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RESEARCH ARTICLE

Study on Improved CG Algorithm for Reradiation Interference Calculation of Transmission Steel Tower

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ABSTRACT With the development of extra-high voltage and ultra-high voltage transmission line in China, the reradiation interference generated by induced current on the surface of transmission steel tower becomes more serious to the radio station in the vicinity. In this paper, the calculation method for reradiation interference of transmission steel tower based on method of moment is analyzed. And in order to reduce the impedance matrix storage data in the memory space and the number of iterations in the calculation, the preprocessing of matrix sparse and diagonal norm precondition is presented to improve the performance of the conjugate gradient algorithm for the reradiation interference calculation. The reradiation interference of a standard 500 kV transmission steel tower is calculated using the improved conjugate gradient algorithm. And the results show that the algorithm enhances the convergence and stability after preprocessing and is suitable to calculate the reradiation interference of super-large metal truss structure target.

INDEX TERMS Conjugate gradient, method of moment, reradiation interference, transmission steel tower.

I. INTRODUCTION

Due to the reverse distribution characteristics between energy resources and power load centers in China, a mount of EHV (Extra-high Voltage) and UHV (Ultra-high Voltage) transmission line have been utilized for the power transmission with long distance, large capacity, small loss and high efficiency [1]. However, transmission lines have massive metal structures in order to satisfy the safety distance between the wire and the ground, the wire and steel tower, and so on. And the induced current on the surface of towers and wires, which are excited by the electromagnetic waves from radio stations in the vicinity, will generate reradiation waves. And these reradiation waves have the same frequency, but the different phases, compared with the waves emitted by the radio stations. The reradiation interference can be generated by the superposition of them and the undesirable distortion can be created in the radiation pattern of radio station [3].

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With the increase of the structure of transmission towers and the limitation of transmission corridor resources, the reradiation interference between the transmission line and the radio station becomes more and more serious [2].

Since the 1960s, scholars have carried out the study on the induced current on the surface of transmission tower and the reradiation analysis by the experimental method. The theoretical reradiation patterns for square section and rectangular section cylinders and the governed factors of the amplitudes of reradiation signals had been discussed [4], [5]. To verify the theoretical results, the scaled transmission line models had been carried out, and the reradiation fields and the reradiation patterns of conductors were measured [6], [7]. Research shows that the maximum reradiation interference occurs when the loop formed by the ground wire and the steel tower resonates, while the reradiation interference contributed by the conductor is very small. Furthermore, the reradiation interference varies with the angle of the incident wave and increases with the frequency. However, limited by experimental conditions, such studies are not suitable for large-scale and systematic research for reradiation interference.

Compared with the complex and costly experimental study on the reradiation phenomenon, simulation research based on the numerical calculation technology has been widely promising. The level of reradiation interference can be obtained by solving the Maxwell partial differential equations. Using the FEM (Finite Element Method) or FDTD (Finite-Difference Time-Domain) method to solve partial differential equations, the entire computational space needs to be included in the model, which makes the unknowns extremely large and difficult to apply in practice. Considering the reradiation interference is generated by the induced current on the target surface, the computational space required by using the electric field integral equation is greatly reduced and is widely used, such as the MOM (Method of Moments). Trueman and Kubina introduced a computational model to simulate the reradiation on a broadcast station at medium frequencies from the transmission line. In the simulation model, the transmission line was made up of a thin wire, and the reradiation interference was obtained by the MOM. In the following studies, the transmission steel tower model was gradually similar to the actual tower [8]–[10]. Zhao used the thin wire instead of the angle steel in the transmission steel tower to generate the wire model and analyzed the reradiation about the loop consisting of two transmission towers, overhead ground wire and the ground image [11], [12]. Tang compared the wire model and the surface model of transmission steel tower in the prediction of the reradiation interference calculation and gave some suggestions about the application of each model [13]–[15].

Although the simulation model should describe the more details of the real transmission steel tower, it increases the difficulty of numerical calculation. In the common band of radio station, transmission steel tower can be regarded as an electrically large object, and composed of a mount of angle steels. Using the MOM to calculated the reradiation interference of typical EHV transmission steel tower in China, the number of unknowns may be $10^5 \sim 10^8$. It is extremely unrealistic to apply the traditional numerical method in the analysis of reradiation interference. Consequently the MOM has been limited to use in the low frequency range for a long time.

