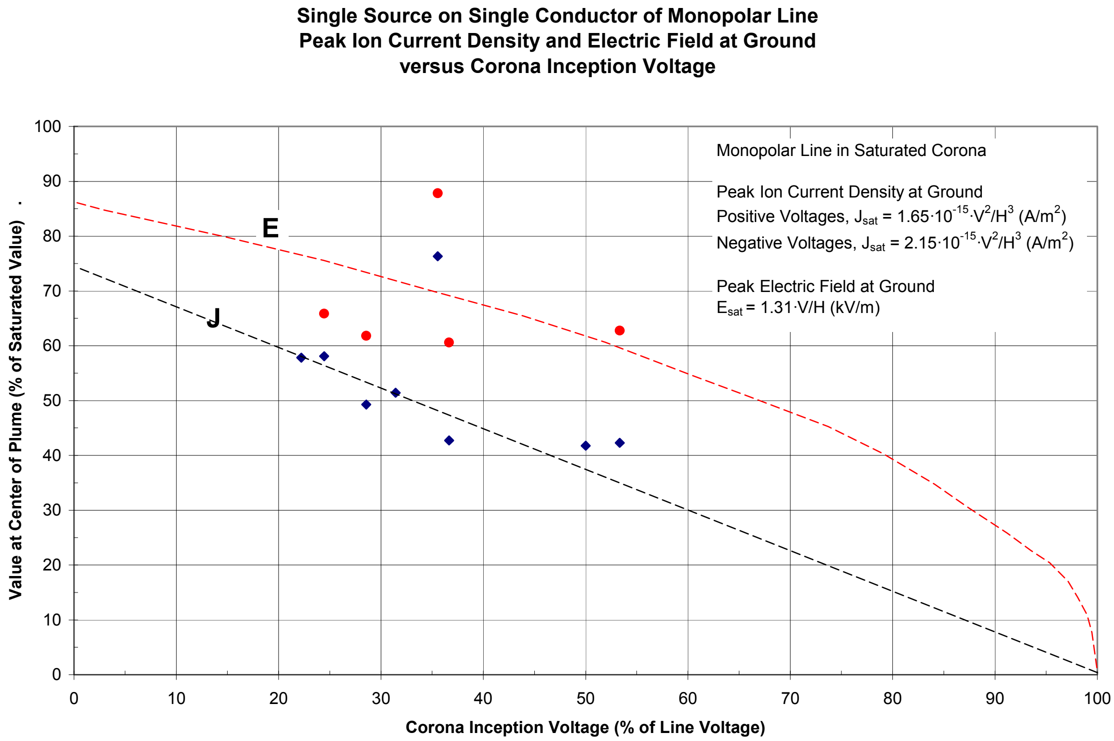

Figure 2-3
Values of J and E at the center of the ion plume of a single source versus corona inception

Bipolar Tests

The ion plume from a single source on a bipolar line produces J and E at ground level described as in the example of Figures 2-4 and 2-5. These figures refer to a single source placed at the bottom of the single conductor of the negative pole of a bipolar line. The line configuration was horizontal with height above ground of 4.45 m and pole spacing of 2.67 m. The conductor diameter was 2.08 cm. The voltage was ± 90 kV.

Each graph reports also the highest values measured at the center of the plume and the values that would occur in saturated corona conditions, with both poles covered with sources with corona inception equal to zero. In this example the peak ion current density at the center of the plume is about 105% of the peak ion current density with both poles in uniform saturated corona. The plume corona inception voltage was about 28% of the line voltage. Much higher ion current densities would occur if the plume inception voltage were zero.

A summary of all ion plume data obtained from 2011–2013 tests on bipolar lines with a single source is reported in Table 2-1.

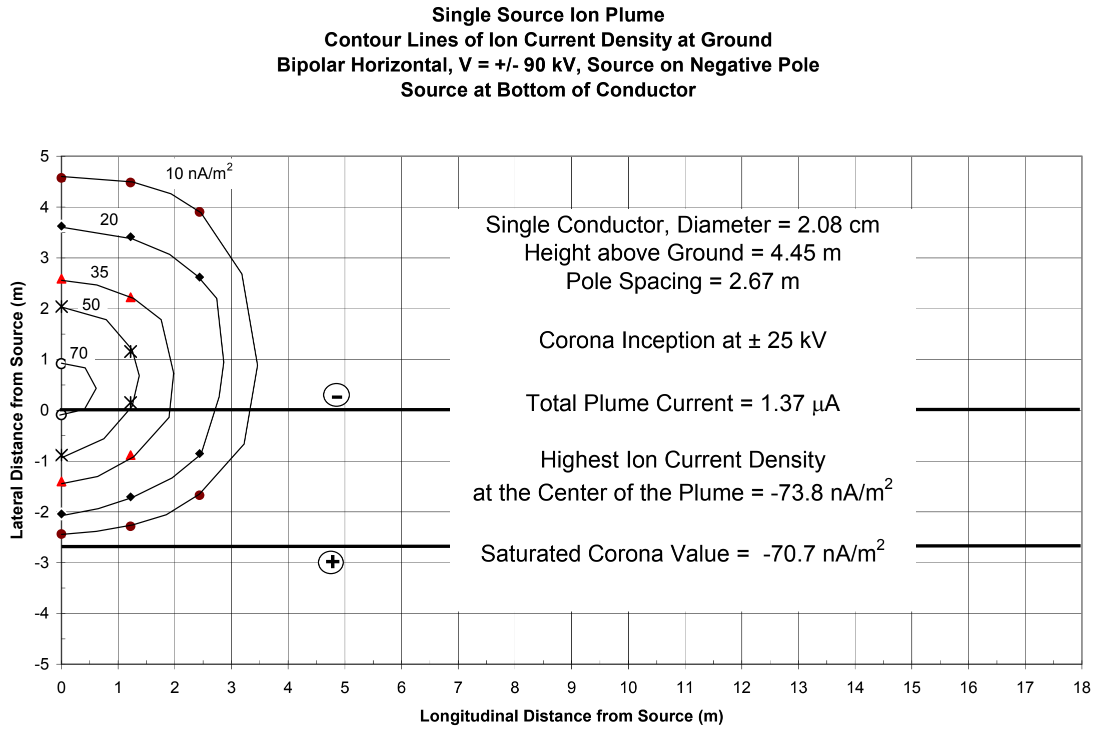

Figure 2-4
Contour lines of ion current density at ±90 kV. Single source at bottom of negative pole

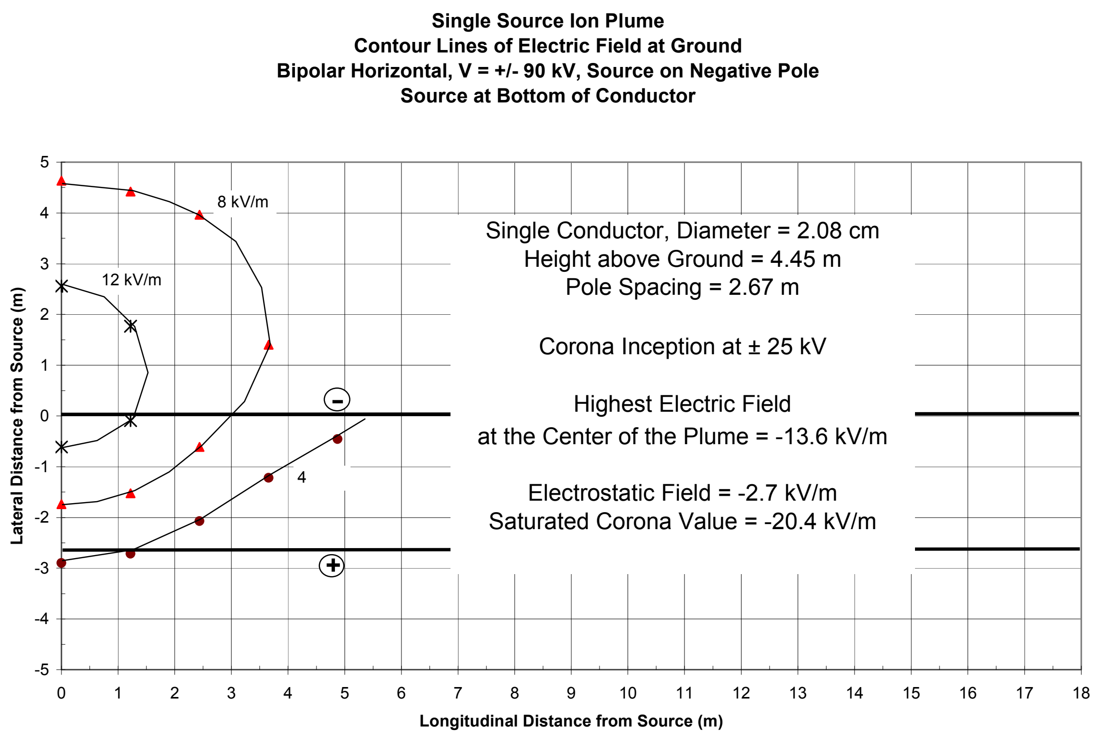

Figure 2-5
Contour lines of electric field at ±90 kV. Single source at bottom of negative pole

Table 2-1
Peak values of J and E – single source on bipolar line

Conduct. nxcm	H m	P m	Source Polarity	V	Inception Voltage		J_s	J Peak		E_0	E_s.	E Peak	
			+ or -	± kV	± kV	%	nA/m²	nA/m²	%	kV/m	kV/m	kV/m	%
2x2.08	4.23	2.24	+	50	27	54	18.6	11.5	62	2.0	11.8	6.75	49
2x2.08	4.23	2.24	-	50	21	41	-24.3	-15	62	-2.0	-11.8	-7.9	60
2x2.08	4.23	2.24	-	50	17	34	-24.3	-23.6	97	-2.0	-11.8	-7.9	60
1x2.08	4.20	4.20	+	30	10	35	9.7	5.75	59	1.3	7.9	6.15	73
1x2.08	4.20	4.20	+	45	10	23	22.2	14.6	66	2.0	12.0	9.45	75
1x2.08	4.20	4.20	-	30	9	31	-12.6	-7.9	63	-1.3	-7.9	-6.3	76
1x2.08	4.20	4.20	-	45	9	21	-29	-25	86	-2.0	-12	-10	80
1x2.08	4.20	4.20	-	60	9	16	-52.6	-45	86	-2.7	-16.1	-14	84
1x2.08	4.45	2.67	-	50	25	50	-21.1	-11.3	54	-1.5	-11.2	-7.1	58
1x2.08	4.45	2.67	-	90	25	28	-70.7	-65.8	93	-2.7	-20.4	-13.5	61
1x2.08	4.45	2.67	+	50	25	50	16.2	12.4	77	1.5	11.2	6.3	50
1x2.08	4.45	2.67	+	90	25	28	54.3	79	146	2.7	20.4	17.5	84
1x2.08	4.45	2.67	-	90	25	28	-70.7	73.8	104	-2.7	-20.4	-13.6	62

The peak values of J and E at ground level may be expressed as degree of corona saturation. The degree of corona saturation of ion plume ground level J is equal to the ratio (which can be expressed as a percentage) between the peak J in the plume and the peak J when both poles are in saturated corona (J_s). The degree of corona saturation of the peak level of J in the ion plume depends on the corona inception voltage of the source, which also may be expressed in percentage of the line voltage. The degree of the peak level of E in the ion plume, $\alpha_{E,plume}$, is referred to the peak level of E when both poles are in saturated corona (E_s), using Equation (2.1) where E_0 is the electrostatic field.

$$\alpha_{E,plume} = 100 \cdot \frac{E_{peak} - E_0}{E_s - E_0} \qquad \textbf{(Eq. 2.1)}$$

The degrees of corona saturation of electric field and ion current density in the ion plume for the tests performed are shown as a function of corona inception voltage in Figure 2-6. The data are scattered in an irregular manner, probably reflecting the effect of different parameters such as single conductors versus bundles and pole spacing to height ratio. There is a clear trend toward increasing E and J values for decreasing corona inception voltages. It is also clear that the ion current density at ground at the center of the plume of a single source of a bipolar line may be greater than the ion current density of the same line when both poles are in saturated corona along the entire length of the line.

