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Optimization of Induction Electricity in Buildings by Ultra High Voltage Transmission Lines

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Abstract: With the rapid development of China's economy, the demand for electricity, as the lifeline of the economy, is naturally increasing year by year. At the same time, China's market-oriented reform of electricity has shown initial results, a diversified competitive pattern is forming, and the commodity attributes of electricity have been further improved. The role of allocating electricity resources is also gradually strengthening, and there is a clear growth trend in market-oriented trading of electricity. There is an imbalance in the distribution and load centers of energy in China, and the corresponding resource points and load centers are also relatively far away. Due to the shortage of transmission corridors in China, a considerable portion of ultra-high voltage lines are distributed in residential areas. At this time, the impact of buildings close to residential areas on high-voltage transmission lines, as well as more in-depth guidance for transmission line installation and distribution in residential areas, will play a certain guiding role. Therefore, it is particularly important to study the influence of electric field distribution under different conditions on transmission lines. This article reasonably simplifies the three-dimensional model of transmission lines and introduces a line charge unit model to simulate the three-dimensional electric field near ultra-high voltage transmission lines. At the same time, simulation research is conducted on the three-dimensional electric field in different situations, namely in buildings of different materials.

Keywords: 500KV double circuit transmission line; Distorted electric field; Optimization of building electric field; Safe height； Finite element analysis

1. Introduction

With the rapid economic development of China and the advancement of socialism with Chinese characteristics entering a new era, the nation's primary contradiction has shifted. It now revolves around the growing demand of the people for a better quality of life, juxtaposed against unbalanced and insufficient development. The progress of any societal sector is inevitably underpinned by the quality of electrical energy supply. As such, a robust expansion of the power transmission network is critical. The development and enhancement of the electric power grid represent an essential component of this progress. However, increasing attention is being directed toward the electromagnetic environmental impacts of ultra-high voltage (UHV) transmission lines, particularly as the scale of their construction accelerates.

The transmission network's electromagnetic environment is of paramount importance, especially given the rising elevation and density of residential buildings near these lines. Distortion of industrial frequency electric fields, especially on rooftops, has emerged as a significant challenge, posing constraints on project planning, construction, and environmental assessments in these areas.

This study constructs a simulation model of a 500 kV double-circuit transmission line, featuring 500 m tower spacing with adjacent ground-level buildings [1]. Using COMSOL Multiphysics, a finite element software, the distribution of electric fields on building surfaces and the resulting distortions under different scenarios were calculated. By altering parameters such as building height, corner radius, and surface materials, we explored methods to mitigate electric field distortion on building surfaces [2]. The findings aim to provide a theoretical basis for the planning and construction of 500 kV double-circuit transmission lines, contributing to more sustainable and efficient power grid development.

2. Methodology

In the calculation of static electric fields, the free charge on the surface of a charged body, along with the bound charge at dielectric interfaces, can be substituted by equivalent charges located in a null region. This approach is commonly referred to as the method of simulated charges, with these equivalent charges termed as "simulated charges" [3].

The simulated charge method is widely employed in electrostatic field computations. Fundamentally, this technique treats the potential function as an unknown variable, solving Laplace's and Poisson's equations to determine the electric field distribution. Its versatility and accuracy make it a central tool in the analysis of electrostatic phenomena.

Potential control equations:

$$\nabla^2 \varphi = -\frac{\rho}{\varepsilon} \quad (1)$$

Type I boundary conditions:

$$\varphi|_{L_1} = f_1(P) \quad (2)$$

Interfacial conditions of different media:

$$\varphi_1 = \varphi_2 \quad (3)$$

$$\varepsilon_1 \frac{\partial \varphi_1}{\partial n} - \varepsilon_2 \frac{\partial \varphi_2}{\partial n} = 0 \quad (4)$$

In the vicinity of high-voltage AC transmission lines, the industrial frequency electric field distribution is often computed using the simulated charge method. However, when buildings or other materials are present near the transmission lines, the electric field becomes distorted at the interface where air and building materials meet. In such cases, the finite element method is typically employed to more accurately calculate the electric field at these junctions [4]-[5].

