Hindawi
International Journal of Antennas and Propagation
Volume 2023, Article ID 4788443, 14 pages
https://doi.org/10.1155/2023/4788443

Research Article

Research on Electromagnetic Scattering Influence of Transmission Towers on Medium Wave Antenna Based on the Characteristic Mode Theory

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Received 1 September 2023; Revised 23 November 2023; Accepted 16 December 2023; Published 26 December 2023

Academic Editor: Truong Khang Nguyen

Electromagnetic scattering from UHV transmission towers is a major factor affecting the safety and stability of the surrounding antenna signal system. In this paper, the electromagnetic scattering effect of ±800 kV UHV DC transmission tower on the medium-wave antenna is investigated based on the characteristic mode theory (CMT). The simulation model of the tower and antenna is established, and the mode selection is carried out according to the percentage of the contribution of the characteristic mode to the total electromagnetic scattering. The effects of electromagnetic scattering under three conditions, namely, the number of towers, the distance between towers and antennas, and different frequencies, are investigated separately. The simulation results show that as the number of towers increases from 1 to 3, it leads to an increase in the electromagnetic scattering impact by about 49.5%. The shape distortion of the antenna's directional map becomes more pronounced and is accompanied by the extension with the direction of the power line. The distance between the tower and the antenna is shortened from 500 m to 125 m, resulting in the growth of the influence of electromagnetic scattering by about 36.4%, and the directional gain of the antenna increases along the direction of the transmission line. As the frequency increases from 600 kHz to 1400 kHz, it leads to the rise of electromagnetic scattering effect of about 32.7% and the antenna directional map becomes more complicated. The research results will provide technical support for developing protective measures against electromagnetic scattering from UHV DC transmission towers to medium-wave antennas.

1. Introduction

With the characteristics of high voltage level, high tower height, large transmission capacity, and wide coverage, the erection and operation of ultrahigh voltage (UHV) transmission lines will have an electromagnetic scattering influence on the surrounding radio signal stations [1–3]. Due to the rapid development of China's power grid construction, the height and density of UHV transmission towers are gradually increasing, and UHV transmission lines around radio signal stations will be built more or less everywhere [4]. This situation will lead to radio signal stations facing more signal interference problems brought about by the natural environment and urban construction [5, 6]. Therefore, it is of great practical significance to analyze the influence law of electromagnetic scattering from towers on signal stations for the problem of electromagnetic scattering from large extra-high voltage transmission towers, so as to effectively solve the electromagnetic compatibility problem of transmission line towers and radio signal stations.

In view of the abovementioned electromagnetic scattering interference problems brought by the towers of ultrahigh voltage transmission lines to the neighboring radio signal systems, experts and scholars at home and abroad have conducted extensive research on the numerical calculation techniques of electromagnetic scattering and electromagnetic interference protection measures, respectively. The electromagnetic scattering phenomenon generated by transmission line towers is the result of the interaction between the electromagnetic waves emitted by the radio signal system and the metal body structure of the tower, and its theoretical basis is the electromagnetic field theory describing the electromagnetic wave phenomenon [7–9]. For the problem of simulating the electromagnetic scattering characteristics of large towers of transmission lines, most of the current research methods use the electric field integral equation for solving. The Pocklington electric field integral equation corresponding to the linear model of high-voltage transmission towers was first proposed by Trueman et al. together with Kubina [10, 11]. The calculation process treats transmission line towers and overhead ground lines as a whole and equates the whole base tower as a line model. With further research and increased demand for rapid national development, the computational accuracy of the electric field integral equation needs to be higher. North China Electric Power University conducted a study for the line model of the tower space structure; however, the roughness of this model still cannot meet the requirements, which leads to the limitation of the frequency of the simulation study [12]. In order to meet the higher requirements of China's electric power development, Three Gorges University proposed a surface model based on the method of moments to solve the passive interference of towers [13]. However, as the electrical size of the tower increases, the number of unknowns after discretization of the matrix equations increases dramatically, resulting in excessive model computation time. The tower model size as well as the applicable voltage level and simulation frequency is specified on the basis of the existing research applications; however, with the restructuring of China's electric energy, the radio stations have higher and higher requirements for the surrounding building height and electromagnetic environment. The construction of UHV transmission line towers has emerged rapidly along with the rapid development of China's power grid, and the electromagnetic scattering influence generated by its unique characteristics of large current flow, high voltage, and large size needs to be further explored in detail. To more accurately solve the interference of transmission towers with various radio stations, more complete transmission tower simulation models and theoretical algorithm breakthrough innovations are needed.

Therefore, this paper analyzes the electromagnetic scattering influence of ±800 kV UHV DC transmission towers on medium-wave signal stations based on the characteristic mode theory and analyzes in detail the electromagnetic scattering influence law under three influencing factors: the number of different transmission towers, the distance between towers and antennas, and the antennas at different frequencies. A detailed comparison and analysis of the two- and three-dimensional electric field direction maps of the antenna and the characteristic angles and modal significance of each characteristic mode are presented. Currently, the CMT is mainly applied to small electrical antennas. There are few studies that analyze the transmission line towers with this method, and the author tries to analyze and study them from this perspective. Due to the special characteristics of UHV transmission line towers such as high current, high voltage, and large size, the electromagnetic impact caused by this type of transmission tower is also a highly relevant research point in the current national development. The aim of this study is to analyze the electromagnetic scattering effects of ±800 kv UHV DC transmission towers on the medium-wave antenna signal system using CMT. The method provides theoretical support and technical reference for the future development of electromagnetic scattering protection measures for UHV transmission line towers.

The rest of this paper is structured as follows. In Section 2, the applied characteristic mode core theory and the technical route are described in detail. In Section 3, the electromagnetic simulation software is applied to simulate and model the ±800 kV UHV DC transmission towers. In Section 4, the simulation results under three different conditions are carefully analyzed by using the electromagnetic simulation software. Section 5 summarizes the research work performed in this paper. Section 6 concludes the study.

2. Method Design

Garbacz et al. were the first to propose CMT and pointed out that characteristic modes can achieve the purpose of diagonalizing the scattering matrix of arbitrary electromagnetic targets [14]. However, due to the complexity of the calculation method of CMT proposed by Garbacz et al., there are many inconveniences in the actual calculation and analysis. After that, Harrington and Mautz proposed to calculate the characteristic modes of arbitrarily shaped metallic bodies based on the integral equation and the method of moments in their paper [15]. Since the physical meaning of this theoretical basis is clear and the calculation process is general and convenient, the CMT has been widely used all over the world.

CMT is widely used to study and analyze the electromagnetic field of arbitrary metallic objects. It is characterized by the fact that the characteristic modes are related only to the intrinsic properties (shape, material, and size) of the metallic object and are independent of other applied excitations [16, 17]. The core of CMT is the generalized eigenvalue equation, which is as follows:

$$\mathbf{X}\mathbf{J_n} = \lambda_n \mathbf{R}\mathbf{J_n}, \tag{1}$$

where λ_n and $\mathbf{J_n}$ represent the eigenvalue and the eigenvector, respectively, and n is the order of the characteristic mode. λ_n and $\mathbf{J_n}$ can be obtained by the MoM impedance matrix as follows:

$$\mathbf{Z} = \mathbf{R} + j\mathbf{X}, \tag{2}$$

where $\mathbf{R}$ and $\mathbf{X}$ are real symmetric matrices, and $\mathbf{R}$ is theoretically a semipositive definite.

