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RESEARCH ARTICLE

Analysis of Influence Factors and Influence Law of Scattering Electric Field of High Voltage Transmission Line in Short Wave Frequency Band

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ABSTRACT The study of the influence factor of transmission line scattering and its influence law is the key to developing the transmission line passive interference suppression strategy. Therefore, the line-surface geometric model of electromagnetic scattering of transmission lines is constructed in this paper. The method of moments (MOM) built in Feko simulation software is used to solve the induced current on the surface of transmission lines and the scattered electric field generated by it. Taking the ±800 kV Xiangjiaba-Shanghai ultra-high-voltage direct current (UHVDC) transmission line as an example, the effects of the ontological structural features such as transmission line ground wire, line span, and tower height on the scattered electric field of the transmission line were investigated. The results show that the ground wire and tower insulation have little effect on the induced currents on the surface of the transmission tower, the scattered electric field at the observation point is less with the increase of the transmission line distance, and the scattered electric field at the observation point decreases with the increase of the height of the transmission tower. The findings of this paper can provide a reference for the protection of passive interference of transmission lines.

INDEX TERMS Transmission line, passive interference, induced current, electromagnetic scattering field, influence factor, body structure characteristics.

I. INTRODUCTION

High-voltage transmission lines (HVTL) with high voltage levels, large transmission capacity, and wide spatial coverage erection and operation will produce passive interference to the nearby wireless stations [1]. However, in the background of China's increasingly limited land space, the current approach of determining the protection spacing to solve the problem of passive interference by relying only on the characteristics of spatial natural attenuation of electromagnetic scattering field intensity is too passive. Therefore, it is necessary to clarify the decisive influencing factors of passive interference to targeted modification of the transmission line. This is significant for effectively solving the electromagnetic compatibility problem between HVTL and wireless stations.

Foreign countries have conducted more in-depth research on the passive interference protection measures for transmission lines at medium-wave frequency bands and their influence factors, and it is believed that the secondary radiation of induced currents is the fundamental reason for the interference [2]. At the same time, there was a resonance phenomenon in the changing characteristics of the passive interference. Hence, destroying the generation conditions of resonance is an effective method for passive interference protection [3]. The standard formulated by IEEE believed that when the resonance phenomenon of passive

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interference occurred, an induced current of large magnitude would be generated in single base towers [4] or in the "loop antenna" circuit composed of power towers and ground wire, resulting in a solid secondary radiation field [5]. Because the structure of the constructed power towers could not be changed, the passive interference could only be reduced by blocking the "loop antenna" circuit with a "detuner" [6], which could reduce the induced current by destroying the generation conditions of the resonance.

However, the studies were only concerned with passive interference in medium waves. Reference [7] studied the passive interference in the working frequency band of the AM radio station (0.526 MHz to 26.1 MHz) and found that the peak value of the passive interference and the frequency at which the peak value appeared were the same in both cases with and without ground wire. This showed that the induced current of the "loop antenna" circuit is no longer the decisive factor for passive interference in shortwaves. Reference [8] further found that when the frequency reaches the shortwave and above, the passive interference is mainly affected by the electromagnetic scattering from metal structures above the ground of transmission lines. Therefore, the impact factors of passive interference in shortwaves must be further discussed.

As a result, this paper starts from the structural characteristics of HVTL, analyses the influence of the impact factors, such as the ground wire, the line span, the number of power towers, and the height of power towers, on the distribution of the induced current, to indirectly clarify the impact factor on the electromagnetic scattered field of HVTL. It also provides a theoretical reference for the passive interference suppression of HVTL.

II. PASSIVE INTERFERENCE AND ITS SUPPRESSION OF HVTL

A. PASSIVE INTERFERENCE OF HVTL

The schematic diagram for passive interference of HVTL to adjacent wireless stations is shown in Fig. 1. HVTL mainly comprises conductors, ground wires, insulator strings, line fittings, power towers, tower foundations, and grounding devices. The metal parts exposed above the ground surface are mainly power towers, conductors, and ground wires [9]. From the perspective of electromagnetism, power towers, con-ductors, and ground wires of HVTL can be regarded as a collection of countless charged particles. The incident electro-magnetic wave emitted by wireless stations interacts with the charged particles in the metal parts of HVTL. Then, a new equivalent charge, current, or field source is generated [10]. With the alternating influence of the incident electromagnetic field, the induced current generated by the metal parts of HVTL is also alternating, and a new electromagnetic field, called the scattered field, is generated in the space near HVTL [11]. To sum up, the metal parts of HVTL belong to scatterers, which are not excitation sources themselves and are excited by external electromagnetic fields to generate scattering.

