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Optimal Phase Sequence of 750 kV Four-Circuit Transmission Lines Considering Electromagnetic Environment

Sen Wang[1], Peng Zhang[1], Nanzhan Feng[2], Zhanchao Si[3],
Fan Yang[3, *], Feng Gao[1], and Wei Shen[1]

Abstract—In order to evaluate the electromagnetic environment of 750 kV four-circuit transmission lines accurately and design the optimal tower type and phase sequence of the four-circuit lines, the finite element method is used to analyze the distribution characteristics of power frequency electromagnetic field under the line. The excitation function method and empirical formula method are used to calculate the radio interference and audible noise distribution under the line, respectively. Electromagnetic environment parameters of various phase sequences of two tower types are analyzed to determine the optimal phase sequence of 750 kV four-circuit transmission lines. The results show that the electromagnetic environment of transmission lines is strongly influenced by different tower types and phase sequences. The magnetic flux density and radio interference of the various phase sequences of the two tower types reach the limit of code, and 43.52% and 64.81% phase sequences reach the audible noise limit conditions, respectively. Electric field intensity is a main influence factor of electromagnetic environment. The optimal phase sequence layouts of the two tower types are 1661 and 1522, and the electric field intensities are 9.66 kV/m and 9.12 kV/m. The calculation method and results can be used for reference in practical engineering.

1. INTRODUCTION

With the increasing construction scale of power grid, in order to increase transmission capacity and save transmission corridor resources, more and more transmission lines adopt the erection method of four circuits on one tower [1, 2]. With the improvement of voltage grade, the electromagnetic environment of transmission line has become an important factor to determine the type of conductor and the height of conductors [3, 4]. The prediction of electromagnetic environmental parameters has become an important link in transmission and transformation engineering line design and environmental evaluation. Due to large increase in the number of phase conductors in four-circuit transmission lines, the coupling between lines is more complicated; the form selection of phase sequence arrangement is more diverse; the tower is higher and larger; and the influence of electromagnetic environment is more complicated; without analysis and control, there will be serious environmental protection problems [5, 6]. Therefore, it is necessary to conduct research on the electromagnetic environment of UHV four-circuit transmission lines with different tower types and phase sequences, and determine the optimal tower type, phase sequence, and conductor structure that can meet the electromagnetic environment control indexes, so as to provide a solid foundation for engineering applications.

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* Corresponding author: Fan Yang (yangfan@cqu.edu.cn).

[1] State Grid Shaanxi Electric Power Research Institute, Xi'an, Shaanxi Province 710100, China. [2] State Grid Shaanxi Electric Power Corporation, Xi'an 710054, China. [3] State Key Laboratory of Power Transmission Equipment & System Security and New Technology (Chongqing University), Chongqing 400044, China.

Some research has been done to study the phase sequence arrangement and electromagnetic environment distribution of multi-circuit transmission lines on one tower. Refs. [7–9] adopted the exhaustive method to analyze the electromagnetic environment and line imbalance degree under all phase sequence arrangement modes of 500 kV four-circuit lines. Research suggested that compared with other electromagnetic environments, power-frequency electric field is the key factor to determine the optimal phase sequence of the line, which determines the demarcation of ground height and corridor width of the line. In [10], the electromagnetic field, radio interference, and audible noise of the 750 kV double-circuit transmission lines were calculated and studied respectively. The influences of ground height, phase sequence arrangement, splitter number, sub-conductor diameter, and splitting distance of the conductor on the electromagnetic environment were analyzed, and suggestions on the arrangement of phase sequence arrangement and lower phase conductor height were put forward. At present, research on the optimal phase sequence arrangement of 750 kV four-circuit lines considering the electromagnetic environmental parameters, such as power frequency electromagnetic field, audible noise, and radio interference, is still blank.

Taking the 750 kV four-circuit transmission lines as an example, combined with charge simulation method and finite element method, the distribution of electromagnetic field, audible noise, and radio interference of transmission line under various phase sequence arrangements of two tower types were calculated by MATLAB program, and the effects of phase sequence arrangement on power frequency electric field, audible noise, and radio interference were analyzed. The optimal phase sequence arrangements of 750 kV four-circuit lines were obtained by using the sequencing method.