According to CMT, the solution of any electromagnetic field problem can be expressed as a linear combination of characteristic modes that are orthogonal to the source (current) and field regions, respectively, expressing the inherent electromagnetic properties of the object [18]. Therefore, the total surface-induced currents of the UHV

DC transmission towers can all be obtained by weighted superposition of the characteristic currents of each characteristic mode as follows:

$$J = \sum_{n} \alpha_n \mathbf{J_n}, \quad (3)$$

where $\mathbf{J}$ is the total surface-induced current on the metal body and α_n is the modal weighting coefficient (MWC), which can be represented as follows:

$$\alpha_n = \frac{\langle \mathbf{E}^{\mathbf{i}}_{\mathbf{tan}}(\mathbf{r}), \mathbf{J_n} \rangle}{1 + j\lambda_n}, \quad (4)$$

where the inner product on the right numerator represents the energy coupling between the external excitation source and each mode, called the modal excitation coefficient (MEC), denoted by V_n. The coupling is related to the position, irradiance, phase, and polarization mode of the excitation source, as shown in equation (5).

However, due to the large electrical dimensions of the transmission towers, the triangular grid cells that are dissected on the surface of the towers are very fine, which leads to a large order of the impedance matrix obtained from the calculations. At this point, the number of eigenmodes obtained by applying the CMT solution is large. Therefore, it is necessary to filter among the feature patterns. The denominator on the right side of equation (4) can be used to define modal significance (MS), as shown in equation (6). In this paper, the MS value is calculated to measure the potential radiation capability of each feature mode and the degree of influence on electromagnetic scattering, and the effective feature modes are screened out.

$$V_n = \oint \mathbf{E}^{\mathbf{i}}_{\mathbf{tan}}(\mathbf{r}) \cdot \mathbf{J_n} dS, \quad (5)$$

$$\mathrm{MS} = \left| \frac{1}{1 + j\lambda_n} \right|. \quad (6)$$

Subsequently, in order to investigate the independent effects of three factors, frequency, distance, and the number of towers, on electromagnetic scattering, it is necessary to ensure that modes with similar radiative capacities are selected among the many characterized modes for comparison of the results. MS indicates the inherent properties of the model, which are related only to the model structure and not to the external excitation. The value of MS ranges from 0 to 1. When the value of MS is larger (closer to 1), it means that the mode is more likely to be excited. When the value of MS is smaller (tends to 0), it means that the mode is less likely to be excited. The MS indicates the contribution of each characteristic mode to the total electromagnetic scattering. A larger MS indicates a larger proportion of the characteristic mode in the total electromagnetic scattering.

Another important parameter in CMT is the characteristic angle (CA), which is represented as follows:

$$\mathrm{CA} = 180^{\circ} - \tan^{-1}(\lambda_n). \quad (7)$$

Electromagnetic scattering from transmission towers affects the amplitude and phase of the signal emitted from the antenna. CA indicates the phase angle between the characteristic current and its associated characteristic electric field. When CA is 180 degrees, it indicates that the antenna reaches the maximum radiation effect at this moment.

3. Simulation Modeling

The UHV transmission towers will have electromagnetic scattering effects due to the excitation of electromagnetic waves from the medium-wave antenna. The medium-wave radio signal system is a radio signal system that implements near-range signal transmission through the wave characteristics of the medium-wave band [19]. In the signal transmission process, the metal structure of the UHV transmission line tower will generate surface-induced currents due to the signal-transmitting antenna radiation field [20–22]. These induced currents will form a new electric field, namely, the secondary radiation field [23, 24]. As the secondary radiation field will be superimposed with the radiation field generated by the transmitting antenna, it will affect the amplitude and phase of the transmitting antenna signal, leading to changes in the directional diagram of the antenna, which in turn will affect the transmission performance of the antenna signal [25].

In this paper, FEKO electromagnetic simulation software is used to establish the model of medium-wave antenna and ultrahigh voltage transmission tower and simulate the electromagnetic field environment through the numerical method of characteristic mode. The characteristic mode theory has been described in detail in Chapter II and will not be repeated here. FEKO is based on the development of Maxwell's integral equations, which is suitable for solving all the high-frequency electromagnetic problems of any complex structure, and is especially suitable for analyzing the problems of general size and large size.

Regarding the modeling of the medium-wave antenna, the complex medium-wave antenna is simplified in the simulation according to our signal safety regulations and the relevant regulations of the national defense forces, and the specific form of the single dipole antenna with a vertical linear structure with a bottom feed is used [26, 27]. The antenna material is set as a perfect electrical conductor (PEC) material, and then, the feed is added at the bottom of the antenna and the ground is set as a PEC plane. This simplification is also consistent with the feature that the undirected electromagnetic waves emitted by the medium-wave antenna are vertically polarized electromagnetic waves. For the choice of the tower model, this paper takes into account the rapid development of China's power grid construction, and the UHV transmission towers play an important role in both the economy and people's livelihood [28, 29]. The voltage level of the tower in the simulation is ±800 kV, the tower height is 68.5 m, the tower structure is a metal structure, and the spacing of the tower is 200 m. The model of the UHV DC transmission tower and the medium-wave antenna established in the simulation software is shown in Figure 1, and the detailed data of the simulation model are shown in Table 1.

In the simulation ground setup, previous studies [18, 30] investigated the effect of the ground on the electromagnetic interference calculation. The conclusion of their study stated that if the absorption loss of the ground to the incident electromagnetic wave is taken into account, the calculated electromagnetic interference level is less than the actual level, but it has some influence on the prediction of the law of electromagnetic scattering. If the ground is set to PEC, the calculated electromagnetic interference level is larger than the actual level, but the modeled electromagnetic scattering effects can be accurately predicted. Therefore, the model used in this study assumes that the ground is PEC to avoid affecting the simulation results. The vertical distance between the medium-wave antenna and the transmitter tower was kept within one wavelength since the limit of the ground boundary that can be reached by the simulation setup cannot be infinite.

In order to ensure the safety and stability of the power transmission process, according to China's national grid company which formulated the "power line engineering design specification" in the provisions of the simulation of this paper, the distance between the transmission towers is set to 200 m. In the actual project, the tower spacing should be based on the specific circumstances of the scientific and reasonable setup, so as to make sure that the power operation is of high efficiency and stability.

4. Simulation Results and Analysis

This section conducts a simulation study for three different conditions of ± 800 kV UHV DC transmission towers for medium-wave antennas, analyzes the characteristic angle, mode significance, and two-dimensional and three-dimensional directional maps of electromagnetic scattering from the towers, and summarizes the influence law of the simulation, respectively. In order to be able to compare the simulation results more clearly, the 3D far-field figures are normalized. The configuration of the simulation computing device is shown in Table 2.

4.1. Distance between Tower and Antenna. This section analyzes the influence of electromagnetic scattering between the transmission tower and antenna at different distances on the medium-wave antenna. Based on the model of the medium-wave antenna and UHV DC transmission tower (Figure 1) established in the electromagnetic simulation software, the simulation parameters are configured as follows. The voltage level is ± 800 kV, the tower height is 68.5 m, the antenna height is 50 m, and the simulation frequency is 600 kHz. The distance between the tower and the antenna considered in the simulation is grouped according to the wavelength of the medium-wave antenna signal, which are of single wavelength ($\lambda = 500$ m), half wavelength ($\lambda/2 = 250$ m), and quarter wavelength distance ($\lambda/4 = 125$ m).

