

Research on the Electromagnetic Environment of High-voltage AC Transmission Wires

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Abstract: With the rapid development of China's economy, the demand for electricity is increasing day by day, due to the inconsistency of China's energy distribution and power load demand, high-voltage transmission wires play a key role in China's power grid because of its high capacity and low loss. Split wires are an essential part of high-voltage AC transmission wires, and they can effectively reduce wire losses and inhibit corona generation. This study conducts a comparative analysis of the internal and external electromagnetic fields associated with both single and split wires through theoretical derivation and finite element analysis. The results show that splitting the wire can effectively reduce the electric field strength and magnetic induction strength around the wire, thereby suppressing the generation of corona and reducing the equivalent resistance of the wire, thereby reducing the loss of the wire. In addition, the distance between the wires and the radius of the wires are also important factors affecting the electric field strength and magnetic induction strength, the larger the distance between the wires, the larger the wire radius, and the smaller the electric field strength and magnetic induction intensity.

Keywords: High-voltage AC transmission wire, Electromagnetic environment, Skin effect, Finite element analysis

1. Introduction

China's energy is mainly distributed in the northwest and southwest, while the demand for electricity is concentrated in the central and eastern regions. Given the economic and ecological challenges associated with conventional fossil fuel energy transmission systems, it is crucial to enhance the distribution of energy resources and facilitate the transfer of electricity from storage facilities to consumption hubs. In this process, high-voltage AC transmission wires occupy a pivotal position in China's power grid due to their advantages of high transmission capacity and low wire loss. As an important part of high-voltage AC transmission wires, split conductors can effectively reduce wire losses and effectively inhibit the generation of corona, and the study of electromagnetic field characteristics is of great significance to ensure the safe and stable operation of power grids. Currently, the electromagnetic environment of UHV AC transmission wires is mainly divided into numerical calculation and corona cage simulation, and data calculation includes simulated charge method, difference method, moment method and finite element method. He Dahai, Yuan Chunyuan, and Sun Chengxian used the finite element method and the simulated charge method to analyze the electric shock effect of vehicles on the human body under high-voltage transmission lines [1]. Building on this, Ai Huiye used the equivalent charge and quasi-static magnetic field model and the DL/T 203 6-

2019 noise model to analyze the electromagnetic environment of a 110kV transmission line in a central province [2]. Subsequently, Chen Yonghong explored the electromagnetic environment of the $\pm 160\text{kV}$ flexible DC transmission wire in wind farms, highlighting the unique challenges and solutions in renewable energy integration [3]. To enhance analytical capabilities, Chen Bin, Lei Dong, Zhang Qi, Liu Fei and Xu Lingyue measured the electric and magnetic field strength on the ground and in residential buildings near a certain line, and analyzed the source, generation mechanism, frequency domain characteristics and spatial attenuation process of electromagnetic interference [4]. Meanwhile, Deng Xuequn, Zhang Yue, Wei Dong and Chen Pujin carried out model prediction of typical single-circuit towers of UHV 1000kV single-circuit transmission lines, and analyzed the possible electromagnetic environmental impact during operation [5]. In a related study, Xu Yixiong examined the electromagnetic environment of $\pm 800\text{kV}/\pm 500\text{kV}$ double-circuit DC wires on the same tower, addressing the complexities of multi-voltage configurations [6]. Further expanding on this, Qi Wuxian, Hao Sipeng, Zhou Ye, and Xun Daoyu investigated methods to improve the electromagnetic environment of mixed-voltage double-circuit DC transmission wires on the same tower, providing valuable insights for grid stability [7]. In addition, Qin Jun took the influence of UHV AC multi-circuit transmission lines on the electromagnetic environment as the research object, and through the analysis of different parameters such as tower shape, conductor height, phase spacing, phase sequence arrangement, number of split wires, split sub-spacing and split sub-conductor diameter adopted by high-voltage multi-circuit lines, and used computer-aided analysis software to obtain specific measures to reduce the impact of UHV electromagnetic environment [8]. Moreover, based on the calculation data of the electromagnetic environment, Lin Fang, Bai Xiaolu, Lv Jianshuang and Wang Yanjun combined with the design and operation experience and results of the existing projects of 1000kV, +800kV, $\pm 1100\text{kV}$, etc, the standard limits of the electromagnetic environment of the $\pm 1500\text{kV}$ UHVDC transmission line are given [9]. Lastly, Shi Lipeng utilized the finite element method to analyze the electric field characteristics of split wire spacer rods, offering a detailed methodological approach to understanding electromagnetic behavior [10]. Collectively, these studies form a robust body of knowledge that significantly advances the field of electromagnetic environment analysis in power transmission systems. It is of great significance to study the internal and external electromagnetic environment of single conductor and split conductor to reduce the overall corona effect of transmission wires and reduce wire losses, and ensure the comprehensive, coordinated sustainable and healthy development of the power industry.