With the rapid development of computational electromagnetics, the CG (Conjugate Gradient) iteration algorithm sharply reduces the amount of computation for solving linear equations and has been applied widely. However, the traditional CG algorithm still has difficulties in the matrix storage space and convergence, when the frequency of incidence waves is increased and more refined transmission steel tower models are used. Thus reducing the storage size of the matrix and enhancing convergence of the algorithm is the key to solving the reradiation interference calculation of the transmission steel tower under the current computer condition.

In this paper, firstly the characteristics of impedance matrix in the traditional MOM method with the RWG (RAO, WILTON and GLISSON) basis function had been introduced. And then a method of sparse impedance matrix was proposed to reduce the memory storage space in the calculation. Furthermore, the diagonal norm precondition was analyzed and applied to improve the performance of the CG algorithm. At last the reradiation interference of a standard 500 kV transmission steel tower had been calculated. And the result had shown that the improved CG algorithm can reduce the impedance matrix storage data in the memory space and the number of iterations in the calculation compared with the traditional CG algorithm. The improved CG algorithm can not only effectively calculate the reradiation interference of large metal structures, but also make use of the existing calculation program, which is convenient for the programming.

II. SOLUTION OF RERADITION INTERFERENCE BASED ON MOM

According the theorem of electromagnetic field, when the electromagnetic wave reaches the metal materials, the induced current will be excited on the surface of metal materials. And the electric field $\boldsymbol{E}_s$ of reradiation wave generated by these induced current can be calculated by the EFIE (Electric Field Integral Equation) as below [16],

$$\boldsymbol{E}_s(\boldsymbol{r}) = j\omega\mu \int_{S'} g(\boldsymbol{r}, \boldsymbol{r}')\boldsymbol{J}(\boldsymbol{r}')dS' - \frac{1}{j\omega\mu}\nabla \int_{S'} g(\boldsymbol{r}, \boldsymbol{r}')\nabla \cdot \boldsymbol{J}(\boldsymbol{r}')dS' \tag{1}$$

where $\boldsymbol{E}_i$ is the electric field of incident wave, $\boldsymbol{J}(\boldsymbol{r}')$ is the induced current density on the surface S of metal materials, $g(\boldsymbol{r}, \boldsymbol{r}')$ is the Green's function and $g(\boldsymbol{r}, \boldsymbol{r}') = \frac{e^{-jk|\boldsymbol{r}-\boldsymbol{r}'|}}{4\pi|\boldsymbol{r}-\boldsymbol{r}'|}$, ω is angular frequency, μ is dielectric constants, and ϵ is magnetic permeability.

Assume the materials of transmission steel tower is a perfect conductor, the tangential component of the electric field on the surface of transmission steel tower should be equal to 0 and the relationship of electric fields between the incident wave and the reradiation wave can be obtained by

$$\hat{\boldsymbol{t}} \cdot [\boldsymbol{E}_s(\boldsymbol{r}) + \boldsymbol{E}_i(\boldsymbol{r})] = 0 \tag{2}$$

where $\hat{\boldsymbol{t}}$ is the tangential unit vector. Substituting (1) into (2), the electric field of incident wave can be calculated by

$$-\hat{\boldsymbol{t}} \cdot \boldsymbol{E}_i\boldsymbol{r} = \hat{\boldsymbol{t}} \cdot [j\omega\mu \int_{S'} g(\boldsymbol{r}, \boldsymbol{r}')\boldsymbol{J}(\boldsymbol{r}')dS' - \frac{1}{j\omega\mu}\nabla \int_{S'} g(\boldsymbol{r}, \boldsymbol{r}')\nabla \cdot \boldsymbol{J}(\boldsymbol{r}')dS'] \tag{3}$$

Once the incident wave is determined, the current density $\boldsymbol{J}(\boldsymbol{r})')$ can be obtained by solving (3).

In order to apply the MOM in the calculation, the surface of transmission steel tower will be subdivided into several triangular elements according to the frequency of incident

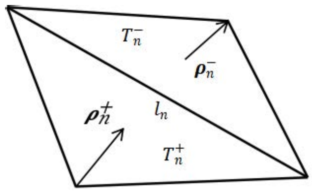

FIGURE 1. There is an adjacent triangle pairs in the RWG basis function.

wave. And the RWG basis function is defined on these adjacent triangle pairs as shown in Fig. 1 [17].