A less disperse correlation between degree of corona saturation of the ion current density of the plume and corona inception voltage is obtained by referring the peak level of J in the plume to the saturated value of a monopolar line with the same height. This is shown in Figure 2-7. It appears that the space charge created by a single source may overwhelm the effect of the charges on the other pole, to the point of making the line appear as monopolar.

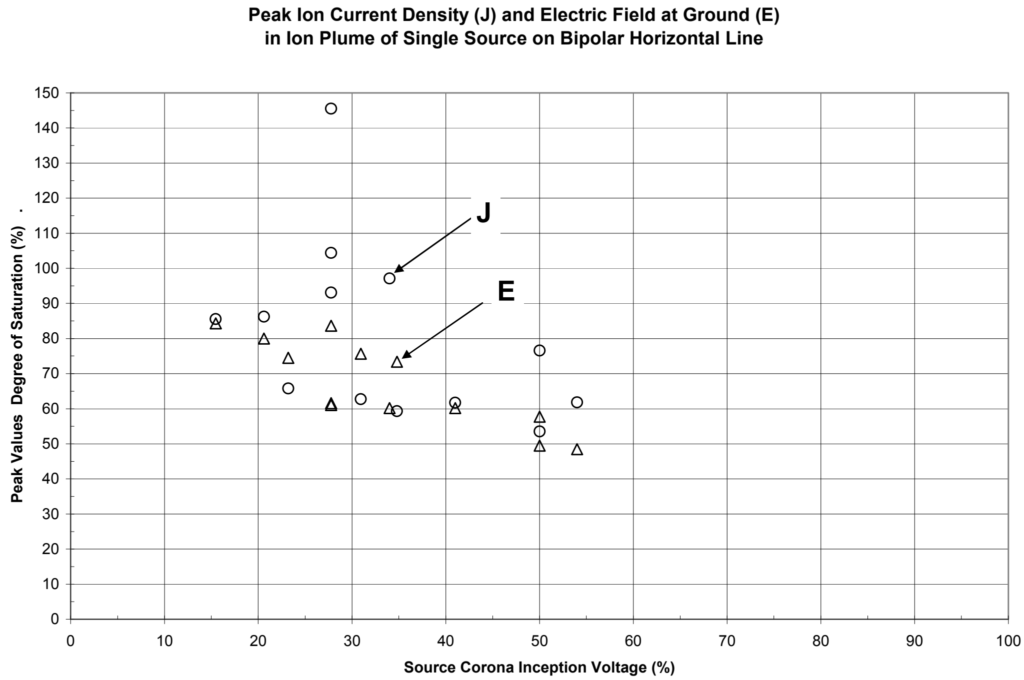

Figure 2-6
Values of J and E at the center of the ion plume of a single source versus corona inception

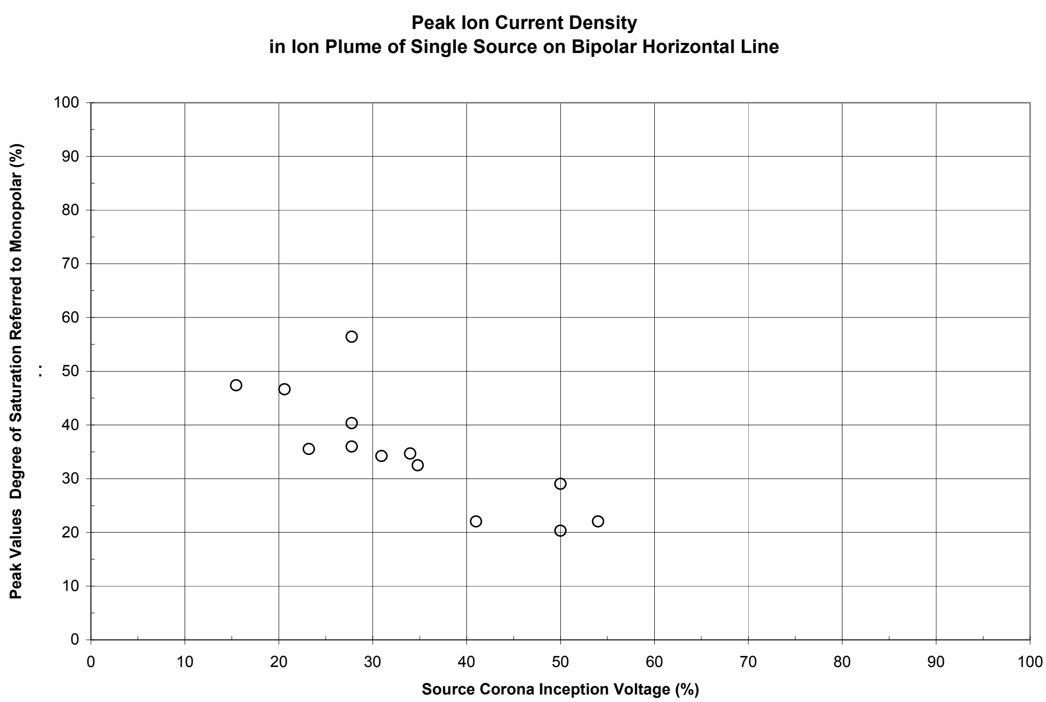

Figure 2-7
Values of J (relative to monopolar saturated values) at the center of the ion plume of a single source versus corona inception

Ion Plume Size

The shape of the ion plume when it reaches ground is shown in Figure 2-1 and Figure 2-4, for the monopolar and for the bipolar pole, respectively. The plume width is characterized by the “half value width”, W_p, defined as the distance between points where the ion current density is one half of that at the center of the plume. The lateral and longitudinal widths are reported in Table 2-2 for all tests performed with a single source on a bipolar line. The plume shape appears independent of the applied voltage. Lateral half-value widths are about equal to the height above ground of the conductor where the source is located. Longitudinal widths are on average 10% shorter than lateral widths. The total width of the plume could be determined accurately in the longitudinal direction only, in which case it was found about 40% larger than the half-value width.

Table 2-2
Lateral and longitudinal widths of ion plume from a single source

Conduct. nxcm	H m	P m	Source Polarity + or -	Lateral Half-Value Width (m)	Longitudinal Half-Value Width (m)	Longitudinal Width (m)
2x2.08	4.23	2.24	+	3.4		
2x2.08	4.23	2.24	-	4.4		
2x2.08	4.23	2.24	-	3.8	2.8	4.3
1x2.08	4.20	4.20	+	4.4	4.1	5.2
1x2.08	4.20	4.20	+	4.5	3.85	6.0
1x2.08	4.20	4.20	-	4.2	4.1	5.0
1x2.08	4.20	4.20	-	4.2	3.85	5.0
1x2.08	4.20	4.20	-	4.2	4.4	5.0
1x2.08	4.45	2.67	-	3.5		
1x2.08	4.45	2.67	-	4.1		
1x2.08	4.45	2.67	+	4.4		
1x2.08	4.45	2.67	-	4.0	4.0	7.5

Corona Sources – Inception Gradient of Insects

Previous research has concluded that the highest levels of fair weather corona occur in the summer and that the predominant sources are insects, mostly mosquitoes, attached to the conductors. This is the experience in Northeastern United States and, presumably, in all the regions where there are mosquitoes. Tests performed in 2012 have found that corona inception of dead insects (mosquitoes, lighting bugs, moths) occurs when the conductor surface electric field is about 7 kV/cm. Tests performed in 2013 (see Appendix 3) have found that mosquitoes have an initial corona inception gradient of 1.5-3 kV/cm, which increases to 5-6 kV/cm within 1 to 3 hours of energization. After that, corona inception remains fairly constant for at least 5 to 7 hours. Eventually [3] the body of the mosquitoes will be dehydrated and eroded under the action of corona and corona inception will rise until, after a few weeks, corona will disappear. The initial very low value of corona inception gradient is attributed to the extremely small size of the legs, as shown in Figure 2-8. Initially the legs are conductive. However, under the action of corona the legs dehydrate and corona inception increases.

Figure 2-8
Mosquito on a test conductor energized with HVDC

HVDC transmission lines operate at conductor surface gradients of 18-26 kV/cm. Therefore, corona inception voltage of a freshly deposited mosquito may start as low as 10% of the operating voltage, rise to about 30% in a couple of hours and remain at that value for several hours.

Water drops are also a major source of corona. The corona inception gradient of a dripping water drop is estimated at about 5 k/cm.

A single corona source located at the bottom of a single conductor of a pole of a bipolar line with height, *H*, and pole spacing, *P*, with no wind produces a peak ion current density, J_{max}, at the center of the plume that may be greater than the value obtained when both poles are in uniform saturated corona. The space charge created by the plumes is making the charge on the other pole, which is not in corona, less significant in determining the shapes of the flux lines. The lateral distance of the plume center moves closer to the point directly underneath the source. As corona from the source increases, the line appears as if it were monopolar, in which case the peak saturated ion current density is significantly greater than for a bipolar line.

Discussion

The peak ion current density and the peak electric field at ground at the center of an ion plume generated by a single corona source on a bipolar HVDC transmission line may have values as high as the largest that could be measured for that line. Corona sources vary in number, depending on season (more fair weather sources are deposited on the conductors in the summer and almost none in the winter) and nature of terrain (more insects are deposited in wooded areas and near wetlands) and on the polarity of the conductor (more insects are deposited on the positive than on the negative pole), and in the value of their corona inception gradient, which depends on the type of source and on the duration of source energization since the time the source is first deposited on the line.