First of all, in order to observe more clearly and intuitively the influence law of electromagnetic scattering from transmission towers at different distances, it is necessary to compare and analyze the simulation results of characteristic angle and mode significance under three conditions. In this paper, the first six characteristic modes are selected for comparative analysis, and a method is proposed to judge the size of the contribution of each characteristic mode to the total electromagnetic scattering by analyzing MS and CA and find out the characteristic modes with similar scattering effects in three different distance cases. Such a mode selection method is adopted in order to carry out the control variables and ensure that the conditions are as constant as possible except for the different distance conditions, so as to observe more intuitively the two-dimensional curve diagram and three-dimensional directional diagram of the tower and analyze the influence law of distance on electromagnetic scattering. The curves of the characteristic angle and mode significance simulation results for three different distance cases are shown in Figures 2 and 3 and Tables 3 and 4.

In order to be able to study the influence of distance on electromagnetic scattering independently, we need to select a set of characteristic modes with similar values of MS and CA so as to ensure that the magnitude of the contribution of this characteristic mode to the total electromagnetic scattering is similar for different distance conditions. In order to visualize the simulation results more closely, some of the data in Figures 2 and 3 have been enlarged. According to the simulation results in Figures 2 and 3 and Tables 3 and 4, it can be observed that the MS and CA values of characteristic mode 3 are similar for different distance conditions. Single wavelength ($\lambda = 500$ m), half wavelength ($\lambda/2 = 250$ m), and quarter wavelength distance ($\lambda/4 = 125$ m) conditions have MS values of 0.0364, 0.0366, and 0.0408, respectively, and CA values of 267.91, 267.90, and 267.66 degrees, respectively. Then, the electric field simulation of electromagnetic scattering is performed for characteristic mode 3, and the electric field direction diagram is analyzed. The three-dimensional directional diagrams of the electromagnetic scattering electric field of the tower under different distance conditions are shown in Figure 4, and the two-dimensional curves and directional diagrams are shown in Figures 5 and 6.

According to the analysis of the simulation results of the three-dimensional electric field diagram in Figure 4 and the two-dimensional direction diagram in Figures 5 and 6, it can be seen that the different distances between the ± 800 kV UHV DC transmission tower and the medium-wave antenna will have different effects on the directionality of the antenna. It can be further analyzed from Figures 5 and 6 that as the distance between the transmission tower and the medium-wave antenna reduces, the influence of tower on antenna's electromagnetic scattering also gets bigger. 90 degrees and 270 degrees are the construction directions of

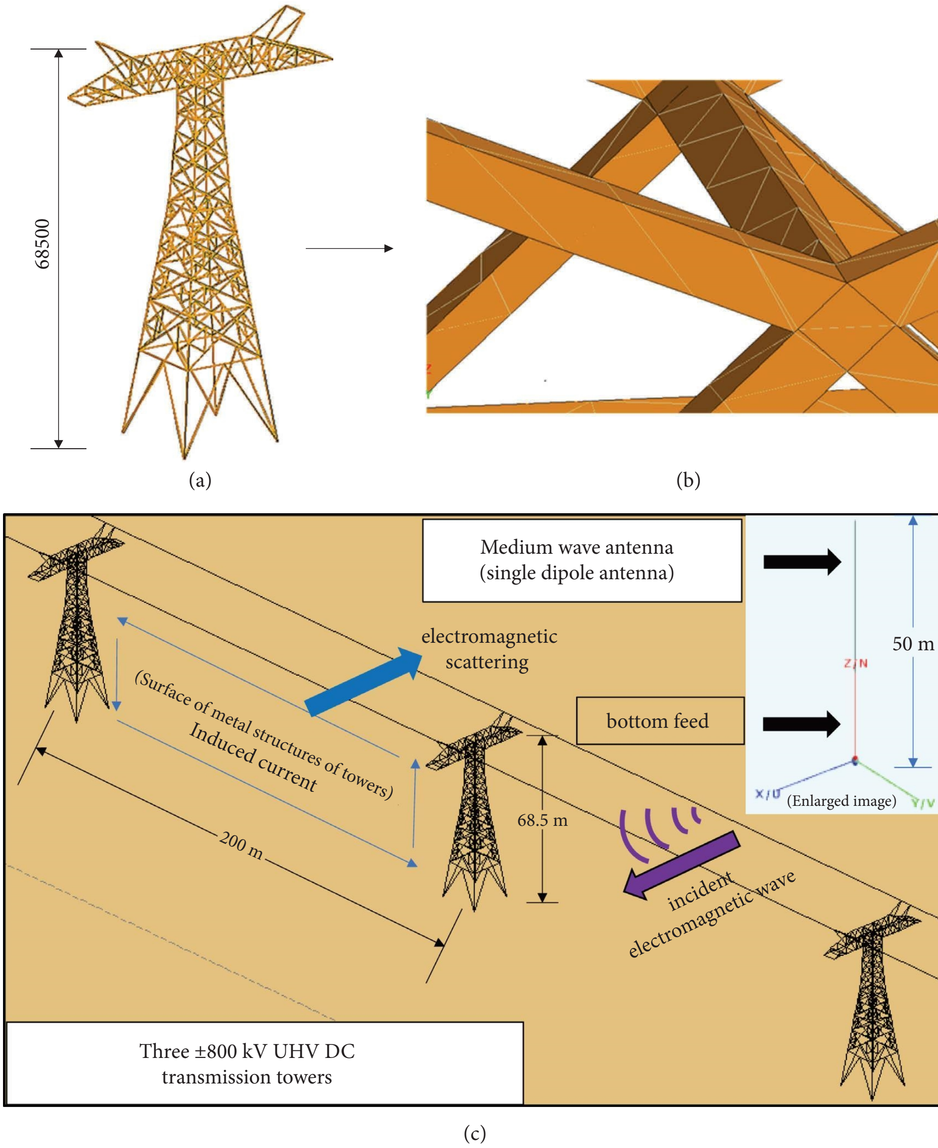


Figure 1: (a) ±800 kV UHV DC transmission tower model (unit: mm). (b) Tower head internal details. (c) Electromagnetic scattering simulation model of three-base UHV transmission towers with medium-wave antennas.

Table 1: Simulation model detailed settings.

Setting object	Simulation setup details
Simulation tower type	UHV DC transmission tower
Voltage level	±800 kV
Tower height	68.5 m
Cross-stretcher width	41 m
Distance between towers	200 m
Number of towers	1, 2, 3
Medium-wave antenna	Single dipole antenna (bottom feed)
Antenna height	50 m
Distance from the antenna to the tower	$\lambda = 500$ m, $\lambda/2 = 250$ m, $\lambda/4 = 125$ m
Simulation band	600 kHz, 1000 kHz, 1400 kHz

the transmission line, with the distance gradually shortened, the directional influence of the antenna is stronger, and the value of gain will increase along the direction of the transmission line. In the direction of the transmission tower line's erection extension, the medium-wave antenna is affected by the electromagnetic scattering from the

Table 2: Simulation equipment hardware information.