Given that the industrial frequency electric field around transmission lines falls within the quasi-static regime, methods used for solving electrostatic fields can be applied to compute the spatial electric field. As a result, the electric field distribution in the surrounding space adheres to the following conditions:

$$E = -D\varphi \quad (5)$$

$$\frac{\partial}{\partial x}(\varepsilon \frac{\partial \varphi}{\partial x}) + \frac{\partial}{\partial y}(\varepsilon \frac{\partial \varphi}{\partial y}) + \frac{\partial}{\partial z}(\varepsilon \frac{\partial \varphi}{\partial z}) = 0 \quad (6)$$

In Eq. (6), ε is the relative dielectric constant of the material, φ as a function of potential.

On the boundaries of the transmission line electrodes:

$$\varphi | \Gamma_1 = \mu_G(s) \quad (7)$$

Eq. (7) where u_G is the excitation function on the electrode boundary and s is the position vector.

Extrapolated on the dielectric dividing surface:

$$\begin{aligned} \varphi_1 &= \varphi_2 \\ \varepsilon_1 \frac{\partial \varphi_1}{\partial n} &= \varepsilon_2 \frac{\partial \varphi_2}{\partial n} \end{aligned} \quad (8)$$

In Eq. (8), is the outer normal vector of the boundary.

Then, the whole operation region is dissected into a finite number of small, non-intersecting and interconnected units, and the operation is developed within each unit. In the finite units, there is a basis function consisting of the unit potential variable and the shape function, and the unit shape function Ni can be solved by the overall risk margin method of Galyokin.

$$(R_{er}(\varphi), N_i) = 0 (i = 0,1,2\ldots) \quad (9)$$

Rer in Eq. (9) is the error margin generated in the control equations by the approximate solution, i tends to positive infinity.

The basis function of the computational domain and the basis function of each cell can be viewed as the whole versus the part, so the solution of the computational domain is approximated by fitting the solution of all the cells to the solution of the computational domain. Let the number of cells be n, then the potential represented by the cell potential variable and the shape function N_i is:

$$\varphi = \sum_{i=1}^{n} N_i \varphi_i \qquad (10)$$

When calculating electric fields using the finite element method, it is important to ensure that the computational domain is bounded. The computational domain can be set by creating artificial boundaries and setting the boundary potential to zero. In this paper, we use to set a large enough air packet to ensure the accuracy of the calculation and to ensure that the electric field profile in the critical region is fine enough.

3. Results and discussion

3.1 Finite element modeling of transmission lines

Based on the actual tower model, according to\the corresponding dimensions, the 500KV transmission line tower model is established by finite element simulation software COMSOL [6]. The model is shown in Figure 1. The line conductor adopts 4×LGJ-400 (four-split steel-core aluminum strand) type aluminum-clad steel-core aluminum strand, with a tower height of 64m, and the height of the lowest conductor from the ground is 30m.

Through the investigation of China's ultra-high voltage transmission line near the civil building materials found that the civil building mainly includes brick and soil and reinforced structure, because the civil building structure has diversity and practicality; combined with the actual situation, the selection of the civil building wall thickness of 0.26m, the length and width of 6m, the height of 8m [7].

The simulated charge of the UHV transmission line is usually in the center of the transmission line, and the corresponding matching point is at a certain point on the boundary of the transmission line. Because there are many steel bars, metal ores and some metal materials outside the building walls in civil buildings, the building under the UHV transmission line can be regarded as a good conductor in the simulation process, and the potential is the same as the earth potential.

In the COMSOL environment to determine the type of different units, materials, etc., and then according to the actual study of the transmission line and civil building size to construct the transmission line and civil building calculation model. Because the experimental line segment distance and transmission conductor, civil building size is very different, in order to enhance the accuracy of the results, the civil building and the ultra-high voltage transmission line center of 3 to 5 times the interval as a radius, the construction of a spherical range, simulation of the real field strength distribution [2].

