Study on Influence of Pollution Factors on Corona Initiation Voltage of Overhead Transmission Line Conductor

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Abstract. The corona discharge phenomenon of transmission lines is a problem that needs to be paid attention to and solved during line design and operation. Since long-distance transmission lines are affected by dust, sand, and other environmental contamination, it is of great academic significance and engineering value to study the effect of contamination on the corona voltage of transmission lines under negative voltage. The electric field strength of the surface of the fouled conductor under a high-voltage electrostatic field is calculated by simulating the charge method, and then the corona voltage calculation model is designed by combining the photoionization model and gas discharge theory. The model is used to systematically analyze the influence of the form, size, and relative dielectric constant of the fouling on the corona initiation voltage of transmission lines under negative voltage. It is shown that the presence of fouling distorts the electric field on the transmission line surface, which increases the electric field strength and reduces the corona voltage. At the same time, the reduction of the radius of curvature of dirt particles will also significantly reduce the corona voltage. An increase in the relative permittivity of the dirt will also significantly reduce the corona voltage of the attached transmission line, but the effect on the corona voltage decreases when the relative permittivity of the dirt is greater than 8.

Keywords: Conductors · Corona Discharge · Dirt · Dielectric Constant

1 Introduction

China has a wide geographical range, uneven distribution of power resources, and large demand for electricity in some areas, so long-distance DC transmission is an important part of the national power system. With the continuous development of the country, the demand for electricity and voltage level is increasing, and the corona discharge phenomenon of the line is becoming more and more serious. Based on the topographic characteristics of China's low east and high west, long-distance DC transmission will face great changes in environmental factors. And China plans to build several ultra-high voltage DC transmission lines that need to cross high-altitude areas. The existence of dust, sand, and other harsh environments in some areas will make the surface of DC

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transmission lines adhere to dirt particles. And for AC transmission lines, DC transmission lines are more likely to produce attached dirt [1]. The attached dirt will make the corona voltage of the wire reduced, and the relative dielectric constant of different materials of dirt is also different. At the same time, the corona voltage is also affected by different shapes and sizes of dirt particles, so the study of the corona characteristics of DC transmission lines affected by the law of dirt has strong theoretical and practical significance.

The current research on the calculation of corona voltage is roughly divided into three methods: the formula empirical method, theoretical simulation method and experimental method. Peek, a foreign scholar summarized the empirical formula for the relationship between the corona voltage and air density. Later, Whitehead, Stochmeyer, Lowke, and others introduced similar formulas one after another, but their studies did not consider that electrons would be attached to air molecules to form negative ions, which would produce relative errors. Although new simulation models have been proposed by many scholars on this basis, the accuracy of the calculation results is insufficient because the parameters of these models are mostly empirical and too idealized [2]. Therefore, this paper adopts the theoretical simulation method in the study, using Matlab software for simulation, and uses the corresponding physical model for simulation. At the same time, for the different relative permittivity of the fouling simulation calculation, in consideration of the AC field simulation can not be achieved, the use of a high-voltage electrostatic field for the replacement, and then studying the fouling on the negative DC wire surface corona voltage effect law.

2 Calculation Model of Corona Onset Voltage with Dirty Negative DC Conductor

2.1 Calculation Model of Negative DC Corona Onset Voltage

The essence of corona generation is a self-sustaining discharge phenomenon formed by the uneven electric field near the uneven conductor, which is a form of gas discharge [3]. In the vicinity of the electric field with uneven distribution of field strength, when the voltage on the curvature of the electrode rises to a certain value, the free electrons in the air are subjected to the action of the electric field force to collide with the gas molecules to ionize the gas molecules, and then the initial electron avalanche is formed. In the process of the initial electron avalanche, the air molecules are ionized, and the ionized molecules continue to collide with photons to form a secondary electron avalanche, and the electron avalanche develops continuously and eventually produces a corona. At this point, the voltage at the time of corona generation is defined as the corona starting voltage.