Hardware equipment	Detailed information
Computer model	MSI GS65 stealth 9SE
Operating system	Windows 10 (x64)
Central processing unit	Intel core i7-9570H
Random access memory	16 GB
Graphic processing unit	NVIDIA GeForce RTX 2060
Hardware equipment	Detailed information

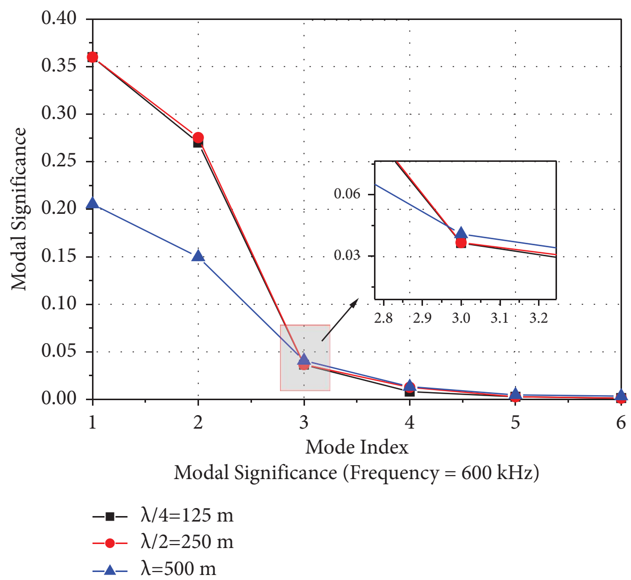


Figure 2: MS of each characteristic mode at different distance conditions.

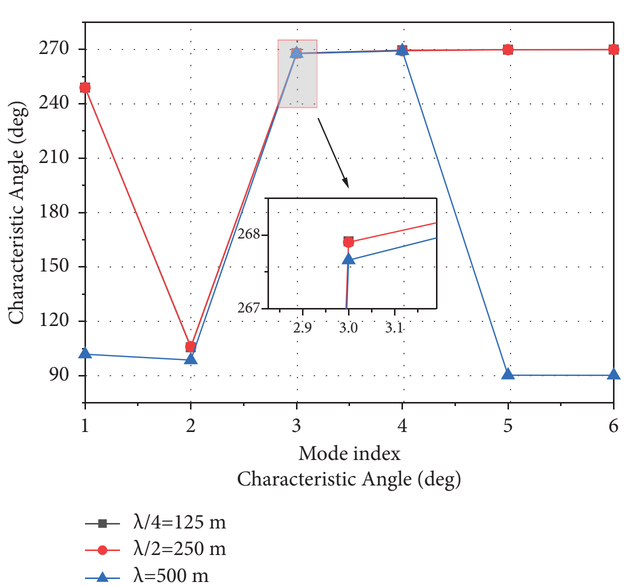


Figure 3: CA of each characteristic mode at different distance conditions.

transmission tower, and the distance between the transmission tower and the antenna changes as follows. The magnitude of the electric field is 8.14 V/m at a single

Table 3: MS of each characteristic mode at different distance conditions.

Characteristic mode	500 m	250 m	125 m
1	2.05*E* − 01	3.60*E* − 01	3.60*E* − 01
2	1.50*E* − 01	2.75*E* − 01	2.70*E* − 01
3	4.08*E* − 02	3.66*E* − 02	3.64*E* − 02
4	1.33*E* − 02	1.26*E* − 02	8.14*E* − 03
5	4.72*E* − 03	2.75*E* − 03	2.75*E* − 03
6	3.43*E* − 03	1.26*E* − 03	1.38*E* − 03

Table 4: CA of each characteristic mode at different distance conditions (unit: degree).

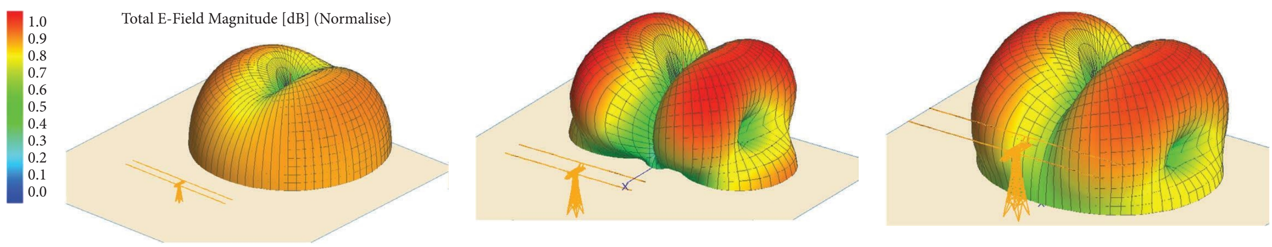
Characteristic mode	500 m	250 m	125 m
1	1.02*E* + 02	2.49*E* + 02	2.49*E* + 02
2	9.86*E* + 01	1.06*E* + 02	1.06*E* + 02
3	2.68*E* + 02	2.68*E* + 02	2.68*E* + 02
4	2.69*E* + 02	2.69*E* + 02	2.70*E* + 02
5	9.03*E* + 01	2.70*E* + 02	2.70*E* + 02
6	9.02*E* + 01	2.70*E* + 02	2.70*E* + 02

wavelength ($\lambda = 500$ m), 9.28 V/m at a half wavelength ($\lambda/2 = 250$ m), and 11.12 V/m at a quarter wavelength ($\lambda/4 = 125$ m). With the distance between the tower and the antenna being shortened from 500 m to 125 m, the electromagnetic scattering influence of medium-wave antenna by transmission tower is increased about 36.4%. The detailed data are shown in Table 5.

4.2. Different Numbers of Transmission Towers. In this section, we simulate and analyze the electromagnetic scattering effects of transmission towers on medium-wave antennas under different quantity conditions. Based on the model of the UHV DC transmission tower (Figure 1) and medium-wave antenna established in the electromagnetic simulation software, the parameters required for the simulation are set as follows. The voltage level is ± 800 kV, the tower's height is 68.5 m, the antenna height is 50 m, and the distance between the transmission tower and the medium-wave antenna is a single wavelength ($\lambda = 500$ m). Using the control variables method, the number of transmission towers for the three simulation groups is 1, 2, and 3, respectively, with other conditions remaining unchanged.

In order to be able to study the effect of different tower numbers on electromagnetic scattering independently, we need to select a set of characteristic modes with similar values of MS and CA, so as to ensure that the magnitude of the contribution of this characteristic mode to the total electromagnetic scattering is similar for different tower numbers, and to ensure that the amplitude and phase of the characteristic angles of the three characteristic modes are similar. The simulation results of characteristic angle and modal significance for three different numbers of transmission towers are shown in Figures 7 and 8 and Tables 6 and 7.

It is necessary to select a set of characteristic modes with similar MS and CA values in order to be able to independently study the effect of the number of transmission



(a) (b) (c)

Figure 4: Three-dimensional electric field diagram of transmission tower and antenna at different distance conditions (Unit: m). (a) $\lambda = 500$ m. (b) $\lambda/2 = 250$ m. (c) $\lambda/4 = 125$ m.