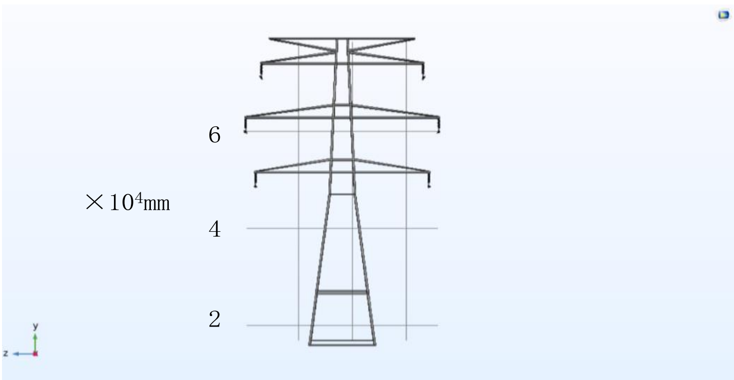

Figure. 1 Line tower model

The overall simulation model is shown in Figure 2 below:

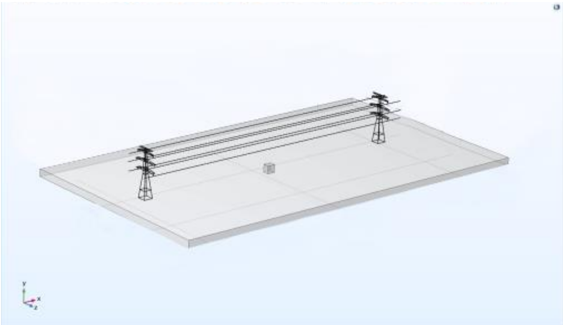

Figure. 2 Overall simulation model

In order to ensure the accuracy of the simulation calculation, on the basis of the automatic grid dissection of the software system, the key areas of the spatial electric field measurement location are further encrypted and dissected, and the size of the encrypted grid cells is limited to no more than 200 mm [8]. The results of the model's grid dissection are shown in Figure 3.

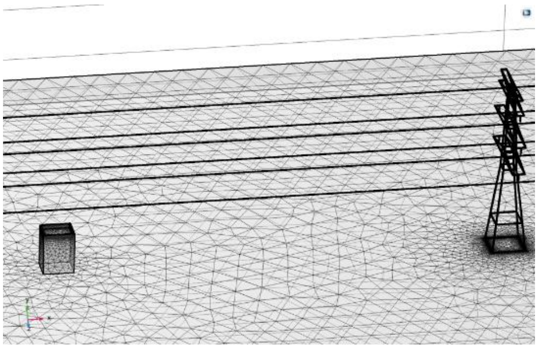

Figure. 3 Physical field meshing

3.2 Model validation

The industrial frequency electric field around a transmission line is the result of the superposition of three-phase voltages, and the magnitude and direction of the field strength at any point in space is periodically time-varying. The presence of ground potential will cause the electric field in the space above the ground to be approximately uniformly dispersed and will decrease rapidly in the distance direction [9]. On the contrary, the presence of a building will cause the power lines to concentrate at the corners of the house, making the electric field significantly distorted. In this paper, the distortion of the electric field on the roof is investigated by comparing simulation calculations and theoretical studies, which in turn verifies the validity of the simulation model.

Firstly, the electric field distribution on the surface of the building is solved under normal conditions as in Fig. 4:

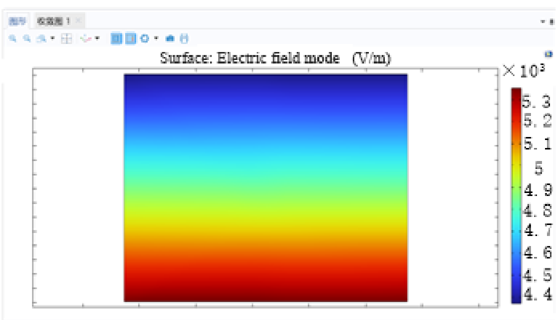

Figure. 4 Distribution of electric field on the building surface under normal conditions

Under normal conditions (i.e., in the absence of building influence, where the building in the simulation is assumed to have the same dielectric constant as the surrounding air), the electric field on the surface of the building varies consistently with the distance from the transmission line. As the distance decreases, the field strength increases, and as the distance increases, the field strength diminishes, following a uniform gradient.

