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Study on Tree-wire Critical Breakdown Distance of 500kV Transmission Lines

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Abstract: Flashover fault is an important cause of trip or even outage of transmission lines. In order to reduce the occurrence of tree flashover failure and strengthen the management of tree growth in the transmission line corridor, it is necessary to study electric field and potential distribution characteristics of trees below transmission lines. Firstly, the influence of tree dielectric constant and conductivity on 3D modelling is analysed. Then the actual 3D simulation model is established. The spatial electric field and potential variation of trees with different shape crowns and different heights and horizontal distances are studied. The starting field strength of flow is used as the gap breakdown criterion, and the critical breakdown distance under different power supply phase angles is calculated. Conclusion shows that the critical distance of tree flashover of 500kV transmission line is 1.76m. In practical applications, trees should be avoided too close to the wire.

1 Introduction

In recent years, tripping faults caused by tree flashover of transmission lines has become a focus of power grid. Although the number of tree fault is lower than that caused by lightning stroke and external breakage, it is difficult to reclose the lines after the occurrence of tree fault, which is very easy to cause line outage[1-3].

Trees are electrically conductive. In addition, the tip of tree has small radius of curvature and sharp tip. When trees are close to transmission line, the top of trees is prone to corona discharge, which not only damages the trees, but also easily causes fires. In-depth study of the variation of electric field and potential distribution in the process of trees approaching transmission lines is of great engineering significance for understanding the formation mechanism of tree faults on transmission lines, calculating the minimum clearance distance and guiding tree management in line corridors.

At present, the relevant researches mostly focus on the calculation of electric field when trees near the UHVDC transmission line, while there is no research on the electric field variation law when trees exist under AC transmission lines[4-6]. In this paper, Ansoft software is used to build a three-dimensional simulation model for the presence of trees under transmission lines. The electric field variation and distribution characteristics of trees approaching in different directions are analyzed, and the electric field characteristics of vertical and horizontal paths are calculated. Finally, the critical breakdown distance between trees and conductors is calculated.

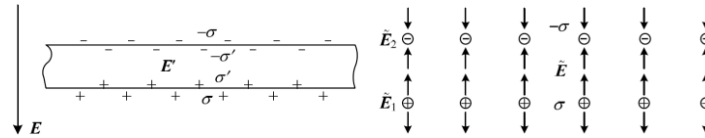
2 The influence of tree conductivity and dielectric constant on modeling

Trees are rich in water and have certain conductive properties, but they are not good conductors. Under the action of electric field, they will produce charge polarization. The effect of dielectric



constant and conductivity of trees on electric field distribution should be taken into account when calculating the electric field variation characteristics of trees near transmission lines.

As shown in Figure 1 (a), E is uniform power frequency electric field, with a thin sheet with relative dielectric constant of ε_r , conductivity of γ in it. Under the action of E , the free charge in the sheet will move to the surface and produce a certain charge density σ on the surface. At the same time, the dipole in the sheet material polarizes under the action of electric field and produces polarized charge density σ' on the surface.



(a) Free charge in the sheet (b) Electric field generated by free charge

Figure.1 Schematic diagram of free charge of sheet material

The electric field produced by free charge density σ can be obtained by using Gauss theorem.

$$E_1 = \frac{\sigma}{\varepsilon_0} \quad (1)$$

Because the direction of E_1 is opposite to that of the original power frequency electric field E , the electric field E_2 acting on the thin sheet material is

$$E_2 = E - E_1 \quad (2)$$

Under the action of E_2 , polarization occurs inside the material, which leads to the decrease of the internal electric field. The electric field strength inside the material is as follows:

$$E_i = \frac{E_2}{\varepsilon_r} = \frac{1}{\varepsilon_r} \left(E - \frac{\sigma}{\varepsilon_0} \right) \quad (3)$$