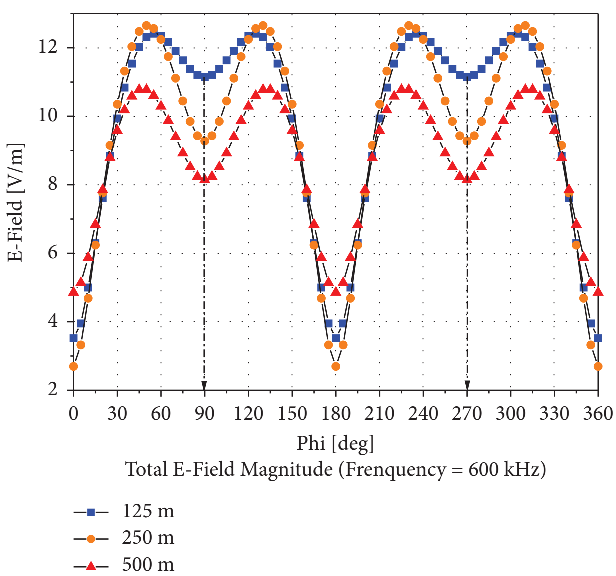


Figure 5: Two-dimensional electric field diagram of ± 800 kV UHV DC transmission tower and medium-wave antenna at different distances (Single wavelength ($\lambda = 500$ m), half wavelength ($\lambda/2 = 250$ m), and quarter wavelength distance ($\lambda/4 = 125$ m)).

towers on electromagnetic scattering. According to the data in Figures 7 and 8 and Tables 6 and 7, it is possible to pick the characteristic mode 1 for the single-tower condition, mode 2 for the two-tower condition, and mode 3 for the three-tower condition, which have similar MS and CA values. The MS and CA values are 0.2053 and 101.85 degrees for the single-tower condition, 0.2045 and 101.80 degrees for the two-tower condition, and 0.2116 and 102.21 degrees for the three-tower condition, respectively. Simulation analysis is performed for these three groups of characteristic modes, and the three-dimensional plots of electromagnetic scattering electric field under the influence of different numbers of transmission towers are shown in Figure 9, and the two-dimensional curve plots and polar coordinate direction plots are shown in Figures 10 and 11.

According to the simulation results of the three-dimensional electric field diagram in Figure 9 and the two-dimensional direction diagram in Figures 10 and 11, it is known that different numbers of ± 800 kV UHV DC transmission towers will have different effects on the directionality of the medium-wave antenna. According to

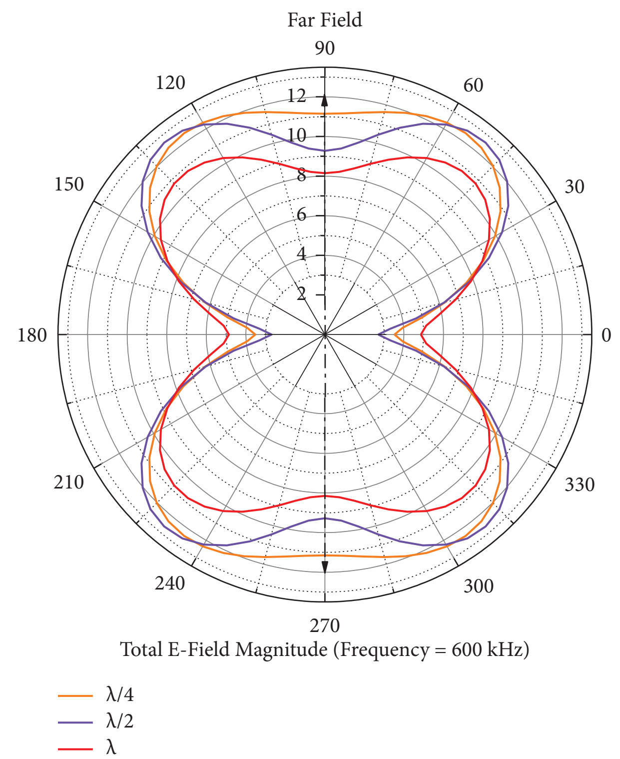


Figure 6: Two-dimensional electric field polar coordinate orientation diagram for different distances between ± 800 kV UHV DC transmission tower and medium-wave antenna.

Table 5: Electric field variation and electromagnetic scattering from transmission tower to medium-wave antenna at different distances.

Distance (m)	Electric field (V/m)	Percentage increase in electromagnetic scattering (%)
$\lambda = 500$	8.14	
$\lambda/2 = 250$	9.28	+36.4
$\lambda/4 = 125$	11.12	

Figures 10 and 11, it can be further known that the influence of towers on the antenna's electromagnetic scattering is getting bigger and bigger as the number of transmission towers increases gradually. In the direction of the extension of the transmission tower line, with the increase in the number of transmission towers, the influence of tower

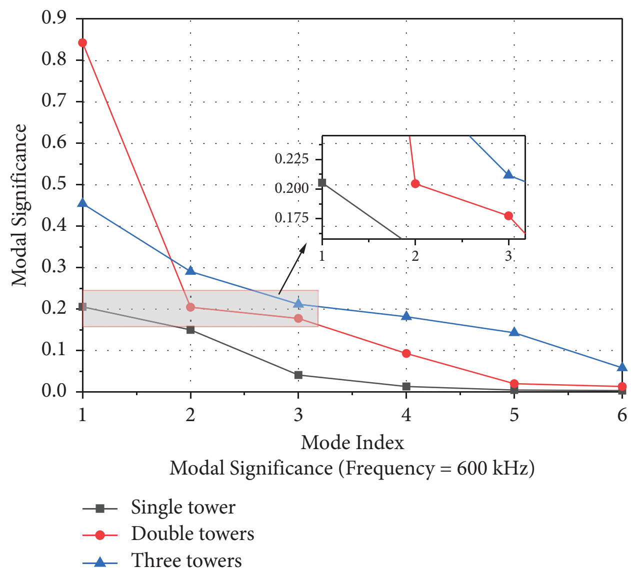


Figure 7: MS of each characteristic mode at different number conditions.

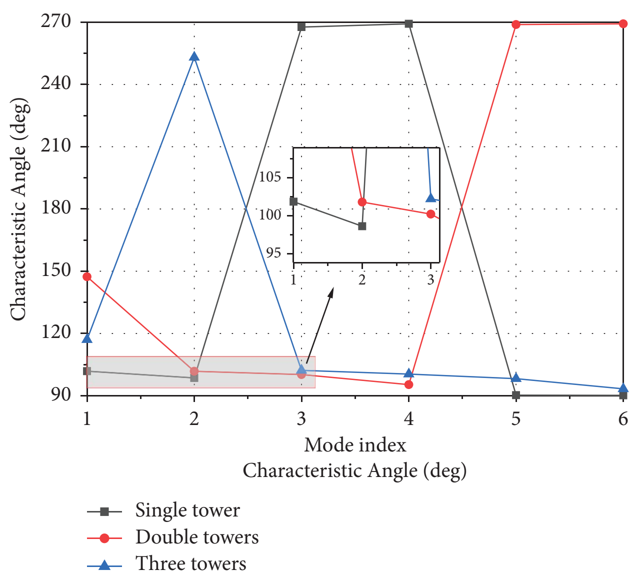


Figure 8: CA of each characteristic mode at different number conditions.

Table 6: MS of each characteristic mode at different number conditions.

Characteristic mode	Single tower	Double tower	Three towers
1	2.05E – 01	8.42E – 01	4.54E – 01
2	1.50E – 01	2.04E – 01	2.91E – 01
3	4.08E – 02	1.77E – 01	2.12E – 01
4	1.33E – 02	9.30E – 02	1.81E – 01
5	4.72E – 03	2.00E – 02	1.43E – 01
6	3.43E – 03	1.32E – 02	5.83E – 02

Table 7: CA of each characteristic mode at different number conditions (unit: degree).