Next, the building material is defined as concrete, and the building's position is moved to the lower left corner, closest to the transmission line. This adjustment allows for the verification of electric field distortion at the local corners of the structure:

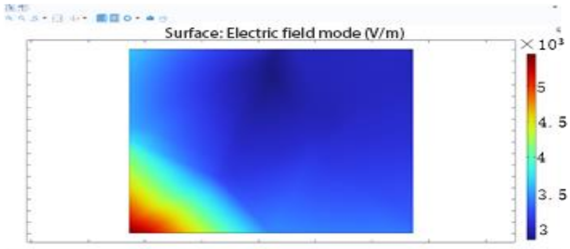

Figure. 5 Localized edge corner electric field distortion

In Fig. 5, the horizontal axis is the distance from the transmission line, the maximum value is at (11.5, 69.5), 5402 V/m, and the minimum value is located at (16.5, 77.5), 2898 V/m. It can be seen that the electric field is still in accordance with the previous law, and it is the largest in the corner close to the transmission line, and the other side has the smallest field strength at the ground prism, which is obviously in good agreement with the previous result The field is obviously in good agreement with the previous results.

3.3 Simulation of electric field distribution and analysis of the effect of distortion factors

The factors influencing electric field distortion on the roofs of houses near transmission lines primarily include the height of the house, the distance from the transmission line, the phase sequence arrangement of the line, as well as the material and shape of the house. Among these, the electric field strength near the line is highest when the double-circuit lines are arranged in the same phase sequence, followed by different phase sequences, and is lowest in reverse-phase configurations [2].

Considering that self-built houses in rural areas are often constructed from various materials and exhibit diverse roof structures, this study employs a univariate analysis method. By altering parameters such as the relative dielectric constant, different roof materials are simulated. The resulting electric field distributions are analyzed to investigate the impact of transmission lines on buildings made from various materials.

(1) Influence of building materials on electric field distribution

When the main body of the building is residential housing.

The main body material of the residential building is mainly concrete, and its relative dielectric constant is taken as 6.4. The residential building is an ordinary three-story small building, for example, with a height of 10m, a width of 8m, and a length of 10m, which is located directly under the transmission line. The electric field simulation results on its surface are shown in Fig. 6 below:

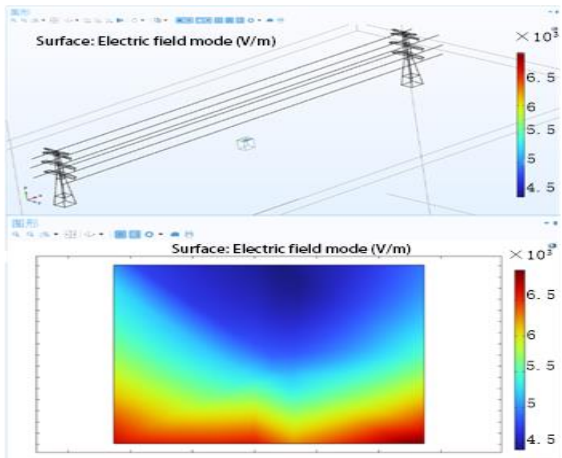

Figure. 6 Building surface electric field (concrete)

In the simulation, the horizontal axis represents the length of the building, while the vertical axis denotes its width. The side experiencing the strongest electric field is the one closest to the transmission line.

As shown in the simulation results (Fig.6), the presence of buildings around UHV transmission lines leads to a noticeable distortion in electric field strength. This occurs because the high-voltage electric field induces surface charges on the building, with the induced charge density increasing as the building moves closer to the line. Consequently, the electric field strength near the prismatic edges of the building is significantly higher than in the surrounding areas, resulting in substantial distortion compared to scenarios without buildings. The maximum electric field strength on the building occurs at the prismatic edge closest to the transmission line, reaching 6903 V/m, in contrast to a maximum field strength of 5342 V/m in the absence of the building.

