Research on impulse impedance model and protection optimization of transmission tower grounding device in mountainous area

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Abstract
The impulse impedance of the tower is the core parameter to evaluate the lightning protection performance of the transmission line. The high soil resistivity and the underground rock layers in the mountainous areas will induce large impulse impedance and further lead to frequent lightning striking accidents. Therefore, this paper proposes a circuit-finite element model (CFEM) and investigates the corresponding impedance-reduction optimization method of the grounding device in mountainous areas. The model takes into account the nonlinear characteristics of the soil. Based on the parallel-plate electrode and the concentric hemispheric test device, the nonlinear curves of the soil resistivity of five typical kinds of soils with the electric field intensity are obtained. To justify the CFEM, the field experiment of a single horizontal conductor is performed, with an average relative error of 4.67%. Based on the CFEM, this paper presents an impedance-reduction optimization method for the grounding device in the mountainous areas, while proposing the best design method and the optimal layout of the grounding device in the rocky zone. The research results can provide a reference for the design transformation and protection optimization of the transmission tower grounding device in mountainous areas.

1 | INTRODUCTION

Lightning strikes are the main factor to result in the trip fault of transmission lines [1], and the impulse impedance under the lightning is closely related to the lightning protection performance of the transmission line. High impulse impedance under the lightning strike may cause a back-flashover accident. Additionally, because of rock layers in mountainous areas (e.g. Guangdong province and northwest China) have high resistivity. The impulse impedance of the grounding device usually fails to meet the safety requirements. Therefore, to reduce the impulse impedance of the grounding device, it is particularly important to establish an accurate grounding system model and to study the best design method and optimal layout of the grounding device in mountainous areas.

On the one hand, an accurate transient model of the grounding system is established to carry out the impedance-reducing and optimal protection research on the impulse impedance of the grounding device in mountainous areas with underground rock layers. Currently, the grounding systems models can be classified into transmission line theoretical models, circuit theoretical models, and electromagnetic field models. Based on transmission line theory, the authors in [2–5] simulated elongated bodies and applied distributed parameters to study the process of the lightning wave. The transmission line model performed high calculation efficiency by considering the effect of soil discharge on the impact characteristics. However, the premise assumed that the conductor was infinitely long, which may not be practical in other application scenarios. In [6–9], based on the circuit theory, the transient characteristics of the

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grounding device transformed the grounding device into a π-type equivalent circuit. The circuit theory model considers the soil ionization area to be the expansion of the radius of the grounding device. In addition, the model can also be used to analyze the impact of lightning current frequency on the impact characteristics of the grounding body [8]. With the application of the electromagnetic field theory method, the authors in [10–15] studied the influence of both soil nonlinear characteristics and grounding grid structure on impact characteristics, and then analyzed the transient characteristics of grounding devices. The calculation model based on the circuit-finite element method proposed in this paper can comprehensively consider the nonlinear effect of the soil and the high-frequency inductance effect of the grounding device. It is more accurate to simulate the impulse characteristics of the grounding device under lightning.

On the other hand, the method of reducing the impulse impedance and ground resistance of the grounding device under the action of lightning and power-frequency source is also the main focus. Yunus et al. conducted high impulse current tests comparisons on different ground electrode types [16]. The experiment results show that the material used for 3-star and vertical earth electrode configuration is only 3/10 of that used for earth grid configuration when the grounding resistances are similar. Yuan et al. [17] reduced the grounding resistance of the grounding system by digging deep holes, developing cracks in the soil using explosions in the holes and filling low-resistivity materials. Some researchers have studied the impulse characteristics of box and ray grounding device [18]. The experiment results found that the ray had an effective length, and the shielding effect among the conductors under the impulse cannot be ignored. Besides, by adding needle-shaped conductors to the proper location of the grounding device, the area of the spark was expanded, and the purpose of the impulse impedance reduction was also achieved to a certain extent [19]. The literature [20] explored the relevant characteristics of the flexible graphite-cooper composited grounding material (FGCG). It found that the power-frequency grounding resistance of FGCG was less than that of steel grounding materials when the soil resistivity exceeded 1000 Ω·m. Although the grounding resistance of FGCG under the power-frequency source has advantages, the impulse impedance under the impulse current has not yet drawn relevant conclusions. Asadpourahmadchali et al. studied the method of determining the effective angle between different horizontal conductors and optimized the multi-span grounding system according to the number of effective branches and the effective conductor length [21].