Characteristic mode	Single tower	Double tower	Three towers
1	1.02*E* + 02	1.47*E* + 02	1.17*E* + 02
2	9.86*E* + 01	1.02*E* + 02	2.53*E* + 02
3	2.68*E* + 02	1.00*E* + 02	1.02*E* + 02
4	2.69*E* + 02	9.53*E* + 01	1.00*E* + 02
5	9.03*E* + 01	2.69*E* + 02	9.82E+01
6	9.02*E* + 01	2.69*E* + 02	9.33*E* + 01

electromagnetic scattering on the direction of the antenna increases, and there is a tendency to gradually extend along the direction of the transmission line, as follows: the electric field strength is 10.1 V/m for a single tower, 12.2 V/m for two towers, and 15.1 V/m for three towers. As the number of towers grows from a single tower to three towers, the electromagnetic scattering influence of medium wave-antenna by transmission towers increases about 49.5%. The detailed data are shown in Table 8.

4.3. Different Frequencies. In this section, we study the electromagnetic scattering effect of transmission towers on the medium-wave antenna which is at different frequencies. Based on the model of the UHV DC transmission tower (Figure 1) and medium-wave antenna established in the electromagnetic simulation software, the parameters required for the simulation are configured as follows. The voltage level is ± 800 kV, the height of the tower is 68.5 m, the antenna height is 50 m, and the distance between the transmission tower and the medium-wave antenna is a single wavelength ($\lambda = 500$ m). Using the control variable method, the frequency parameters in the three sets of simulations are changed to 600 kHz, 1000 kHz, and 1400 kHz, respectively, while the other conditions remain unchanged.

In order to be able to study the effect of frequency on electromagnetic scattering as independently as possible, the characteristic modes with similar MS and CA values in the three sets of simulations need to be selected for comparative analysis. Similar MS values ensure that the magnitude of the characteristic modes' contribution to the total electromagnetic scattering is similar, and CA values ensure that the amplitude and phase of the characteristic angles are similar. The modal significance and characteristic angle simulation results of transmission towers for medium-wave antennas at three different frequencies are plotted in Figures 12 and 13 and shown in Tables 9 and 10.

According to the data in Figures 12 and 13 and Tables 9 and 10, three groups of characteristic modes with similar MS and CA values at different frequencies can be selected, i.e., characteristic mode 5. The MS values of these three groups of characteristic modes at different frequencies are 0.0047, 0.0309, and 0.0477, and the CA values are 90.27, 91.77, and 92.73 degrees, respectively. For the simulation analysis of

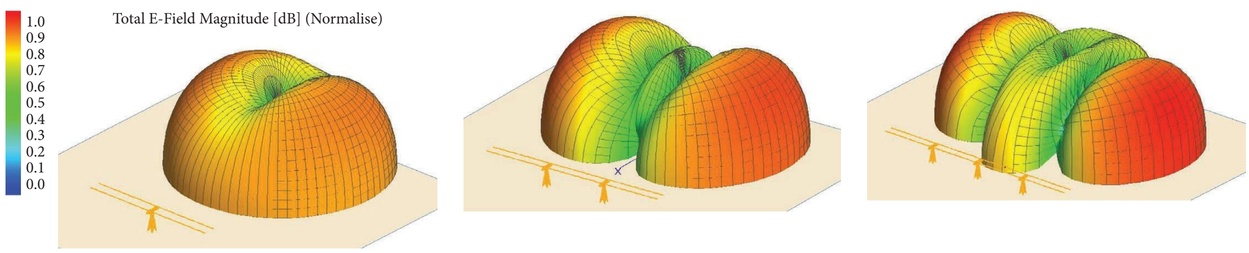


FIGURE 9: Three-dimensional electric field diagram of electromagnetic influence of different numbers of transmission towers on medium-wave antenna. (a) Single transmission towers. (b) Double transmission towers. (c) Three transmission towers.

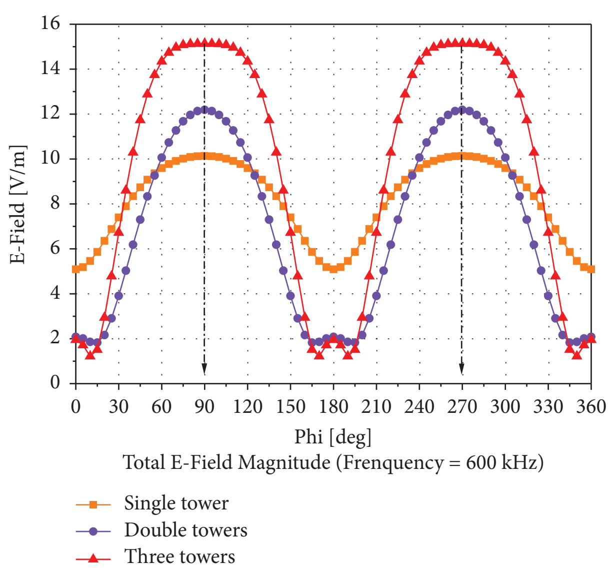


FIGURE 10: Two-dimensional electric field diagram of ±800 kV UHV DC transmission tower and medium-wave antenna at different number of conditions.

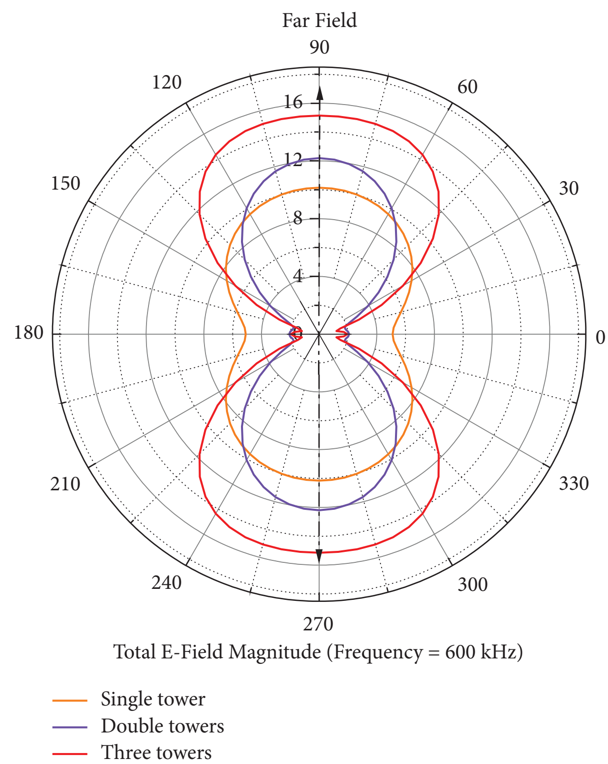


FIGURE 11: Two-dimensional electric field polar coordinate orientation diagram of ±800 kV UHV DC transmission tower and medium-wave antenna at different number of conditions.

these three groups of eigenmodes, the three-dimensional electric field diagram of the influence of the transmission tower on the electromagnetic scattering of the medium-wave antenna at different frequencies is shown in Figure 14, and the two-dimensional curve diagram and polar coordinate direction diagram are shown in Figures 15 and 16.

According to the simulation results of the three-dimensional electric field diagram in Figure 14 and the two-dimensional directional diagram in Figures 15 and 16, it can be seen that the ± 800 kV UHV DC transmission tower will have different effects on the medium-wave antenna at different frequencies. According to further analysis of the results in Figures 15 and 16, it can be seen that with the gradual increase of frequency, the influence of the tower on the antenna's electromagnetic scattering will be more and more significant, and the distortion of the antenna's directionality will be more and more drastic. The gain of the antenna can be found to increase with increasing frequency in the direction of extension of the transmission tower line and along the direction of the transmission tower line. The influence of the medium wave antenna by the electromagnetic scattering from the transmission tower varies with the rise in frequency as follows. The magnitude of the electric field is 8.14 V/m at a frequency of 600 kHz, 8.16 V/m at a frequency of 1000 kHz, and 10.81 V/m at a frequency of 1400 kHz. As the frequency grows from 600 kHz to 1400 kHz, the electromagnetic scattering influence of the medium-wave antenna by the transmission tower increases about 32.7%. The detailed data are shown in Table 11.