When the roof of the building is covered with glass, a common material with a dielectric constant of 4.94, the simulation is recalculated. The glass surface alters the distribution of the electric field, providing further insight into the effect of different materials on electric field distortion.

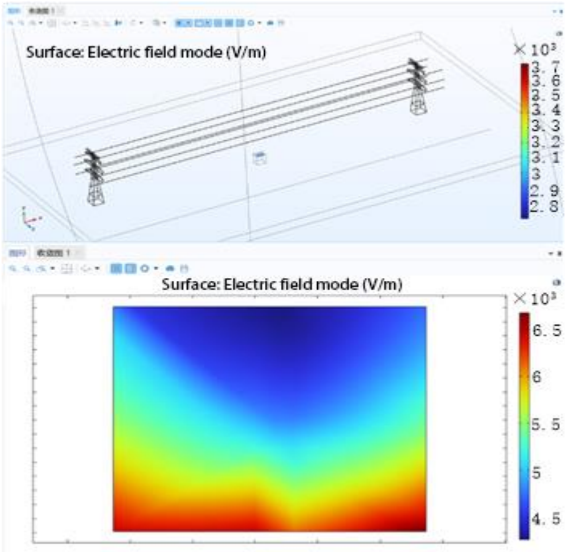

Figure. 7 Building surface electric field (glass)

The general trend of electric field variation, as depicted in Fig. 7, remains consistent with the case of concrete materials, though specific values differ. The maximum electric field strength reaches 6638 V/m, while the minimum is 4264 V/m. As expected, the field strength is greater on the side closer to the transmission line and decreases with increasing distance from the line [10].

When the building is modeled as a vegetable shed, the footprint remains unchanged, and only the effect of different materials on the electric field is considered. Vegetable greenhouses are common structures in rural open areas and frequently found under ultra-high-voltage transmission lines. Given that polyvinyl chloride (PVC) is the typical material used in these greenhouses, with a relative dielectric constant of 3.4, the same building is simulated to study the electric field distribution on its surface.

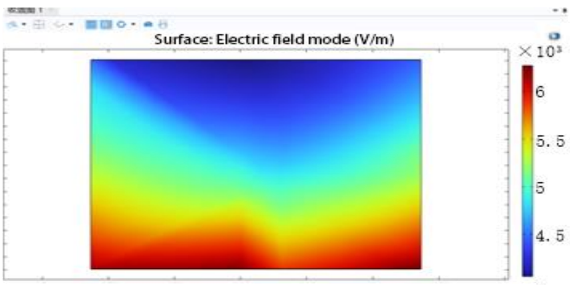

Figure.8 Surface electric field distribution (polyvinyl chloride)

As shown in Fig. 8, for buildings with the same structure, the electric field exhibits a similar distribution pattern. Differences in the relative dielectric constant primarily affect the specific values of the field strength. The maximum field strength is 6208 V/m, while the minimum is 4062 V/m.

The results indicate that the distorted electric field above the roof varies between 6208 V/m and 6903 V/m depending on the building material, while the minimum value ranges from 4206 V/m to 4376 V/m. The distribution pattern remains consistent, with the largest field distortion occurring near the edges. Notably, there is a significant disparity between the maximum and minimum field strength on the same surface. To reduce the induced voltage, buildings located beneath transmission lines can be covered with materials such as polyvinyl chloride (PVC), which have relatively low dielectric constants.

(2) Effect of building height on electric field:

To investigate the impact of building height on electric field distortion, a univariate analysis was conducted. The building was placed at a fixed distance from the transmission line, and its height was incrementally increased to compare the electric field strength at different heights. The heights were set at 4 m, 8 m, and 12 m, respectively. The simulation results are illustrated in Fig. 9.