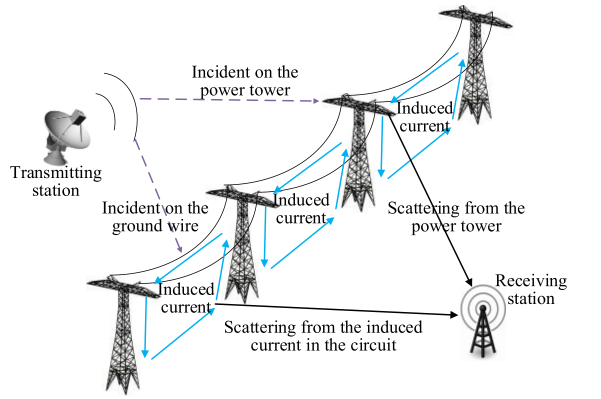


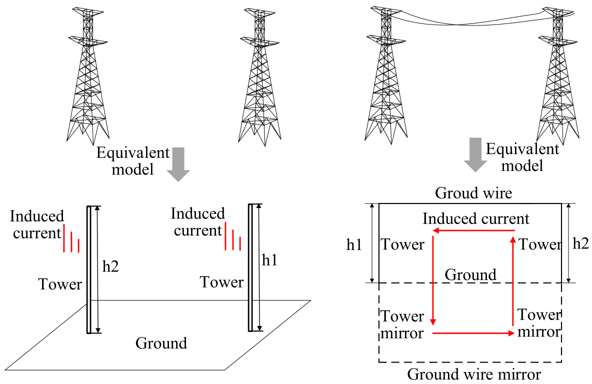
FIGURE 1. The schematic diagram for passive interference of HVTL to adjacent wireless stations.

The electromagnetic wave generated by the electromagnetic scattering of HVTL is superimposed with the original incident electromagnetic wave, which changes the magnitude and phase of the original incident electromagnetic wave, thereby causing interference to the transmitting or receiving signals of the wireless stations, resulting in radio measurement errors. The intensity of the scattered field of HVTL depends on the excitation field's intensity and the conductor's physical characteristics. For HVTL, it mainly depends on the structural characteristics of the transmission lines [12], [13], [14].

B. SUPPRESSION OF PASSIVE INTERFERENCE

Currently, the main method to solve the passive interference problems of HVTL to adjacent wireless stations is to propose a protective distance according to the electromagnetic environment protection standards and then require HVTL to be constructed outside the protective distance of wireless stations [15]. If the distance between the HVTL and the wireless station is less than the protection distance specified in the standard, the path of the HVTL needs to be changed, and the HVTL needs to go around with a larger radius around the wireless station to meet protection requirements, which will result in serious financial losses, even if the transmission line cannot be built. Therefore, this type of protection, which only relies on the attenuation of electromagnetic fields with spatial distance, is a passive protection method.

This passive protection method relying on distance regulations not only brings difficulties to actual engineering construction but also cannot solve the passive interference problem between existing transmission lines and wireless stations due to the short distance. Therefore, Zhao Peng et al. propose a method to change the resonant frequency of the transmission lines and actively suppress the electromagnetic scattered field of transmission lines by the "avoidance frequency" [16]. The core idea is that under the action of exciting electromagnetic waves, the power tower can be equivalent to a wire antenna vertical to the ground, as shown



(a) Wire Antenna (b) Loop Antenna

FIGURE 2. **Schematic diagram of wire antenna and loop antenna for transmission lines.**

in Fig. 2(a), and the transmission line can form multiple "loop antennas" as shown in Fig. 2(b) according to the line span.

For the wire antenna vertical to the ground in Fig. 2(a), according to the half-wave antenna theory, it is considered that when the height of the power tower reaches $\lambda/4$ (λ is the wavelength), the power tower and its ground mirror form a half-wave antenna, and the alternating electromagnetic field generates a maximum induced electromotive force in the power tower perpendicular to the ground, and the corresponding induced current on the surface of the power tower is also at its maximum. Currently, the secondary radiation field generated by the induced current is the strongest, and the passive interference to the wireless station is also the most serious.

When the transmission tower is not insulated from the ground wire, the ground wire connects the adjacent two power towers within one span and mirrors them to the ground to form a "loop antenna" as shown in Fig. 2(b). According to the radiation characteristics of the "loop antenna," when the length of the "loop antenna" is an integer multiple of the wavelength of the electromagnetic wave emitted by the wireless station, a resonance phenomenon will occur, and a peak value of induced current will appear in the circuit, resulting in a peak value of secondary radiation and correspondingly a peak value of passive interference.

Therefore, many current studies of passive interference try to predict the resonant frequency for the passive interference of transmission lines to avoid the interference resonance or destroy the resonance condition and limit the induced current of transmission lines, thereby reducing the electromagnetic scattered field of transmission lines. However, reference [7] found that with the increase of the frequency of the electromagnetic wave, especially when the frequency reaches the shortwave and above, the electrical dimension effect of the tower detail gradually becomes non-negligible relative to the shrinking of the wavelength, which is why the IEEE standard itself limits these conclusions to the medium wave, and preferably below 1.7 MHz.