Then the RWG basis function can be written as below

$$\boldsymbol{f}_n(\boldsymbol{r}) = \begin{cases} \dfrac{l_n}{2A_n^+}, & on\ T_n^+ \\ -\dfrac{l_n}{2A_n^-}, & on\ T_n^- \\ 0, & other \end{cases} \tag{4}$$

where $T_n^{\pm}$ are the triangle pairs with the area $A_n^{\pm}$ and the common edge l_n, $\boldsymbol{\rho}_n^{\pm}$ are the vector from the vertex of l_n to any point on the triangle surface. Using the RWG basis function, the current density $\boldsymbol{J}$ on the surface can be discrete as below,

$$\boldsymbol{J} = \sum_{n=1}^{N} I_n \boldsymbol{f}_n(\boldsymbol{r}) \tag{5}$$

where N is the number of the RWG basis function, I_n is the unknown current density coefficients. Using the Galerkin test method and substituting (5) to (3), the linear system of I_n can be obtained as below

$$\boldsymbol{ZI} = \boldsymbol{V} \tag{6}$$

where $\boldsymbol{Z}$ is the impedance matrix of transmission steel tower, $\boldsymbol{I}$ is the vector of unknown current density coefficients, and $\boldsymbol{V}$ is the excitation vector. After the elements in the matrix $\boldsymbol{Z}$ and the vector $\boldsymbol{V}$ have been obtained, the unknown current density coefficients $\boldsymbol{I_n}$ can be solved using (6) by the CG algorithm. Then the electric field $\boldsymbol{E}_s$ can be calculated out using (1).

In order to evaluate the reradiation from the transmission steel tower, the RCS (Radar Cross Section) is used and calculated by

$$\sigma = \lim_{R\to\infty} 4\pi R^2 \frac{|\boldsymbol{E}_i|^2}{|\boldsymbol{E}_s|^2} \tag{7}$$

III. IMPROVE CG ALGORITHM IN SOLVING EQUATIONS

In the reradiation interference calculation of the transmission steel tower, the edge length of triangular facets normally is divided by the $1/12$ wavelength to ensure the calculation accuracy of the MOM. Thus with the frequency increasing, the number of unknown current density coefficients I_n and the size of the impedance matrix $\boldsymbol{Z}$ will increase rapidly. As the standard 500 kV cat-head type transmission steel tower, the height of tower is almost 51.5 m and the number of the triangles in the mesh is close to 30000 at a frequency of 100 MHz. The relationship between the frequency and the number of the triangles in the mesh had been shown in Fig. 2.

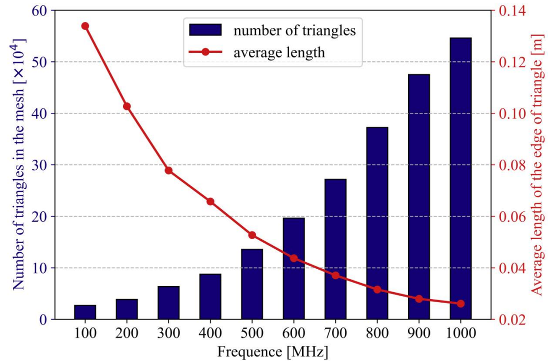

FIGURE 2. The number of triangles becomes larger and the average length becomes shorter with the frequency increasing.

In order to speed up the solution process of the matrix equations, the preprocessing method include sparse impedance matrix and diagonal norm precondition were implemented in the paper.

According to the RWG basis function, the elements of impedance matrix $\boldsymbol{Z}$ can be written as

$$Z_{mn} = \frac{jkZ}{16\pi}\left[Z_{mn}^{++} + Z_{mn}^{--} - Z_{mn}^{+-} - Z_{mn}^{-+}\right] \tag{8}$$

where

$$\begin{aligned} Z_{mn}^{\pm\pm} &= \frac{l_m l_n}{A_m^{\pm} A_n^{\pm}} \int_{S_m^{\pm}} \int_{S_n^{\pm}} \rho_m^{\pm} \rho_n^{\pm} \frac{e^{-jk|\boldsymbol{r}-\boldsymbol{r}'|}}{|\boldsymbol{r}-\boldsymbol{r}'|} dS_n^{\pm} dS_m^{\pm} \\ &\quad - \frac{4}{k^2} \frac{l_m l_n}{A_m^{\pm} A_n^{\pm}} \int_{S_m^{\pm}} \int_{S_n^{\pm}} \frac{e^{-jk|\boldsymbol{r}-\boldsymbol{r}'|}}{|\boldsymbol{r}-\boldsymbol{r}'|} dS_n^{\pm} dS_m^{\pm} \end{aligned} \tag{9}$$