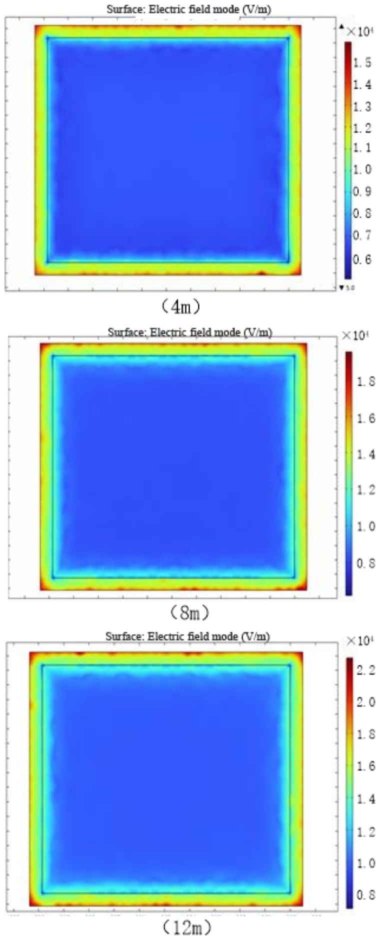

Figure.9 Distribution of electric fields at different heights

Comprehensive analysis reveals that as building height increases, both the electric field strength on the roof and the degree of distortion rise correspondingly, exhibiting a positive correlation. Additionally, taller buildings result in a larger area of electric field distortion, with the most pronounced distortion typically occurring at the edges and corners. Therefore, it is essential to strictly control the height of buildings located beneath transmission lines to reduce both the magnitude and extent of electric field distortion. By carefully optimizing building height, the impact of the transmission lines on nearby structures can be mitigated.

(3) Numerical analysis of electric field processed by edge fillet

Analysis indicates that electric field distortion is most likely to occur at the edges and corners of buildings. To explore more effective methods for mitigating such distortion, the corners of building rooftops near ultra-high voltage transmission lines were treated with rounded edges. The radii of these rounded corners were varied systematically at 0 cm, 2 cm, 4 cm, 6 cm, 8 cm, and 10 cm, while maintaining a constant distance from the transmission line. Simulation results of the electric field strength on the rooftops for these different corner radii are presented in Fig. 10.

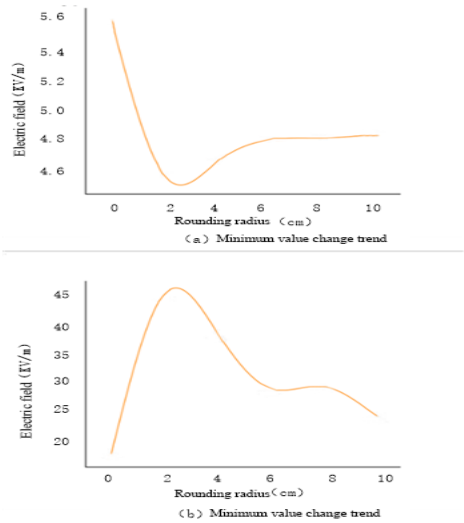

Figure.10 Trend of surface electric field

Analysis of the data reveals that after rounding the corners, the minimum value of the surface electric field decreases significantly. As the radius of the rounded corners increases, the minimum value initially decreases, then gradually increases, and eventually stabilizes. In contrast, the maximum value exhibits an initial increase followed by a continuous decrease, eventually approaching the value observed without corner rounding. To better understand the distortion of the surface electric field, a comparison of the distortion range on the surface is presented in Fig. 11.

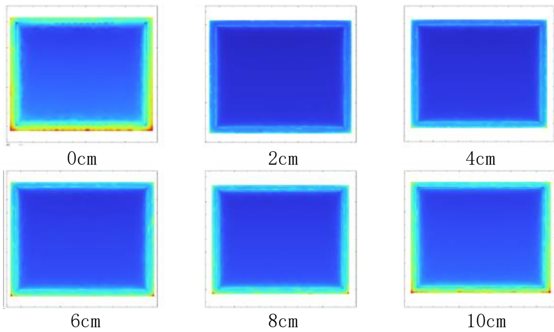

Figure.11 Comparison of electric field distortion ranges

The simulation results indicate that as the radius of the rounded corners increases, the electric field distortion initially decreases but then slightly increases. The most favorable distortion condition is observed with a corner radius of 4 cm, where the maximum distortion occurs only at the corner nearest to the transmission line. In contrast, when the corners are not rounded, the electric field distortion is greatest, with the maximum distortion occurring at the edge closest to the transmission line [11].

