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RESEARCH ARTICLE

Research on Electromagnetic Scattering Characteristics of Transmission Tower With Different Tower Types in Short Wave Band Based on the Characteristic Mode Theory

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ABSTRACT This research aims to provide a suitable method to analyze high-frequency electromagnetic scattering from extra-high voltage (EHV) transmission line towers with different tower types using characteristic mode theory (CMT). Different from the traditional idea of passive protection based on spatial avoidance, this method combines the existing electromagnetic scattering and CMT with modal decomposition to decompose the total scattering responses of transmission towers into the superposition of characteristic modal responses through mathematical operators and energy relations. The research realizes the correlation analysis between the structural characteristics of transmission towers and the scattering field variation, which provides ideas for the future application of CMT to analyze the electromagnetic scattering from transmission line towers. In this paper, simulation calculations of different types of towers of EHV transmission lines are carried out, and the simulation results are compared and verified with those of the traditional method of moments (MoM). The results show that the tower structure will affect the electromagnetic scattering intensity, and the characteristic current with a larger weight factor will dominate the degree of electromagnetic scattering influence. Compared with the results of the traditional method, the maximum relative error of the simulation results of three different tower structures does not exceed 3%, which verifies the reliability and validity of the method.

INDEX TERMS Characteristic mode theory, transmission lines tower, electromagnetic scattering characteristics, body structure, induced current.

I. INTRODUCTION

The electromagnetic scattering phenomenon of transmission line towers is an important factor limiting the construction of power grids and radio stations [1]. As the height and density of high-voltage transmission line towers increase, the electromagnetic scattering problem generated by high-voltage transmission line towers is increasingly becoming a dominant factor affecting communication quality [2]. In the natural space coordinate system, as the incident electromagnetic wave (excitation field) changes, the equivalent charged particles of the metal parts on the ground form a new field source, thus presenting the electromagnetic scattering phenomenon of large metal bodies in half-space [3], [4]. In the vicinity of various types of communications, transportation, meteorology, and even some national defense facilities, there may be a situation that affects the work of radio stations and poses a potential threat to economic production and national defense security [5].

In response to the above problems, scholars at home and abroad have conducted extensive research in both numerical calculation techniques and interference protection measures

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for electromagnetic scattering from transmission line towers, respectively. The electromagnetic scattering phenomenon of transmission line towers is the result of the interaction between the electromagnetic waves emitted from the surrounding radio stations and the metal components of transmission towers, and its theoretical basis is the electromagnetic field theory describing the scattering phenomenon of electromagnetic waves [6]. For the problem of solving the scattering characteristics of the large metal tower with complex spatial structure in transmission lines, existing studies have used the electric field integral equation (EFIE) corresponding to the electric large size metal structure body to solve [7]. The Pocklington electric field integral equation corresponding to the linear model of high-voltage transmission towers was first proposed by C.W. Trueman and S.J. Kubina [8], [9]. However, with subsequent research, it was found that the accuracy of its calculation results depends on the closeness of the geometric model to the actual line and that the cross-sectional dimensions of the tower are not negligible compared to the wavelength of the electromagnetic wave as the frequency of the electromagnetic wave increases [9], [10]. Later, Tsinghua University and China Electric Power Research Institute proposed a line model considering the spatial structure of the tower, respectively [5], [11]. However, this tower line model was too rough to reflect the induced currents uniformly distributed on the surface of the tower, which eventually resulted in its limited frequency applicability [12], [13]. Then, in order to solve the problem of electromagnetic scattering calculation at higher frequencies, Three Gorges University proposed a geometric model of the tower surface based on the integral equation of the electric field [14], [15]. However, in the solution process of the method of moments (MoM), the solution accuracy of the integral equation depends on the discrete degree of the induced current on the conductor surface [16]. As the electric size of the transmission tower electromagnetic scattering increases dramatically, it leads to a rapid increase of unknown quantities after the matrix equation discretization, which eventually makes the model calculation time too long [17], [18]. The existing research gives the range limitation of model size and applicable frequency, and it is also worth noting that various numerical calculation methods are always limited to the ideological framework of discretized solution of electric field integral equation, resulting in the inability to understand the influence mechanism of such ontological characteristics of transmission tower space structure on electromagnetic scattering in actual engineering, which seriously hinders the current power grid construction and normal work of powerless stations [19], [20].

In this paper, an analysis method of electromagnetic scattering from transmission towers based on the characteristic modes theory (CMT) is proposed for solving the electromagnetic scattering problem of transmission towers to the surrounding radio stations. Compared with traditional methods, the proposed method in this paper has three major advantages, including:

i. This method breaks through the technical bottleneck of the traditional mesh discretization numerical solution method, to have a more intuitive understanding of the meaning of the physical aspects of the electromagnetic scattering law of power transmission tower.
ii. The CMT is used to decompose the total scattering response of the transmission tower into the superposition of individual characteristic mode responses, and to realize the correlation analysis between the structural characteristics of the tower body and the scattering field variation.
iii. It changes the passive protection idea of traditional space avoidance type method and provides the theoretical basis for future application of CMT to analyze electromagnetic scattering from transmission line towers.

The method also faces some challenges in the process of applying the numerical computation of CMT. In the process of solving the eigenvalue equation, the method has some limitations in terms of the size of the study model, computa-tional complexity, material discontinuities, excitation sources limitations and frequency dependency of characteristic modes. These aspects mentioned above will affect the computational speed and accuracy of the method to some extent. Therefore, it is necessary to adjust the simulation settings according to the actual hardware conditions. This is also the main challenge of CMT at present.

To verify the method, three different tower types of transmission line towers are studied in this paper. In contrast to the traditional passive protection method of spatial avoidance, the new method can correct the electromagnetic scattering characteristics by actively optimizing the characteristic currents. The simulation results for each type of tower are within the acceptable error range, verifying the validity and accuracy of the method.

The remaining parts of this paper are organized in the following pattern. In Section II, the CMT theory is briefly introduced to draw out the main innovation points of this paper. In Section III, the core theory of the proposed method for active protection against electromagnetic scattering from transmission towers and the technical route are described in detail. Section IV verifies the proposed method with electromagnetic simulation software. Some discussions on the proposed method and results are presented in Section V. Some conclusions are drawn in Section VI.