These findings make it obvious that the predictions of ion current density and electric field at ground cannot be made using the assumption of uniform corona along the line with a given corona inception gradient. Ion current density and electric field vary greatly from time to time and from location to location. Their magnitude can be expressed only as a statistical quantity by estimating the values that will not be exceeded for a given percentage of time, for instance L50 (value not exceeded 50% of the time) and L95 (value not exceeded 95% of the time). These non-exceedance values may be estimated by long-term measurements at a location that is typical of the section of the line under study. The findings of the corona source study re-enforce the validity of the approach developed by EPRI [3] and described in Section 1 of this report. The ACDCLINE software is based on this approach and is applicable to the Northeast climate and, presumably, to all the regions where there are mosquitoes. Following this approach, for instance, in summer fair weather a bipolar line operating at a conductor surface gradient of 21 kV/cm has a degree of corona saturation $\alpha 50 = 36\%$ and $\alpha 95 = 70\%$ for positive polarity and $\alpha 50 = 16\%$ and $\alpha 95 = 44\%$ for negative polarity. By comparison a single source consisting of a freshly deposited mosquito has a corona inception gradient of 7-14%, to which corresponds a degree of corona saturation around 100%. In 1-3 hors corona inception rises to 25-30%, to which corresponds a degree of corona saturation around 80%. Obviously, the probability that the ion current density is measured exactly at the center of a single source plume is very small. In addition, wind and other sources will smooth out the effect of a single source. In sum, single source value may be reached occasionally and at few points, but can hardly be used to predict the statistical behavior of HVDC corona.

References

1. *Electrical Effects of HVDC Transmission Lines - 2011. Tests and Results from the EPRI High Voltage Laboratory*. EPRI, Palo Alto, CA: 2011. 1021958.
2. *Electrical Effects of HVDC Transmission Lines - 2012*. EPRI, Palo Alto, CA: 2012. 1024328.
3. *HVDC Transmission Line Reference Book*. EPRI, Palo Alto, CA: 1993. TR-102764.

3
CONCLUSIONS AND RECOMMENDATIONS

It was found that the algorithms currently used by ACDCLINE software to calculate electrical effects are not valid for HVDC line configurations different from monopolar and bipolar horizontal or when the ratio between pole spacing and height above ground is less than 1. As a result of the tests performed in 2012 and 2013 a modification of correction factors used by ACDCLINE is recommended. The new correction factors are described in the "Conclusions" of Section 2, equations (1-21), (1-22), and (1-23).

The study of the characteristics of ion plumes generated by individual sources of corona has evidenced the complexity of the electric field and ion environment of an HVDC/Hybrid line and demonstrated the wisdom of the empirical approach used by ACDCLINE. Ion current density and electric field vary greatly from time to time and from location to location. Their magnitude can be expressed only as a statistical quantity by estimating the values that will not be exceeded for a given percentage of time, for instance L50 (value not exceeded 50% of the time) and L95 (value not exceeded 95% of the time). These non-exceedance values may be estimated by long-term measurements at a location that is typical of the section of the line under study. ACDCLINE software is based on this approach and is applicable to the Northeast climate and, presumably, to all the regions where there are insects that may be deposited on the conductors. It is recommended that the findings of the individual source study be published in order to stimulate a discussion on the implications of the study regarding line design.

It is recommended to continue research on methods to reduce electric fields and ion current densities at ground. Both passive and active shielding should be considered. Passive shielding consists of stringing wires at grounds potential above the area to be shielded. Active shielding consists of stringing special wires at ground potential under the HVDC conductors. These special wires should be either of small diameter or with protrusions such to produce corona and emit ions of opposite polarity to those produced by the line conductors, in order to neutralize the electrical effects of the line. It is recommended to develop design rules derived from well planned model tests. The design rules should then be validated by full-scale line tests.

A

TESTS PERFORMED IN 2013

Test Requirements

The tests performed in 2013 consisted of reduced-scale tests. As a result of tests performed in previous years, there were 4 aluminum conductors (diameter = 2.08 cm) that could be strung from one side to the other side of the UHV building in a setup that allows adjusting their height above the floor and lateral location with respect to each other. No other aluminum conductors were needed. Stringing of two Bekinox conductors was required during the tests. The following other requirements were followed:

- The test area below the conductors was made free as much as possible, by removing and placing elsewhere objects that were in the test area.
- A new ion current plate was constructed. It consisted of a square, 19" x 19", aluminum plate with a 2" guard ring and a ½" gap between plate and guard ring. Plate and guard ring were glued on a square (24" x 24") sheet of insulation. Another aluminum plate (24" x 24") was glued below the insulation. The bottom plate and the guard ring were connected to the grounded shield of a coaxial cable, while the top plate was connected to the center conductor of the cable. The plate equivalent area was 0.2453 m^2.
- Generators, divider, field meter, and ion current plate instrumentation were setup. Two generators were used. The + (or -) 100 kV HVDC supply, which can reach 90 kV, and a supply rated 120 kV (positive polarity only). The maximum voltage needed for the tests was ± 90 kV. A Phoenix Technology divider was used to measure the voltage. Two DC electric field meters (Monroe DC Electric Field Probes) were connected to a Field Meter Monroe Electronics Model 171. The ion current plate was connected to a Keith Electrometer 610 CR.
- During the tests the door of the building remained closed to avoid movement of air inside the building.

Calibration and Test Setup

Calibration of the E-Field meters was performed by placing the field meter at the center of the bottom plate of a two plate setup. The plates were made of aluminum and were 6 feet long and 4 feet wide. One plate was placed on the ground and the other on post insulators directly above the bottom plate. The separation between plates was H = 25 ¼". The plate end effect at the meter location was determined to be k = 1.025. The unperturbed electric field at the meter location was calculated, $E = V/(k{\cdot}H)$. A voltage from 0 to 25 kV, both positive and negative, was applied to the top plate, while the bottom plate was grounded. The calibration factor, that is, the ratio between calculated electric field and field meter readout was found independent of applied voltage value and polarity; 0.393 (kV/m)/readout.

Tests were performed from May 21 to May 29, 2013.

Table A-1
Test Sequence

Test (#)	Mon. or Bip.	Single or Bundle	Conductor Type	H1 (m/ft)	H2 (m/ft)	P (m/ft)	V (kV)	Test Type	Profile Lat. or Long.
1									
Bekinox – Monopolar and Bipolar Horizontal									
1.1	M	S	Bekinox	3.83 m 12’7”			0 to -70	E and J	Under conduct.
1.2	B	“	“	4.66 m 15’3 1/4”	4.66 m 15’3 1/4””	0.953 m 3’1.5”	± 71.6	“	Lateral
1.3	“	“	“	4.36 m 14’3 1/2”	4.36 m 14’3 1/2””	1.9 m 6’3”	± 71.1	“	“
1.4	“	“	“	4.48 m 14’8 1/2”	4.48 m 14’8 1/2””	3.43 m 11’4”	± 71.1	“	“
2									
Bekinox – Bipolar Vertical									
2.1	B	S	Bekinox	3.81 m 12’6”	4.76 m 15’7.5	0.95 m 3’1.5”	±70 + on top	E and J	Lateral
2.2	“	“	“	3.81 m 12’6”	4.76 m 15’7.5	0.95 m 3’1.5”	±70 - on top	“	“
2.3	“	“	“	3.8 m 12’6”	5.7 m 18’9”	1.9 m 6’3”	±70 + on top	“	“
2.4	“	“	“	3.8 m 12’6”	5.7 m 18’9”	1.9 m 6’3”	±70 - on top	“	“

Table A-1 (continued)
Test Sequence

Test (#)	Mon. or Bip.	Single or Bundle	Conductor Type	H1 (m/ft)	H2 (m/ft)	P (m/ft)	V (kV)	Test Type	Profile Lat. or Long.
3									
Bekinox – Monopolar									
3.1	M	S	Bekinox	4.66 m 12’6”			-70	E and J	Lateral
3.2	“	“	“	4.66 m 12’6”			+70	“	“
4									
Single Corona Source – Bipolar – Single Conductor (P = H) Source on Negative Conductor									
4.1	B	B	d = 2.08 cm	4.2 m 13’ 10”	4.2 m 13’ 10”	4.2 m 13’10”	0 to ±90	Corona Inception	
4.2	“	“	“	“	“		±30 ±45 ±60	E and J	Lateral
4.3	“	“	“	“	“		±30 ±45 ±60	J	Longit.

Table A-1 (continued)
Test Sequence

Test (#)	Mon. or Bip.	Single or Bundle	Conductor Type	H1 (m/ft)	H2 (m/ft)	P (m/ft)	V (kV)	Test Type	Profile Lat. or Long.
5									
Single Corona Source – Bipolar – Single Conductor (P = H) Source on Positive Conductor									
5.1	B	B	d = 2.08 cm	4.2 m 13'10"	4.2 m 13'10"	4.2 m 13'10"	0 to ±90	Corona Inception	
5.2	"	"	"	"	"		±30 ±45 ±60	E and J	Lateral
5.3	"	"	"	"	"		±30 ±45 ±60	J	Longit.
6									
Four different insects were placed, two on the positive conductor (16' from each other) and two on the negative (16' from each other). A bipolar voltage, ± 60 kV was applied for 6.5 hours. Ion current density was monitored under each source.									
6.1	B	S	d = 2.08 cm	4.2 m 13' 10"			±60	J	Under each source
6.2	"	"	"	"	After 6.5 hours of energization		0 to ±90	Cor. Inc.	Under each source

B
RESULTS OF TESTS ON CONDUCTORS WITH SATURATED CORONA

The measured lateral profiles of electric field and ion current density at ground are shown in Figures B-1 to B-6. The peak values of measured electric field and ion current density at ground are reported in Table 1 of this Appendix. The table reports also the values calculated using three different methods: (1) ACDCLINE without correction factors, (2) ACDCLINE with correction factors, and (3) empirical equations described in "HVDC Transmission Line Reference Book, EPRI TR-102764, September 1993" (and shown in the equations below).