2. Base model

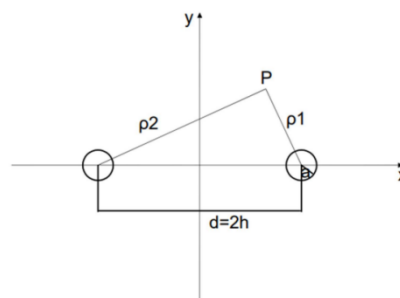


Figure 1: Basic structure of transmission wires

Figure 1 shows the basic structure of transmission wires.

2.1. Electric field

For a transient moment, let the voltage between the two wires is U_0 . Solved by using the simulated charge method, the equivalent charge on the unit length of the wire is τ , and the electric field strength is

$$E_1 = \frac{\tau}{2\pi\epsilon_0\rho_1} e_{\rho_1} \quad (1)$$

$$E_2 = \frac{-\tau}{2\pi\epsilon_0\rho_2} e_{\rho_2} \quad (2)$$

Calculate the potential at any point in space

$$\varphi_{Q_1} = A + \int_{\rho_1}^a \frac{\tau}{2\pi\epsilon_0\rho_1} d\rho_1 \quad (3)$$

$$\varphi_{Q_2} = B + \int_{\rho_2}^a \frac{\tau}{2\pi\epsilon_0\rho_2} d\rho_2 \quad (4)$$

$$\varphi = \varphi_{Q_1} + \varphi_{Q_2} = A + B + \frac{\tau}{2\pi\epsilon_0} \ln \frac{\rho_2}{\rho_1} \quad (5)$$

At the origin, $\varphi = 0$, thus $A + B = 0$

$$\varphi = \frac{\tau}{2\pi\epsilon_0} \ln \frac{\rho_2}{\rho_1} \quad (6)$$

And then according to

$$\varphi_1 - \varphi_2 = U_0 \quad (7)$$

It can be calculated that

$$\tau = \frac{-\pi\epsilon_0 U_0}{\ln \frac{a}{2h}} \quad (8)$$

According to the superposition theorem

$$E = E_1 + E_2 = \frac{\tau h}{\pi\epsilon_0 h^2 - \pi\epsilon_0 x^2} \quad (-h + a < x < h - a) \quad (9)$$

$$E_m = \frac{\tau}{2\pi\epsilon_0} \left(\frac{1}{a} + \frac{1}{2h-a} \right) \quad (x = h - a \text{ 或 } x = -h + a) \quad (10)$$

Because $2h \gg a$

$$E_m = \frac{U_0}{2a \ln \frac{a}{2h}} \quad (11)$$

It can be seen that the maximum value of the electric field strength is mainly related to the distance between the two wires and the radius of the wire.

2.2. Magnetic field

Let the currents on the two wires be $\sum I - I$, the magnetic induction intensity is

$$B = \frac{\mu_0 I}{2\pi\rho_1} e_{\phi_1} + \frac{-\mu_0 I}{2\pi\rho_2} e_{\phi_2} \quad (12)$$

$$B_m = \frac{\mu_0 I}{2\pi} \left(\frac{1}{a} - \frac{1}{2h-a} \right) \quad (13)$$

Because $2h \gg a$

$$B_m = \frac{\mu_0 I}{2\pi a} \quad (14)$$

It can be seen that the maximum value of the magnetic induction intensity is mainly related to the radius of the wire.