II. BASIC CMT AND TECHNICAL IDEAS

In recent years, in the field of antenna engineering, CMT is applied to the analysis of radiation scattering problems of antennas to guide antenna design [21], [22], [23]. CMT has two outstanding features that other numerical analysis methods do not have:

a) It is the characteristic mode analysis that clearly shows the current distribution of the antenna structure in the case of unexcited source, thus providing the possibility of optimal design of antenna feed.

b) In the case of unexcited source, the characteristic mode parameters (eigenvalues, eigencurrents, etc.) reveal the resonant characteristics of the antenna. These two features provide a basis for predicting the radiation potential of the antenna and then for the comprehensive design of the antenna structure, so now CMT has become one of the mainstream choices for antenna systematization analysis and design [24], [25], [26].

In fact, from the time-varying electromagnetic field theory, the incident electromagnetic wave (excitation field) emitted by the radio station will produce an induction electromotive force on the surface of the metal parts of the transmission tower with a positive correlation with the excitation field strength, and this induction electromotive force will excite an alternating induction current on the metal surface. The alternating induced current emits a scattered field to the external space at the same frequency as the excitation field, thus causing interference to the received signal of the radio station.

Therefore, in a sense, the metal parts of transmission towers can be equated to large and complex antenna com-ponents under the excitation of external electromagnetic fields. In this way, CMT can be applied to analyze the induced currents on the surface of transmission towers, and then study the scattering field variation law to realize the correlation analysis between the structural characteristics of transmission line tower and the scattering field variation.

III. DESIGN METHOD

As is well known, the kernel of the CMT is the generalized eigenvalue equation given by the following equation:

$$\boldsymbol{X}\boldsymbol{J_n} = \lambda_n \boldsymbol{R}\boldsymbol{J_n} \tag{1}$$

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

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

where $\boldsymbol{R}$ and $\boldsymbol{X}$ are real symmetric matrices, and $\boldsymbol{R}$ is theoretically semi-positive definite.

According to CMT, the solution of any electromagnetic field problem can be expressed as a linear combination of characteristic modes that are orthogonal in the source and field regions, respectively, expressing the inherent electromagnetic properties of the object [27], [28], [29]. Therefore, the impedance matrix is considered to relate the induced currents to the electric fields they generate. Moreover, the eigenfunctions all satisfy orthogonality, and it can be considered that these eigenfunctions correspond to the eigencurrents. Thus, the induced currents on the transmission tower surface are defined as a series of eigencurrents with weighting factors and orthogonal expansions [30]. The eigencurrent $\boldsymbol{J_n}$ is normalized according to (3), and it satisfies the orthogonality property (4)-(6) in the source region, including the orthogonality of the polarization characteristics and the amplitude orthogonality.

$$\langle \boldsymbol{J_n}, \boldsymbol{R}\boldsymbol{J_n} \rangle = 1 \tag{3}$$

$$\langle \boldsymbol{J_m}, \boldsymbol{R}\boldsymbol{J_n} \rangle = \langle \boldsymbol{J_m^*}, \boldsymbol{R}\boldsymbol{J_n} \rangle = \delta_{mn} \tag{4}$$

$$\langle \boldsymbol{J_m}, \boldsymbol{X}\boldsymbol{J_n} \rangle = \langle \boldsymbol{J_m^*}, \boldsymbol{X}\boldsymbol{J_n} \rangle = \lambda_n \delta_{mn} \tag{5}$$

$$\langle \boldsymbol{J_m}, \boldsymbol{Z}\boldsymbol{J_n} \rangle = \langle \boldsymbol{J_m^*}, \boldsymbol{Z}\boldsymbol{J_n} \rangle = \left(1 + j\lambda_n\right) \delta_{mn} \tag{6}$$

where

$$\delta_{mn} = \begin{cases} 1, & m = n \\ 0, & m \neq n. \end{cases}$$

Mathematically, each group of eigencurrent is a full-domain basis function over the entire scatterer surface and orthogonal to each other, and the scattered field of the transmission tower can be characterized as a weighted linear sum of the eigenfields. In this way, the electromagnetic scattering field variation law of the transmission tower can be transformed into the study of the eigencurrent.

Then, dividing (5) by (4), it is easy to obtain the following equation:

$$\lambda_n = \frac{\langle \boldsymbol{J_n^*}, \boldsymbol{X}\boldsymbol{J_n} \rangle}{\langle \boldsymbol{J_n^*}, \boldsymbol{R}\boldsymbol{J_n} \rangle} \tag{7}$$

Thus, from (7) we can obtain the physical meaning of the eigenvalue λ_n as follows:

the eigenvalue λ_n represents the ratio between stored energy and radiation energy.

- When λ_n is zero, the magnetic field energy storage is equal to the electric field energy storage and the characteristic mode is resonant.
- When λ_n is greater than zero, the magnetic field energy storage is greater than the electric field energy storage, and the characteristic mode is inductive.
- When λ_n is less than zero, the magnetic field energy storage is less than the electric field energy storage, and the characteristic mode is capacitive.

Therefore, the study of eigenvalues can analyze the transmission tower electromagnetic scattering resonance phenomenon from the perspective of electromagnetic energy conversion.

However, analyzing only the variation of eigenvalues cannot be combined with the ontological characteristics of transmission towers such as shape and size, so a correlation coefficient is needed to represent the contribution of the characteristic currents of different tower structures to the total induced current. The characteristic modes are a special set of orthogonal modes that can be used to unfold any induced current of the excitation source on the object [31], [32], [33]. That is, the induced current on a metallic body can be unfolded as a linear superposition of the metallic body characteristic modes as follows:

$$\boldsymbol{J} = \sum_n \alpha_n \boldsymbol{J_n} \tag{8}$$

where $\boldsymbol{J}$ is the induced current on a metallic body. α_n is the Modal Weighting Coefficient (MWC), which can be represented as:

$$\alpha_n = \frac{\left\langle \boldsymbol{E}^i_{\tan}(\boldsymbol{r}), \boldsymbol{J}_n \right\rangle}{1 + j\lambda_n} \tag{9}$$

where the inner product on the right numerator of the equation represents the energy coupling between the external excitation source and each mode, called the Modal Excitation Coefficient (MEC), whose coupling is related to the position, the irradiance, phase, and polarization mode of the excitation source. The denominator on the right side of the equation can be used to define Modal Significance (MS), as shown in equation (10).

$$\text{MS} = \left| \frac{1}{1 + j\lambda_n} \right| \tag{10}$$

MS and λ_n are inherent properties of each mode independent of the excitation source and represent the energy coupling capability of each mode to the external excitation source. The resonance characteristics of the target object over a wide frequency band can be observed more clearly using MS.