The corona onset voltage is influenced by many internal and external factors. Among them, whether a free electron can be generated on the cathode surface to trigger the formation of a secondary electron avalanche when the initial electron avalanche occurs is the key to the self-sustainability of the pulse discharge [4]. While the mechanism of secondary electron emission from the cathode surface is still in disagreement among different researchers, here we consider a combination of two mechanisms: surface photoelectron emission and positive ion collision emission [5–9]. These two mechanisms are collectively referred to as the photoionization model. The corona voltage is calculated based on the photoionization model and the gas discharge theory, which is a more mature and widely accepted method.

A plane right-angle coordinate system is used, and the origin of the coordinates is set at the point of the wire nearest to the earth, with the p-coordinate direction vertically downward and the q-coordinate direction parallels to the earth. Assume that there exists a free electron on the cathode surface, which will develop downward to form an initial electron avalanche. When the initial electron collapse develops to p, the number of electrons $N_e(p)$ contained in the electron collapse is

$$N_e(p) = \exp(\int_0^p (\alpha(p^{'}) - \eta(p^{'}))dp^{'}) \tag{1}$$

where $\alpha(p^{'})$ is the ionization coefficient and $\eta(p^{'})$ is the attachment coefficient. The electrons generated at coordinate p cause collisional ionization at Δp distance, and the number of photons generated while collisional ionization is

$$\Delta n_{\text{ph}}(p) = \alpha^*(p)N_e(p)\Delta p \tag{2}$$

where $\alpha^*(p)$ is the photon production rate, proportional to the ionization coefficient, with a scale factor of k.

Because some of the photons formed from the initial electron avalanche will be directed towards the cathode surface, and while emitting towards the cathode surface, the photons will be irradiated evenly in different directions, and at the same time, some of the photons will be attracted by the surrounding air molecules during the process of irradiation towards the cathode surface, which affects the number of photons reaching the cathode surface, so the number of photons reaching the cathode surface is

$$\Delta n_{\text{ph}}^s = k\alpha(p)N_e(p)\Delta p g(p)e^{-\mu p} \tag{3}$$

where $g(p)e^{-\mu p}$ is the ratio of photons reaching the cathode surface to the total number of photons generated at p. It is a function of the distance p from the electrode structure $g(p)$ to the cathode surface and the air photon absorption coefficient μ. The formula for $g(p)$ can be found in the literature [10].

When the effective ionization coefficient $\alpha(p) - \eta(p) < 0$, the number of electrons in the electron avalanche stops increasing and gradually attaches to the molecules thus forming negative ions. The number of photons produced is very small and the vast majority is absorbed by the air molecules and can be neglected.

The ionization region has a radius of p_i. Photons reaching the cathode surface produce at least one photoelectron at the surface, a new secondary electron avalanche can be formed, and the negative DC corona can be self-sustaining. As in Eq. (4).

$$N_{eph} = \gamma_{ph} \int_0^{p_i} \alpha(p)g(p)\exp(-\mu p + \int_0^p \left(\alpha(p') - \eta(p')\right)dp')dp \geq 1 \tag{4}$$

N_{eph} is the number of photoelectrons on the cathode surface, γ_{ph} is the surface photoelectron emission coefficient, and the scaling factor k is included in γ_{ph} because it is considered a constant.

To calculate the negative DC wire corona onset voltage U, the voltage is continuously increased in steps of ΔU, and the spatial electric field distribution is calculated using the simulated charge method to calculate the ionization coefficient, attachment coefficient, electrode structure, and the number of photoelectrons on the cathode surface for different electric field strengths in space. The voltage corresponding to Eq. (4) when the equal sign holds is the negative DC corona onset voltage U. The formulas and values of the parameters used in the calculation can be found in the reference [11].