According to paper[4], under the action of alternating electric field, the electric field intensity has the following relationship with the free charge density:

$$\sigma = \frac{\gamma E_i}{j\omega} \quad (4)$$

$$E_i = \frac{1}{[1 + \gamma / (j\omega\varepsilon_0\varepsilon_r)]} \cdot \frac{E}{\varepsilon_r} \quad (5)$$

The conductivity of active tree materials is generally $1e^{-3} \sim 1e^{-1} \text{ S/m}$ and the relative dielectric constant is between 2 and 10[1]. Under the action of power frequency electric field, $\gamma / \omega\varepsilon_0\varepsilon_r \ll 1$ is satisfied, equation (5) can be simplified as follows:

$$E_i = \frac{j\omega\varepsilon_0 E}{\gamma} = \frac{J}{\gamma} \quad (6)$$

In the formula, J is the conduction current density. As can be seen from Formula (6) that the material conductivity of the tree is the same as that of metal. Therefore, when calculating the electric field variation characteristics of the tree adjacent to the transmission line, the tree material is defined as good conductor, and the tree potential is kept at zero.

3 Gap breakdown criterion and three-dimensional finite element simulation model

3.1 Gap Breakdown Criterion

Tree-wire gap is a slightly uneven field or a very uneven field, and its discharge breakdown process belongs to the category of long air gap discharge under the power frequency voltage. The process of gap breakdown is very complex, with acoustic, optical and electro thermal effects. Flow discharge is an important stage of long air gap discharge, and its initial characteristics can be used as an important reference for gap breakdown characteristics. According to this paper, the starting criterion of the typical extremely uneven field rod-plate gap flow proposed by paper [5] is used:

$$E_{i\text{-impulse}} = 22.8(1 + \frac{1}{\sqrt[3]{R}} + \frac{0.22R + 0.08}{R^2} \sqrt{\frac{dU}{dt}}) \quad (7)$$

In the formula, $E_{i\text{-impulse}}$ is the starting field strength of the stream, kV/cm, R is the average radius of the electrode, dU/dt is the rate of change of applied voltage, the unit is kV/ μ s.

Under the power frequency voltage, equation (8) is satisfied.

$$\frac{0.22R + 0.08}{R^2} \sqrt{\frac{dU}{dt}} \approx 0 \quad (8)$$

Therefore, equation (7) can be simplified to

$$E_{i\text{-impulse}} \approx 22.8(1 + \frac{1}{\sqrt[3]{R}}) \quad (9)$$

When the composite field intensity at the top of the tree crown reaches $E_{i\text{-impulse}}$, it is the critical breakdown state. At this time, the height of the tree is the critical tree height, and the distance between the tree and the conductor d_{ij} is the critical breakdown distance.

3.2 Establishment of three-dimensional simulation model

Trees contain a large number of leaves and branches, and their structure is extremely complex, in addition, the types and shapes of trees are different, which needs to be simplified when modeling. In order to simplify the analysis, three common types of trees are selected for analysis. The crowns of three trees shown in Figure.2 are ellipsoid, cone and ball in turn. Figure.2 (b) is their respective simulation models.

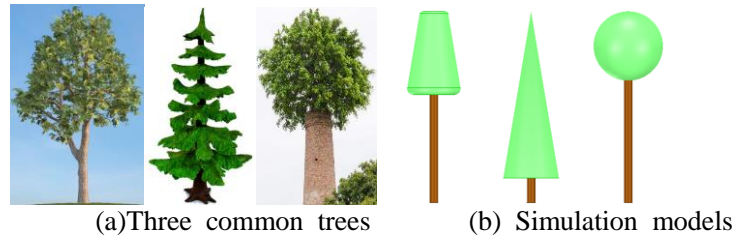


Figure 2 Three common trees and their 3D simplified simulation model

When trees are located in the center of transmission line spacing, the distance between trees and towers is relatively far, usually more than 100 m. Towers have little effect on the electric field near trees, which can be ignored. In addition, neglecting the parts which have little influence on the electric field distribution near trees, such as metal fittings, shock hammers and insulators, can greatly simplify the calculation.