In this paper, we need to judge and filter the characteristic modes in the simulation Mode Bandwidth (MBW) of the tower. Finally, the characteristic modes that have a significant effect on the electromagnetic scattering from the tower are selected for comparison and verification. The MBW equation is as follows:

$$\text{MBW} = \frac{f_H - f_L}{f_{res}} \tag{11}$$

where f_{res}, f_H, and f_L are the mode resonant frequency, the high end frequency of the band, and the low end frequency of the band, respectively, and satisfy the following equation:

$$\text{MS}(f_{res}) = 1 \tag{12}$$

$$\text{MS}(f_H) = \text{MS}(f_L) = \frac{1}{\sqrt{2}} \tag{13}$$

From (13), it can be seen that a particular mode meets MS not less than 0.707 in the corresponding mode bandwidth, then the mode is said to be significant. Conversely, when MS is less than 0.707, the mode is said to be non-significant.

Combining the λ_n, MS and MWC results, the magnitude of the contribution of each mode to the total electromagnetic response under the characteristic excitation conditions can be measured. When a transmission tower is affected by a specific excitation source, the induced current on the surface of the tower can be expanded using the eigencurrent as a basis function to obtain a matrix equation of the eigencurrent and the scattered field containing weighted coefficients, thus realizing a mathematical characterization of the induced current based on the weighted eigencurrent. Therefore, the larger the value of α_n taken, the greater the proportion of the corresponding eigencurrent in the total current. Changing the transmission tower body characteristics and optimizing the eigencurrent can correct the electromagnetic scattering characteristics of the transmission line tower.

Finally, the maximum relative error between CMT and MOM simulation results is calculated according to Equation (14), so as to verify the reliability and accuracy of the method.

$$Er_{max} = \left| \frac{f_{resc} - f_{resm}}{f_{resm}} \right| \tag{14}$$

where Er_{max}, f_{resc} and f_{resm} are the maximum relative errors of the method used in this paper and the MoM standard solution, the resonant frequency point of the simulation calculated by the CMT solution and the frequency point corresponding to the maximum value of the surface current calculated by MoM, respectively.

IV. NUMERICAL VERIFICATIONS

For the choice of tower model, transmission line towers are generally divided according to their shape: wine glass type, cat head type, top type, dry type and barrel type five. Their structure is characterized by various tower types are space bracket structures, the tower is mainly composed of a single equilateral angle or combination of angle steel. In this paper, considering the rapid development of China's power grid construction, three common tower types are selected, which have certain universality. The specific model parameters are shown in the following subsections.

The frequency range of the shortwave band is 3-30 MHz. According to our signal safety regulation and the relevant regulations of the national defense army, the frequency range of this study simulation is 5-10 MHz.

In previous studies, [34], [35] investigated the influence of the ground on electromagnetic interference calculations. They concluded that considering the absorption loss of the ground for incident electromagnetic waves, the calculated electromagnetic interference level is smaller than the actual one, while it has some influence on the prediction of resonant frequency. If the ground is an ideal conductor, the calculated electromagnetic interference level will be larger than the actual one, but the resonant frequency corresponding to the model can be predicted accurately. Therefore, the models used in this study assume that the ground is the Perfect Electric Conductor (PEC).

Since the polarization characteristics of radio waves depend on the polarization characteristics of the antenna system. The receiving antenna must have the same polarization and rotation characteristics as the transmitting antenna, so as to achieve polarization matching and thus receive the entire energy. If the polarization does not match (such as one vertical and the other horizontal), the received energy will be greatly attenuated. Since the simulated tower model in this paper can be considered as a vertical metal grounded body, we consider the case where the radio wave signal is most severely interfered by the tower in our simulation. The incident wave electric field intensity direction in this case is perpendicular to the ground. Therefore, the vertically polarized electro-magnetic wave is chosen as the incident wave in the simulation. The calculation uses the idea of normalization, setting the excitation electromagnetic field strength of 1 V/m. The incident wave is emitted from the transmitting antenna of the radio signal station, and is incident at an angle of φ with the positive direction of the x-axis, to study the electro-magnetic scattering intensity of the transmission tower at this time.

In the numerical calculation of characteristic modes, the number of characteristic modes is closely related to the number of RWG meshes for model dissection. As the frequency of the simulation gradually increases, the more detailed the triangular cells segmented on the model, the greater the number of characteristic modes eventually calculated. Since the simulation model in this paper belongs to large size metal body. The simulation frequency band is high frequency. The number of RWG after meshing the simulation model has reached thousands. Due to the functional limitations of the simulation hardware equipment, it is not possible to analyze such a large number of characteristic modes all together. The MS value reflects the intensity of electromag-netic scattering from the simulated tower. The MS value tends to be infinitely close to zero indicating that the effect on electromagnetic scattering is negligible. Ignoring the characteristic modes whose MS value tends to zero infinitely not only improves the computational speed but also narrows the scope of analysis of the model characteristic modes.

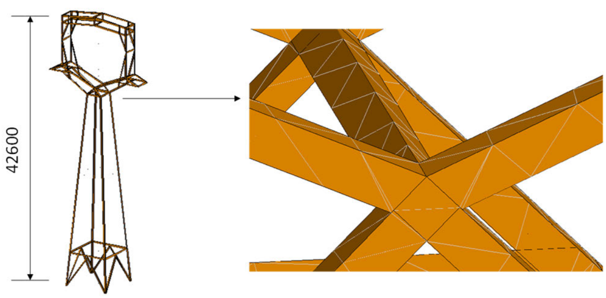

FIGURE 1. **Cathead tower model and tower head internal details. (Unit: mm).**

TABLE 1. **Cathead tower simulation setup.**

Setting object	Simulation setup details
Simulation tower type	Self-supporting linear tower (T500ZM)
Voltage level	500 kV
Tower height	42.6 m
Cross-stretcher width	16 m
Number of profiles	3696 RWG edge elements
Simulation band	5-10 MHz
Frequency step size	0.1 MHz

A. CATHEAD TRANSMISSION TOWER

The first transmission tower model (Cathead Tower, T500ZM) studied in this paper and its internal detail diagram of the tower head are shown in Figure 1. This type of tower is a self-supporting linear tower with a voltage level of 500 kV, a tower height of 42.6 m, a cross-stretcher width of 16 m. The simul-ation model is meshed into 3696 Rao-Wilton-Glisson (RWG) edge elements. The band range considered for the simulation is 5 to 10 MHz with a frequency step of 0.1 MHz. The specific details of the simulation setup are shown in Table 1.