2.2 Modeling of the Voltage Solution at the Corona Point of the Attached Fouling Conductor

Before calculating the onset voltage of the corona of the wire, the spatial electrostatic field distribution of the wire is required. Here, the simulated charge method is used for the calculation [12]. Compared with the finite difference method, the simulated charge method can avoid the numerical differentiation of the potential and directly calculate the field strength at any point in the field, and is not limited by the size of the area [11, 13–15].

The shape of the attached dirty wire is simulated by setting a number of linear charges of infinite length in an infinitely large region. The electrostatic field in the space of the attached wire is then calculated by superposition. In order to facilitate the analysis of the complex situation of the attached dirt in the actual environment, this paper classifies the dirt into three shapes, as shown in Fig. 1, which are conical, spherical, and hemispherical.

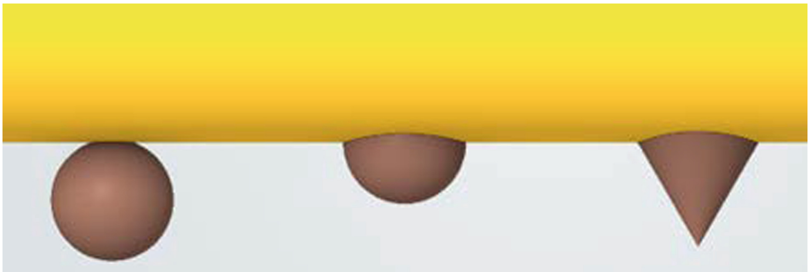

Fig. 1. Sketch map of dirt shape.

Accordingly, the design of the corresponding electric field of the corona of the attached wire corona voltage calculation process is shown in Fig. 2, considering the high-voltage transmission line for the ideal state, is a smooth surface cylindrical shape. The radius of the wire is r, and the height of the wire to the ground is h.

Simulate the charge distribution in the interface section of the attached wire, set the corresponding matching points on the surface of the wire, set the radius of the wire r as 0.005 m, and the height of the wire to the ground h as 0.4 m. Set a distance of 0.1 m, in the vertical direction of the wire and the ground down to 10,000 calculation points.

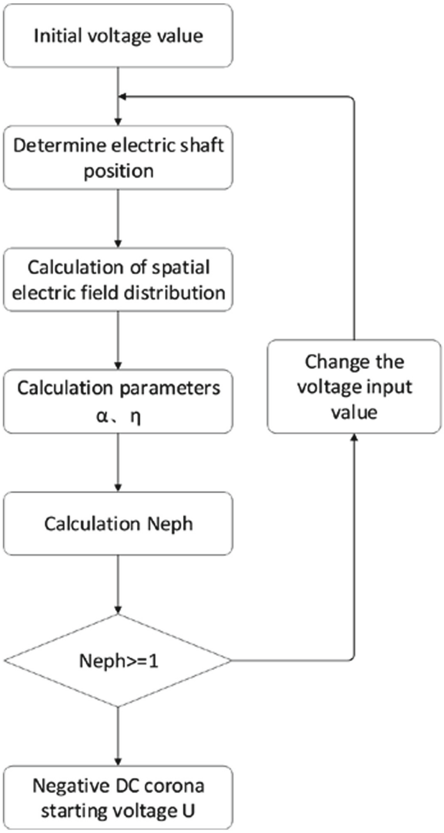

Fig. 2. Calculation process of corona onset voltage of attached dirty conductor.

3 Calculation Results

3.1 Data Comparison

The calculated results of the starting corona voltage when spherical dirt is attached to the smooth conductor are compared with the experimental data done by Zhou at North China Electric University [16]. The radius of the smooth wire is 20.5 mm, and the radius of the dirty particles is 150, 250, and 550 μm. It can be seen from Table 1 that as the dirty particles grow, the degree of reduction of the corona voltage of the wire in the experiments done by Zhou and the calculated results are basically the same.

It shows that the designed simulation experiment can reflect the effect law of dirt on the corona onset voltage of the wire.