For bipolar horizontal lines with height above ground H, pole spacing P, and voltage V:

$$E_{\max} = 1.31 \cdot \frac{V}{H} \cdot (1 - e^{-1.7 \cdot P/H}) \text{ for both polarity} \qquad \textbf{(Eq. B-1)}$$

$$J_{\max}(+) = 1.65 \cdot 10^{-15} \cdot \frac{V^2}{H^3} \cdot (1 - e^{-0.7 \cdot P/H}) \qquad \textbf{(Eq. B-2)}$$

$$J_{\max}(-) = -2.15 \cdot 10^{-15} \cdot \frac{V^2}{H^3} \cdot (1 - e^{-0.7 \cdot P/H}) \qquad \textbf{(Eq. B-3)}$$

For bipolar vertical lines with lower pole height above ground H, pole spacing P, and lower pole voltage V:

$$E_{\max} = \frac{V}{H} \cdot (0.75 + 0.56 \cdot (1 - e^{-1.7 \cdot P/H}) \qquad \textbf{(Eq. B-4)}$$

$$J_{\max}(+) = 0.77 \cdot 10^{-15} \cdot \frac{V^2}{H^3} \cdot (0.75 + 0.56 \cdot (1 - e^{-1.7 \cdot P/H}) \qquad \textbf{(Eq. B-5)}$$

$$J_{\max}(-) = 1.00 \cdot 10^{-15} \cdot \frac{V^2}{H^3} \cdot (0.75 + 0.56 \cdot (1 - e^{-1.7 \cdot P/H}) \qquad \textbf{(Eq. B-6)}$$

The voltage and height above ground varied from test to test. In order to better compare the results, the normalized electric field and the normalized ion current density were calculated. The normalized electric field was calculated multiplying the electric field by H/V. The normalized positive ion current density was obtained multiplying the ion current density by H^3/V^2. The normalized negative ion current density was obtained multiplying the ion current density by 0.76 H^3/V^2, where 0.76 is the estimated ratio between positive and negative ion mobility. In this way positive and negative ion current density calculated by ACDCLINE and by the empirical equations will coincide. The normalized electric field and ion current densities for the tests performed are shown in Table 2 of this Appendix.

Table B-1
Test Results Compared with Calculations

					HVDCLINE w/o Correction		Length Correction			DB Correction			HVDCLINE with Correction		Measured		Ref. Book Equations	
	V	H	P	H/P	E	J	L/H	FFE	FFJ	DB	FFFE	FFFJ	E	J	E	J	E	J
	(kV)	(m)	(m)		(kV/m)	(nA/m2)							(kV/m)	(nA/m2)	(kV/m)	(nA/m2)	(kV/m)	(nA/m2)
Monopolar +	70	3.75	∞	0	23.7	111	1.00	1.00	1.00	1.00	1.02	1.27	24.2	144	20.8	85.6	24.45	153.3
Monopolar -	-70	3.75	∞	0	-23.7	-145	1.00	1.00	1.00	1.00	1.02	1.27	-24.2	-183	-24.7	-153	-24.45	-199.8
Monopolar -	-70.1	3.835	∞	0	-23.2		1.00	1.00		1.00	1.02		-23.7		-24.7		-23.95	
Monopolar -	-70.4	3.835	∞	0		-137.1	1.00		1.00	1.00		1.27		-174.1		-167.1		-188.9
Monopolar +	70.5	3.71	∞	0	24.1	109.0	1.00	1.00	1.00	1.00	1.02	1.27	24.6	138.5	23.67	106	24.90	160.8
Bipolar Vertical;	±70	3.81	1.905	2	20	93.8	1.00	1.00	1.00	5	0.76	0.58	15.1	54.4	18.9	99.9	19.67	71.44
Bipolar Vertical;	±70	3.81	1.905	2	-20	-122.3	1.00	1.00	1.00	5	0.76	0.58	-15.1	-70.9	-19.3	-147	-19.67	-93.09
Bipolar Vertical;	±70	3.81	0.95	4	18.5	84.5	1.00	1.00	1.00	9	0.55	0.44	10.2	36.9	15.3	73.4	17.33	57.10
Bipolar Vertical;	±70	3.81	0.95	4	-18.5	-110	1.00	1.00	1.00	9	0.55	0.44	-10.2	-48.5	-16.9	-95.8	-17.33	-74.41
Bipolar Horizontal; Positive side	±71.2	4.48	3.434	1.31	16.6	53.3	1.03	0.999	0.997	3.61	0.878	0.714	14.6	37.7	14.5	39.5	15.16	38.63
Bipolar Horizontal; Negative side	±71.2	4.48	3.434	1.31	-16.6	-69	1.03	0.999	0.997	3.61	0.878	0.714	-14.6	-49.2	-15.7	-52	-15.16	-50.33
Bipolar Horizontal; Positive side	±71.1	4.36	1.9	2.29	14.95	44.2	1.15	0.993	0.987	5.59	0.715	0.545	10.7	24	11.45	20.7	11.18	26.46
Bipolar Horizontal; Negative side	±71.1	4.36	1.9	2.29	-14.95	-57.8	1.15	0.993	0.987	5.59	0.715	0.545	-10.7	-31.3	-14.8	-33.2	-11.18	-34.48
Bipolar Horizontal; Positive side	±71.6	4.66	0.953	4.89	12.2	27.2	1.38	0.983	0.967	10.77	0.512	0.419	6.2	11.3	10.8	15.3	5.91	11.15
Bipolar Horizontal; Negative side	±71.6	4.66	0.953	4.89	-12.2	-35.8	1.38	0.983	0.967	10.77	0.512	0.419	-6.2	-14.9	-10.85	-22.8	-5.91	-14.53

Table B-2
Normalized Data

					HVDCLINE w/o Correction		HVDCLINE with Correction		Measured		Reference Book Equations	
	V	H	P	H/P	E	J	E	J	E	J	E	J
	(kV)	(m)	(m)									
Monopolar +	70	3.75	∞	0	1.27	1.19	1.30	1.55	1.11	0.92	1.31	1.65
Monopolar -	-70	3.75	∞	0	1.27	1.20	1.30	1.51	1.32	1.26	1.31	1.65
Monopolar -	-70.1	3.835	∞	0	1.27		1.30		1.35		1.31	
Monopolar -	-70.4	3.835	∞	0	0.00	1.20		1.52		1.46		1.65
Monopolar +	70.5	3.71	∞	0	1.27	1.12	1.29	1.42	1.24	1.08	1.31	1.65
Bipolar Vertical; Bottom +	± 70	3.81	1.905	2	1.09	1.06	0.82	0.61	1.03	1.13	1.07	0.81
Bipolar Vertical; Bottom -	± 70	3.81	1.905	2	1.09	1.06	0.82	0.61	1.05	1.27	1.07	0.81
Bipolar Vertical; Bottom +	± 70	3.81	0.95	4	1.01	0.95	0.56	0.42	0.83	0.83	0.94	0.64
Bipolar Vertical; Bottom -	± 70	3.81	0.95	4	1.01	0.95	0.56	0.42	0.92	0.83	0.94	0.64
Bipolar Horizontal; Positive side	± 71.2	4.48	3.434	1.31	1.04	0.95	0.92	0.67	0.91	0.70	0.95	0.69
Bipolar Horizontal; Negative side	± 71.2	4.48	3.434	1.31	1.04	0.94	0.92	0.67	0.99	0.71	0.95	0.69
Bipolar Horizontal; Positive side	± 71.1	4.36	1.9	2.29	0.92	0.72	0.66	0.39	0.70	0.34	0.69	0.43
Bipolar Horizontal; Negative side	± 71.1	4.36	1.9	2.29	0.92	0.73	0.66	0.39	0.91	0.42	0.69	0.43
Bipolar Horizontal; Positive side	± 71.6	4.66	0.953	4.89	0.79	0.54	0.40	0.22	0.70	0.30	0.38	0.22
Bipolar Horizontal; Negative side	± 71.6	4.66	0.953	4.89	0.79	0.54	0.40	0.23	0.71	0.35	0.38	0.22

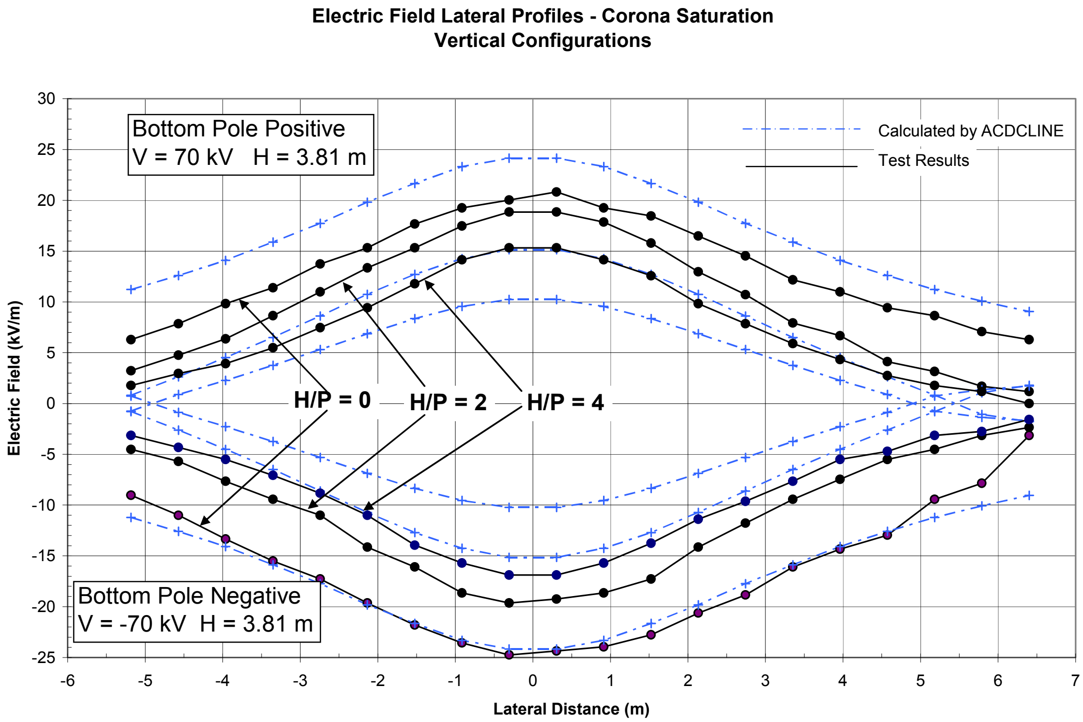

Figure B-1
Lateral profiles of electric field at ground for bipolar vertical configurations. Comparison with ACDCLINE.