In addition, when studying the electromagnetic scattering characteristics of the inherent structure of this tower, the mode significance and energy conversion law of each characteristic mode is analyzed without considering the specific excitation because the characteristic modes are independent of the excitation source. The calculated eigenvalues and mode significance curves for the first six characteristic modes are shown in Figure 2. It can be observed that the electromagnetic scattering resonance phenomenon of the transmission tower at this time, three characteristic modes (1, 3 and 6) resonate respectively, and they are marked by the red circles at 5.5, 8.3 and 9 MHz, and the eigenvalues of these three characteristic modes are zero and the MS values reach the peak at this time. The characteristic modes are judged and filtered according to Equation (13). This means that the characteristic modes 1, 3 and 6 play a major radiating role in the simulated frequency band, while the rest of the characteristic modes do not have a significant radiating role. In addition, the energy transformation law of transmission towers can be studied according to the eigenvalues. The electromagnetic energy storage reflected by the eigenvalues is described in detail in Chapter III and will not be repeated here. However, the analysis of the eigenvalue and MS can only study the inherent characteristics of the tower electromagnetic scattering, but not a comprehensive study of the shape, structure and size of the ontological characteristics of electromagnetic scattering influence law.

TABLE 2. **MWC for each characteristic mode at 8.2MHz.**

Characteristic mode	Modal Weighting Coefficient
1	1.14E-05
2	4.04E-07
3	1.23E-04
4	3.20E-03
5	1.38E-06
6	8.55E-01

Next, the study is continued with the method proposed in this paper. Firstly, the mathematical model of electromagnetic scattering from the transmission tower is established, as shown in Figure 3. The tower is located at the coordinate origin. Since the tower can be viewed as a vertical metal grounded body, the vertical polarized plane electromagnetic wave ($\varphi = 0°$) is used to apply excitation to the model considering the most serious signal interference from the tower to the wireless station. The calculation uses the normalization idea and sets the electric field strength of the excitation

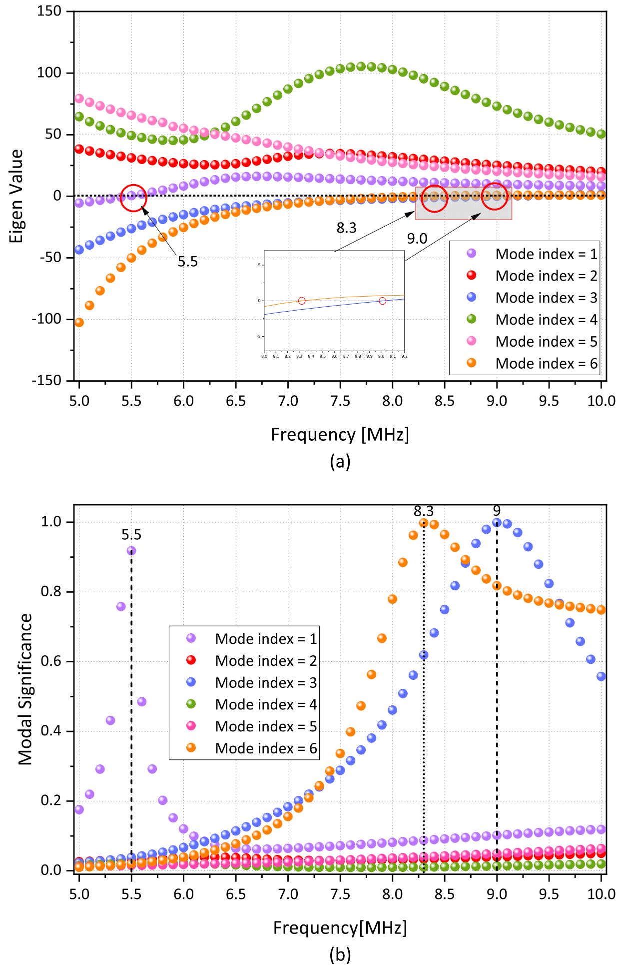

FIGURE 2. Calculated eigenvalues and modal significance of 5-10 MHz transmission towers in the absence of excitation source. (a) Eigenvalue. (b) Modal significance.

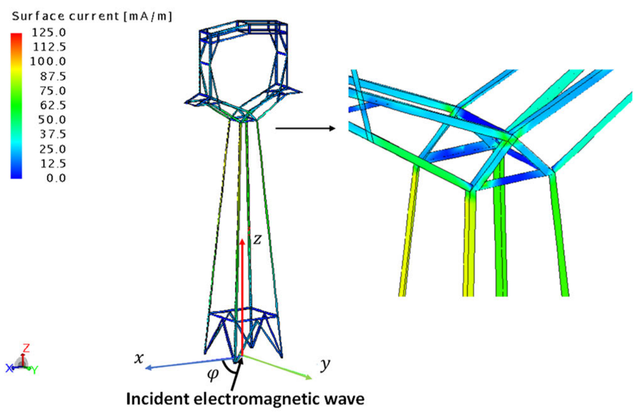

FIGURE 3. Cathead tower simulation mathematical model and its surface induced current distribution (including local enlargement).

electromagnetic wave to 1 V/m. The excitation electromagnetic wave is incident at an angle of φ with the positive direction of the x-axis, and the variation law of MWC with frequency of the transmission tower is calculated at this time,

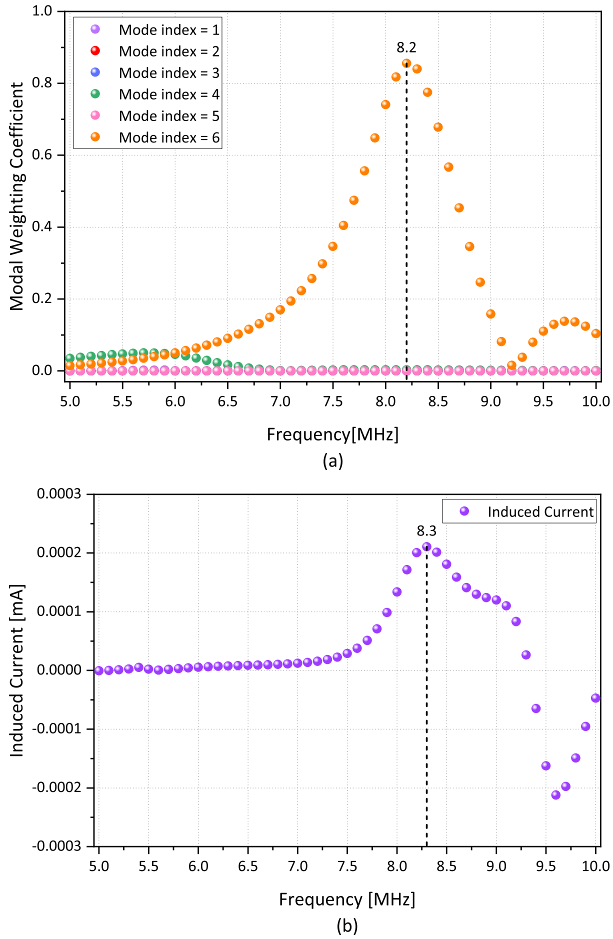

FIGURE 4. (a) MWC of the cathead tower. (b) Surface induced current calculated by MoM.