3.2 Effect of Conical Dirty Particles on Corona Voltage

The physical characteristics of cone contamination are analyzed, and the factors affecting cone contamination include bottom radius, height, and relative dielectric constant. Based

Table 1. Degree of influence of the growth of the radius of dirty particles on the starting voltage of the corona.

Dirty particles increase radius (μm)	100	300
Dirty particle radius increase ratio	66.67%	120%
Experimental corona voltage reduction ratio	8.85%	6.95%
Simulation of corona voltage reduction ratio	10.26%	8.52%

on this, experiments were designed to calculate the corona onset voltage of the attached cone-contaminated conductor.

The radius length of the bottom of the cone-contaminated conductor was set to 300, 400, and 500 μm respectively. Its height was varied and the corresponding corona onset voltage was calculated. The simulation results are shown in Fig. 3. As the height of the cone increases, the corona onset voltage of the conductor with different bottom radius cone contamination increases.

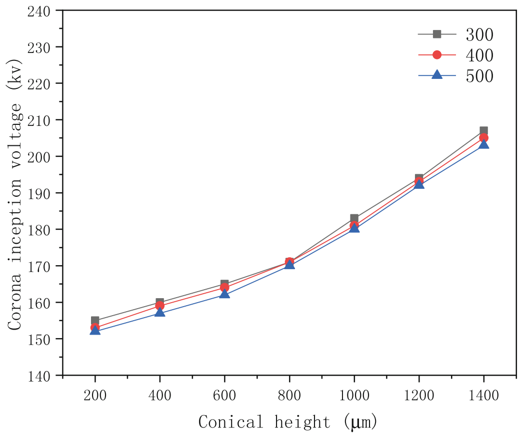

Fig. 3. Variation of corona inception voltage of conical dirt with height.

The height of the cone contamination is set to 400, 500, and 600 μm, the bottom radius is varied and the corresponding corona onset voltage is calculated. The simulation results are shown in Fig. 3. Unlike varying the height, the corona onset voltage of the conductor decreases and then increases as the radius of the bottom of the cone increases, but all are much lower than the corona onset voltage of the smooth conductor (Fig. 4).

Finally, varying the relative permittivity of the cone contamination, the simulation results are shown in Fig. 5. With the increase of relative permittivity, the corona initiation voltage of the conductor gradually decreases.

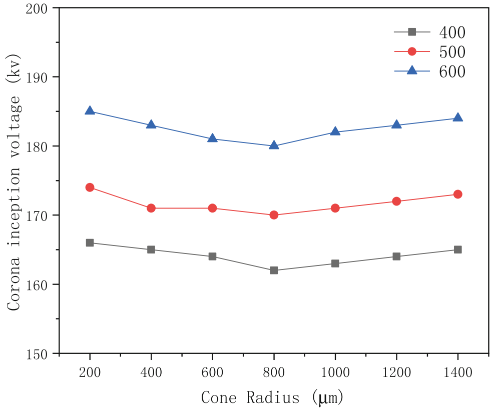

Fig. 4. Variation of corona inception voltage of conical dirt with radius.

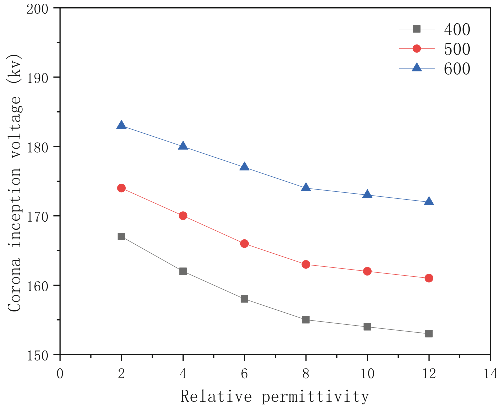

Fig. 5. Variation of corona initiation voltage of conical dirt with relative dielectric constant.