2. LINE PARAMETERS AND PHASE SEQUENCE ARRANGEMENT

2.1. Line Parameters

The 750 kV AC four-circuit transmission lines have two types of towers: tower type A with six cross-arms arranged vertically and tower type B with four cross-arms. The line model and line parameters are shown in Figure 1 and Table 1.

Table 1. Transmission line and ground wire parameters.

Parameters	**Wire type**	**Number of splits**	**Wire diameter (mm)**	**Split spacing (mm)**	**arc sag (m)**
Transmission line	JL1/G1A-500/45	6	30	400	22
Ground wire	JLB20A-150	/	15.75	/	20

2.2. Phase Sequence Arrangement

The phase sequence arrangement of four-circuit transmission lines can be various. The four circuits of transmission lines are composed of wires numbered 1–12, and wire numbering method is shown in Figure 2. The three wires of each circuit have six phase sequence arrangements, which can be represented by numbers 1–6, as shown in Table 2. Further, the 4-bit code is used to represent the phase sequence of the four-circuit line. For example: "1234" means phase sequence arrangement of ABC-ACB-BAC-BCA. Therefore, from 1111–6666, it is possible to traverse the 1296 phase sequence arrangement of four-circuit transmission lines [7].

Table 2. Phase sequence code of one circuit.

Phase sequence	ABC	ACB	BAC	BCA	CAB	CBA
Code	1	2	3	4	5	6

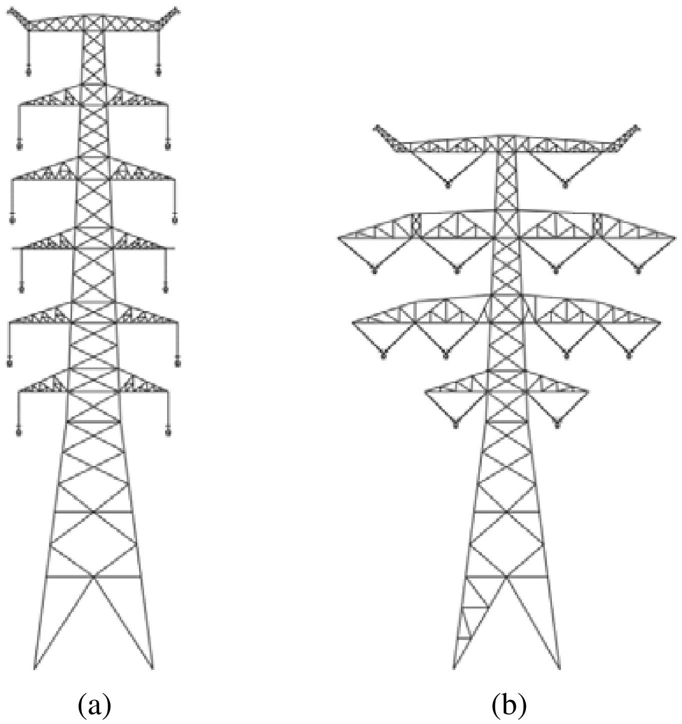

Figure 1. Two tower structures of 750 kV four-circuit transmission lines: (a) tower type A and (b) tower type B.