In summary, there are two main deficiencies in the existing research. One is that most works focus on the impulse characteristics of different types of grounding devices and grounding conductor materials. Nevertheless, the optimization and improvement of the existing typical grounding devices are significantly neglected. The other is that the specific environment around the grounding device (e.g. the existence of rock layer under the grounding device) is not given into full exploration. Furthermore, there are few optimization studies on the impulse impedance reduction of the grounding device in the rocky area under the mountain surface.

To address the aforementioned problems, the flowchart of the research procedure can be seen in Figure 1.

Besides, two contributions are presented:

1. A circuit-finite element model (CFEM) is proposed, which comprehensively considers the nonlinear effect of the soil and the high-frequency inductance effect of the grounding device. First, the impulse characteristics of five typical soils in Guangdong, China were studied, and the curves of resistivity of different soils with electric field intensity were obtained through parallel plate electrode experiments. Second, build a finite element model that combines the soil nonlinear curve, and carry out concentric hemispheric experiments to verify the soil nonlinear effect of the model. Third, considering the self-inductance and mutual inductance effects of the grounding device, the CFEM of the grounding device is finally established, and the field experiment of a single horizontal conductor is carried out. The calculation results of the model are in good agreement with the experimental results.

2. An impedance-reducing optimization method is proposed for the grounding device located at places where are 2 m and 10 m below the surface of mountainous areas, respectively. Additionally, the optimal design method of grounding devices is also proposed for those in the rocky area. The research results can provide specific theoretical guidance and data support for the design transformation and protection optimization of the transmission tower grounding device in mountainous areas.

2 MODELLING OF THE GROUNDING SYSTEM

2.1 Theoretical analysis of CFEM

In CFEM, the finite element part and the circuit part are connected and interacted with each other. Electrical parameters such as current and potential are jointly solved according to
the electromagnetic field and circuit theory. Furthermore, the grounding conductor is segmented, and the inductance components in the circuit are used to replace the self-inductance of the conductor and the mutual inductance among the conductors. To prevent the occurrence of current between two adjacent conductors after the segmentation, an insulating interval area is added between the conductors. In the finite element part, namely the electromagnetic field part, CFEM fully considers the impulse dispersion characteristics and the nonlinear characteristics of the soil. The functional relation of soil resistivity and electric field intensity is combined with Maxwell’s equations as a control equation. By this means, the spark effect of the soil around the grounding device under a large impulse current can be reflected. To be more technically specific, the CFEM of the box-shaped grounding device is shown in Figure 2. With the injection of high-frequency lightning current, the grounding device is effectively divided into segments and contains nodes after the segmentation.

Using the node voltage method, the node potential and current meet Equation (1):

$$I = Y_b \psi$$  \hspace{1cm} (1)

where $Y_b$ is the node admittance matrix; $\psi = (\varphi_1, \varphi_2, \ldots, \varphi_k)^T$ is the potential of each node; $I = (I_1, I_2, \ldots, I_k)^T$ is the current injected into the node.