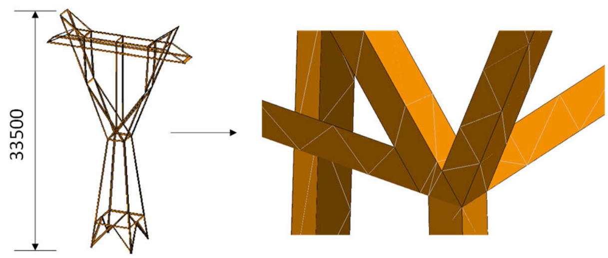

FIGURE 5. Wine glass tower model and tower head internal details. (Unit: mm).

and the induced current on the surface of the transmission tower is calculated by the MoM, as shown in Figure 4 (a)-(b). Table 2 shows the MWC at 8.2 MHz for each characteristic mode after being influenced by the excitation source. According to Table 2 and Figure 4 (a), it is clear that the weight coefficient of characteristic mode 6 after being influenced by the excitation electromagnetic wave reaches a peak at 8.2 MHz in the test band with a value as high as 0.855. On the contrary, the MWC of the remaining characteristic modes is relatively low. Clearly, this indicates that characteristic

TABLE 3. **Wine glass tower simulation setup.**

Setting object	Simulation setup details
Simulation tower type	Self-supporting linear tower (T500ZB)
Voltage level	500 kV
Tower height	33.5 m
Cross-stretcher width	23.6 m
Number of profiles	3634 RWG edge elements
Simulation band	5-10 MHz
Frequency step size	0.1 MHz

mode 6 has the greatest correlation with the electromagnetic scattering from this transmission tower throughout the test band. Then, the comparison is verified with MoM, and it can be seen by Fig. 4 (b) that the resonant frequency and the maximum value of surface induced current of this transmission tower occur at 8.3 MHz. The error calculation is performed according to Equation (14). The maximum relative error of the calculation results of the two methods is about 1.21 %, which verifies the reasonableness and reliability of the proposed method. Therefore, if the characteristic current of characteristic mode 6 at 8.2 MHz can be suppressed, the overall electromagnetic scattering effect of this transmission tower can be reduced, as described in Section III.

B. WINE GLASS TRANSMISSION TOWER

The second type of transmission tower under study is a wine glass tower, and the tower model and internal details of the tower head are shown in Figure 5. The transmission tower is a self-supporting linear tower (T500ZB) of voltage level 500 kV with a tower height of 33.5 m and a cross-stretcher width of 23.6 m. The simulation model is meshed into 3634 RWG edge elements. The simulation frequency range is 5-10 MHz with a step size of 0.1 MHz. The specific details of the simulation setup are shown in Table 3.

Figure 6(a) shows the calculated eigenvalues of the first 6 characteristic modes of the wine glass tower without a specific excitation source, and the part from 8.5 to 9.0 MHz has been scaled up for clarity. It can be clearly observed that the modes become more and more crowded as the frequency increases, and there are more cross-mode pairs (characteristic modes cross and overlap with each other) in the higher frequency bands. In addition, the resonance characteristics and energy conversion pattern of the tower can be seen. A total of three characteristic modes produce resonance in the tested frequency band, namely modes 1, 2 and 3. The resonant frequencies are 5.7, 8.7 and 8.8 MHz, in that order, when the magnetic energy stored in the transmission tower is equal to the electrical energy. The electromagnetic energy storage reflected by the eigenvalues is described in detail in Chapter III and will not be repeated here.

The MS of the intrinsic structure of the tower can also be observed in conjunction with Figure 6 (b). The characteristic modes are judged and filtered according to Equation (13).

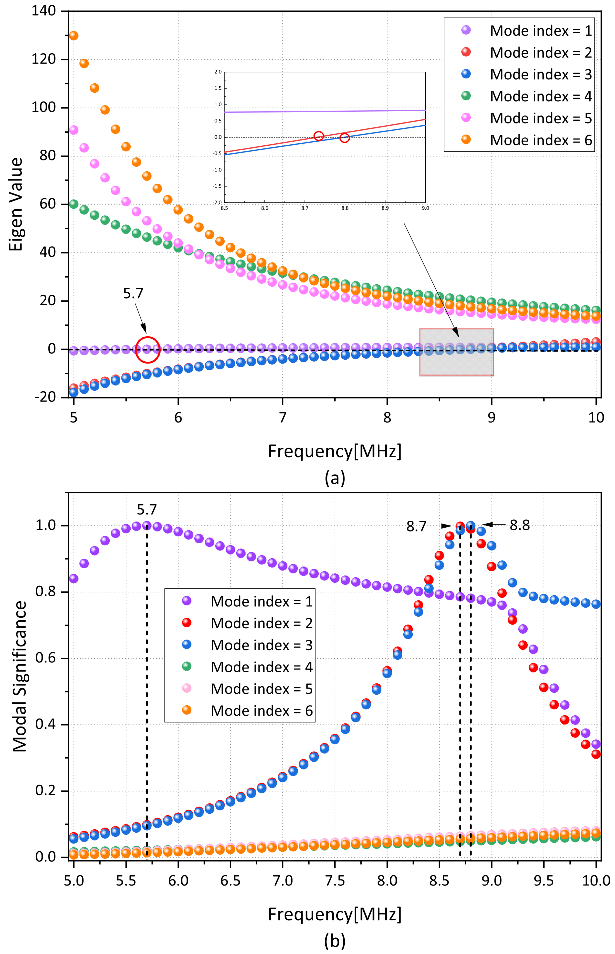

FIGURE 6. **Eigenvalues and MS calculated by the characteristic mode method for the wine glass tower in the absence of excitation source. (a) Eigenvalues. (b) Modal significance.**

TABLE 4. **MWC for each characteristic mode at 8.5MHz.**

Characteristic mode	Modal Weighting Coefficient
1	7.03E-04
2	2.16E-01
3	3.15E-04
4	6.57E-05
5	2.86E-04
6	6.71E-02

Within 5.0-8.3 MHz, mode 1 is the significant mode and plays a major radiative role for electromagnetic scattering. As the frequency increases, modes 2 and 3 increase their radiative power. Within the 8.3-9.3 MHz band, modes 1, 2 and 3 are the same significant modes and play a major radiative role. However, in the 9.3-10 MHz band, the frequency continues to rise, mode 1 and 2 radiation capacity weakens, leaving only mode 3 as a significant mode, playing a major role in electromagnetic scattering radiation. The rest of the characteristic modes are relatively weak in radiation ability in the test band.