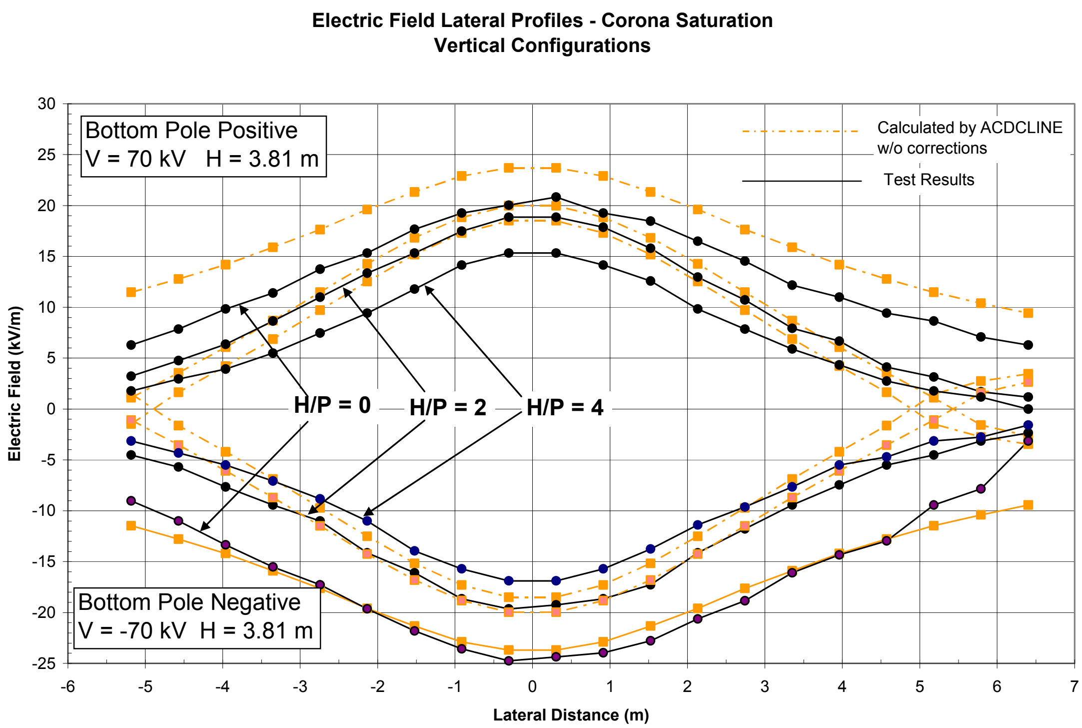

Figure B-2
Lateral profiles of electric field at ground for bipolar vertical configurations. Comparison with ACDCLINE without corrections.

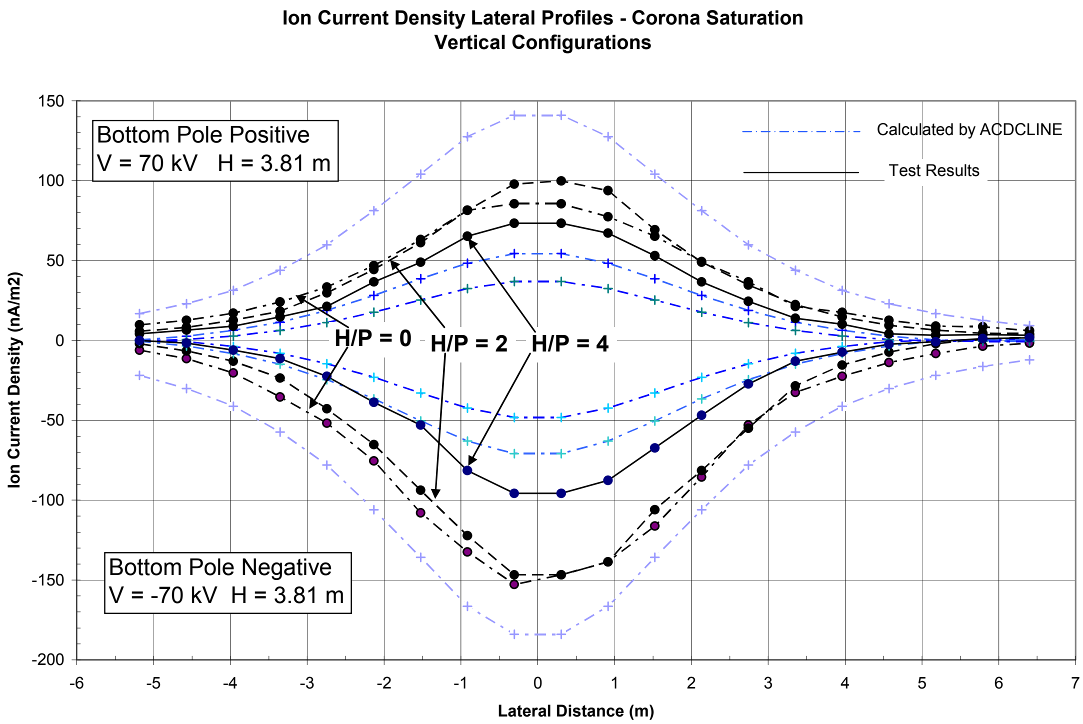

Figure B-3
Lateral profiles of ion current density at ground for bipolar vertical configurations. Comparison with ACDCLINE.

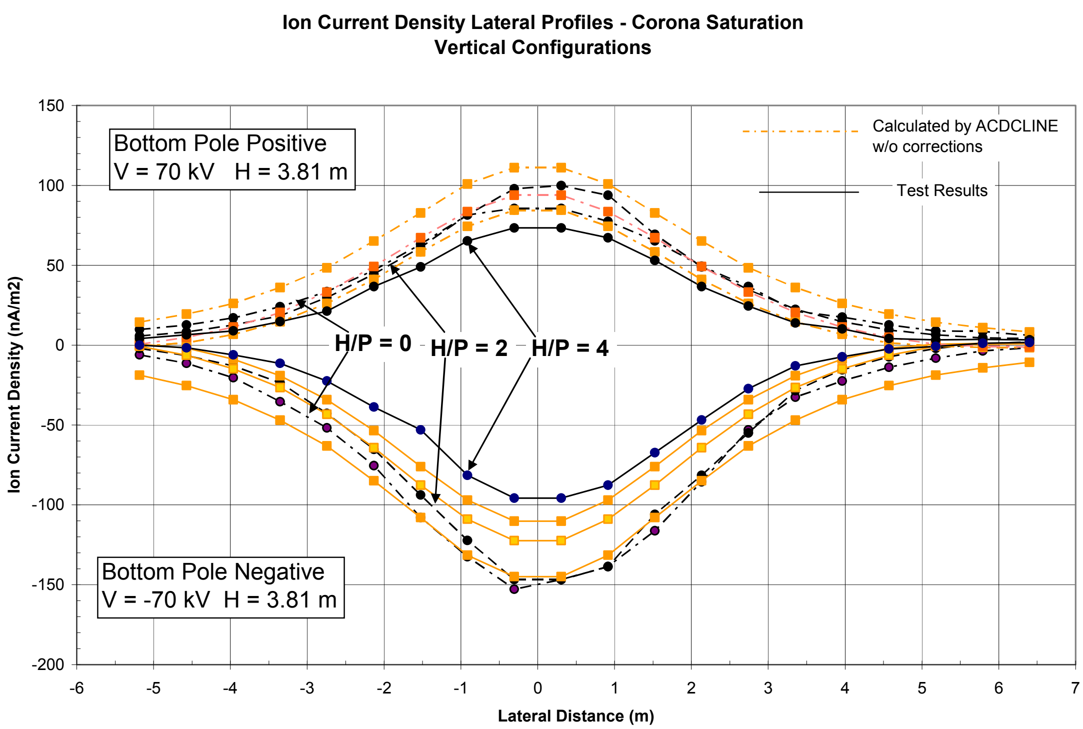

Figure B-4
Lateral profiles of ion current density at ground for bipolar vertical configurations. Comparison with ACDCLINE without corrections.

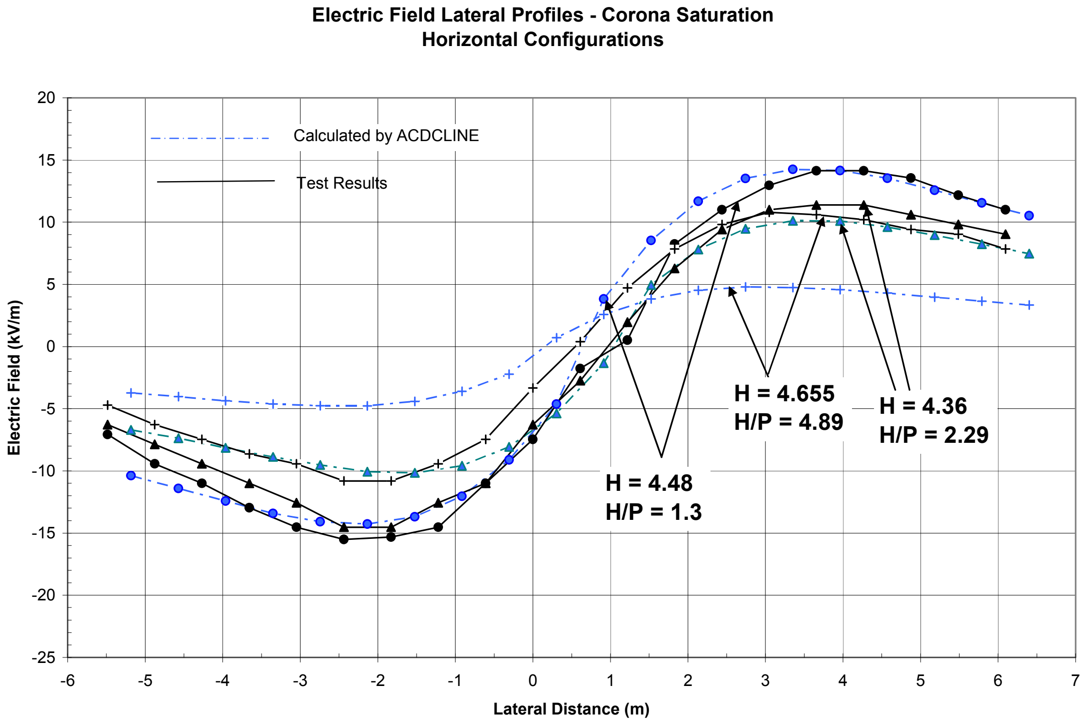

Figure B-5
Lateral profiles of electric field at ground for bipolar horizontal configurations. Comparison with ACDCLINE.

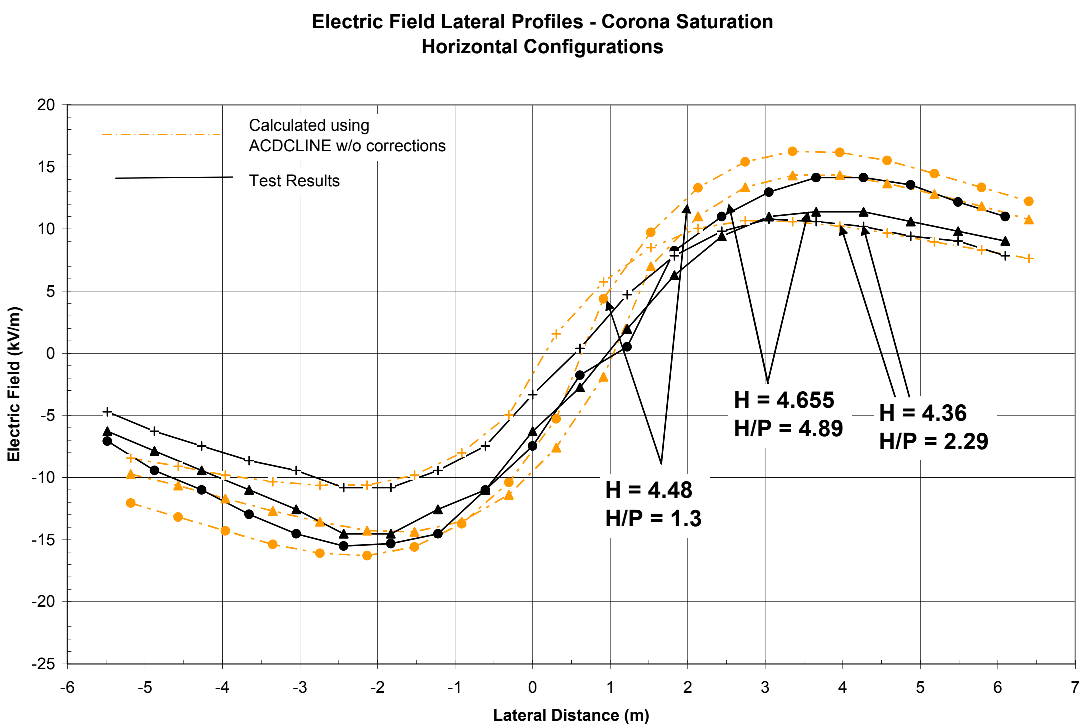

Figure B-6
Lateral profiles of electric field at ground for bipolar horizontal configurations. Comparison with ACDCLINE without corrections.