Table 8: Electromagnetic scattering effects and electric field variations of different numbers of transmission towers on medium-wave antenna.

Number of transmission towers	Electric field (V/m)	Percentage increase in electromagnetic scattering (%)
1	10.1	
2	12.2	+49.5
3	15.1	

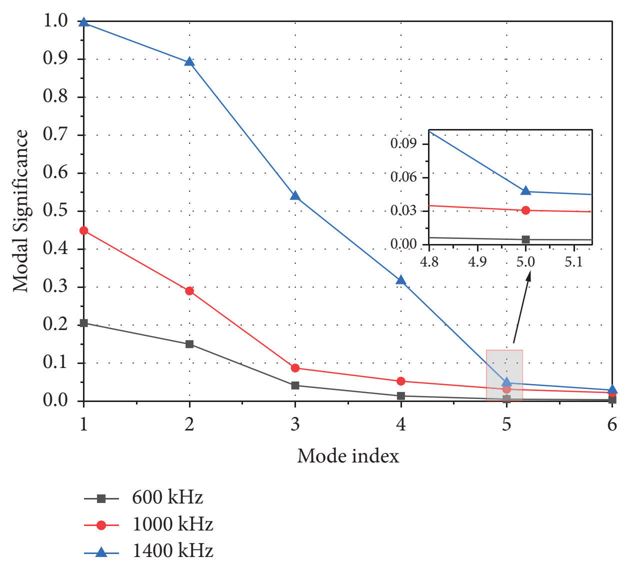


Figure 12: MS of each characteristic mode at different frequency conditions.

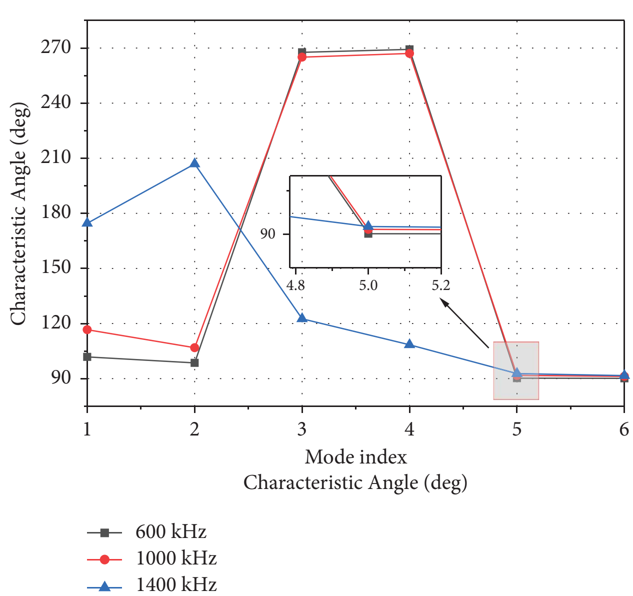


Figure 13: CA of each characteristic mode at different frequency conditions.

Table 9: MS of each characteristic mode at different frequency conditions.

Characteristic mode	600 kHz	1000 kHz	1400 kHz
1	$2.05E-01$	$4.49E-01$	$9.96E-01$
2	$1.50E-01$	$2.90E-01$	$8.92E-01$
3	$4.08E-02$	$8.69E-02$	$5.39E-01$
4	$1.33E-02$	$5.21E-02$	$3.16E-01$
5	$4.72E-03$	$3.09E-02$	$4.77E-02$
6	$3.43E-03$	$2.19E-02$	$2.88E-02$

Table 10: CA of each characteristic mode at different frequency conditions (unit: degree).

Characteristic mode	600 kHz	1000 kHz	1400 kHz
1	$1.02E+02$	$1.17E+02$	$1.75E+02$
2	$9.86E+01$	$1.07E+02$	$2.07E+02$
3	$2.68E+02$	$2.65E+02$	$1.23E+02$
4	$2.69E+02$	$2.67E+02$	$1.08E+02$
5	$9.03E+01$	$9.18E+01$	$9.27E+01$
6	$9.02E+01$	$9.13E+01$	$9.17E+01$

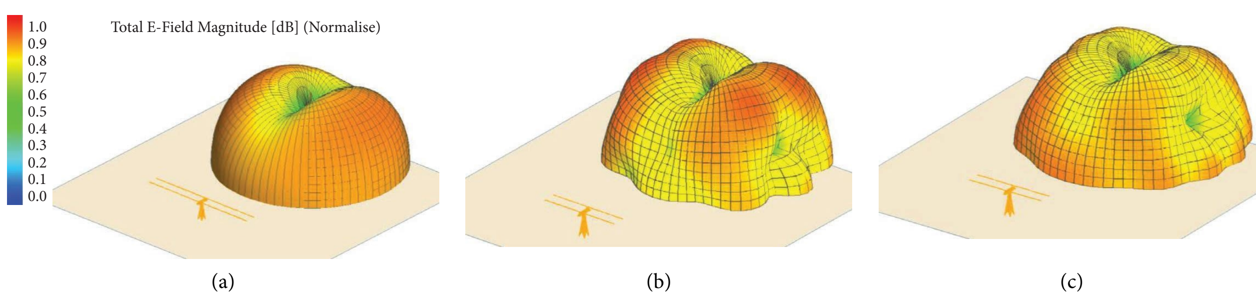


Figure 14: Three-dimensional electric field diagram of transmission tower and antenna at different frequency conditions. (a) $f = 600$ kHz. (b) $f = 1000$ kHz. (c) $f = 1400$ kHz.

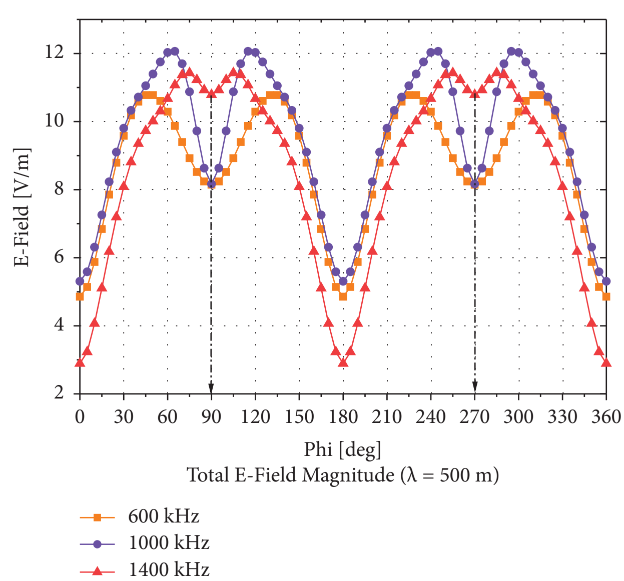


Figure 15: Two-dimensional electric field diagram of ±800 kV UHV DC transmission tower and medium-wave antenna at different frequency conditions.