Next, considering the case where the tower is most severely disturbed by radio signals, a 1V/m vertically polarized plane wave is applied to the wine glass tower using the normalization idea to study the influence law of this tower structure on electromagnetic scattering. Firstly, the mathematical model of electromagnetic scattering from the wine glass tower is established, as shown in Figure 7. The tower is located at the coordinate origin, and the excited electromagnetic wave is incident at an angle φ $=0^{\circ}$ with the positive direction of the x-axis. The variation law of MWC with frequency is calculated for this tower, and the surface induced current of this tower is used to compare the simulation with MoM, as shown in Fig. 8(a)-(b). Table 4 records the MWC of each eigenmode at 8.5 MHz after being influenced by the excitation electromagnetic wave. From Table 4 and Figure 8(a), it can be seen that the weight coefficient of the eigenmode 2 after being excited by the electromagnetic wave peaks at 8.5 MHz in the test band with a value of 0.216, and the MWC of the remaining modes is relatively low. Obviously, this indicates that mode 2 has the greatest degree of influence on the electromagnetic scattering from this structural tower and the rest of the modes have less influence.

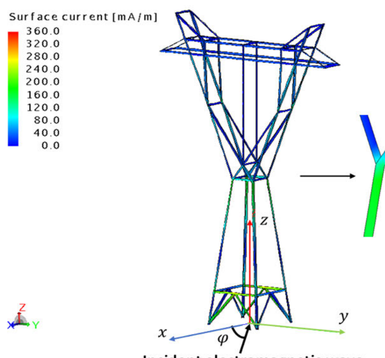

FIGURE 7. Wine glass tower simulation mathematical model and its surface induced current distribution (including local enlargement).

Thereafter, comparing with the results in Fig. 8(b), the maximum values of resonant frequency and surface induced current calculated by MoM appear at 8.4 MHz. The error calculation is performed according to Equation (14), and the maximum relative error of the results of the two methods is about 1.17 %, which again verifies the validity and reliability of the proposed method. Therefore, if the characteristic current of mode 2 at 8.5 MHz can be actively suppressed after the wine glass tower is affected by this excitation electromagnetic wave, the overall electromagnetic scattering effect of the transmission tower can be reduced.

C. DRYING TRANSMISSION TOWER

To compare the degree of electromagnetic scattering effects of the tower with different structures, the third transmission tower studied in this paper is a drying tower, and the tower model and internal details of the tower head are shown in Figure 9. This transmission tower is a self-supporting linear tower (T500ZG) with voltage level 500 kV, tower height 50.5m, cross-stretcher width 40.8 m. The simulation model is meshed into 3455 RWG edge elements. The simulation frequency band is set to 5-10 MHz. The frequency step is set to 500 kHz, different from parts A and B in Section IV, to increase the calculation points and thus improve the calculation accuracy. The specific details of the simulation setup are shown in Table 5.

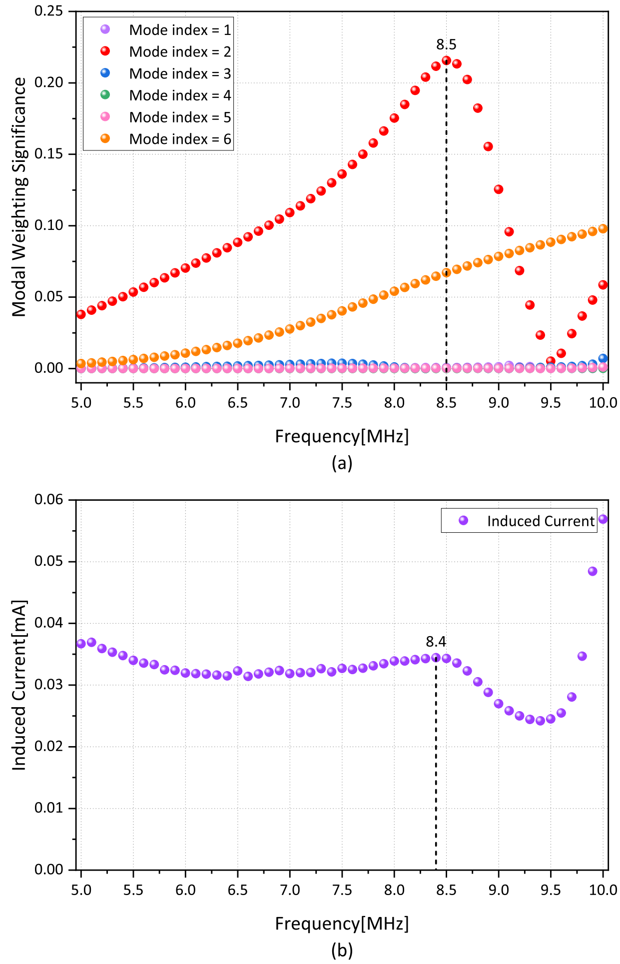

FIGURE 8. (a) MWC of the wine glass tower. (b) Surface induced current calculated by MoM.

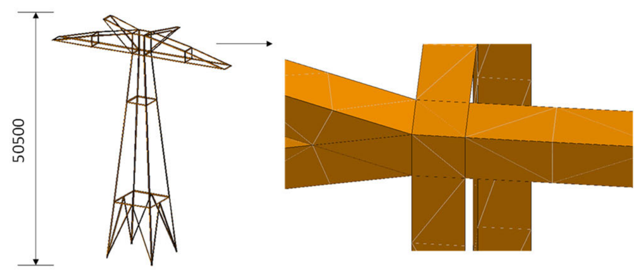

FIGURE 9. Drying transmission tower model and tower head internal details. (Unit: mm).