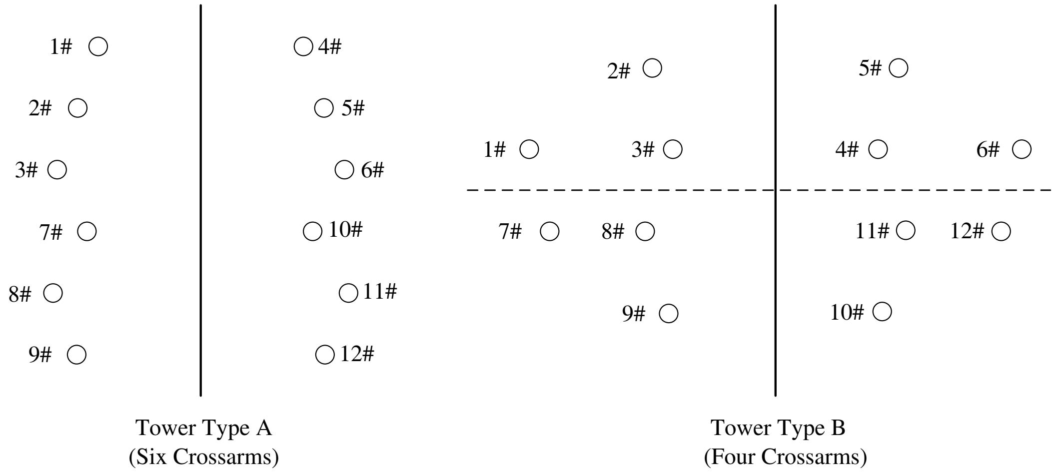

Figure 2. Specific numbering method of 12 wires of two tower types.

3. ELECTROMAGNETIC ENVIRONMENT CALCULATION METHOD

3.1. Electric Field Calculation

When calculating power frequency electric field of an AC transmission line, since charge simulation method can be used to easily calculate the electric field of each phase sequence using MATLAB programming, the optimal phase sequence can be obtained by a simple charge simulation method. Meanwhile, for charge simulation method, the calculation accuracy is limited due to the limitation of the position and quantity of simulated charge, and the position of equivalent electric axis needs to be considered for multiple transmission lines. Therefore, the power frequency electric field distribution can be accurately solved by establishing the finite element model for the optimal phase sequence.

Charge simulation method is mainly divided into two steps: 1) calculate the equivalent charge per unit length of the wire; 2) calculate the electric field generated by the equivalent charge. The equivalent charge of transmission line is regarded as line charge, and the equivalent single conductor is used to replace the split conductor to simplify the calculation. Let the ground be a good conductor of zero potential, and calculate the equivalent charge Q on the transmission line by the method of images.

$$[Q] = [\lambda]^{-1}[U] \tag{1}$$

where $[Q]$ is the equivalent charge matrix of each wire; $[U]$ is the voltage matrix of each wire, which is determined by the actual running voltage and phase of the wire, and is represented by a complex number;

$[\lambda]$ is the n-order square matrix composed of the potential coefficients of each wire (n is the number of wires), which is obtained by the mirror principle, as shown in Figure 3. i and j are actual wires parallel to each other, and i' and j' are mirror images of the wire with respect to the ground.

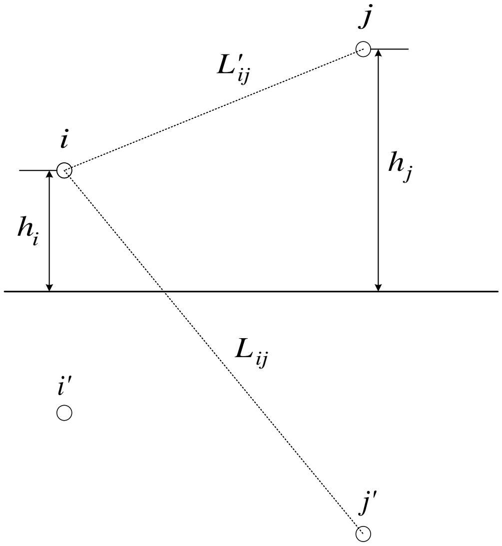

Figure 3. Infinite long line charge and its image charge.

The potential coefficient is calculated by the following formula:

$$\begin{cases} \lambda_{ii} = \dfrac{1}{2\pi\varepsilon_0} \ln \dfrac{2h_i}{R_i} \\ \lambda_{ij} = \dfrac{1}{2\pi\varepsilon_0} \ln \dfrac{L'_{ij}}{L_{ij}} \\ \lambda_{ij} = \lambda_{ji} \end{cases} \tag{2}$$

where ε_0 is the dielectric constant of air; h_i is the height of the wire, m; L_{ij} is the distance between the mirror image of the i-th wire and the j-th wire, m; L'_{ij} is the distance between the i-th and j-th wires, and R_i is the wire equivalent radius, m.