Using the numerical integration of triangular facets, the elements $Z_{mn}^{\pm}$ can be obtained. And it is obvious that the impedance matrix Z is a symmetric matrix. Applying the traditional direct solution algorithm to solve (6), such as Gauss elimination algorithm, LU decomposition algorithm, and so on, there may be some difficulties in the consumption of CPU time and memory space. However, the iteration algorithm can avoid the time-consuming calculation of the inverse matrix and the CG algorithm converges not only for any initial value, but also to the minimum value of the quadratic functional. Thus the CG algorithm has been widely used in large-scale numerical calculation. Considering the number of iterations in the CG algorithm is related to the condition number of matrix, it is necessary to apply the proper preprocess to satisfy the reradiation interference calculation.

If $L \gg \lambda$, the length of common edge $l_{m,n}$ in the RWG basis function can be approximate to the average length of the triangular surface elements, which value is almost same as the $1/12$ wavelength in the ideal mesh. According to the first order numerical integration formula of triangular facets, $\rho_{m,n}^{\pm} \approx \frac{2}{3} l_{av}$. Let $L = |\boldsymbol{r} - \boldsymbol{r}'|$, and the elements $Z_{mn}^{\pm\pm}$ can be calculated as,

$$\begin{aligned} Z_{mn}^{\pm\pm} &\approx l_{av}^2 \left(\frac{1}{3} l_{av}^2 \frac{e^{-jkL}}{L} - \frac{4}{k^2}\frac{e^{-jkL}}{L}\right) \\ &= l_{av}^4 \left(\frac{1}{3} - \frac{36}{\pi^2}\right) \frac{e^{-jkL}}{L} \end{aligned} \tag{10}$$

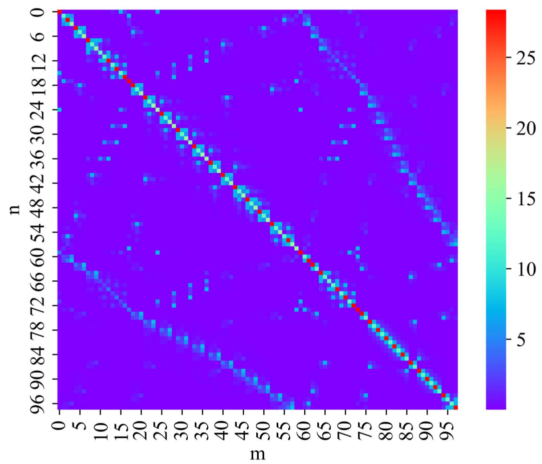

FIGURE 3. The distribution diagram of the magnitude of elements in impedance matrix.

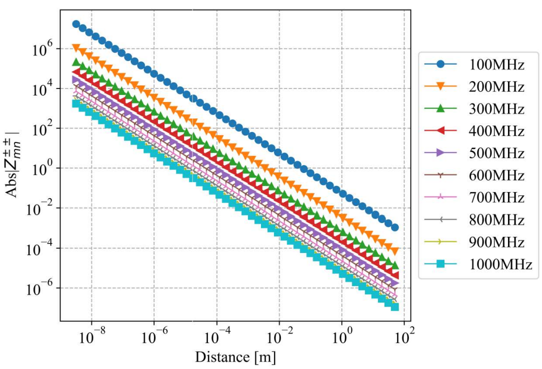

FIGURE 4. The relationship between the magnitude of $Z_{mn}^{\pm\pm}$ and the distance in the different frequencies.

It is easy to find that the values of $Z_{mn}^{\pm}$ are all close to each other between the two far away RWG basis function elements. Then the element Z_{mn} can be ignored and it means that in the physical sense there is no interaction between the two far away RWG basis function elements.