Figure 10 (a)-(b) shows the variation pattern of eigenvalues and MS with frequency for the first 6 eigenmodes of the drying tower without the influence of the excitation source, and the results in the 6.7-7.0 MHz band are enlarged for a better observation of the eigenvalues. The resonance characteristics and energy transformation law of the drying tower can be seen, with modes 1, 3 and 6 producing resonances, respectively, marked by the red circles in the figure. The resonant frequency points correspond to 6.35, 6.85 and 8.85 MHz, respectively. at this time, the eigenvalue is zero, the MS curve of the characteristic mode reaches its maximum value, and the electrical energy stored in the drying tower is equal to the magnetic energy. The electromagnetic energy storage reflected by the eigenvalues is described in detail in Chapter III and will not be repeated here. Moreover, according to Equation (13) and Fig. 10 (b), modes 1, 3 and 6 have the greatest effect on electromagnetic scattering in the tested frequency band, and this result is only for the intrinsic structure of the drying tower without excitation source. Therefore, further simulations are needed to analyze the electromagnetic scattering characteristics under the influence of electromagnetic wave excitation.

TABLE 5. Drying tower simulation setup.

Setting object	Simulation setup details
Simulation tower type	Self-supporting linear tower (T500ZG)
Voltage level	500 kV
Tower height	50.5 m
Cross-stretcher width	40.8 m
Number of profiles	3455 RWG edge elements
Simulation band	5-10 MHz
Frequency step size	500 kHz

TABLE 6. MWC for characteristic mode at 6.3 and 8.55 MHz.

Characteristic mode	MWC at 6.3MHz	MWC at 8.55MHz
1	1.66E+00	3.10E-02
2	2.24E-06	2.00E-05
3	1.32E-01	1.00E+00
4	1.06E-05	1.54E-06
5	1.20E-06	4.17E-06
6	2.10E-05	2.77E-05

Then, the mathematical model of electromagnetic scattering from the drying tower is established, as shown in Figure 11. The tower is located at the coordinate origin, and since the tower can be seen as a vertical metal grounded body, the vertical polarized plane electromagnetic wave is used to apply excitation to the model considering the most serious signal interference from the tower. According to the normalization idea, the excitation electromagnetic wave field strength is set as 1V/m, and the angle of incidence with the positive direction of x-axis is $\varphi = 0°$. The MWC variation law with the frequency of the tower is analyzed in this case, and the induced current and resonant frequency points on the surface of the tower are calculated by MoM, as shown in

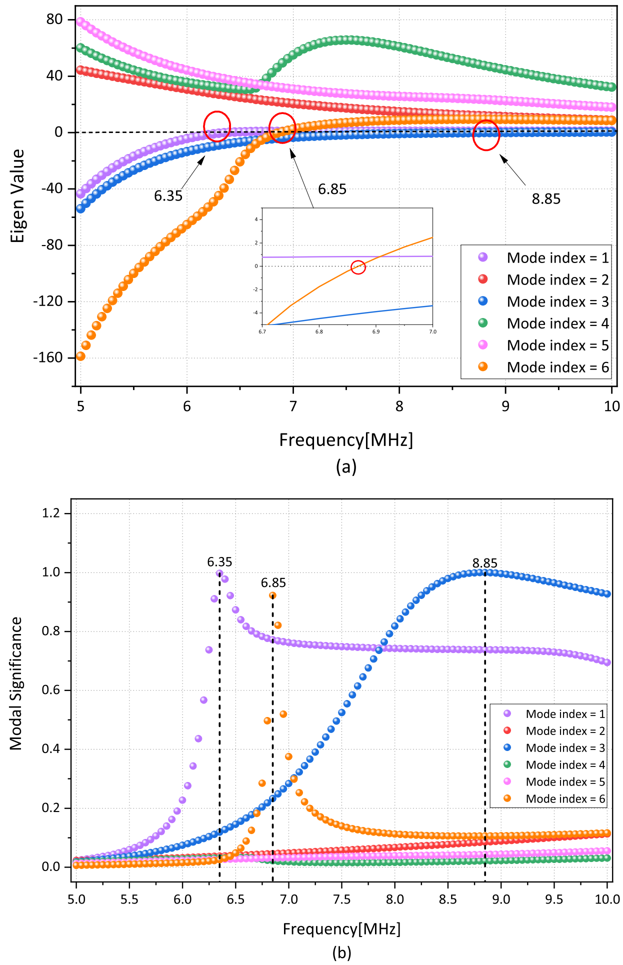

FIGURE 10. **Eigenvalues and MS calculated by the characteristic mode method for the drying transmission tower in the absence of excitation source. (a) Eigenvalues. (b) Modal significance.**

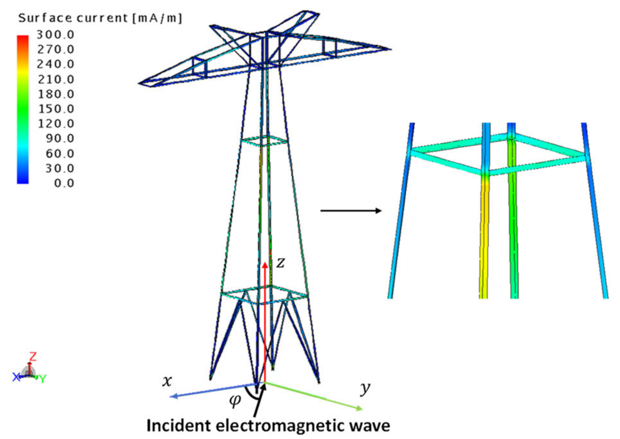

FIGURE 11. **Drying tower simulation mathematical model and its surface induced current distribution (including local enlargement).**

Figs. 12(a)-(b). Table 6 shows the MWC for each characteristic mode of this tower at 6.3 and 8.55 MHz, respectively.

According to Table 6 and Figure 12(a), the peak frequency points of the MWC curves occur at 6.3 and 8.55 MHz with values of 1.66206 and 1.00118, respectively. Therefore, modes 1 and 3 play the main radiation role after the tower is excited by the vertical polarization plane wave, and the remaining modes have low correlation with the tower electromagnetic scattering. By comparing with the MoM calculation results in Fig. 12(b), the resonant frequency and surface induced current maxima of this transmission tower occur at 6.45 and 8.65 MHz. The error calculation is performed according to Equation (14). The errors of the results of the two methods are 2.32 % and 1.15 %, which again verify the reasonableness and validity of the method. Therefore, the degree of the overall electromagnetic scattering influence of the drying tower can be reduced if the characteristic currents of mode 1 at 6.3 MHz and mode 3 at 8.55 MHz can be actively suppressed after being influenced by the excitation electromagnetic waves.