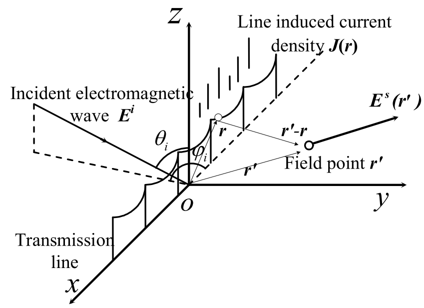


FIGURE 3. **A mathematical model for solving electromagnetic scattered field of HVTL.**

To sum up, the decisive impact factors of passive interference can be clarified, and reducing the induced current to suppress the interference is suitable for the medium and long wave frequency bands. Still, it is unsuitable for wireless stations working in shortwave or higher frequency bands. Therefore, the induced current distribution of passive interference in the shortwave frequency band needs to be further discussed in combination with the structural characteristics of transmission lines.

III. THE SOLUTION OF THE ELECTROMAGNETIC SCATTERED FIELD FOR HVTL

A. ELECTRIC FIELD INTEGRAL EQUATION AND INDUCED CURRENT OF PASSIVE INTERFERENCE

The mathematical model of the passive interference generated by transmission lines to the adjacent wireless stations is shown in Fig. 3. Fig. 3 contains a rectangular coordinate system (x, y, z) and a spherical coordinate system (r, θ, φ). Assuming that the transmission line is an ideal conductor, the power towers are evenly arranged along the x-axis with a certain line span, the angle at which the electromagnetic wave $\boldsymbol{E}^i$ is incident on the transmission line is (θ_i, φ_i), $\boldsymbol{J}(\boldsymbol{r})$ is the induced current density at any point on the transmission line, which will radiate into space, $\boldsymbol{E}^s$ is the electromagnetic scattered field at the field point $\boldsymbol{r}$' where the wireless receiving station is located.

According to the electromagnetic field theory, the incident electromagnetic wave (excitation field) emitted by wireless stations will generate an induced electromotive force on the surface of the metal parts of transmission lines that is positively correlated with the excitation field intensity, the induced electromotive force will excite an alternating induced current on the surface of metal parts [17]. According to the skin effect of metal conductors, the induced current is mainly concentrated on the surface of the conductors. After that, the induced current concentrated on the surface of conductors will act as a new excitation source to emit a scattered field with the same frequency as the excitation field, that is, the secondary radiation field, causing interference to the wireless stations adjacent to transmission lines.

Based on the above electromagnetic scattering mechanism and the electrical dimension proportional relationship between the wavelength of the electromagnetic wave and the target scatterers, reference [9] constructed a line-surface hybrid model, which is combined with the three-dimensional surface model for power towers and the line model for ground wires, for the solution of the passive interference for transmission lines in shortwave, and the line and surface electric field integral equations for a model solution and the solution algorithm based on induced current dispersion are also given. Through the comparative analysis with the experimental data of the scaled model of the Beijing Kangxi Grassland transmission line, the mathematical model and algorithm have good accuracy [18].

When using the line model to calculate the passive interference of transmission lines, the corresponding line electric field integral equation is used as:

$$-\boldsymbol{l}\cdot\boldsymbol{E}^i(\boldsymbol{r}') = j\omega\mu\boldsymbol{l}\cdot\int_{l}\boldsymbol{l}g\left(\boldsymbol{r}',\boldsymbol{r}(\boldsymbol{l})\right)I(\boldsymbol{l})\,\mathrm{d}l - \frac{1}{j\omega\varepsilon}\frac{\mathrm{d}}{\mathrm{d}l}\int_{l'}g\left(\boldsymbol{r}',\boldsymbol{r}(\boldsymbol{l})\right)\frac{\mathrm{d}I(\boldsymbol{l})}{\mathrm{d}l}\mathrm{d}l \tag{1}$$

where $\boldsymbol{l}$ is the unit vector along the axis of the thin wire; $\boldsymbol{E}^i(\boldsymbol{r}')$ is the electric field intensity of the incident electromagnetic wave; ω is the angular frequency of the incident electromagnetic wave; μ is the magnetic permeability; ε is the dielectric constant; $g(\boldsymbol{r}', \boldsymbol{r}(\boldsymbol{l}))$ is the Green's function; $I(\boldsymbol{l})$ is the line current density in the direction of the axis of the thin wire, $I(\boldsymbol{l}) = 2\pi a\boldsymbol{J}(\boldsymbol{l})$; a is the equivalent radius of the line model.