2.3. Current distribution within the wire

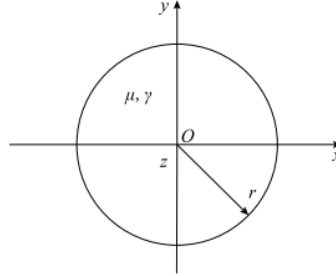


Figure 2: Cylindrical conductor

Figure 2 shows cylindrical conductor. The parameters of the cylindrical conductor are shown in the figure, and Maxwell's equations under the magnetic quasi-static electromagnetic field can be simplified as

$$\begin{cases} \nabla \times H = J \\ \nabla \times E = -\frac{\partial B}{\partial t} \\ \nabla \cdot B = 0 \\ \nabla \cdot D = \rho \end{cases} \quad (15)$$

According to the isotropic linear medium, there is a constitutive relation

$$\begin{cases} B = \mu H \\ J = \gamma E \end{cases} \quad (16)$$

It can be calculated that

$$\nabla^2 E = j\omega\mu\gamma E \quad (17)$$

It can be solved that

$$J(x) = J_0 e^{\frac{x-b}{\delta}} \quad (18)$$

Among that, J_0 is the current density on the outer surface of the conductive rod of the casing, δ is the skin depth [11].

$$\delta = \sqrt{\frac{2}{\omega\mu\sigma}} \quad (19)$$

The equivalent resistance of a cylindrical conductor is the resistance corresponding to the skin depth δ .

3. Introduction to finite element modeling

Finite element analysis (FEA) is a numerical method extensively utilized in engineering and physics to address complex mechanical issues, including structural mechanics, heat conduction, fluid mechanics, and electromagnetics. FEA simplifies a continuous system by breaking it down into a finite number of discrete elements, enabling the approximation of system behavior. This approach is especially advantageous for intricate problems that resist direct analytical solutions, such as stress analysis, heat transfer, fluid dynamics, and electromagnetic fields [12].

3.1. Basic steps

(1) Divide the area: Divide the electromagnetic field analysis area into a limited number of elements. Commonly used element shapes include triangles and tetrahedra (for both 2D and 3D problems). Depending on the need, different element types can be chosen, such as lower-order elements (linear) or higher-order elements (quadratic).

(2) Select Shape Function: Select a shape function suitable for describing changes in the strength of electric and magnetic fields. These functions are usually polynomials and ensure that the values of the nodes can fit the field quantities within the element. A normal function in polynomial form is usually used for electromagnetic fields to satisfy the continuity of the electric and magnetic fields.

(3) Establish electromagnetic equations: Derive local equations from Maxwell's equations for each element, such as the interplay between electric and magnetic fields via Faraday's law and Ampere's theorem. The electromagnetic equation encompasses the gradient of electric field strength (E) and the curl of magnetic field strength (H).

(4) Assembling Global Equations: Assemble the local equations of all elements into a global equation as a whole through the connection relationships between nodes. This process needs to ensure the continuity of the electric and magnetic field strength at the shared nodes.

(5) Boundary Condition Setting: Boundary conditions are imposed on the global equation based on the specific electromagnetic problem. These include insulation conditions for electric fields, conductor conditions, and radiation conditions. For instance, the potential at the surface of an electrical conductor can be defined as zero.

(6) Solve the equations: Use appropriate numerical methods (such as the Laplace method, the conjugate gradient method, or the time-domain finite element method) to solve the global equations to obtain the electric and magnetic field components for each node. It is important to note that a time-stepping solution may be required to account for time variation.

(7) Post-processing: Analyze the calculation results and use special software to generate electromagnetic field distribution maps, contour maps, current density maps, etc. These visualization tools can help understand the distribution and variation of electric and magnetic fields across the field.

3.2. Advantages

(1) It has a great deal of flexibility in meshing and is able to achieve great accuracy.

(2) No matter how complex the boundaries and interfaces of the field are, the finite element method can effectively mesh and accurately simulate.

(3) The resulting matrix of equation coefficients is sparse and symmetrical, simplifying the solution process, making the calculation more efficient, less time-consuming, and taking up less memory.

(4) Boundary conditions can be easily integrated into the mathematical model of the finite element method, which reduces the difficulty of writing computer programs [13].

4. Case analysis

4.1. Introduction of COMSOL multiphysics

COMSOL Multiphysics is a large-scale, advanced numerical simulation software. It is widely used in scientific research and engineering computing in various fields, simulating various physical processes in the field of science and engineering. COMSOL Multiphysics employs the finite element method to address real-world physical phenomena through the resolution of partial differential equations, whether single or multi-field, for accurate simulations [14].