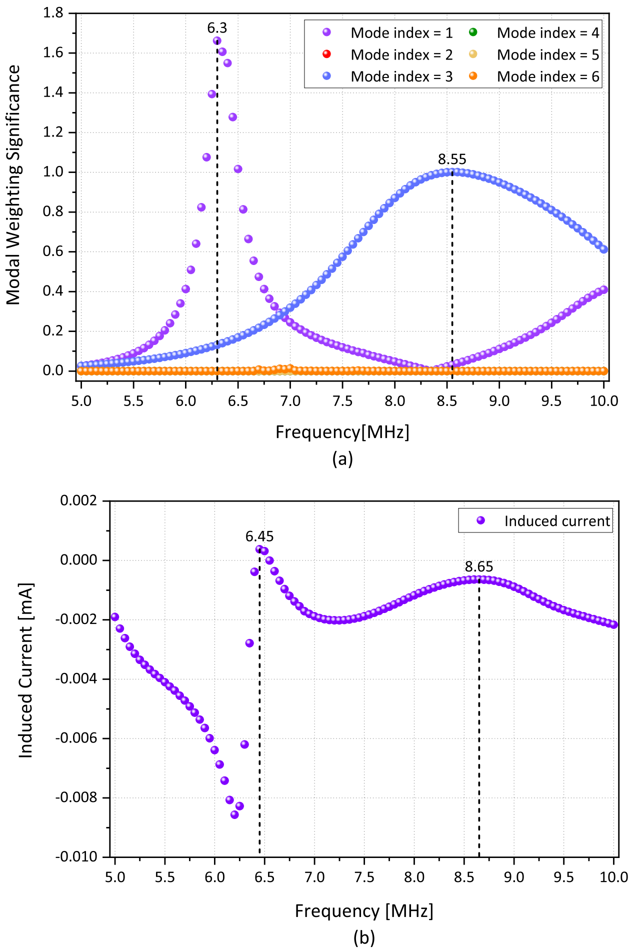

FIGURE 12. (a) MWC of the drying tower. (b) Surface induced current calculated by MoM.

V. DISCUSSION

The proposed method shows good performance in analyzing the electromagnetic scattering problem from transmission line towers to neighboring radio stations. In traditional engineering problems, the corresponding spatial avoidance measures are generally proposed by analyzing the spatial field strength variation law. However, this traditional method is too sensitive to the unknown quantity and size degree after the grid discretization, which can lead to a passive situation of electromagnetic scattering protection. Compared with previous works, the proposed method in this paper decomposes the total electromagnetic scattering response of transmission line tower by mode decomposition through characteristic modes theory to reveal the variation law of electromagnetic scattering from physical essence.

TABLE 7. Simulation equipment hardware information.

Hardware Equipment	Detailed Information
Computer Model	MSI GS65 Stealth 95E
Operating System	Windows 10 (x64)
Central Processing Unit	Intel Core i7-9570H
Random Access Memory	16 GB
Graphic Processing Unit	NVIDIA GeForce RTX 2060

TABLE 8. Simulation of time and RAM usage for each tower type.

Tower type	Time (min)		RAM Usage (MByte)	
	CMT	MoM	CMT	MoM
Cathead tower	39	51	192.1	203.3
Wine glass tower	31	48	186.4	197.2
Drying tower	27	42	181.2	193.3

The error of the three transmission tower simulation calculation results in Section IV mainly comes from the amount of the contribution of the resonance-generating characteristic modes to the radiation in the total electromagnetic scattering. The higher MWC, the more contribution, the smaller error with the MoM calculation results, and the greater impact on the total electromagnetic scattering field of the transmission tower. However, it should be mentioned that, as with other numerical tracking methods, the complexity of the proposed method will increase with the number of tracking modes. Although we apply the CMT method of studying small antennas to large transmission towers, change the traditional passive protection idea of electromagnetic scattering from transmission towers, and verify the correctness and feasibility of the method by comparison. However, the ground has a certain degree of influence on the electromagnetic environment, and it is necessary to take the ground factor into consideration and conduct in-depth research in the future. In addition, the method adjusts the frequency step in Section IV-C. This allows for accuracy tuning according to actual engineering needs, with some adaptability and flexibility in step size and grid size. The hardware details of the simulation equipment are shown in Table 7. The time and random access memory (RAM) usage for simulating each tower type is shown in Table 8. The simulation times for CMT and MoM on the cathead tower are 39 minutes and 51 minutes, respectively. Under the same simulation conditions, the simulation times are 31 min (CMT) and 48 min (MoM) for the wine glass tower, and 27 min (CMT) and 42 min (MoM) for the dry word tower, respectively. This means that if larger frequency steps and grids are used, there will be substantial savings in computational time costs.

The results of this paper can be used in the design process of power transmission towers to give a theoretical basis for the structural design of towers. Considering that the structure of transmission towers is determined by a combination of factors. For the already built transmission towers, the analysis results of CMT can be used first, while adding other methods (such as insulated cross-arms, installation of magnetic rings, etc.) to suppress electromagnetic scattering from transmission towers. The development of more effective active protection measures is the next research direction for us to fundamentally solve the electromagnetic scattering from transmission towers.

VI. CONCLUSION

Rather than the traditional method of analyzing the electromagnetic characteristics of transmission line towers, this paper proposes an analysis method based on the CMT.

- By analyzing the tower eigenvalues and the MWC, thus clarifying the transmission line tower energy conversion law and the influence of different transmission line tower body structures on the electromagnetic scattering field.
- By decomposing the total electromagnetic scattering from the transmission tower into the superposition of each characteristic mode component, the proportion of each mode to the total scattering is calculated, so that only the eigencurrents components with large weight factors need to be optimized to correct the overall electromagnetic scattering characteristics.

Three different tower types of transmission line towers were tested by simulations. Under the same excitation source conditions:

a) The contribution of the cathead tower characteristic mode 6 to the total electromagnetic scattering of the tower at the resonant frequency point (8.2 MHz) is about 98.8%.
b) The wine glass tower mode 2 at the resonant frequency point (8.5 MHz) is 98.83%.
c) The drying tower modes 1 and 3 at the resonant frequency point (6.3 and 8.55 MHz) are 97.68% and 98.85%, respectively.

The results show that the tower structure will affect the electromagnetic scattering intensity. The larger the value of the structure-related weighting factor, the larger the proportion of the corresponding characteristic current in the total current, and the greater the degree of influence on the electromagnetic scattering from the tower. The maximum relative error of the method compared with the calculation results of traditional MoM does not exceed 3% (According to equation (14), Section IV-A 1.2%, Section IV-B 1.17%, Section IV-C 1.15% and 2.32%), verifying the simulation results and the proposed method, which provides important theoretical support and technical guidance for analyzing the influence of electromagnetic scattering of radio signals from transmission line towers.

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