When using the surface model to calculate the passive interference of transmission lines, the corresponding surface electric field integral equation needs to be used as:

$$-\boldsymbol{t}\cdot\boldsymbol{E}^i(\boldsymbol{r}') = j\omega\mu\boldsymbol{t}\cdot\int_{S'}g\left(\boldsymbol{r}',\boldsymbol{r}\right)\boldsymbol{J}_{S'}(\boldsymbol{r})\,\mathrm{d}S' - \frac{1}{j\omega\varepsilon}\boldsymbol{t}\cdot\nabla\int g\left(\boldsymbol{r}',\boldsymbol{r}\right)\nabla'\cdot\boldsymbol{J}_{S'}(\boldsymbol{r})\,\mathrm{d}\boldsymbol{S}' \tag{2}$$

where: $\boldsymbol{t}$ is the unit tangential vector; $\boldsymbol{E}^i(\boldsymbol{r}')$ is the electric field intensity of incident electromagnetic wave; $\boldsymbol{J}_{S'}(\boldsymbol{r})$ is the induced current of the surface model.

The solution of the discrete induced current on the line-surface model of transmission lines can be based on the principle of MoM [19]. The induced current on the line-surface model is first discretized using an appropriate basis function. The expansion coefficient of the basis function is the induced current on each corresponding discretized unit. Equation (3) expresses the induced current distributed on the surface of transmission lines.

$$\boldsymbol{J}(\boldsymbol{r}) = \sum_{n=1}^{N_s}\boldsymbol{I}_n^s\boldsymbol{f}_n^s(\boldsymbol{r}) + \sum_{n=1}^{N_w}\boldsymbol{I}_n^w\boldsymbol{f}_n^w(\boldsymbol{r}) + \sum_{n=1}^{N_j}\boldsymbol{I}_n^j\boldsymbol{f}_n^j(\boldsymbol{r}) \tag{3}$$

where $\boldsymbol{J}(\boldsymbol{r})$ is the total induced current on the surface of transmission lines, composed of the surface-induced current on the surface of power towers, the line-induced current on the ground wire, and the induced current at the line-surface connection point; $\boldsymbol{f}_n^s(\boldsymbol{r})$ is the triangular surface element basis function of the surface model; $\boldsymbol{f}_n^w(\boldsymbol{r})$ is the basis function of line element for the line model; $\boldsymbol{f}_n^j(\boldsymbol{r})$ is the basis function of the connection point between surface element and line element; $\boldsymbol{I}_n^s$, $\boldsymbol{I}_n^w$, and $\boldsymbol{I}_n^j$ are the expansion coefficients of the corresponding basis functions; N_s is the number of joint edges of the triangular surface element; N_w is the number of line elements, and N_j is the number of connection points between triangular surface elements and line elements.

After obtaining the induced current expressed by the basic functions, substitute it into the electric field integral equation of equations (1) and (2), and the difference function is obtained by the equation transformation. Then, the difference function is combined with the Rao-Wilton-Glisson (RWG) basis function as the test function, and the matrix equation system about the expansion coefficient of the basis function is obtained as:

$$\begin{bmatrix} Z_{ss} & Z_{sw} & Z_{sj} \\ Z_{ws} & Z_{ww} & Z_{wj} \\ Z_{js} & Z_{jw} & Z_{jj} \end{bmatrix}\cdot\begin{bmatrix} \boldsymbol{I}_s \\ \boldsymbol{I}_w \\ \boldsymbol{I}_j \end{bmatrix} = \begin{bmatrix} \boldsymbol{V}_s \\ \boldsymbol{V}_w \\ \boldsymbol{V}_j \end{bmatrix} \tag{4}$$

where the impedance matrix on the left side of equation composed of 9 elements, Z_{ss} represents the self-acting impedance of triangular surface elements; Z_{ww} represents the self-acting impedance of line elements; Z_{jj} represents the self-acting impedance of the line-surface connection points; Z_{sw} and Z_{ws} represent the interaction impedance between triangular surface elements and line elements; Z_{sj} and Z_{js} represent the interaction impedance between triangle surface elements and line-surface connection points; Z_{wj} and Z_{jw} represent the interaction impedance between line elements and line-surface connection points; $\boldsymbol{I}_s$ represents the induced current on the surface model; $\boldsymbol{I}_w$ represents the induced current on the line model; $\boldsymbol{I}_j$ represent the induced current at the line-surface connection point; The right side of the equation is the voltage matrix, $\boldsymbol{V}_s$ represents the induced voltage on the surface model; $\boldsymbol{V}_w$ represents the induced voltage on the line model; $\boldsymbol{V}_j$ represents the induced voltage at the line-surface connection point.

Finally, by solving equation (4), the expansion coefficient group of the induced current basis function, namely $\boldsymbol{I}_s$, $\boldsymbol{I}_w$, and $\boldsymbol{I}_j$, is obtained, and the induced current $\boldsymbol{J}(\boldsymbol{r})$ of the whole line-surface model is also obtained. Finally, the electromagnetic scattered field at the observation point is obtained by solving.