In the model, lightning arrester, conductor, tree and ground materials are all set to aluminum. The ground is simulated by a metal sheet of 600m*60m*0.05m. The conductor is four-split and the outer diameter of the single conductor is 30.2 mm. It is simulated by four cylindrical rods with equal outer diameter. The lightning arrester, conductor layout and inspection path diagram are shown in Figure.3. There are two paths in Figure.3. The vertical path (referred to as path 1, the same below) is a straight line with a length of 2m below the central B phase conductor. Horizontal path (hereinafter referred to as path 2, the same below) is a straight line segment 2.5m below the B-phase wire and 10m horizontally outward.

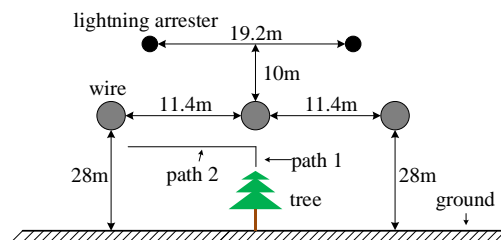
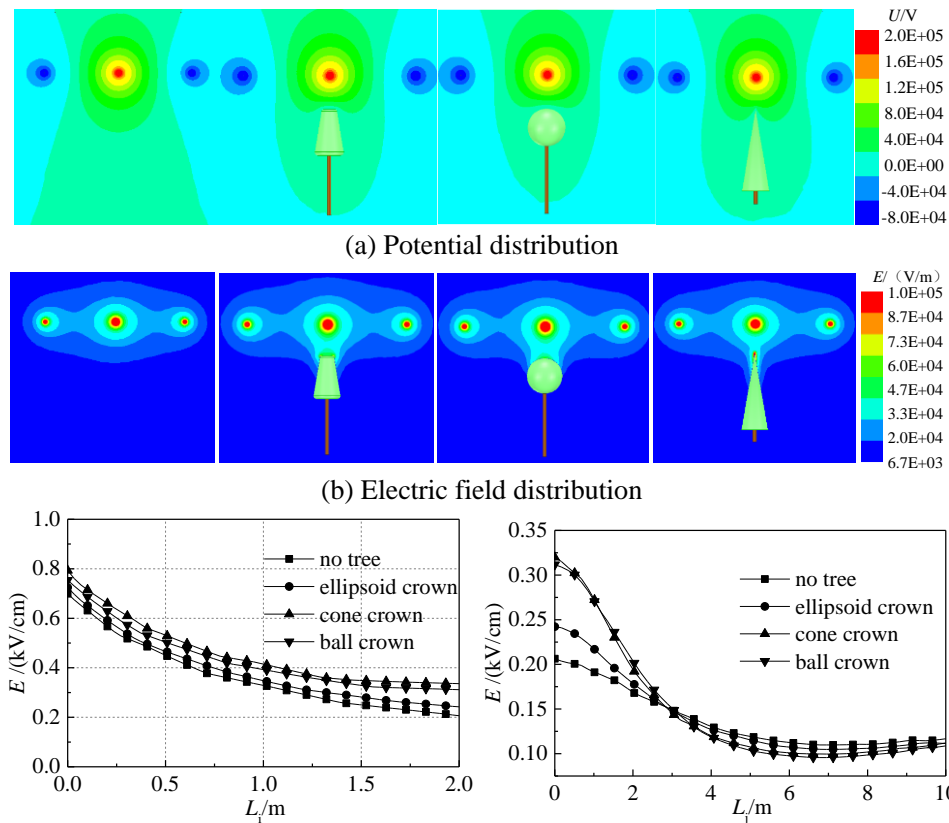


Figure 3 Schematic layout of 500kV transmission line tower

4 Simulation results and analysis

4.1 Characteristics of electric field and potential distribution

The applied voltages of phase A, B and C wires are -204.1 kV, 408.2 kV and -204.1 kV, respectively. Trees are located directly below the B-phase conductor in the center of the spacing, and the vertical distance from the wire is 4m. The spatial electric field and potential distribution characteristics of different trees are shown in Figure.4:



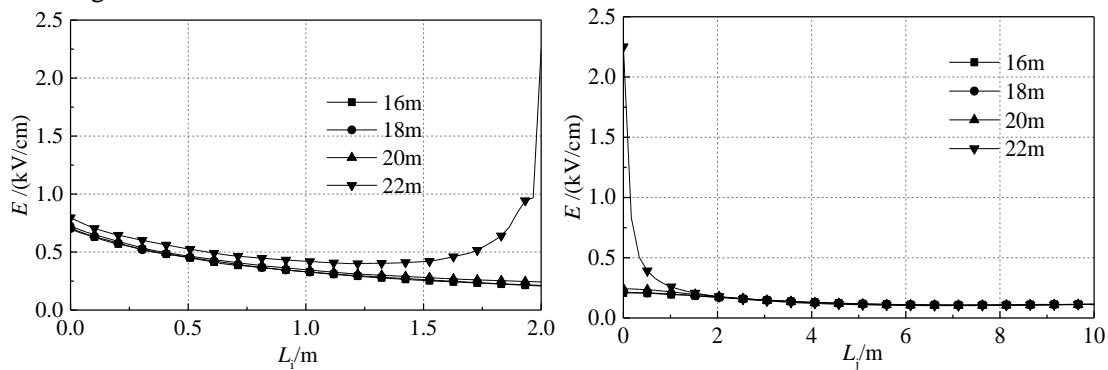
(c) Electric field distribution along path 1 (d) Electric field distribution along path 2
Figure 4 Comparison of electric field and potential when different trees exist

It can be seen from Figure.4 (a) and Figure.4 (b) that distribution of electric field and potential near trees is obviously distorted, and the distribution of electric field under different crowns is different. The electric field near cone crown is the most distorted, its maximum electric field intensity is more than 2.9 kV/cm, while the maximum electric field intensity on the surface of ball crown and ellipsoid crown is 1.1 kV/cm and 1.4 kV/cm, respectively. In Figure.4(c), L_i is the distance between the inspected point and the starting point on path 1. In Figure.4 (c), the electric field distribution of path 1 under three tree crowns is higher than that without tree. Because the trees are far away from the wires, the electric field strength along the path 1 is low, both below 1kV/m. In Figure.4 (d), along the path 2, as the distance increases, the field strength decreases sharply first and then tends to be constant. In the case of a cone crown, a spherical crown, an ellipsoidal canopy, and no trees, the maximum field strength on path 2 is 0.33 kV/cm, 0.32 kV/cm, 0.24 kV/cm, and 0.21 kV/cm, respectively.

4.2 The influence of tree height on calculation results

According to the conclusion of 4.1, the top field strength of the cone crown in the three trees is the largest, so the latter analysis only considers the cone crown. Increase the height of the trees to reduce the vertical distance between the trees and the wires, simulating the natural tree growth process. When the height of the trees is 16m, 18m, 20m, 22m, the field strength distribution of path 1 and path 2 is as

shown in Figure. 5.

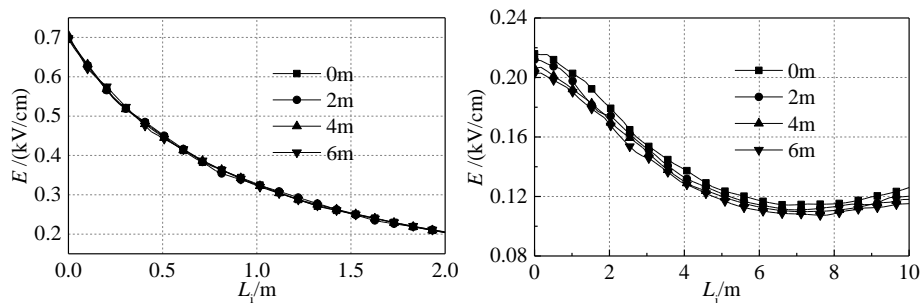


(a) Electric field distribution along path 1 (b) Electric field distribution along path 2
Figure 5 Distribution of electric field along different paths under different tree heights