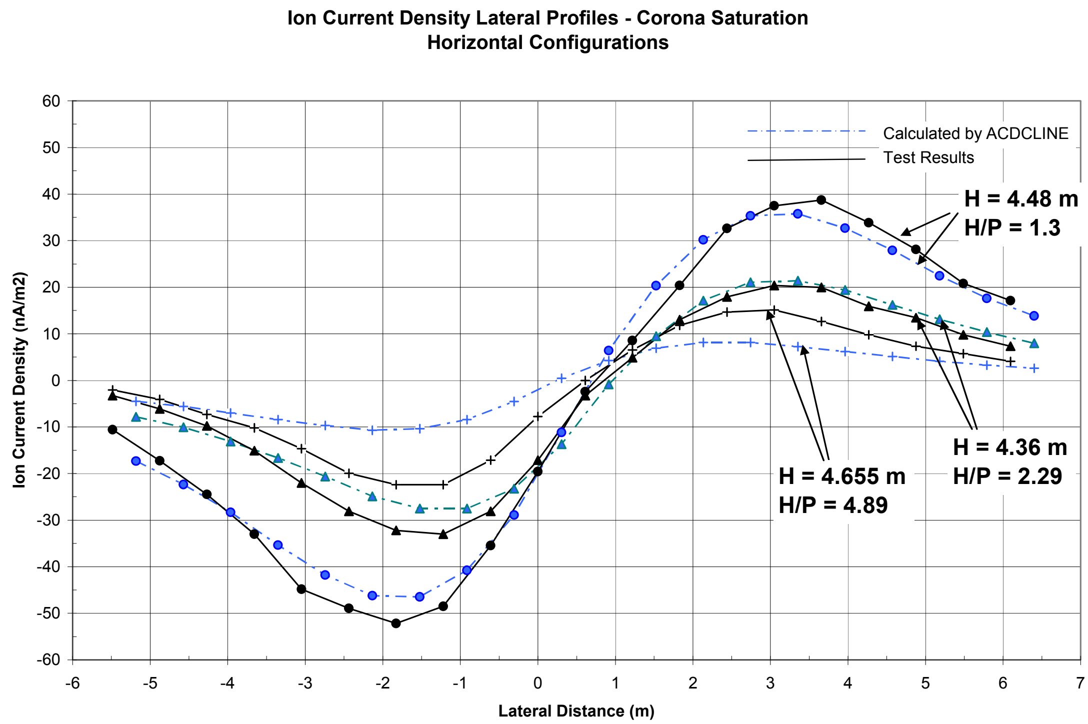

Figure B-7
Lateral profiles of ion current density at ground for bipolar horizontal configurations. Comparison with ACDCLINE.

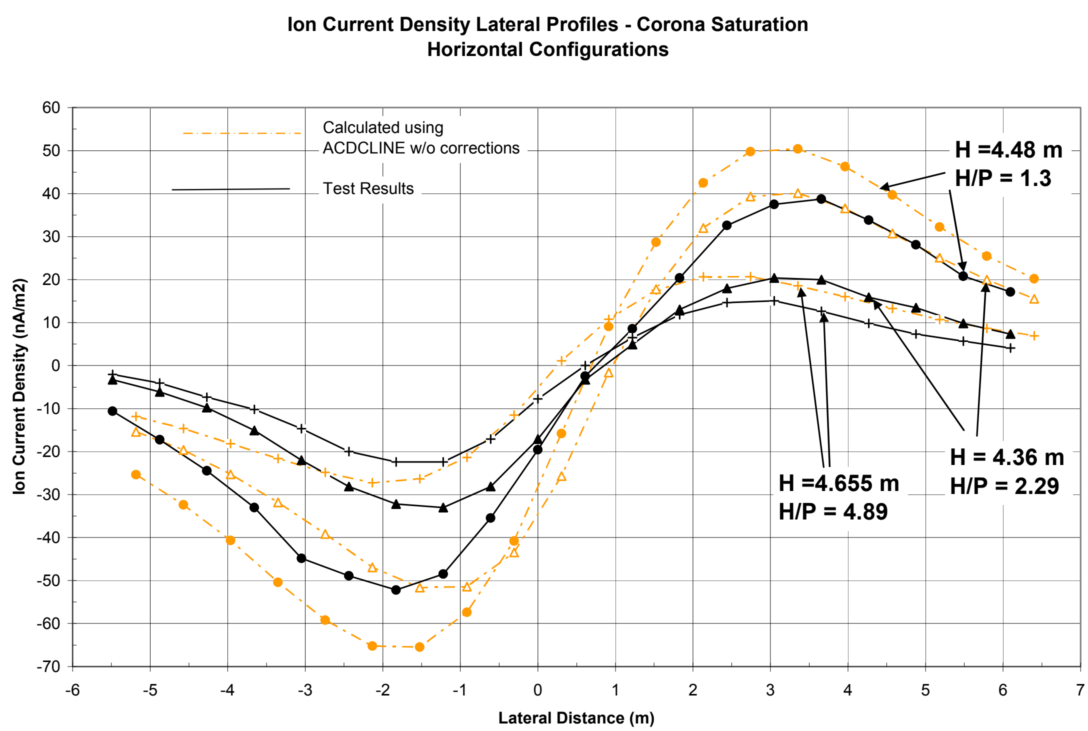

Figure B-8
Lateral profiles of ion current density at ground for bipolar horizontal configurations. Comparison with ACDCLINE without corrections.

C
RESULTS OF TESTS ON SINGLE CORONA SOURCES

The corona source study was initiated in 2012 and was completed in 2013. The tests performed in 2013 are described in this Appendix.

Study of the Ion Plume Generated by a Single Corona Source

The test setup consisted of a bipolar horizontal configuration. Each pole had a single, 2.08 cm conductor. The height above ground was H = 4.2 m (13 ft 10 in.) and the pole spacing was P = 4.2 m (13 ft 10 in.). The surface gradient, calculated without corona, was ±16.3 kV/cm for an applied voltage of ±100 kV.

A single corona source was placed on one pole. The source consisted of a small wire protruding for about 1.25 cm from the surface of the conductor. The source was placed at the point on the surface located at 45 degrees from the bottom and away from the center of the configuration as shown in Figure C-1.

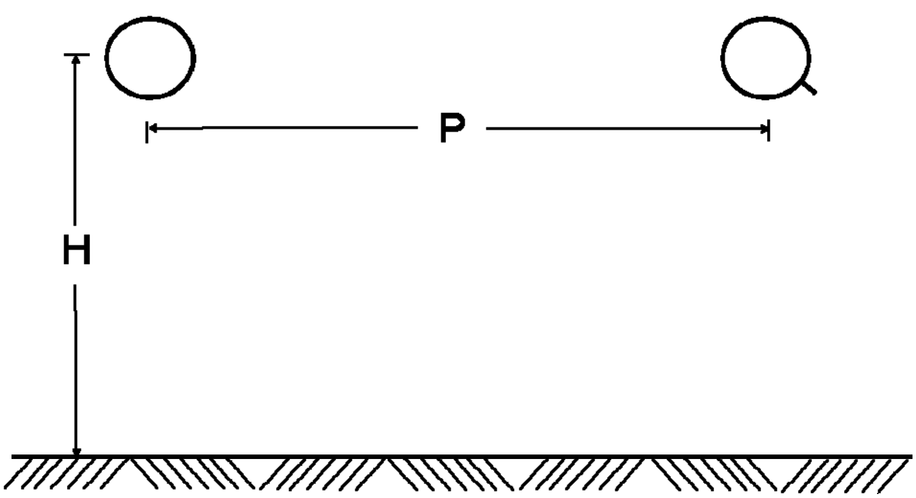

Figure C-1
Test setup with a single corona source

The conductor with the source was alternatively energized with a negative and with a positive voltage, while the other conductor was energized with a voltage of opposite polarity.

Corona inception voltage was determined by measuring the ion current collected by a plate placed under the source with voltages from 0 to ±90 kV. The ion current data were interpolated with a curve of the type: $I = k(V\text{-}V_{inc})^2$. The test results are shown in Figure C-2. The value of the inception voltage, V_{inc} , that corresponded to the best fit was:

Negative polarity: V_{inc} = -9.28 kV, surface gradient, G_{inc} = -1.51 kV/cm

Positive polarity: V_{inc} = 10.44 kV, surface gradient, G_{inc} = 1.70 kV/cm

Ion Current under Corona Source

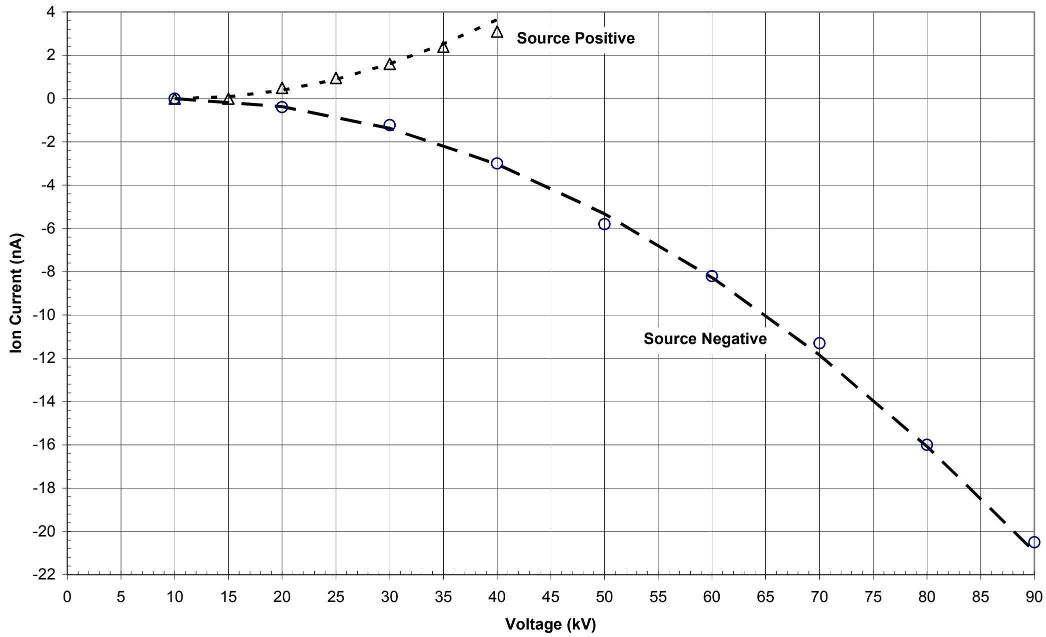

Figure C-2
Results of single source corona inception tests

Lateral profiles of ion current density were obtained by moving the ion current plate on the ground perpendicular to the line at the location of the source. Longitudinal profiles were obtained by moving the ion current plate on the ground in the direction parallel to the line at a distance from the center line were the lateral profile peak was measured. Profiles were obtained at three different voltages: ±30 kV, ±45 kV, and ±60 kV. The conductor where the source was located was alternatively energized with negative polarity (see Figures C-3 and C-4) and with positive polarity (see Figures C-5 and C-6).