B. INDUCED CURRENT DISTRIBUTION CHARACTERISTICS OF HVTL

The induced current on the line-surface model of transmission lines directly affects the electromagnetic scattered field distribution of transmission lines, so by analyzing the change of the induced current on the line-surface model of the transmission line, the change of the electromagnetic scattered field of transmission lines can be indirectly reflected.

To study the impact factors of the induced current on the line-surface model of transmission lines, the solution equation (4) of the induced current is analyzed.

In equation (4), the voltage matrix on the right side of the equation is a known quantity, and its value depends on the magnitude, incident angle, and frequency of the incident electromagnetic wave. The left side of the equation is the impedance matrix of transmission lines and the induced current matrix to be solved. According to the element composition of the impedance matrix, it can be known that it is closely related to the structural characteristics of transmission lines. Take Z_{ss} as an example, which is related to the structural characteristics of the surface model for power towers that are:

$$Z_{ss} = j\omega\mu \int_{S'} g\left(\boldsymbol{r}', \boldsymbol{r}\right) \mathrm{d}S' \cdot \int_{S-r} \left(\boldsymbol{f}_m\left(\boldsymbol{r}'\right)\boldsymbol{f}_n(\boldsymbol{r}) - \frac{1}{k^2}\nabla_{S'} \cdot \boldsymbol{f}_m(\boldsymbol{r})\nabla'_{S'} \cdot \boldsymbol{f}_n(\boldsymbol{r})\right)\mathrm{d}S \tag{5}$$

where S is the surface area of the surface model for power towers; g ($\boldsymbol{r}$', $\boldsymbol{r}$) is the electric Green's function; $\boldsymbol{f}_m(\boldsymbol{r}')$ and $\boldsymbol{f}_m(\boldsymbol{r})$ are the test function when the Galerkin test method is selected; k is the wave number, $k = \sqrt{\mu\varepsilon}$.

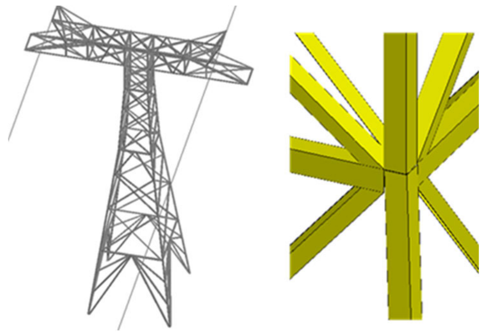
The integral region in equation (5) is the metal surface of power towers, that is, the region where the induced current is distributed. When the height of the power tower, structure, or number of power towers changes, the integral region for the solution of element Z_{ss} must change, finally leading to the differences in the elements Z_{ss}.

In the same way, it can be seen that Z_{ww} depends on the structural characteristics of the line model for ground wires, the change in the number of ground wires and the length of ground wires (line span) will inevitably lead to changes in the integral region for the solution of the element Z_{ww}, finally leading to the differences in the elements Z_{ww}; The elements Z_{sw} and Z_{ws}, Z_{sj} and Z_{js}, and Z_{wj} and Z_{jw} are related to the connection between power towers and ground wires. When the number of power towers changes, it will cause a change in the number of connection points between the line model and the surface model, which will change the impedance matrix.

In summary, the solution of the induced current is directly influenced by the impedance matrix of transmission lines, and the elements of the impedance matrix are closely related to structural characteristics, such as the ground wire, line span, number of power towers, and height of power towers. When the structural characteristics of transmission lines change, it will inevitably lead to changes in the distribution of induced current on transmission lines, making the electromagnetic scattered field at the observation point also change.

IV. RESPONSE ANALYSIS FOR THE IMPACT FACTORS OF ELECTROMAGNETIC SCATTERED FIELD

Taking the ±800 kV Xiangjiaba-Shanghai UHVDC transmission line as an example, the induced current and scattered field intensity of the transmission line is analyzed by Feko when the ground wire, line span, number of power towers, and height of the power tower are changed. The degree of impact of various structural characteristics of the transmission line on the scattered electric field is studied.



(a) Overall Model (b) Local Mode for Angle Steel Connection Points

FIGURE 4. The line-surface model of the ZP30101 power tower.

A. RESPONSE CHARACTERISTICS FOR GROUND WIRES

Taking the actual size of the ZP30101 tower of ±800 kV Xiangjiaba-Shanghai UHVDC transmission line as an example, the line-surface hybrid model for solving the passive interference of transmission lines is established as shown in Fig. 4. The height of the power tower is 63 m and the length of the cross arm is 42.2 m. The type of ground wire is 6×ACSR-720 / 50, the outer diameter of the ground wire is 36.24 mm, and the split interval is 450 mm. The power tower is connected with double ground wires, the type of ground wire is LBGJ-180-20AC, the diameter of the ground wire is 17.5 mm, and the distance between the two ground wires is 32.4 m.