3.3 Effect of Spherical Dirty Particles on the Starting Corona Voltage

The physical properties of the spherical contamination are analyzed, respectively, the radius of the spherical contamination and the relative permittivity. Accordingly, experiments were designed to calculate the corona onset voltage of additional spherical contaminated conductors.

The relative permittivity of the spherical contamination was set to 4, 6, and 8. The radius was varied and the corresponding corona onset voltage was calculated. The simulation results are shown in Fig. 6. As the radius of the spherical contamination increases, the corona onset voltage of the conductor decreases continuously.

The radii of the spherical contamination were set to 1000, 800, and 600 μm. The relative permittivity is changed and the corresponding corona onset voltage is calculated. The simulation results are shown in Fig. 7. As the relative permittivity increases, the corona onset voltage of the conductor gradually decreases.

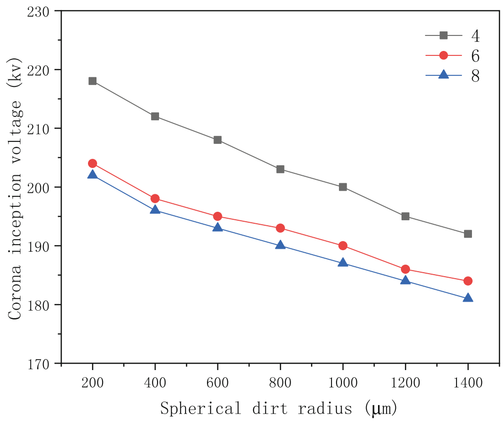

Fig. 6. Variation of corona inception voltage of spherical dirt with radius.

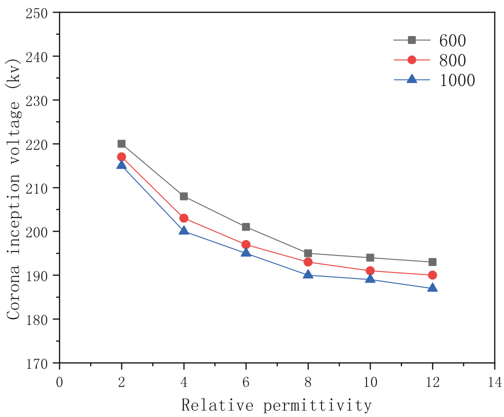

Fig. 7. Variation of corona initiation voltage of hemispherical dirt with relative dielectric constant.

3.4 Effect of Hemispherical Dirty Particles on Corona Voltage

Analysis of the physical properties of hemispherical contamination shows that its properties are similar to those of spherical contamination. It is also influenced by the radius and its relative permittivity.

Accordingly, experiments were designed to calculate the corona onset voltage of the attached hemispherical contaminated conductor by varying its radius to calculate the corresponding corona onset voltage. The simulation results are shown in Fig. 8. As the radius of hemispherical contamination increases, the corona onset voltage of the conductor continues to decrease.

Likewise, the corona onset voltage of the conductor gradually decreases as the relative permittivity of the hemisphere increases. The results are shown in Fig. 9.

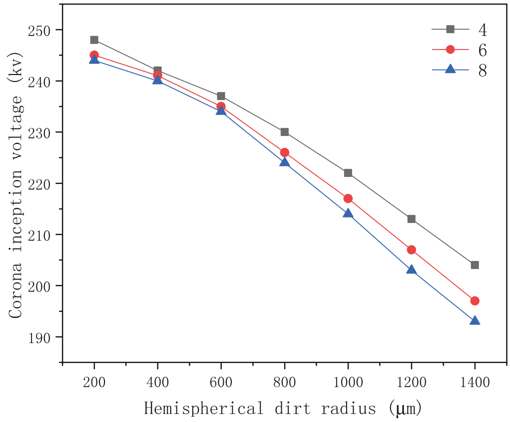

Fig. 8. Variation of corona inception voltage of spherical dirt with radius.