From the above two equations, the equivalent charge amount Q per unit length of each wire can be obtained. The electric field strength at any point in the space can be calculated according to the superposition principle. The electric field strength at the (x, y) point can be expressed as:

$$\begin{cases} E_x = \dfrac{1}{2\pi\varepsilon_0} \displaystyle\sum_{i=1}^{m} Q_i \left(\dfrac{x - x_i}{L_i^2} - \dfrac{x - x_i}{(L'_i)^2} \right) \\ E_y = \dfrac{1}{2\pi\varepsilon_0} \displaystyle\sum_{i=1}^{m} Q_i \left(\dfrac{y - y_i}{L_i^2} - \dfrac{y - y_i}{(L'_i)^2} \right) \end{cases} \tag{3}$$

where m is the number of wires; x, y are the horizontal and vertical coordinates of the wire; and L_i, $L_i^{'}$ are the distance of the wire and its mirror to the calculated point.

3.2. Magnetic Field Calculation

The magnetic field of the power frequency line is generated by electric current, and the magnetic field distribution of the wire can be obtained according to the Ampere loop law and the superposition principle. When the mirror-image method is used, the influence of the earth is equivalent to the influence of the ground equivalent current. Different from the electric field strength calculation, the mirror depth of the magnetic field calculation is much larger than the height of the wire from the ground under normal conditions. Therefore, ignoring the influence of the mirror wire, only the influence of the actual wire is calculated. The formula for calculating the magnetic field strength is:

$$H = \frac{I}{2\pi\sqrt{h^2 + L^2}} \tag{4}$$

where h is the height difference between the wire and the calculated point, m; L is the horizontal distance between the wire and the calculated point, m; and I is the wire running current, A.

3.3. Radio Interference Calculation

A supplemental version of CISPR18-3 in 1996 recommended a radio interference calculation formula for the calculation of multi-split conductors (> 4 splits) using the excitation function method. The excitation function method is based on the excitation function under the heavy rain condition measured by the test circuit or the corona cage. Through a certain modulus conversion, the pulse current of each phase conductor is obtained, thereby obtaining the field generated by these currents, that is, radio interference [11]. The calculation steps include: calculating the excitation function and correction of the meteorological influence, then calculating the distribution of the interference field strength according to the mode propagation principle, finally, calculating the radio interference field strength value at 20 meters outside the outermost phase transmission line and 2 meters above the outermost phase [12]. The excitation function is as follows:

$$\Gamma = 70 - 585/g_{\max} + 35\lg(d) - 10\lg(n) \tag{5}$$

where Γ is the excitation function under heavy rain; g is the maximum surface potential gradient of the sub-conductor, kV/cm; d is the diameter of the sub-conductor, cm; n is the number of split conductors.

3.4. Audible Noise Calculation

Most countries calculate the audible noise of transmission lines by statistical analysis of corona cage simulation or long-term measured data on test lines. Because the audible noise prediction formula recommended by the Bonneville Power Administration (BPA) is derived from the long-term measured data of actual lines of different voltage levels and split modes, and the formula prediction result is consistent with the experimental results, it is considered to have better representativeness and accuracy [13]. The BPA audible noise prediction formula is as follows:

$$\begin{cases} \mathrm{PWL}(i) = -164.6 + 120\lg E + 55\lg d_{eq} \\ \mathrm{SLA} = 10\lg \displaystyle\sum_{i=1}^{Z} \lg^{-1}\left[\frac{\mathrm{PWL}(i) - 11.4\lg R_i - 5.9}{10}\right] \end{cases} \tag{6}$$

where SLA is the A-weighted sound level, dB; PWL is the sound power level of each phase conductor; R is the distance between each conductor and the measuring point, m; Z is the phase number; E is the surface electric field strength of the wire, kV/cm; d_{eq} is the equivalent radius of the wire, mm.