Figures C-3 to C-6 show the shape of the ion plume when it reaches ground. The plume width was characterized by the "half value width", W_p, defined as the distance between points where the ion current density is one half of that at the center of the plume. W_p is indicated in the figures for both the lateral and the longitudinal directions. The width of the plume was found slightly larger when the source was on the positive pole than when it was on the negative. In both cases the plume shape was found fairly independent of the applied voltage.

Polarity of Source	Voltage (kV)	Lateral Half Value Width (m)		Longitudinal Half Value Width (m)	
-	± 30	4.15	Average = 4.15 m	3.6	Average = 3.75 m
-	± 45	4.15		3.8	
-	± 60	4.15		3.85	
+	± 30	4.4	Average = 4.3 m	4.1	Average = 4.1 m
+	± 45	4.5		3.85	
+	± 60	4.05		4.4	

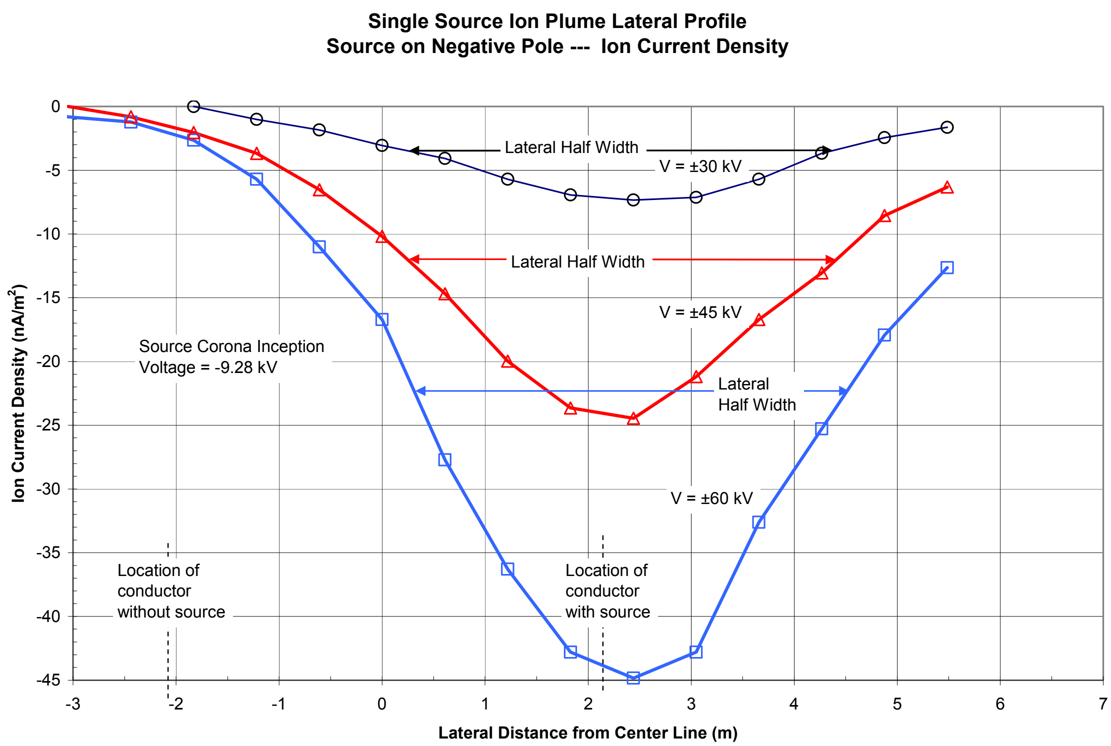

Figure C-3
Lateral profiles of ion current density at the location of a corona source. Source on negative pole.

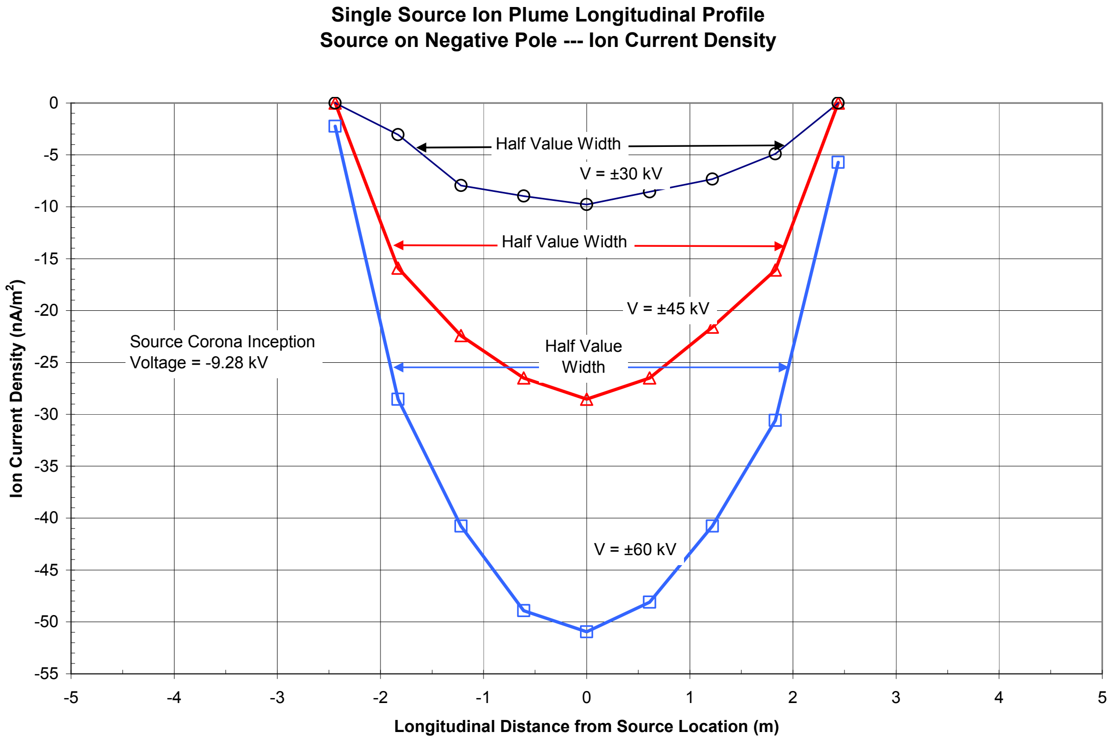

Figure C-4
Longitudinal profiles of ion current density at the location of a corona source. Source on negative pole.

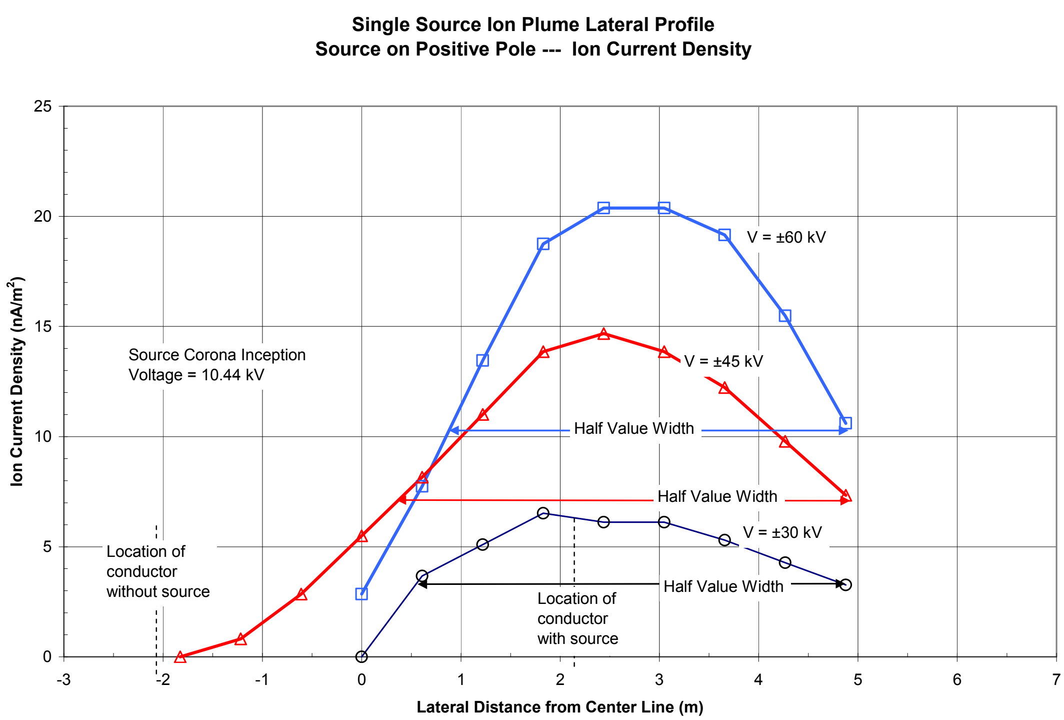

Figure C-5
Lateral profiles of ion current density at the location of a corona source. Source on positive pole.

