Simulation Research on Distribution Characteristics of Electromagnetic Field of AC UHV Transmission Line

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Abstract. With the development of UHV and long-distance power transmission technology in my country's power grid, the electromagnetic environment of 100kV UHV transmission lines will be one of the key issues affecting the feasibility of UHV transmission. The impact of low-frequency noise from UHV AC transmission lines on the lives of residents along the corridor should not be ignored. In particular, pure AC sound attenuates slowly along the line and spreads far away, which often has more serious impacts on the lives of nearby residents. In order to study the distribution law and influence degree of pure sound, this article mainly conducts a more in-depth study on the wiring method of UHV transmission lines through theoretical calculation and computer simulation.

Keywords: Computer analysis, UHV transmission lines, physical electromagnetic fields, spectrum histograms, noise emission standards.

1. Introduction
At present, there are many researches on the electromagnetic environment of high-voltage and ultra-high voltage transmission lines. However, for the electromagnetic environment of UHV AC transmission lines, they mainly focus on theoretical calculations. For example, the successive mirroring method is used to calculate the power frequency electric field of UHV AC lines. Analyze the relationship between the electric field distribution and various factors; use the improved mirror image method under complex conditions for simulation calculation, calculate the demarcation range of the line, optimize the line layout, and recommend the use of equilateral and inverted triangle layout Method; and the related experimental research is relatively few. Therefore, in order to rationally guide the design, construction and environmental impact assessment of UHV AC transmission lines, this paper combines field measurement and simulation calculations to analyse the electromagnetic field distribution of UHV AC transmission lines under different arrangements, general conditions and distortions. The law has been studied, and requirements for the safety protection of UHV AC transmission lines have been put forward [1].
2. Power frequency electric field of UHV transmission line
When the AC transmission line is working, the charge on the wire will generate a power frequency electric field in space, and the current in the wire will generate a power frequency magnetic field in space. The electric field is generally described by electric field strength. The power frequency electric field can induce voltage on people and objects. In a strong electric field, a person who is insulated against the ground touches a grounded object, and if a person at ground potential touches an object that is insulated against the ground, there may be a sensible current flowing through the human body or unpleasant spark discharge. This is the short-term effect of the power frequency electric field. Another question about the power frequency electric field is whether the power frequency electric field will have a long-term ecological impact. With the improvement of voltage levels, especially the UHV stage, the long-term ecological impact of the power frequency electric field and magnetic field of power transmission projects has become the focus of attention. In addition to considering the electric strength factor when choosing a transmission line corridor, the electric field strength under the transmission line is an important factor. From the related calculation method of power frequency electric field intensity, it can be seen that the electric field intensity value of a certain point in space is related to the amount of charge on each wire and the distance between that point and the wire; the amount of charge on the wire is related to the applied voltage, it is also related to the geometric location and size of the wire. Therefore, the layout of the wires, the distance to the ground and the distance between phases, the number of split roots, and the phase sequence of the voltage between the two loops in a double loop, all directly affect the distribution and size of the electric field strength under the line [2].

2.1. Theoretical calculation of power frequency electric field of UHV lines
To calculate the power frequency electric field using the instantaneous value of the voltage, a simple mathematical model is derived through derivation, which can not only save computer memory and increase the calculation speed, but also can be applied to different working conditions, that is, it is suitable for various power frequency processes. Voltage or harmonic resonance overvoltage. The same as the method of processing wire voltage when calculating the power frequency electric field, the three-phase symmetrical current is also expressed in the form of instantaneous value, and a simple mathematical model for calculating the power frequency magnetic field is obtained. For transmission lines with single conductors per phase, the charge on the conductors per unit length can be calculated by Maxwell’s potential coefficient method. Suppose there is a multi-conductor system, the number of conductors is n, and the line-to-ground voltage of each conductor is \( U_1, U_2, \ldots, U_n \). Since the distance between parallel conductors and between the conductors and the ground is relatively large relative to the diameter of the conductors, each the charge on the wire is represented by the line charge concentrated in the centre of the wire. Set the line charge density on each wire as \( \theta_1, \theta_2, \ldots, \theta_n \) (hereinafter referred to as charge), they can be obtained by the following matrix equation:

\[
[\theta] = [a]^T [U]
\]  

(1)

Where \([\theta]\) and \([U]\) are the column matrices of the charge and voltage on the wire, respectively. And \([a]\) is a square matrix composed of the self-potential coefficient and the mutual-potential coefficient of the wire. They can be obtained directly by the mirror method. The composite electric field intensity at point p is:

\[
e_p = \left[ e_{p1} + e_{p2} \right] = KU \sqrt{\left( M \cos \varphi + N \sin \varphi \right)^2 + (M \cos \varphi + N \sin \varphi)^2}
\]  

(2)
2.2. Theoretical calculation of the power frequency magnetic field of the UHV

The accurate calculation of the magnetic field requires the Carlson formula to estimate the bad conduction effect of the earth. But in general, only the wire in space is considered, and its mirror image is sufficiently accurate. When the wire does not consider the mirror image, the magnetic field intensity and its horizontal and vertical components generated by a single transmission line with a current of \( I \) are:

\[
B = \frac{\mu_0 I}{2\pi r} \frac{u_0 I}{2\pi \sqrt{(x-x_0)^2 + (y-y_0)^2}}
\]

(3)

In the formula: \( \mu_0 \) is the air permeability; \( x_0, y_0 \) is the abscissa and ordinate of the wire; \( x, y \) are the abscissa and ordinate of the point P in the space where the field strength is to be determined; \( u_0 \) is the distance between the point P in the space and the wire. In the same way as the method of processing the wire voltage when calculating the power frequency electric field, the three-phase symmetric current \( I_a, I_b, I_c \) is expressed as an instantaneous value, and the phase angle of the A-phase current is \( \phi_a \).