4.2. Simulation condition settings

When studying the external electromagnetic field environment of the wire, because the internal structure of the wire has little influence on the external electromagnetic field, a cylinder can be used instead of the internal structure of the wire, the voltage between the wires is set to be 330kV, the current on the wire is 400A, and the parametric sweep is set to explore the influence of the distance between the wires and the radius of the wire on the electric field strength and magnetic induction intensity.

In this paper, the current distribution in the steel core aluminum stranded wire is simulated, and Figure 3 shows the specific structure and partition results.

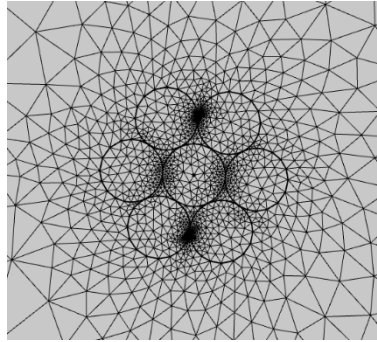


Figure 3: Meshing results

5. Results&discussion

5.1. Results

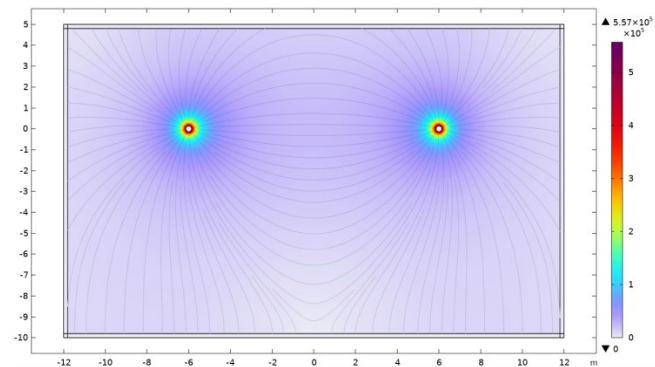


Figure 4: Electric field strength around a single wire

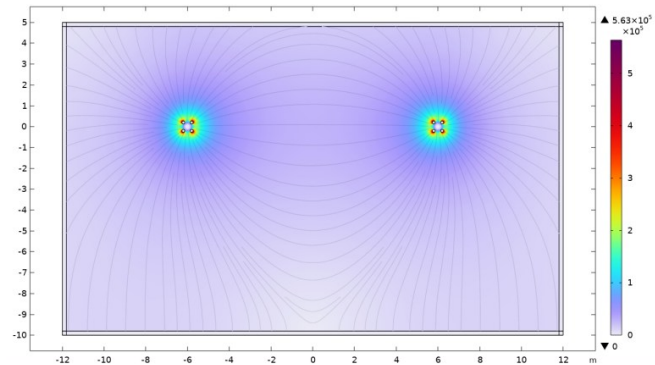


Figure 5: Electric field strength around the four-split wire

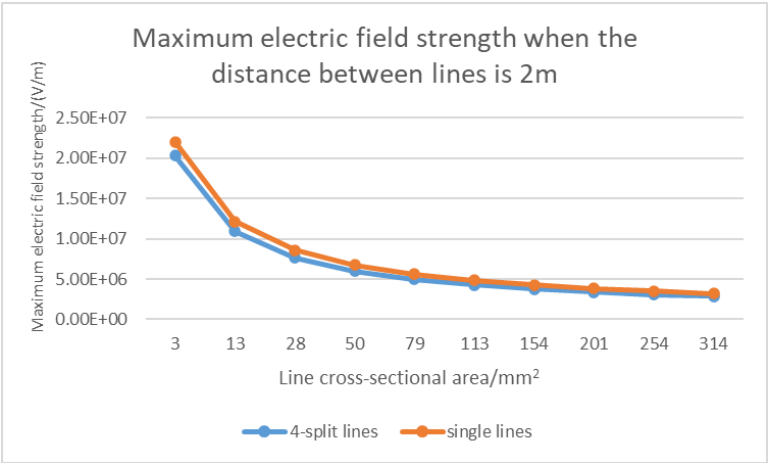


Figure 6: Maximum electric field strength when the distance between the wires is 2m