On the other hand, when $L \rightarrow 0$, the difference of $Z_{mn}^{\pm\pm}$ between the two closed RWG basis function elements become larger. And the interaction between these two RWG basis function elements is strong, especially the elements on the main diagonal of the impedance matrix will be the maximum value in the row. In Fig. 3, taking the angle steel model as an example, most of the elements in the impedance matrix are close to 0. As the distance increases, the magnitude of the element $Z_{mn}^{\pm\pm}$ also decreases exponentially, as shown in Fig. 4.

Select a threshold value for each row in the impedance matrix, and set the element in the row to 0 when its value is smaller than the threshold value, and the original impedance matrix will be transformed from a full matrix to a sparse matrix. The threshold value ϵ_i on the ith row can be calculated using the norm of row vector as below

$$\epsilon_i = k\frac{||Z_{ii}||_\infty}{N} \quad i = 1, 2, \ldots, N \tag{11}$$

where k is the sparseness degree of impedance matrix. When k is larger, the impedance matrix is more sparse, and the error of calculation will also increase. Normally, the value of k is taken between 40 and 100.

In order to improve the convergence of CG algorithm due to the large matrix condition number in the iterative process, a non-singular matrix $\boldsymbol{M}$ is introduced for a precondition in the method. Invert the matrix $\boldsymbol{M}$ and multiply it by both sides of (6), then

$$\boldsymbol{M}^{-1}\boldsymbol{Z}\boldsymbol{I} = \boldsymbol{M}^{-1}\boldsymbol{V} \tag{12}$$

Obviously, if $\boldsymbol{M} = \boldsymbol{Z}$, the condition number of $\boldsymbol{M}^{-1}\boldsymbol{Z}$ must be equal to 1, which is also the smallest value of condition number. At the same time, for the convenience of calculation, it is best that the matrix $\boldsymbol{M}$ is a diagonal matrix.

According to the matrices spectrum decomposition, the impedance matrix $\boldsymbol{Z}$ can be expressed as

$$\boldsymbol{Z} = \boldsymbol{P}\boldsymbol{\Lambda}\boldsymbol{P}^{\boldsymbol{T}} \tag{13}$$

and $\boldsymbol{M}^{-1}\boldsymbol{Z}$ can be expressed as

$$\boldsymbol{M}^{-1}\boldsymbol{Z} = \boldsymbol{Q}\boldsymbol{\Delta}\boldsymbol{Q}^{\boldsymbol{T}} \tag{14}$$

where $\boldsymbol{P}, \boldsymbol{Q}$ are the orthogonal matrices, $\boldsymbol{\Lambda}$, $\boldsymbol{\Delta}$ are the diagonal matrices. Assume the eigenvalues of the matrix $\boldsymbol{M}^{-1}\boldsymbol{Z}$ is d_i, $i = 1, 2, \ldots, N$. The spectral condition number of $\boldsymbol{M}^{-1}\boldsymbol{Z}$ can be obtained as below

$$cond\left(\boldsymbol{M}^{-1}\boldsymbol{Z}\right) = \frac{d_{max}}{d_{min}} \tag{15}$$

According to (13) and (14), the matrix $\boldsymbol{\Delta}$ can be written as

$$\boldsymbol{\Delta} = \boldsymbol{Q}^{-1}\boldsymbol{M}^{-1}\boldsymbol{Z}\boldsymbol{Q}^{-T} = \boldsymbol{Q}^{-1}\boldsymbol{M}^{-1}\boldsymbol{P}\boldsymbol{\Lambda}\boldsymbol{P}^{\boldsymbol{T}}\boldsymbol{Q}^{-T} \tag{16}$$

And the condition number of diagonal matrix $\boldsymbol{\Delta}$ is the same as the condition number of matrix $\boldsymbol{M}^{-1}\boldsymbol{Z}$ according to (15). Then in order to minimize the condition number of matrix $\boldsymbol{M}^{-1}\boldsymbol{Z}$, the condition number of $\boldsymbol{Q}^{-1}\boldsymbol{M}^{-1}\boldsymbol{P}\boldsymbol{\Lambda}\boldsymbol{P}^{\boldsymbol{T}}\boldsymbol{Q}^{-T}$ should have the minimum value. According to the formula of the condition number $cond\,(\boldsymbol{AB}) \leq cond\,(\boldsymbol{A})\, cond\,(\boldsymbol{B})$ [18], the following equation can be obtained

$$cond\left(\boldsymbol{Q}^{-1}\boldsymbol{M}^{-1}\boldsymbol{P}\boldsymbol{\Lambda}\boldsymbol{P}^{\boldsymbol{T}}\boldsymbol{Q}^{-T}\right) \leq cond\left(\boldsymbol{M}^{-1}\boldsymbol{\Lambda}\right) \tag{17}$$