With the increasing height of trees, the electric field distribution along path 1 and path 2 shows an upward trend. The closer to the top of tree crown, the more obvious the electric field distortion. In addition, the maximum field strength at the top of the tree increases with the height of the tree. When the height of the tree is 16m, 18m, 20m, 22m, the maximum field strength at the top of the tree is 1.2kV/cm, 1.8kV/cm, 2.6kV/cm, 4.4kV/cm, respectively. It can be inferred that the higher the tree, the more likely the tree failure will occur.

4.3 Effect of horizontal distance of trees on the calculation results

The horizontal distance between trees and wires is also an important factor affecting the failure of the trees. Distribution of electric field along different paths when horizontal distance changes are shown in Figure.6.



(a) Electric field distribution along path 1 (b) Electric field distribution along path 2
Figure 6 Distribution of electric field at different horizontal distances

In Figure.6, horizontal distance $s=0\text{m}$ means that the tree is directly below the wire. From Figure.6 (a), it can be seen that when the horizontal distance increases, the electric field distribution of path 1 does not change much. This is because that when the tree is located on the side of the transmission line, the distance between the tree and the path 1 is more than 10m, which is far enough that the existence of the tree has little influence on the electric field of the path 1. Therefore, when s changes, the electric field distribution of the path 1 remains unchanged. However, the electric field distribution of path 2 increases significantly as s decreases. When s decreases, the distance between the top of the tree and the wire decreases, resulting in a significant increase in the maximum field strength at the top of the tree. When $s=6\text{m}$, 4m , 2m , 0m , the field strength of the top of the tree is 0.4kV/cm, 0.6kV/cm, 1.1kV/cm, 3.4kV/cm, respectively. In conclusion, the smaller the horizontal distance is, the greater the field strength is, so the flashover is more likely to occur.

4.4 The effect of the number of trees on the simulation results

The types, quantity and distribution of trees in the transmission line corridor are random. The number

of trees in the simulation is taken as 1, 3, 5 and 9 respectively. The distribution of trees is shown in Figure.7. The wires are all facing the trees, and the distance between the trees and the trees is 6m. The simulation results are shown in Figure.8.

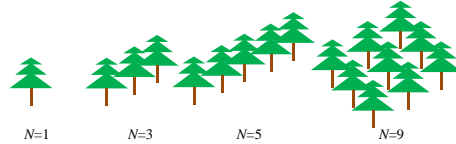
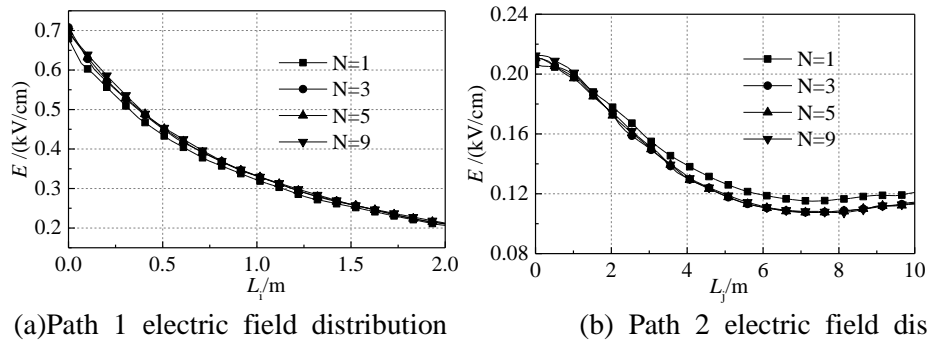


Figure 7 Sketch map of tree distribution



(a) Path 1 electric field distribution

(b) Path 2 electric field distribution

Figure 8 Electric field distribution when different number of trees exist

From Figure.8, it can be seen that the number of trees has little effect on the electric field distribution of Path 1 and Path 2, and the maximum difference of electric field intensity is less than 10%. It shows that the number of trees has little effect on the electric field distribution near trees, and the number of trees can be neglected in calculation.