Considering that the wavelength of the shortwave is 10 m, which is much smaller than the distance between the transmission line and the radio station in km, the excitation electromagnetic waves of various wireless stations to the transmission line are plane waves. Because the power tower is vertical to the ground, the vertical polarization plane wave, which causes the most serious interference to adjacent wireless stations, is used for excitation, and its electric field intensity is 1 V/m. According to the reference [8], the measurement antenna for passive interference of transmission lines is at a height of 2 m above the ground, and the vertical distance between the observation point and the direction of the transmission line is 2000 m, so the coordinates of the observation point are (0, 2000, 2). The relative position of the transmission line and observation point is shown in Fig. 5.

According to the analysis in Chapter 2, it can be seen that the passive interference of transmission lines is affected by the electromagnetic scattering from metal structures above the ground of transmission lines, i.e., mainly affected by the induced current on the surface of the power tower.

Therefore, to study the influence of the ground wire on the electromagnetic scattered field in shortwave, controlling the line span, number of power towers, and height of

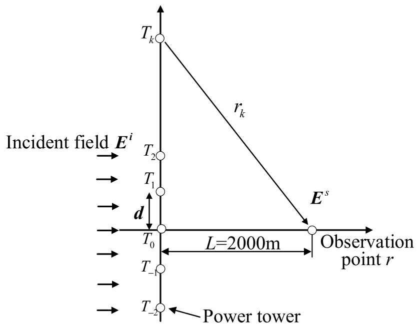


FIGURE 5. The relative position of the transmission line and observation point.

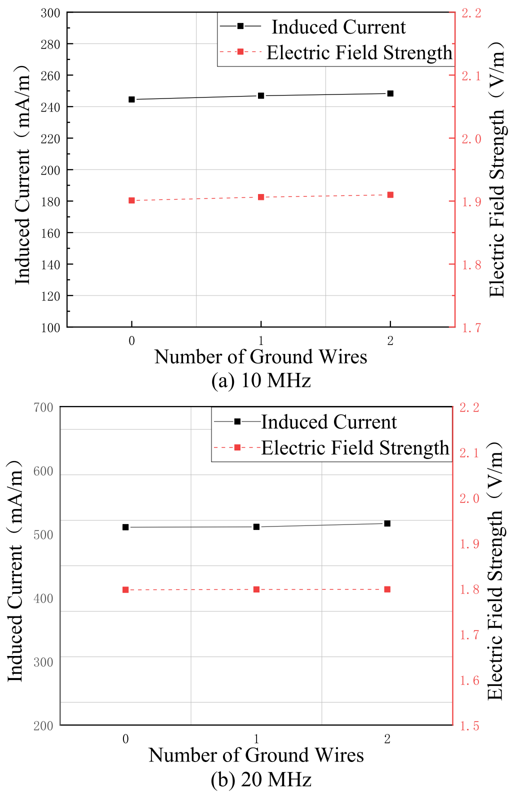


FIGURE 6. Influence of ground wire on induced current and electric field intensity of HVTL.

power towers remain unchanged, the induced current on the surface of power towers and the electric field intensity at the observation point are simulated and solved respectively under the conditions of no ground wire, single ground wire and double ground wires. From the solution, the variation of the maximum magnitude of the induced current on the power tower and the electric field intensity at the observation point at 10 MHz is shown in Fig. 6(a), and the corresponding quantities at 20 MHz are shown in Fig. 6(b).

In Fig. 6(a), for the 10 MHz bands, the induced current on the power tower is the smallest when there is no ground wire, with a minimum value of 244.51 mA/m; the induced current on the power tower is the largest when there are two ground wires, with a maximum value of 248.34 mA/m. The maximum difference in the value of induced current is 1.5%. For the 20 MHz band shown in Fig. 6 (b), the maximum difference in the value of induced current is even smaller, which is 0.53%.

In addition, by analyzing the variation of the electric field intensity at the observation point in Fig. 6, we can see that the maximum differences in electric field intensity at 10 MHz and 20 MHz are, respectively, 0.46% and 0.048%. These results show that whether the ground wire and the tower are insulated in shortwave has little effect on the induced current on the power tower, and the effect of the ground wire on the inter-ference becomes gradually smaller as the frequency increases. This law is consistent with the findings of the reference [7].

Also, it can be seen from Fig. 6 that the electric field intensity at the observation point and the induced current on the power tower follow the same trend when the ground wire changes, which further indicates that the electromagnetic scattered field of transmission lines is mainly influenced by the induced current on the power tower.