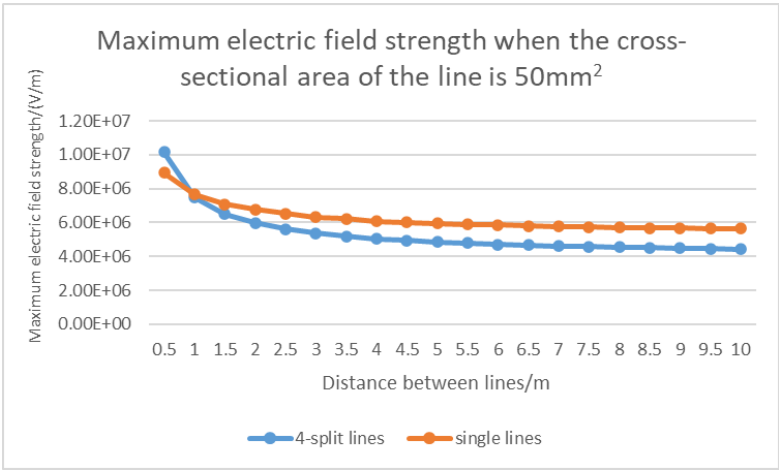


Figure 7: Maximum electric field strength when the cross-sectional area of the wire is 50mm2

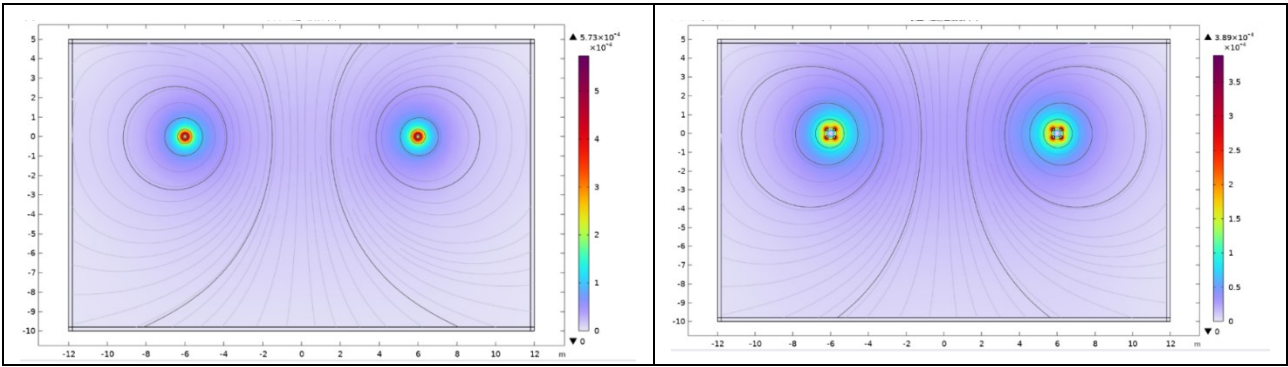


Figure 8: Magnetic induction intensity around a single wire
 Figure 9: Magnetic induction intensity around the quadruple split wire

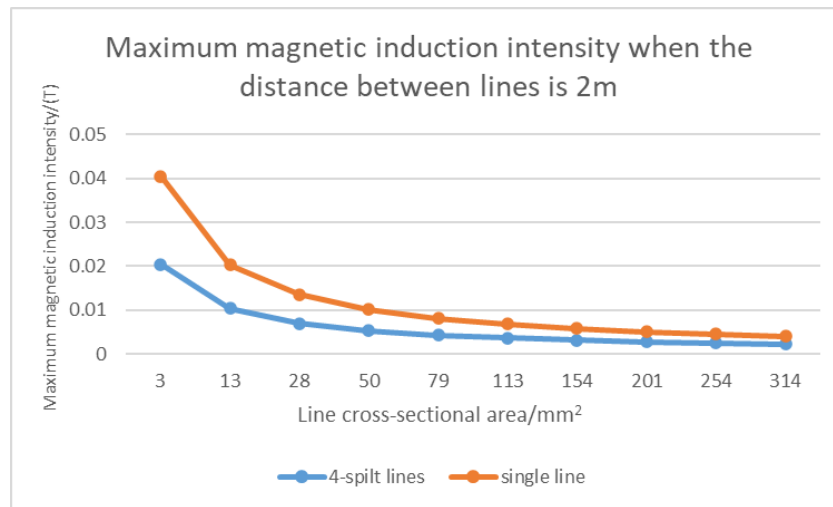


Figure 10: Maximum magnetic induction intensity when the distance between wires is 2m