Taking into account that the matrix $\boldsymbol{M}$ is preferably a diagonal matrix, it is obvious to obtain $\boldsymbol{M} = \boldsymbol{\Lambda}$. In this case, the condition number of the matrix $\boldsymbol{M}^{-1}\boldsymbol{Z}$ tends to be close to 1. Since the eigenvalues of impedance matrix $\boldsymbol{Z}$ are not easy to obtain, in the reradiation interference calculation, the norm of each row in the matrix can be used to approximate the diagonal matrix $\boldsymbol{M}$. Thus the diagonal norm precondition of $\boldsymbol{M}$ can be obtained and applied in the CG algorithm.

Through the preprocessing of sparse matrix and diagonal norm precondition mentioned above, the efficiency and stability of CG algorithm are improved for solving (6).

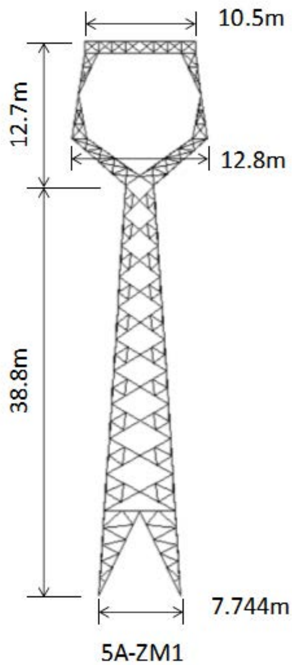

FIGURE 5. Outline dimension of a typical 500 kV cat-head type transmission steel tower.

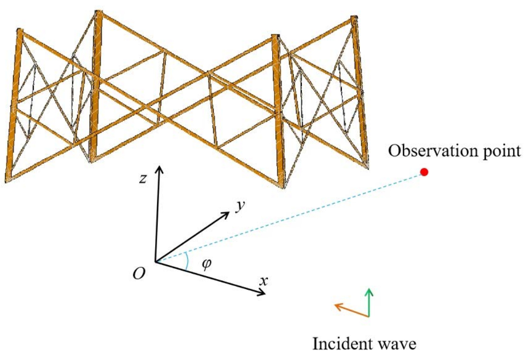

FIGURE 6. A section of the transmission steel tower and the triangular elements in the mesh.

IV. CASE STUDY

A standard 500 kV cat head type transmission steel tower model of State Grid Corporation of China was established by the combination of angle steels. And the specific parameters of the transmission steel tower were shown in Fig. 5. Considering the thickness of the angle steel is sufficiently thin, comparable to the wavelength of the incident electromagnetic wave, the induced current on the inner surface and the outer surface of the angle steel will be thought to follow the same pattern as the incident electromagnetic wave. Thus the thickness of the angle steel could be neglected in the calculation and the angle steel was modeled with the two adjacent conductor surfaces. Therefore, using the parametric modeling method, the coordinates of the angle steel in the steel tower were automatically calculated through the structural dimensions, and the reradiation interference of the model was analyzed by the python programming in the laboratory.

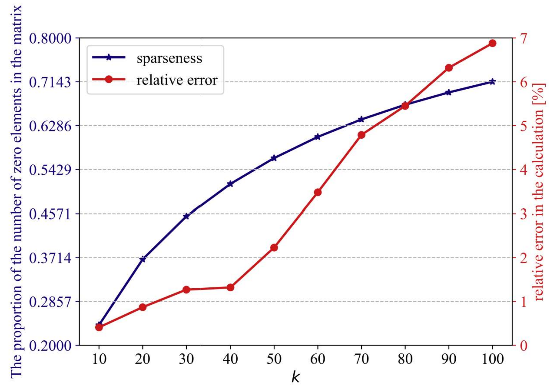

FIGURE 7. The influence of different *k* values on matrix sparsity and the relative error in the calculation.