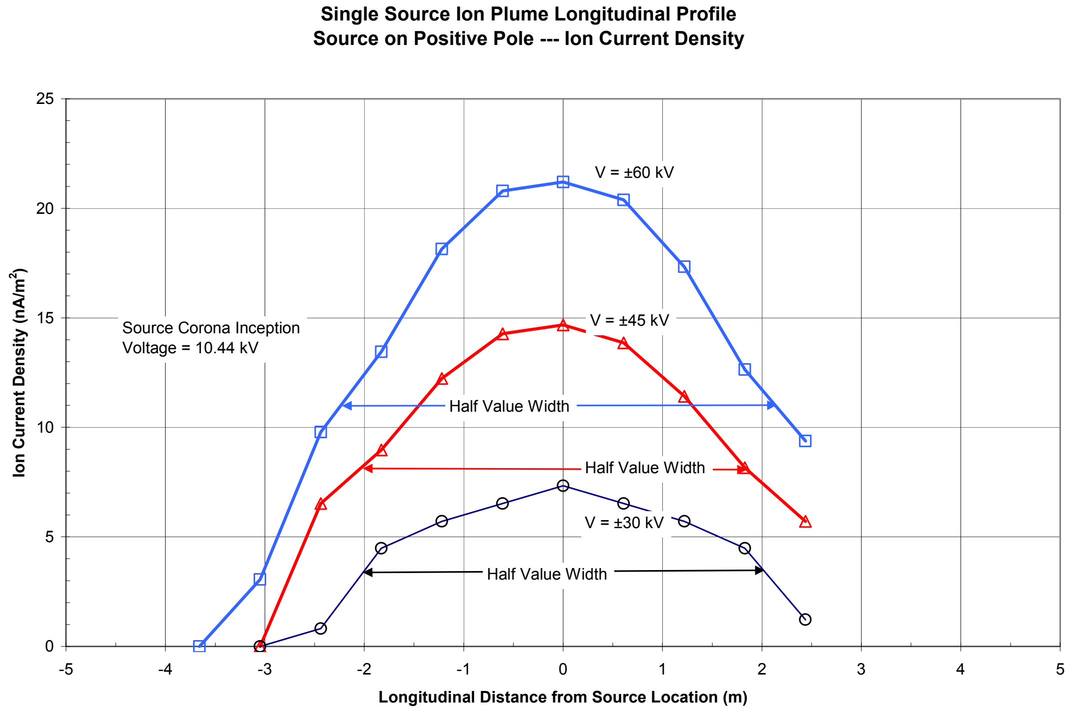

Figure C-6
Longitudinal profiles of ion current density at the location of a corona source. Source on positive pole.

Lateral profiles of the electric field were measured as well. They are shown in Figures C-7 and C-8. Longitudinal electric field profiles were not measured.

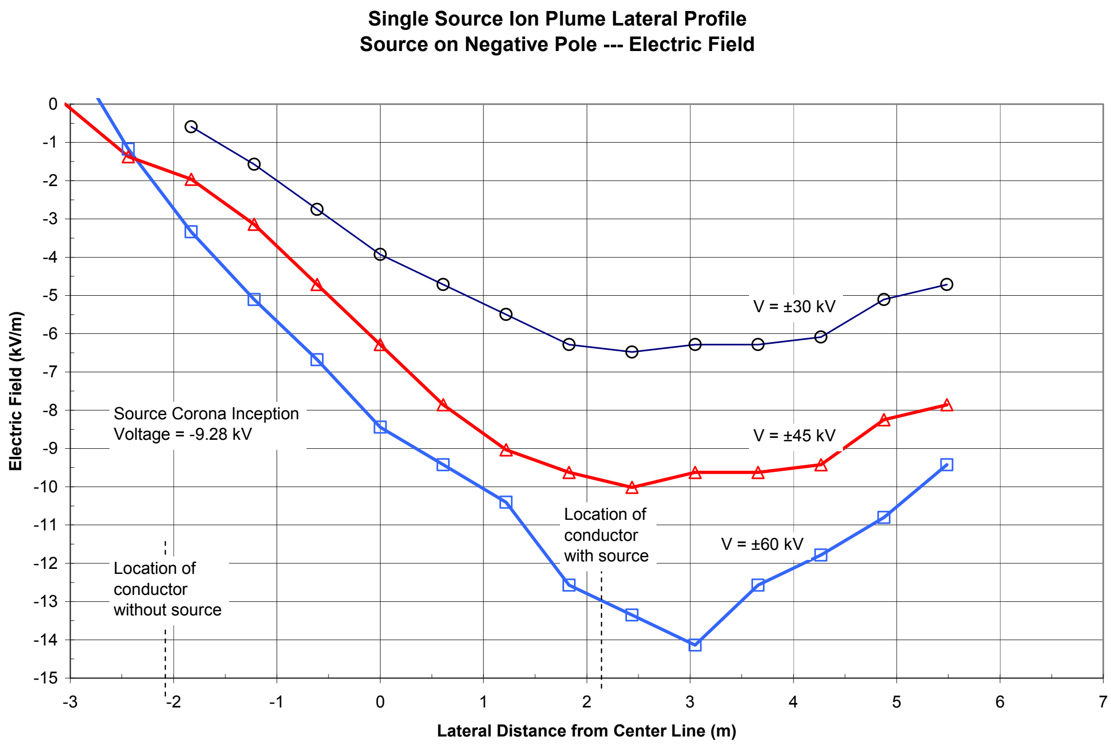

Figure C-7
Lateral profiles of electric field. Source on negative pole.

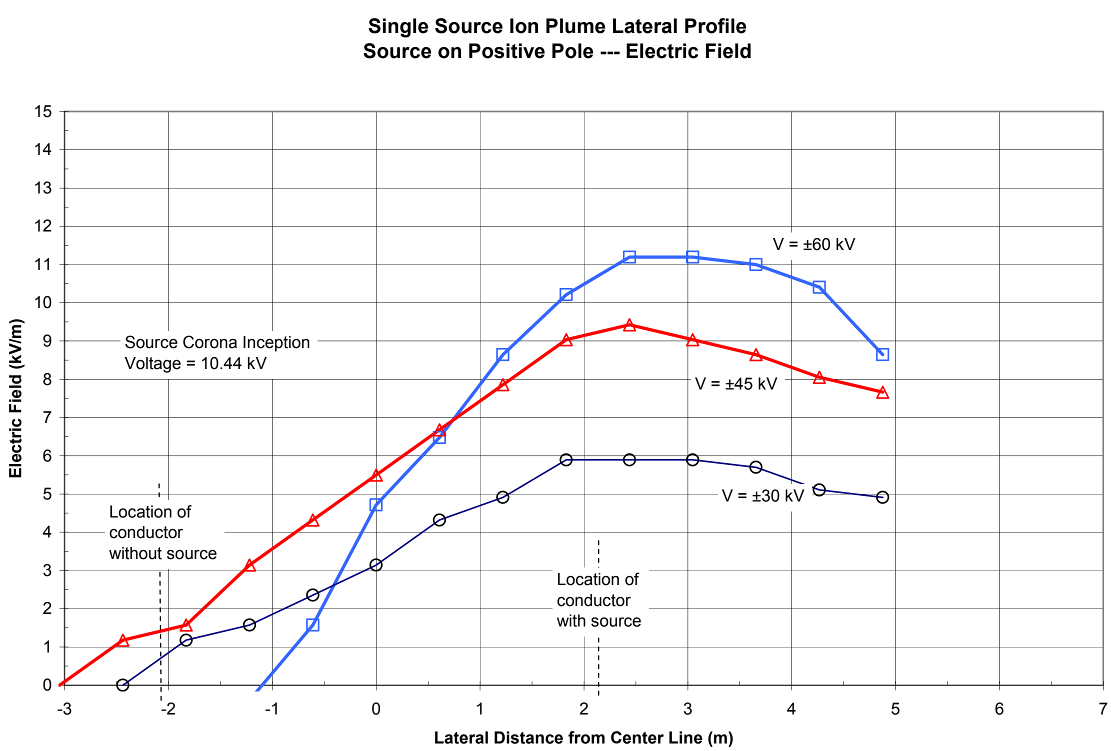

Figure C-8
Lateral profiles of electric field. Source on positive pole. Corona source aging test.

The change in ion emission of an insect was studied by applying a voltage much higher than corona inception and periodically measuring corona inception voltage. The results are shown in Figure C-9.

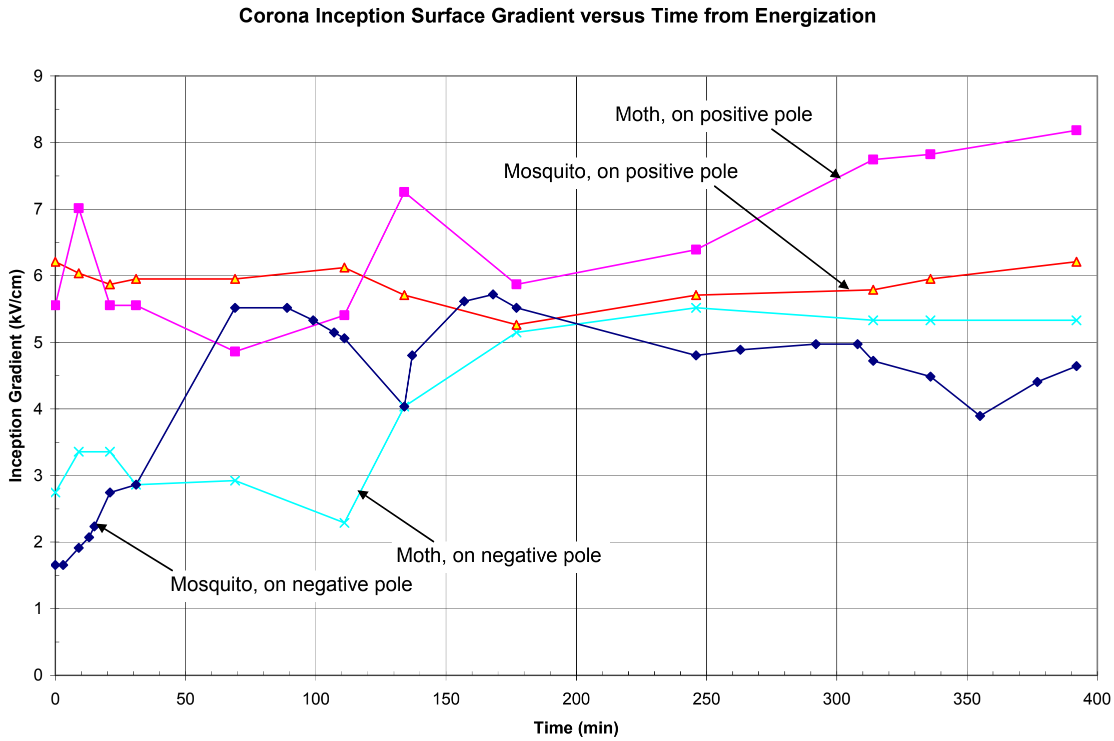

Figure C-9
Variation of corona inception gradient with time from energization for insects Deposited on an HVDC line.

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Electric Power Research Institute
3420 Hillview Avenue, Palo Alto, California 94304-1338 • PO Box 10412, Palo Alto, California 94303-0813 • USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com