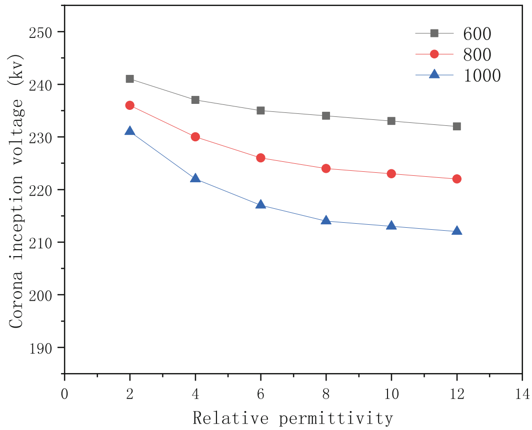

Fig. 9. Variation of corona initiation voltage of hemispherical dirt with relative dielectric constant.

4 The Relationship Between the Attached Fouling and the Corona Starting Voltage of the Wire

4.1 The Effect of Dirt on the Electric Field Strength of the Wire Surface

When three kinds of dirt are attached to the wire, the presence of dirt will make the wire surface electric field intensity increase significantly. The calculated results are shown in Table 2. Compared with the surface electric field strength of the smooth wire, it can be seen that the presence of dirt will make the wire surface electric field distortion, which will affect the corona onset voltage of the wire.

Among them, the impact caused by conical dirt is the most obvious, so the presence of conical dirt caused by the corona onset voltage reduction is also the most dramatic.

Table 2. The electric field strength on the surface of the wire in different cases.

Wire attachment dirt condition	Maximum electric field strength on the surface of the conductor ($kV \cdot cm^{-1}$)
Smooth wire	11826.84
Hemispherical dirt	15041.75
Spherical dirt	19478.99
Conical dirt	35373.07

4.2 Effect of Relative Dielectric Constant of Dirt on Corona Voltage

By comparing the three shapes of soiling in Fig. 10, it is easy to see the effect of changing their relative permittivity on the corona starting voltage. Regardless of which type of soiling, the larger the relative permittivity, the larger the relative permittivity, which makes the corona starting voltage of the attached soiled wire appear to drop significantly. When the relative permittivity is in the range of 2 to 8, the decline is faster. When the relative permittivity is greater than 8, the decrease of corona voltage caused by the increase of relative permittivity slows down significantly.

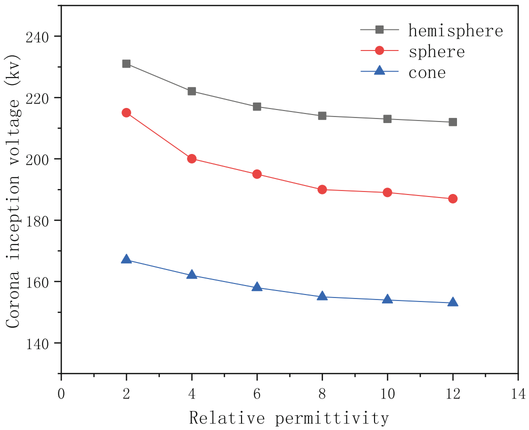

Fig. 10. The corona inception voltage of three shapes of dirt varies with the relative dielectric constant.

5 Conclusion

(a) The presence of contamination distorts the electric field on the surface of the conductor, increasing the electric field strength and thus reducing the corona onset voltage of the conductor.
(b) By comparing the degree of reduction in the corona onset voltage caused by the three types of contamination, it is known that the smaller the radius of curvature of the contamination, the more likely the conductor is to corona.
(c) The relative permittivity of the contamination has a significant effect on the corona starting voltage. As the relative dielectric constant of contamination increases, the corona voltage of the wire will gradually decrease, when the dielectric constant increases from 2 to 8, the corona voltage decreases more obviously. When the dielectric constant is greater than 8, its increase on the corona onset voltage effect gradually weakened.

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