3. Calculation model of power frequency electric field in cross area

Since the actual high-voltage transmission lines are more complicated, and the influence of some factors is small and can be ignored, it is necessary to appropriately simplify the actual lines. In this paper, the three-dimensional calculation model of the power frequency electric field of AC UHV transmission lines is simplified as follows:

1) The ground is an infinite conductor, the potential is zero, and the ground resistivity is the same along the line. 2) The transmission wire is equivalent to a long straight wire, each phase split wire is equivalent to a wire, and the same type wires in the same pitch have the same equivalent radius and are parallel to each other, and the wire surface is equipotential. 3) Only consider the electric field formed by wires, ignore the influence of nearby objects such as towers, fittings, insulators, etc., and ignore the end effects of wires and overhead ground wires. 4) It is considered that there is no distortion of the charge distribution along the length of the wire, and the change of the potential on the wire is not considered. 5) The induced voltage between the crossing lines is not considered. 6) The power frequency alternating electric field is regarded as a quasi-static field. Through the above simplification, the calculation formula of the equivalent radius of the split wire is used in the modelling, see equation (4), and the equivalent radius of each phase wire is obtained.

\[
R_i = R \sqrt{mR}
\]

(4)

In the formula, \( R \) is the equivalent conductor radius of the split wire, \( m \) is the number of wire splits, \( r \) is the radius of the sub-wire, and \( R \) is the radius of the split circle, as shown in Figure 1.
Figure 1. Equivalent radius of split conductor

Because the electric field distribution under the line is solved, the split conductor can be replaced with a single equivalent conductor to reduce the gap between the size of the conductor and the solution area, so as to avoid errors in interface meshing and reduce the number of meshes. Improve calculation efficiency. The simplified calculation model of crossover line is shown in Figure 2.

Figure 2. Three-dimensional simulation model of power frequency electric field in the crossover area

In the calculation, the line voltages of UHV and UHV transmission lines are taken as 1050kV and 525kV respectively. Since the power frequency electric field under the transmission line is basically a vertical component, the horizontal component is close to zero [3]. Therefore, when the three-dimensional static field calculation method is adopted, when t=T/4, the instantaneous voltage of the three-phase conductor is loaded, and the ground is loaded with zero potential, and adaptive grid division is adopted. After the solution is completed, the corresponding electric field distribution cloud diagrams at 1.5m above the ground are obtained, as shown in Figure 3.
In order to describe the change curve of the electric field at the 1.5m projection above the ground, the line is bisected by the intersection angle of the phase conductors in the two circuits. In this paper, when $t=0$ and $t=T/4$, the corresponding electric field intensity is calculated by root-mean-square calculation to obtain the effective value of electric field intensity above the ground. At the same time, without changing the parameters of single-circuit 500kV and single-circuit 1000kV transmission lines, calculate the power frequency electric field under the line. According to the path, the corresponding power frequency electric field distributions are obtained for single-circuit 500kV, single-circuit 1000kV and the two crossing conditions [4]. The peaks of the power frequency electric field appear on the outside of the wire projection, and the electric field value of the centre of the crossing line is small. Their maximum values are 5.6kV/m, 5.9kV/m, and 8.93kV/m, respectively, and the maximum value of the electric field intensity in the crossing area is 50% higher than that of a single pass. The overall electric field intensity under the crossover area is larger than that of a single pass. Therefore, when the transmission line is designed, measures need to be taken to improve the offline electric field value [5].

4. Electromagnetic field distribution characteristics of linear tower
The electromagnetic field test of the linear tower is the same as that of the noise measurement. The measuring equipment is an EFA-300 low-frequency electromagnetic analyser of Nard Company. The measuring position is from the centre of the wire to the attenuation close to zero. The test condition temperature is 30 °C, relative humidity is 68%, and wind speed is 2.1 m/s. In order to avoid the influence of leakage current on the measurement results, a wooden tripod is used to arrange the measurement probe to measure the electromagnetic field intensity at a distance of 1.5 m from the ground [6]. The measurement results are shown in Table 1. The electromagnetic field change curve from the centre of the line to the edge phase conductor 100 m away is shown in Figure 4.
Table 1. Electromagnetic field measurement values of double-circuit AC lines on the same tower

| Distance/m | Electric field/(kV·m⁻¹) | Magnetic field/μT |
|------------|--------------------------|------------------|
| 0          | 3.226                    | 1.984            |
| 5          | 3.522                    | 1.975            |
| 10         | 3.258                    | 1.953            |
| 15         | 3.094                    | 1.892            |
| 20         | 2.768                    | 1.828            |
| 25         | 2.443                    | 1.746            |
| 30         | 2.133                    | 1.592            |
| 50         | 0.726                    | 0.885            |
| 60         | 0.338                    | 0.632            |
| 80         | 0.041                    | 0.346            |