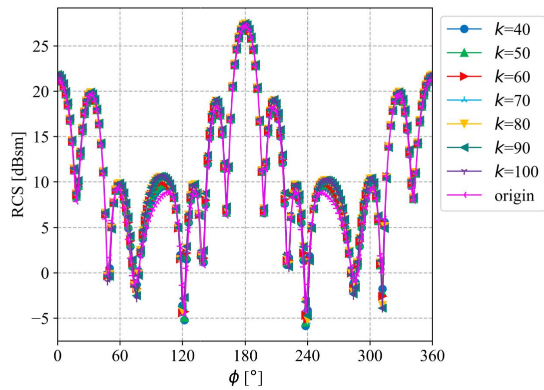

FIGURE 8. The comparison of the RCS result with different sparse impedance matrix.

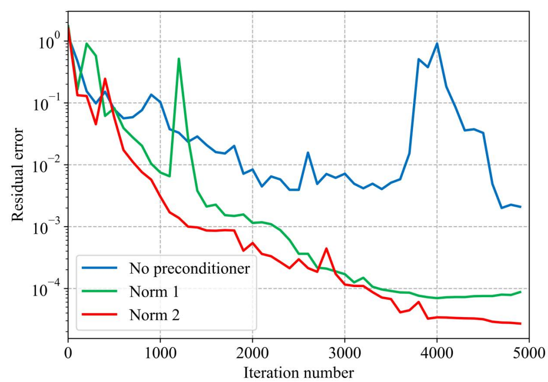

FIGURE 9. Comparing the impact of different diagonal norm precondition in the calculation.

Taking a section of the transmission steel tower as an example, the RCS at observation point with the azimuth angle ϕ generated by the 100 MHz incident electromagnetic wave along the x-axis was investigated as shown in Fig. 6. In the meshing, there were 1849 triangles and 2133 RWG basis function elements according to the rule that the length of edge should not exceed 0.25 m. Using (8) and (9), the impedance matrix were generated. Define the sparseness degree S of

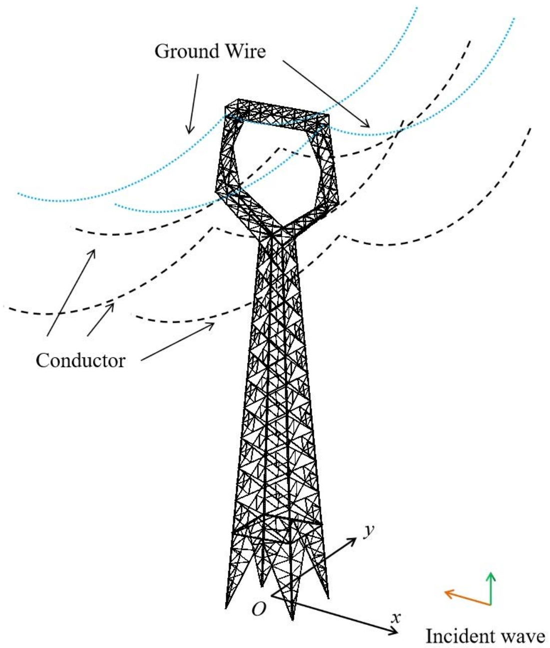

FIGURE 10. The calculation model of the typical 500 kV cat-head type transmission steel tower.

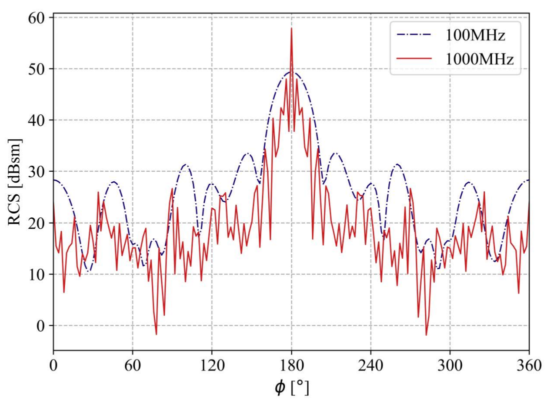

FIGURE 11. The RCS results of the transmission steel tower at frequencies of 100 MHz and 1000 MHz.

matrix as

$$S = \frac{N_z}{N_{all}} \tag{18}$$

where N_z is the number of the zero elements in the matrix, N_{all} is the number of the total elements in the matrix. And the relative error e_r in the RCS calculation was defined by

$$e_r = \frac{max|R_f - R_s|}{max|R_f|} \times 100\% \tag{19}$$

where R_f is the value of RCS result using the original full impedance matrix, R_s is the value of RCS result using the sparse impedance matrix. Changing the sparseness degree k from 10 to 100, the sparseness degree S of matrix and the relative error e_r in the RCS calculation were obtained in Fig. 7.