B. RESPONSE CHARACTERISTICS FOR LINE SPAN (NUMBER OF POWER TOWERS)

The span of transmission lines and the number of power towers are the same impact factors. For a given length of transmission line, the larger the line span, the fewer power towers, and vice versa. Therefore, to further study whether the transmission line span is the decisive influence factor of the electromagnetic scattering field of the transmission line, the total length of the line is set to 1500 m, 300 m, 375 m, and 500 m are taken as the line span, respectively. The induced current on the surface of the transmission tower and the electric field intensity at the observation point are solved under different spans. Among them, factors such as line ground wire and tower height are kept unchanged. Finally, the maximum magnitude of the induced current on the power tower and the electric field intensity at the observation point at 10 MHz are shown in Fig. 7(a), and the corresponding quantities at 20 MHz are shown in Fig. 7(b).

As shown in Fig. 7, the electric field intensity at the observation points and the induced current on the power tower follow the same trend when the line span changes, and they decrease with the increase of the line span. For Fig. 7(a) in 10 MHz, the induced current on the power tower is the smallest at the line span of 500 m, with a minimum value of 1764 mA/m; the induced current on the power tower is the largest at the line span of 300 m, with a maximum value of 2234 mA/m, and the maximum difference of the induced current is 21.0% when the line span changes. For Fig. 7(b) in 20 MHz, the maximum difference of the induced current is 20.9% when the line span changes. In addition, for the variation of the electric field intensity at the observation point, the maximum differences for the electric field intensity at 10 MHz and 20 MHz are, respectively, 6.3% and 14.4%. These results show that the line span greatly affects the

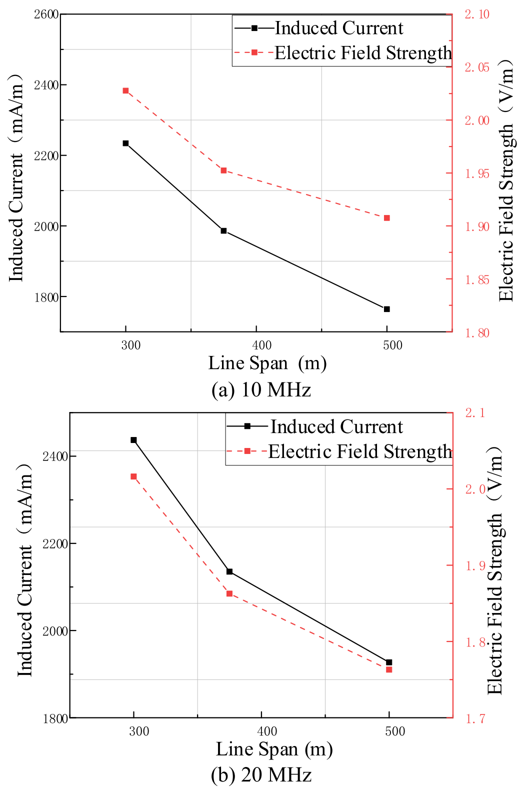


FIGURE 7. Influence of line span on induced current and electric field intensity of HVTL.

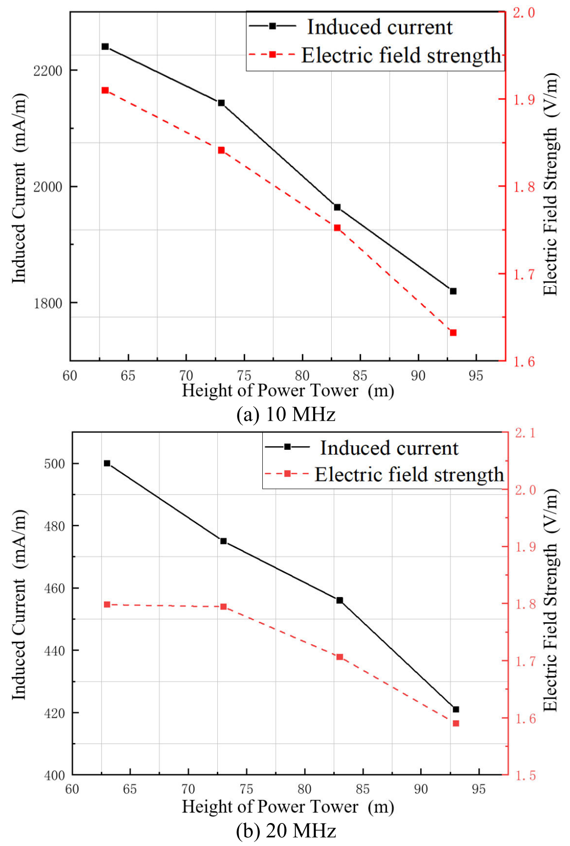


FIGURE 8. Influence of power tower height on the induced current and electromagnetic scattered field of HVTL.

induced current and scattered electric field of transmission lines in shortwave.