Figure 4. The electromagnetic field change curve from the centre of the line to 100 m away from the side conductor

It can be seen from Figure 4 that the magnetic induction intensity of the UHV AC line gradually decays away from the centre of the line; the electric field intensity first increases and then decreases with the increase of distance, and reaches the maximum at 5m outside the side-phase conductor. Both of them decay to zero at 80m outside the edge phase conductor. The electric field strength is faster than that of the magnetic field. At present, the electromagnetic field limit of UHV AC lines is implemented in accordance with HJ/T24-1998 "Technical Specification for Environmental Impact Assessment of Electromagnetic Radiation for 500kV Ultra-High Voltage Transmission and Transformation Projects." The International Radiation Protection Association's power frequency limit of 100μT when the public is radiated throughout the day is used as the evaluation standard of the magnetic induction intensity. From the measurement results, the maximum values of the electric field and magnetic field are 3.522kV/m and 1.984μT, which are all lower than the standard limit [7].

During the measurement process, when a person passed under the line and raised an umbrella to a certain height, there was a belching sound, and there was no hemp inductance when the hand touched the umbrella surface and the iron rod. Lift the umbrella slowly from the ground [8]. When the top of the umbrella surface is 2.2m from the ground, the noise begins to appear, the noise value is 43.2dB, and the electric field strength at the same height as the umbrella surface is 4.016kV/m. Remove the umbrella at this time. After that, the noise is reduced to the background noise level, and the electric field intensity at the same height is 3.916kV/m, both of which are closer to 4kV/m. Therefore, the
evaluation standard of 4kV/m is the electric field intensity at which people or other objects pass under the line and start to appear noise. The electric field intensity below which will not cause this phenomenon, proves that the electromagnetic environment design of the AC UHV line strictly follows the 4kV/m standard Take control.

5. Conclusion
The main factors that affect the electric field strength under the high-voltage transmission line are: the height of the phase conductor to the ground, the distance between phases, the number of split conductors, the split spacing, and the diameter of the sub conductors. Increasing the height of the phase conductor to the ground, reducing the distance between phases, reducing the number of splits, shortening the split spacing, and choosing small cross-section sub-conductors can all reduce the ground field strength. The height of the phase conductor to the ground has the greatest influence on the ground field strength. The greater the height of the phase conductor to the ground, the smaller the ground field strength. However, reducing the distance between the wires will be limited by the insulation between the phases, and reducing the number of split wires will cause an increase in radio interference and audible noise levels. Therefore, the ground field strength can be controlled by raising the erection height of the phase conductor.

References
[1] Shilong, H. Yunpeng, L., Shaoshuai, C., Wangling, H., Baoquan, W., & Lihua, X., et al. Corona loss characteristics of bundle conductors in uhv ac transmission lines at 2200m altitude. Electric Power Systems Research, 166 (1) (2018) 83-87.
[2] Milioudis, A. Andreou, G., & Labridis, D. Optimum transmitted power spectral distribution for broadband power line communication systems considering electromagnetic emissions. Electric Power Systems Research, 140 (11) (2016) 958-964.
[3] Tang, B. Jiang, H., Cao, H., Sun, R., & Liu, R. Resonant frequency evaluation on reradiation interference from power transmission line based on the generalized resonance. IEEE Transactions on Applied Superconductivity, 26 (7) (2016) 1-5.
[4] Rizk, F. A. M. Modeling of uhv and double-circuit ehv transmission-line exposure to direct lightning strikes. IEEE Transactions on Power Delivery, 32 (4) (2017) 1739-1747.
[5] Zheng, T. Liu, X., & Huang, T. Novel protection scheme against turn-to-turn fault of magnetically controlled shunt reactor based on equivalent leakage inductance. International Journal of Electrical Power & Energy Systems, 112 (11) (2019) 442-451.
[6] Bareev, D. D. Gavrilenko, V. G., Grach, S. M., & Sergeev, E. N. Estimation of hf artificial ionospheric turbulence characteristics using comparison of calculated plasma wave decay rates with the measured decay rates of the stimulated electromagnetic emission. Advances in Space Research, 57(3) (2016) 802-812.
[7] Zhaobin, C. Weili, L., Jinyang, L., Xiaochen, Z., Dong, L., & Meimei, Z. Research on the temperature field of high-voltage high power line start permanent magnet synchronous machines with different rotor cage structure. Energies, 10(11) (2017) 1829.
[8] Yang, L. Rui, T., & Yau, D. K. Y. Natural timestamps in powerline electromagnetic radiation. ACM Transactions on Sensor Networks, 14(2) (2018) 1-30.