4.5 Critical breakdown distance

The calculation process is as follows:

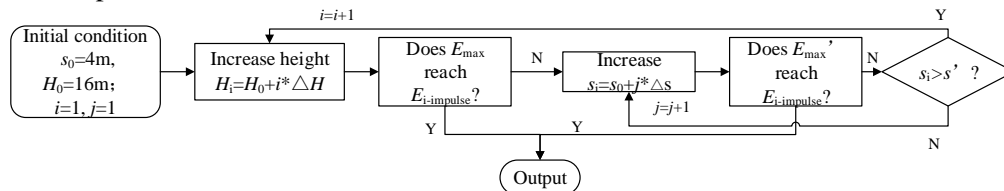


Figure 9 Calculation process of critical tree height

In Figure.9, α_0 is the phase angle of the power supply, s' is the maximum horizontal displacement, ΔH is the height increment, and Δs is the horizontal distance increment. According to the actual line layout, $\Delta H = 0.2\text{m}$ and $\Delta s = 0.3\text{m}$ are selected. The process of determining critical breakdown distance according to the flow chart shown in Figure.9 is as follows: Firstly, the appropriate phase angle α_0 , tree height H_0 , and horizontal distance s_0 are found, and then the horizontal distance is gradually increased to the maximum value s' . During the process, the field intensity at the top of the tree canopy does not reach $E_{i\text{-impulse}}$. H_0 and s_0 are taken as the initial values of simulation. Then the height of trees is increased by ΔH , and the horizontal distance is increased by step Δs . The top field strength of trees is calculated at different horizontal distance. If the field strength reaches $E_{i\text{-impulse}}$, the distance between the tree and the wire is the critical breakdown distance under the current applied voltage. On the contrary, the height of trees is increased and the above process is repeated.

Table.1 Critical breakdown distance at different power supply phase angles

Phase/°	U_A/kV	U_B/kV	U_C/kV	d_i/m
0	408.2	-204.1	-204.1	1.52
45	288.6	105.6	-394.2	1.36
90	0	353.5	-353.5	1.55
135	-288.6	394.3	-105.6	1.46
180	-408.2	204.1	204.1	1.76
225	-288.6	-105.6	394.3	1.68
270	0	-353.5	353.5	1.44
315	288.6	-394.3	105.6	1.71

Table.1 shows that the critical breakdown distance varies with different power supply phase angles. When the instantaneous value of side-phase voltage is at the peak of negative polarity, streamer discharge occurs at the top of the tree crown when the distance between the tree and the conductor is within 1.76m. At a specific phase angle, the distance between the tree and the conductor should be within 1.36m. Because of the dispersion of discharge and the influence of environment and the state of tree itself, tree-wire discharge may occur at any phase angle of the power supply. In order to retain enough safety margin, the critical breakdown distance between trees and conductors should be 1.76m, that is, the distance between trees and conductors should not be less than 1.76m, otherwise it is easy to cause tree flashover failure.

5 Conclusion

1) Under the action of power frequency electric field, the conduction characteristics of trees are similar to those of metals, and good conductors can be used to simulate the effects of trees on power frequency electric field distribution.

2) With the increase of tree height and the decrease of horizontal distance between tree and transmission line, the spatial electric field distribution increases gradually. The trees with higher apex have more obvious influence on the space electric field, which is more likely to cause electric field distortion and flash.

3) For the example line in this paper, when the distance between the tree and the conductor reaches 1.76m, the field intensity at the top of the tree exceeds the initial field intensity of the streamer, which is easy to cause tree flashover fault. Therefore, in order to avoid the occurrence of the fault, the distance between the tree and the conductor should be greater than 1.76m.

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