In Fig. 7, it can be found that with the increasing of the k value, the sparseness of the impedance matrix increased,

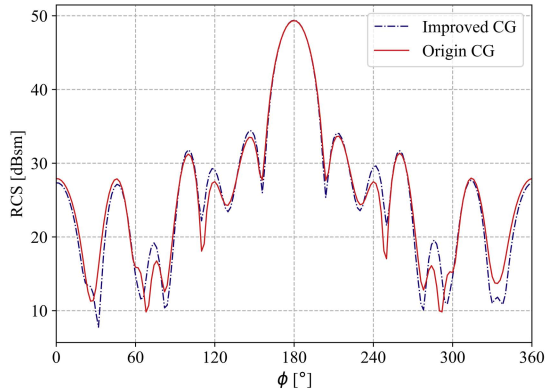

FIGURE 12. The comparison of the RCS results of the transmission steel tower at 100 MHz between the improved CG and the origin CG algorithm.

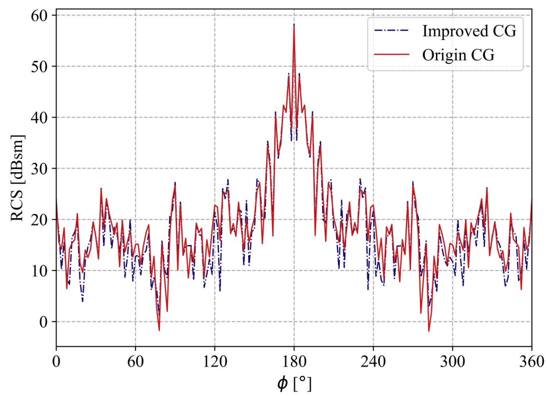

FIGURE 13. The comparison of the RCS results of the transmission steel tower at 1000 MHz between the improved CG and the origin CG algorithm.

and the corresponding error of the RCS calculation was also increasing. The two values maintained a positive correlation, which satisfied the previous analysis. And it can also be found that the sparseness of matrix has a certain saturation phenomenon with the increase of k. Thus the sparseness of the matrix cannot be effectively enhanced with a large value of k. On the contrary, the error of calculation may become larger. It is important to select an appropriate value of k for the reradiation interference calculation of transmission steel tower. The RCS results with the different k were shown in Fig. 8.

Using the diagonal norm precondition in the CG algorithm, the different norms were employed to compare the residual error and the number of iterations. Although the condition number of the impedance matrix was 4.7735×10^4, the diagonal norm precondition can effectively reduce the number of iterations in the calculation as shown in Fig. 9.

The whole transmission steel tower model also had been used to calculate the reradition interference at frequencies of 100 MHz and 1000 MHz with the help of the improved CG algorithm as shown in Fig. 10. The results show that the reradiation interference of transmission steel tower has different properties at different frequencies. In Fig. 11, as the frequency increases, the RCS changes dramatically from smooth to rough, indicating that the influence of the truss structure of the transmission steel tower has been enhanced. The analysis of reradiation interference to the transmission steel tower requires a more accurate model at high frequencies to represent the influence of the details of the transmission steel tower. And it is also acceptable to choose a simplified model in certain cases where the frequency is not too high.

Comparing the results of the improved CG algorithm and the origin CG algorithm at frequencies of 100 MHz and 1000 MHz, it can be found that the improved CG algorithm almost has the consistent result with the origin CG algorithm and the error is mainly caused by matrix sparseness degree, as shown in Fig. 12 and Fig. 13.

V. CONCLUSION

In this paper, in order to calculate the reradiation interference of transmission steel tower, the MOM was used to compute the induced current density coefficient on the surface of tower and the impedance matrix generated by the RWG basis function had been analyzed. And the preprocessing method include sparse impedance matrix and diagonal norm precondition were investigated to improve the CG iteration algorithm performance. By calculating the reraditaion interference of standard 500 kV transmission steel tower, the result shows that the convergence and stability of CG iteration algorithm are enhanced after preprocessing. Especially the improved CG algorithm is suitable to calculate the reradiation interference of super-large metal truss structure target.

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