C. RESPONSE CHARACTERISTICS FOR THE HEIGHT OF THE POWER TOWER

To study whether the height of a power tower is the decisive impact factor for the electromagnetic scattered field of transmission lines, controlling the ground wire, line span, and the number of power towers remain unchanged, and the induced currents on the power tower are respectively calculated when the height of power tower is 63 m, 73 m, 83 m, and 93 m. Finally, the maximum magnitude of the induced current on the power tower and the electric field intensity at the observation point at 10 MHz are shown in Fig. 8(a), and the corresponding quantities at 20 MHz are shown in Fig. 8(b).

It can be seen from Fig. 8(a) at 10 MHz that the induced current on the power tower is the smallest when the height of power tower is 93 m, with the minimum value of 1821 mA/m; the induced current on the power tower is the largest when the height of power tower is 63 m, with the maximum value of 2236 mA/m, and the maximum difference of the induced current is 18.6% when the height of power tower changes. For Fig. 8(b) at 10 MHz, the maximum difference of the induced current when the height of the power tower changes is 15.8%. In addition, for the variation of electric field intensity at the observation point, the maximum differences of the electric field intensity at 10 MHz and 20 MHz are, respectively, 14.5% and 11.6%. These results show that the height of the power tower greatly influences the induced current and scattered electric field of transmission lines in shortwave.

To further study the shielding and scattering effects of the complex metal structure of the tower head on electromagnetic waves, reduce the height of the tower head to just block the observation point, then set the height variation range of the tower head with the height of 2 m as the center. As shown in Fig. 9, calculate the electric field intensity of the observation point at 10 MHz when the height of the tower head is 0.5 m, 1 m, 1.5 m, 2 m, 3 m, 4 m, and 5 m, respectively, to study the shielding and scattering effects of the tower head on electromagnetic waves, the calculation results are shown in Fig. 10. It should be noted that the height of the tower head is 4.6 m when the height of tower head is less than 2 m, it belongs to the situation that the tower head blocks the observation point (at this time, the electromagnetic wave does not directly pass through the tower body to reach the observation point). Therefore, the calculation and analysis should be carried out at an additional interval of 0.5 m below 2 m to further study the influence of increasing height of the tower head on the electric field intensity at the observation point under the shielding situation.

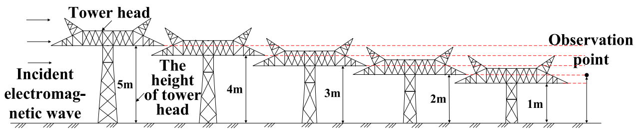


FIGURE 9. Schematic diagram of the relative position of the observation point and the tower head.

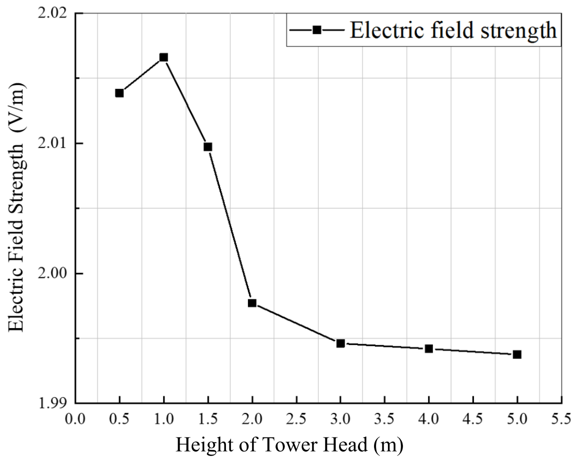


FIGURE 10. The electric field intensity at the observation points changes with the height of the tower head.

It can be seen from Fig. 10 that when the height of the tower head is 1m, that is, the electromagnetic wave is blocked by the tower head, the electric field intensity at the observation point reaches the maximum, while the other heights decrease with the shielding area of the tower head to the electromagnetic wave. The field strength gradually decreases, and the simulation results are consistent with the theoretical analysis. However, on the whole, although the change in tower head height affects the changing trend of electric field intensity at the observation point, it has little effect on the value of electric field intensity. Therefore, it can be considered that the influence of the change in the height of the tower head on the electric field intensity at the observation point is very weak.

V. CONCLUSION

(1) The metal structure of the power tower is the decisive impact factor for the passive interference of transmission lines in shortwave. At the same time, the more tower materials in the sight of electromagnetic waves, the greater the electromagnetic scattered field will be generated.

(2) The influence of body structure characteristics such as ground wire, line span, and tower height on the scattering electric field of transmission lines is studied. The results of the study show that the ground line and tower insulation have little effect on the induced currents on the surface of the transmission tower, the scattered electric field at the observation point is less with the increase of the distance between the transmission line stalls, and the scattered electric field at the observation point decreases with the increase of the height of the transmission tower.

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