4. CALCULATION AND ANALYSIS

4.1. Limit Value of Electromagnetic Environment

Referring to the Chinese national standard “GB8702-2014 electromagnetic environment control limit”, the power frequency electromagnetic field control limit of 1.5 m high near the 750 kV four-circuit transmission lines is as follows: For the residential area, the public exposure limit must be controlled at 4 kV/m, for cultivated land, pasture, roads, and other places under overhead transmission lines. The electric field intensity control limit is 10 kV/m, and the control limit of power frequency magnetic flux density is 100 µT [14]. According to the “GB/T15707-2017 limit of radio interference of HVAC overhead transmission lines”, the limit of radio interference of 750 kV overhead transmission lines is 58 dB at the projection 20 m of the distance conductor, and the limit should not be greater than 55 dB in good weather [15]. “GB3096-2008 urban area environmental noise standard” provides noise limits for two periods and five regions, among which the noise control of transmission lines is generally in accordance with the requirements of residential areas in daytime, that is, the noise limit at the projection 20 m of the edge wire is no more than 55 dB [16]. The electromagnetic environment limits of the 750 kV four-circuit transmission lines are summarized in Table 3.

Table 3. Electromagnetic environment public exposure control limit.

$E/$ (kV·m^{-1})	$B/$µT	$RI/$dB	$AN/$dB
4	100	58	55

4.2. Calculation Results

750 kV four-circuit lines system parameters: The transmission lines adopt JL/G1A-500/45 steel-cored aluminum stranded wire. The maximum operating voltage is 800 kV; the transmission capacity is 2300 MW; the conductor sag is 22 m; the minimum height of the tower type A is 16 m; and the minimum height of the tower type B is 15 m. The calculation model is established according to the actual parameters, calculates the electric field intensity distribution at a height of 1.5 meters below the line, and obtains the optimal phase sequence arrangement of the electromagnetic environment of different tower types.

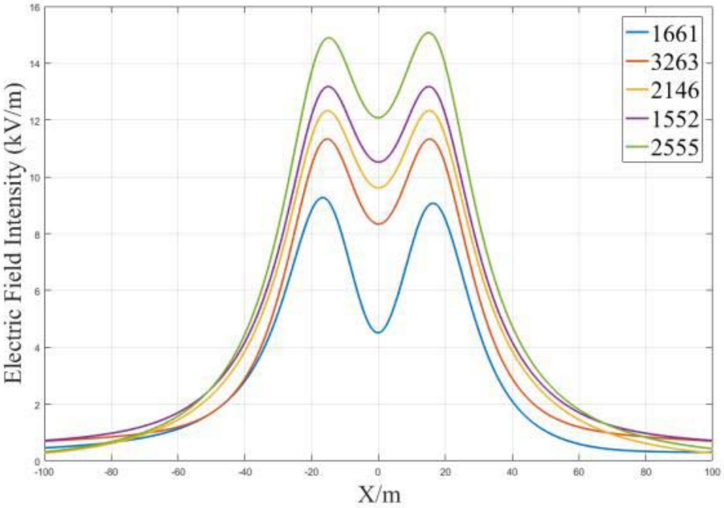

Figure 4. Electric field intensity distribution of some typical phase sequence of tower type A.

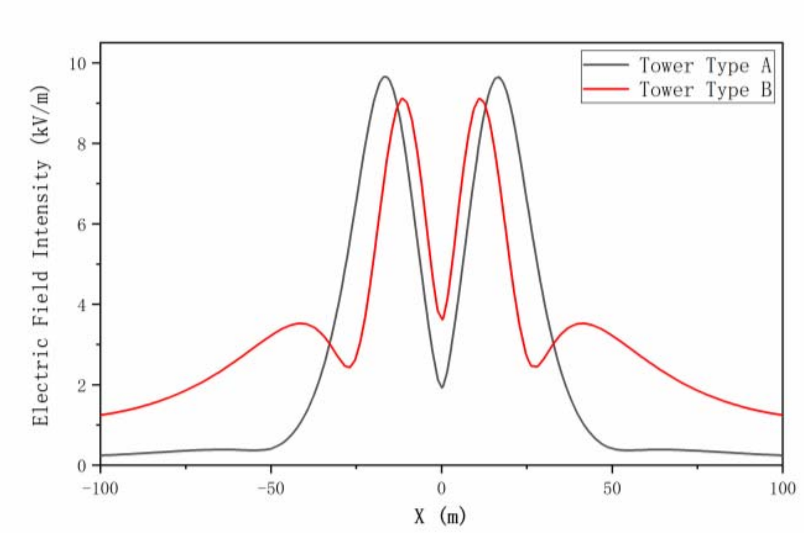

Figure 5. Electric field intensity distribution of the optimal phase sequence of two tower types.