Overall, the analysis shows that while rounding the corners can lead to an increase in the maximum value of electric field distortion, it significantly improves both the minimum value of distortion and the distortion range. To optimize the surface electric field conditions for buildings under transmission lines, rounding the corners to a radius of 6 cm, combined with enhanced protection at the four corners, offers a balanced approach to reducing both the extent and magnitude of electric field distortion [12].

(4) Comparative analysis of the horizontal distance from the line

The height of the fixed house is 12m, and when the house is 0m, 6m, 8m, 10m, 14m and 16m from the line (the minimum horizontal distance of the line near the tower of the house boundary line) respectively, the edges are rounded by 0cm, 2cm, 4cm, 6cm, 8cm and 10cm, and the electric field of the roof is simulated. The results are shown in the table below:

Table 1 Distribution Table of Minimum Electric Field Values（KV/m）

Rounding radius distance	0cm	2cm	4cm	6cm	8cm	10cm
0m	5.51	4.61	4.68	4.82	4.83	4.85
6m	4.73	4.06	4.11	4.25	4.17	4.27
8m	4.46	3.88	3.93	4.07	3.94	4.10
10m	4.22	3.73	3.79	3.79	3.79	3.93
14m	3.94	3.37	3.44	3.46	3.49	3.51
16m	3.79	3.21	3.24	3.35	3.27	3.37

Table 2 Distribution Table of Maximum Electric Field Values（KV/m）

Rounding radius distance	0cm	2cm	4cm	6cm	8cm	10cm
0m	19.9	43.1	37.5	29.2	29.5	25.3
6m	18.5	46.1	31.5	26.5	24.5	23.5
8m	18.4	43.6	29.8	27.0	26.9	23.7
10m	17.5	35.0	29.3	26.1	25.6	22.6
14m	17.3	35.0	25.4	23.1	22.2	23.1
16m	16.1	31.1	31.8	24.4	20.5	19.1

Tables 1 and 2 present the statistical results of the simulations regarding the effects of corner radius. It is evident that, with all other conditions held constant, the maximum and minimum values of electric field distortion both decrease as the distance from the transmission line increases. Specifically, the minimum value can decrease by up to 31.2%, and the maximum value can decrease by up to 19.17%. When buildings are closer to the transmission line, the minimum surface electric field is more sensitive to distance variations, while the maximum surface electric field shows a gradual decrease with increasing distance. The impact of corner rounding on the electric field exhibits a similar trend regardless of the building's position relative to the transmission line.

4. Conclusion

A computational model incorporating conductors, steel structures, and air domains was established, and a finite element model was used to analyze the industrial frequency electric fields near 500 kV ultra-high voltage double-circuit AC transmission lines. The electric field distortions and maximum distortion values for buildings made from various materials were simulated and compared.

When buildings are situated near ultra-high voltage double-circuit transmission lines, the electric field on the building’s roof is higher compared to scenarios where no building is present. The field distortion at the edges of the building is severe, with greater distortion observed on the side closer to the transmission line.

For a fixed horizontal distance from the transmission line, an increase in vertical distance results in a more severe induced electric field and more pronounced distortion. Implementing corner rounding on the edges of the building can improve the distortion situation. The distortion initially decreases with increasing corner radius, then slightly increases, while the maximum value of the distorted electric field also increases. Therefore, appropriate material coverage and corner rounding on buildings can mitigate electric field distortion.

Declaration of Conflicting Interests

The author(s) declared no potential conflicts of interest with respect to the research, author-ship, and/or publication of this article.

Data Sharing Agreement

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

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