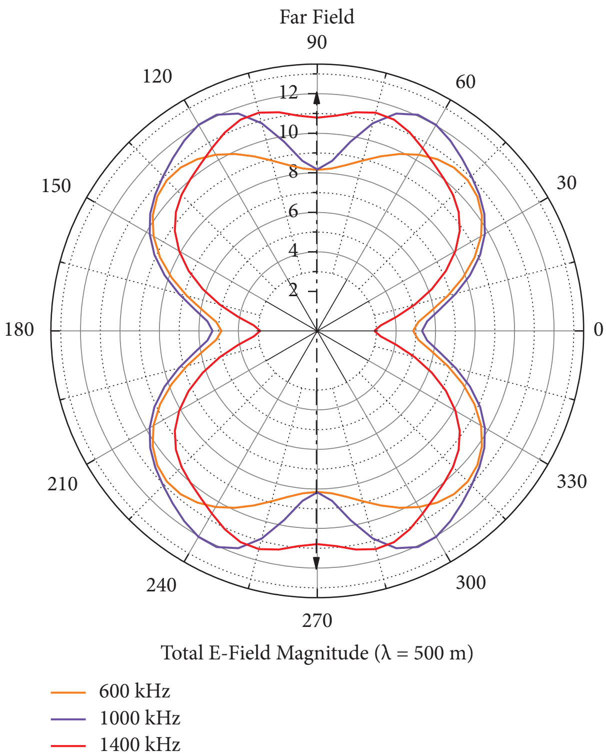


Figure 16: Two-dimensional electric field polar coordinate orientation diagram of ±800 kV UHV DC transmission tower and medium-wave antenna at different frequency conditions.

Table 11: Electromagnetic scattering and electric field from a transmission tower to medium-wave antenna at different frequencies.

Frequency (kHz)	Electric field (V/m)	Percentage increase in electromagnetic scattering (%)
600	8.14	
1000	8.16	+32.7
1400	10.81	

5. Discussion

5.1. Polarization State and Electric Field Components. For a plane electromagnetic wave propagating in the z-direction, the electric field E can be decomposed into two components, E_x and E_y, as shown in the following equation:

$$\vec{E} = \vec{a}_x E_x + \vec{a}_y E_y. \tag{8}$$

Then, the instantaneous equation for the electric field E is represented as follows:

$$\vec{E}(z,t) = \vec{a}_x E_{x0} \cos(\omega t - kz) + \vec{a}_y E_{y0} \cos(\omega t - kz - \varphi). \tag{9}$$

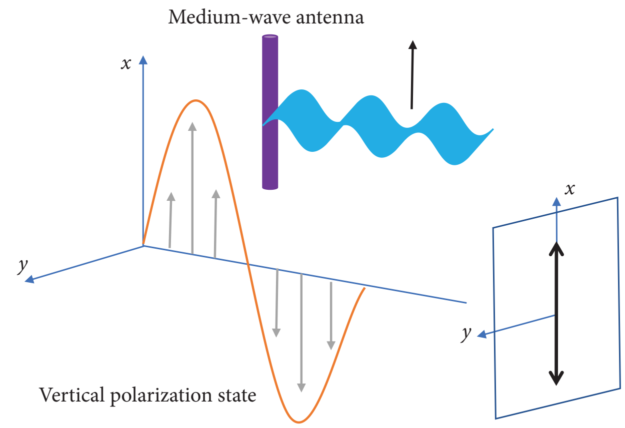


Figure 17: The state of vertical polarization of an electromagnetic wave emitted by a medium-wave antenna.

The antenna chosen for the simulation in this paper is the medium-wave antenna. The medium-wave antenna is erected perpendicular to the ground and transmits vertically polarized plane waves, as shown in Figure 17.

At this time, the two components of the electric field E (E_x and E_y) are in phase or have a phase difference of 180°, i.e., when φ is 0° or 180°. The two components of the electric field E are represented as follows:

$$\begin{aligned} E_x(z,t) &= E_{x0}\cos(\omega t - kz), \\ E_y(z,t) &= E_{y0}\cos(\omega t - kz - \varphi), \end{aligned} \tag{10}$$

when φ is 0° or 180°, the trajectory equation of the electric field can be simplified as follows:

$$E_y(z,t) = \pm \frac{E_{y0}}{E_{x0}} E_y(z,t). \tag{11}$$

5.2. Impedance Match. Future studies may consider the effect of antennas mounted on transmission towers on the input impedance. Due to the rapid development of mobile communications, many areas of the country currently exist in the situation of multiple networks coexisting, that is, A, B, and G three networks coexist. In order to make full use of resources and realize resource sharing, we generally adopt the form of an antenna common tower. This involves the correct installation of antennas, that is, how to install them to minimize the mutual influence between antennas. In engineering, we generally use the isolation degree index to measure, which usually requires that the isolation degree should be at least more than 30 dB to meet this requirement, and is often used to make the antenna in the vertical direction or in the horizontal direction of the separation method. When the antenna spacing is the same, vertical installation can get more isolation than horizontal installation.

(a) Tower-side installation of directional antenna: In order to reduce the influence of the antenna tower on the antenna directivity map, it should be noted during installation that the maximum directivity outside the tower can be obtained when the distance from the center of the directional antenna to the tower is $\lambda/4$ or $3\lambda/4$.

(b) Tower-side mounting of omnidirectional antennas: In order to minimize the effect of the antenna tower on the antenna's directional map, in principle, the antenna tower must not be a reflector for the antenna. Therefore, in the installation, the antenna should always be mounted on the prongs, and the nearest distance between the antenna and any part of the tower should be greater than λ.

(c) Multiantenna common tower: To minimize the coupling effect and mutual influence between the receiving and transmitting antennas of different networks and to increase the isolation of antennas from each other, the best way is to increase the distance between each other. When the antennas share the tower, vertical installation should be given priority.

6. Conclusion

In this paper, the influence of electromagnetic scattering from UHV DC transmission towers on medium-wave antenna signal stations is taken as the background, and the influence factors of electromagnetic scattering from transmission lines are studied by combining the CMT. The simulation models of ±800 kV UHV DC transmission towers and medium-wave antenna are established by electromagnetic simulation software. Different numbers of towers, different distances between towers and antennas, and different frequencies of antennas are studied, respectively. The simulation compares and analyzes the characteristic angle, model significance, and two- and three-dimensional electric field diagrams in three different conditions, proposes the characteristic model screening rules based on the percentage of electromagnetic scattering contribution, and further studies obtain the electromagnetic scattering influence law of UHV transmission towers on medium-wave antennas.

The results show that the shortening of the distance between the transmission tower and the antenna, the increase in the number of towers, or the increase in frequency will lead to an increase in electromagnetic scattering effects. The specific values are as follows:

(i) The distance between the tower and the antenna is shortened from a single wave ($\lambda = 500$ m) to a quarter wave ($\lambda/4 = 125$ m), and the antenna is affected by the electromagnetic scattering from the tower by an increase of about 36.4%

(ii) The number of towers increases from a single tower to three towers, and the effect of electromagnetic scattering from the towers increases the antenna by about 49.5%

(iii) The frequency increases from 600 kHz to 1400 kHz, and the antenna is affected by the electromagnetic scattering from the transmitting tower by an increase of about 32.7%

(iv) The directional distortion of the medium-wave antenna becomes more complex and has a tendency to extend (90 or 270 degrees) along the transmission tower lines

When an antenna communication system exists in the vicinity of a UHV transmission tower, the electromagnetic scattering from the transmission tower becomes one of the main factors affecting the safety and stability of the surrounding radio signal system, and it needs to be considered at the time of deployment. The research results of this paper can provide theoretical guidance and technical reference for the development of electromagnetic scattering protection measures for UHV DC transmission towers.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

This work was supported by Joint Funds of the National Natural Science Foundation of China under Grant U20A20305.

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