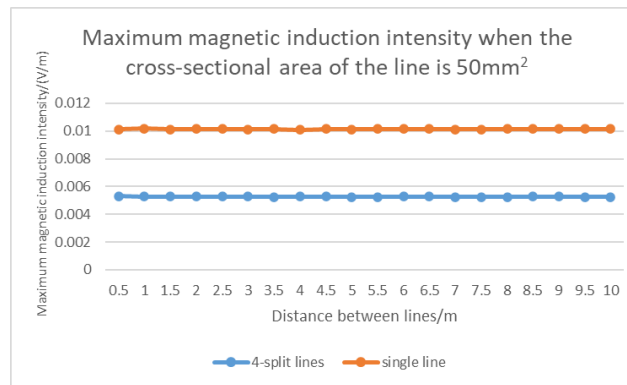


Figure 11: Maximum magnetic induction intensity when the cross-sectional area of the wire is 50mm²

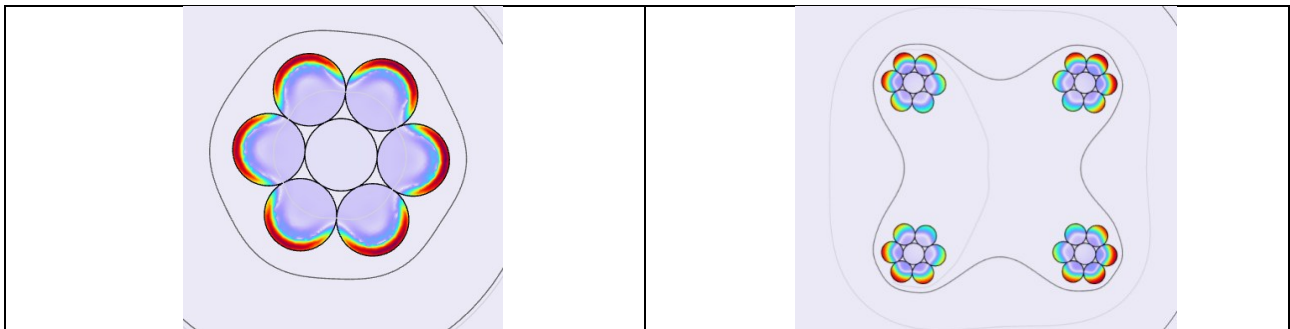


Figure 12: Distribution of current in a single wire

Figure 13: Distribution of current in a quadruple split wire

Figures 4 and 5 illustrate that splitting the wire can effectively reduce the electric field strength. Figure 6 illustrates that the electric field strength decreases as the cross-sectional area of the wire decreases. Figure 7 illustrates that the electric field strength decreases as the distance between the wires decreases. When the distance between the wires is too close, the electric field strength of the split wire is larger than that of the non-split wire, because the effective radius of the split wire is not infinitesimal and cannot be ignored. Figures 8 and 9 illustrate that splitting a wire can effectively reduce the magnetic induction intensity. Figure 10 illustrates that the smaller the cross-sectional area

of the wire, the smaller the magnetic induction. Figure 11 illustrates that the maximum magnetic induction intensity is independent of the distance between the wires. Figures 12 and 13 show the distribution of the current in the wire, and it can be seen that the utilization rate of the quadruple split wire is higher.

5.2. Discussion

- (1) The greater the distance between the wires, the larger the radius of the wires, and the smaller the electric field strength and magnetic induction intensity, which is consistent with the theoretical derivation.
- (2) Splitting the wire can effectively reduce the electric field strength and magnetic induction strength.
- (3) Due to the skin effect, the current is only distributed on the surface in the wire, which results in a lower utilization rate of wires, and splitting the wire helps to alleviate this.
- (4) When the radius of the conductor reaches a certain level, the downward trend of the electric field strength and magnetic induction intensity slows down, and considering the cost and the difficulty of building the transmission line, the larger the radius of the conductor is not the better.
- (5) In high humidity or polluted environments, the distortion of the electric field may lead to the enhancement of partial discharge, and the benefit of simply increasing the spacing will be weakened, and it is necessary to cooperate with the optimization of insulators.