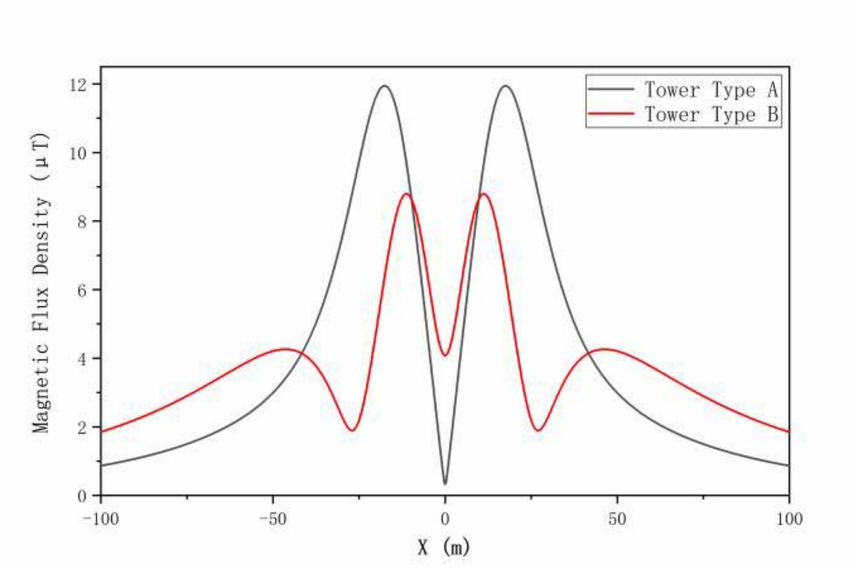

Figure 6. Magnetic flux density distribution of the optimal phase sequence of two tower types.

The electric field intensity distribution of each phase sequence under two tower types is calculated by charge simulation method. Figure 4 shows the distribution of electric field intensity of five different phase sequences of tower type A. The phase sequence with the smallest electric field in all phase sequences is obtained, and the exact distribution of electric field strength is calculated by finite element method, as shown in Figure 5. The maximum electric field intensity distribution of each phase sequence of tower type A is 9.66–17.75 kV/m; the optimal phase sequence is 1661; the maximum power frequency electric field below the line is 9.66 kV/m; and the width of transmission corridor is 60.48 m. The maximum electric field intensity distribution of each phase sequence of tower B is 9.12–15.62 kV/m; the optimal phase sequence is 1522; the maximum power frequency electric field below the line is 9.12 kV/m; and the transmission corridor width is 42.55 m.

The magnetic flux density distribution of each phase sequence is calculated by Ampere's loop law. Figure 6 shows the magnetic flux density distribution of the optimal phase sequence of two tower types. Calculation indicates that the magnetic flux density of each phase sequence of tower type A is between 11.95 and 22.34 μT, and the optimal phase sequence is 1342. The magnetic flux density of each phase sequence of tower B is between 8.79 and 25.41 μT, and the optimal phase sequence is 1522. Since the