6. Conclusion

This study reveals a synergistic link between theoretical derivation and finite element simulation, indicating that wire segmentation significantly reduces electric field intensity and magnetic induction strength, while also decreasing equivalent resistance. Additionally, wire spacing and radius are critical factors; greater distances and larger radii correspond to lower electric field and magnetic induction intensities. The analysis focuses solely on a transient moment, omitting the intricate time-domain variations. Future research should model three-phase electricity to explore complex interactions, incorporating structures such as transmission towers, isolation rods, trees, and residential buildings to investigate detailed electromagnetic fields in three-dimensional space.

References

- [1] He, D., Yuan, C., & Sun, C. (2024). Study on the power frequency electric field of high voltage transmission lines based on finite element method and simulated charge method. *Modern Engineering Technology*, 3(12), 25-28.
- [2] Ai, H. (2025). Electromagnetic environment calculation of 110 kV transmission lines. *Electrical Engineering Technology*, (1), 173-179, 212. <https://doi.org/10.19768/j.cnki.dgjs.2025.01.050>
- [3] Chen, X. P. (2020). Research on the electromagnetic environment of ± 600 kV direct current transmission lines [Master's thesis, Changsha University of Science and Technology].
- [4] Chen, B., Lei, D., Zhang, Q., et al. (2024). Study on the impact of urban high voltage AC transmission lines on the electromagnetic environment. *Technology Innovation and Application*, 14(16), 112-115. <https://doi.org/10.19981/j.CN23-1581/G3.2024.16.026>
- [5] Deng, X., Zhang, Y., Wei, D., et al. (2024). Prediction and evaluation of electromagnetic environment impacts of 1000 kV ultra-high voltage single circuit transmission lines. *Environment and Development*, 36(1), 60-65. <https://doi.org/10.16647/j.cnki.cn15-1369/X.2024.01.011>
- [6] Xu, Y. X. (2023). Research on the electromagnetic environment of ± 800 kV/ ± 500 kV dual-circuit direct current lines on the same tower [Master's thesis, Guangxi University].
- [7] Qi, W. X., Hao, S. P., Zhou, Y., et al. (2024). Research on improving the electromagnetic environment of mixed-pressure dual-circuit direct current transmission lines on the same tower. *Environmental Technology*, 42(3), 183-190. <https://doi.org/10.3969/j.issn.1004-7204.2024.03.037>

- [8] Qin, J. (2023). *Study on the electromagnetic environment impact of multi-circuit ultra-high voltage transmission lines on the same tower*. *Electrical Engineering Technology*, (3), 202-206. <https://doi.org/10.19768/j.cnki.dgjs.2023.03.052>
- [9] Lin, F., Bai, X., Lv, J., et al. (2022). *Electromagnetic environment and minimum ground distance selection of ± 1500 kV ultra-high voltage direct current transmission lines*. *Jilin Electric Power*, 50(3), 25-29. <https://doi.org/10.3969/j.issn.1009-5306.2022.03.006>
- [10] Shi, L. P. (2020). *Analysis of the electric field characteristics of split conductor spacing rods based on the finite element method*. Master's thesis, North China Electric Power University.
- [11] Du, L., Zhang, K., Feng, H., et al. (2023). *Analysis of structural losses in bushings considering the skin effect*. *Transactions of China Electrotechnical Society*, 38(17), 4746-4756. <https://doi.org/10.19595/j.cnki.1000-6753.tces.211633>
- [12] Pu, B., Chen, W., Zhang, Z., Chen, Z., Zhao, Y., Hao, Q., & Sun, N. (2025). *A retrospective on the hot topics of numerical simulation calculation and multiphysics collaborative research in 2024*. *Science and Technology Review*, 43(1), 118-131.
- [13] Wang, B. Z., & Electromagnetics. (2023). *Computational Electromagnetics (3rd ed.)*. Science Press.
- [14] COMSOL China. (n.d.). Retrieved from <http://cn.comsol.com/>