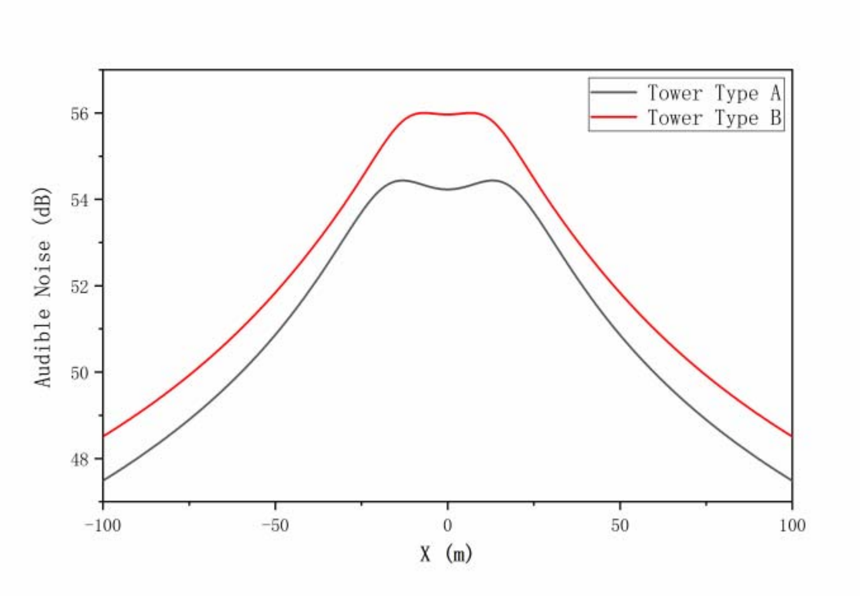

Figure 7. Audible noise distribution of the optimal phase sequence of two tower types.

limit value of the power frequency magnetic field is 0.1 mT, the magnetic flux density of each phase of the two tower types is far less than the national standard limit.

The audible noise distribution of each phase sequence is calculated by the BPA formula. Figure 7 shows the audible noise distribution of the optimal phase sequence of two tower types. The noise intensity reaches the maximum under the line and gradually decreases on the outside of the wire. The audible noise value at 20 meters outside the edge of each phase sequence of tower type A is between 51.99 and 62.22 dB; the optimal phase sequence is 1342; the maximum audible noise is 51.99 dB; the audible noise value at 20 meters outside the edge of each phase sequence of tower B is between 52 and 61.52 dB; the optimal phase sequence is 3266; and the maximum audible noise is 52 dB. According to statistics, 43.52% and 64.81% of each phase sequence of the two towers satisfy the audible noise limit.

According to the calculation results of the radio interference field strength, the radio interference of each phase sequence of tower A is distributed between 44.23 and 50.5 dB; the minimum value is 44.23 dB when the phase sequence is 1615; and the maximum value is 50.5 dB when the phase sequence is 6611. The radio interference of each phase sequence of tower type B is between 38.8 and 44.63 dB; the minimum value is 38.8 dB when the phase sequence is 1263; and the maximum value is 44.63 dB when the phase sequence is 6155. Therefore, the radio interference field strength values of each phase sequence of the two tower types meet the limit requirements.

Table 4. Optimal phase sequence electromagnetic environment of two tower types.

Tower Type	Phase Sequence	E (kV/m)	B (μT)	AN (dB)	RI (dB)
A	1661	9.66	12.46	52.71	45.36
B	1522	9.12	8.79	43.62	44.60

5. CONCLUSION

Based on the corresponding electromagnetic environment calculation method, the numerical distribution and optimal phase sequence of electric field intensity (E), magnetic flux density (B), audible noise (AN), and radio interference (RI) of the 750 kV four-circuit lines are obtained for the two tower types, and the main conclusions are as follows:

(1) The phase sequence arrangement of the four-circuit lines has obvious effect on the

electromagnetic environmental characteristics of the line, and selecting suitable phase sequence arrangement is an economic and effective measure to reduce electric field intensity, magnetic flux density, audible noise, and radio interference below the line. The values of magnetic flux density and radio interference field intensity of all phase sequences of the two tower types can meet the relevant standard limits, and regarding the audible noise calculations of the two tower types, 43.52% and 64.81% of the phase sequences respectively can meet the relevant standard limits.

(2) The electric field strength of the line determines the height of the line to the ground and the width of the line corridor. It is the key factor determining the optimal phase sequence of the four-circuit lines. Considering the electromagnetic environment of the line, the optimal phase sequence of the two tower types of the 750 kV four-circuit transmission lines are 1661 and 1522, respectively. The electromagnetic environment distribution is shown in Table 4.

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Amendment to "Optimal Phase Sequence of 750 kV Four-Circuit Transmission Lines Considering Electromagnetic Environment"

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[*] Corresponding author: Fan Yang (yangfan@cqu.edu.cn).

[1] State Grid Shaanxi Electric Power Research Institute, Xi'an, Shaanxi Province 710100, China. [2] State Grid Shaanxi Electric Power Corporation, Xi'an 710054, China. [3] State Key Laboratory of Power Transmission Equipment & System Security and New Technology (Chongqing University), Chongqing 400044, China.