Since the injection source belongs to a high-frequency lightning current, this paper only considers the self-inductance and mutual inductance of the grounding conductor in the circuit, while ignoring the internal resistance of the conductor. Consequently, Equation (2) can be obtained:

$$Y_b = AY_bA^T$$  \hspace{1cm} (2)

where $A$ is the correlation matrix of order $k \times m$, $Y_b$ is the branch admittance matrix, the mutual inductance can be regarded as the current control voltage source. So Equation (3) can be deduced as follows:

$$Y_b = Z_b^{-1}$$  \hspace{1cm} (3)

where $Z_b$ is the branch impedance matrix. For the segmented grounding device, $Z_b$ can be determined as (4):

$$Z_b = \begin{bmatrix} j\omega L_{11} & j\omega M_{12} & \cdots & j\omega M_{1m} \\ j\omega M_{21} & j\omega L_{22} & \cdots & j\omega M_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ j\omega M_{m1} & \cdots & j\omega L_{mm} \end{bmatrix}$$  \hspace{1cm} (4)

where $\omega$ is the angular frequency; $L_{ij}$ ($i = 1, 2, \ldots, m$) means the self-inductance of the $i$-th segment conductor; $M_{ij}$ ($i = 1, 2, \ldots, m; j = 1, 2, \ldots, i-1, i+1, \ldots, m$) denotes the mutual inductance of the $j$-th section conductor to the $i$-th section conductor.

When the lightning current flows into the soil from the grounding device, the dynamic physical process of the grounding system can be expressed by the quasi-static Maxwell equations, which can be expressed as (5):

$$\begin{align} \nabla \times H &= J_c + j\omega D \\
\nabla \cdot E &= 0 \\
\n\nabla \cdot J &= 0 \end{align}$$  \hspace{1cm} (5)

where $H$ represents magnetic field intensity, $J_c$ is the conduction current density in the soil, $D$ is the electric displacement vector, $E$ is the electric field intensity, $J$ is the total current density composed of the conduction current and the displacement current. The above parameters should also satisfy the constitutive equations, as shown in (6):

$$\begin{align} J_c &= \gamma E \\
D &= \varepsilon E \\
E &= -\nabla \varphi \end{align}$$  \hspace{1cm} (6)

where $\gamma$ represents soil electrical conductivity, $\varepsilon$ means soil dielectric constant, and $\varphi$ denotes scalar potential. Combining the constitutive equations and Maxwell equations, the potential control equation of the dispersed current is

$$D(\varphi(x, y, z)) = (\gamma + j\omega\varepsilon) \left( \frac{\partial^2 \varphi}{\partial x^2} + \frac{\partial^2 \varphi}{\partial y^2} + \frac{\partial^2 \varphi}{\partial z^2} \right) = 0$$  \hspace{1cm} (7)

Formula (7) should meet several boundary conditions. The potential at infinity is zero, which can be shown in (8):

$$\varphi = 0, \ r \to \infty$$  \hspace{1cm} (8)

On the surface, the normal current density is zero, as expressed in (9):

$$(\gamma + j\omega\varepsilon)\nabla \varphi \cdot n = 0$$  \hspace{1cm} (9)
At the current injection point, the conductor cross-section follows the following constraint:

$$\int_{s} - (\gamma + j \omega \varepsilon) \nabla \varphi \cdot n ds = I$$  \hspace{1cm} (10)$$

where $n$ is the normal vector at the interface; $I$ is the injection current amplitude; $s$ is the cross-section of conductor at the injection point. The combination of formulas (1) and (10) can achieve the coupling solution of the circuit and the electromagnetic field.

### 2.2 Calculation of inductance effect parameters of grounding devices

The lightning current can be decomposed into multiple high-frequency sine and cosine waves by Fourier transform. The inductance effect of the grounding conductor under high-frequency current cannot be ignored, including the self-inductance and the mutual inductance between the grounding conductors. Based on the circuit theory, a typical $\pi$ type equivalent circuit is constructed, then the conductor is segmented, each of which is with a length of $\Delta l_i$. Through massive simulation and experiment comparisons and theoretical analysis, it can be drawn out that the constraint of (11) can guarantee the accuracy of the final calculation results [5]:

$$\Delta l_i \leq \frac{\lambda}{10}$$  \hspace{1cm} (11)$$

where wavelength $\lambda$ is expressed as (12):

$$\lambda = \frac{2\pi}{\omega \sqrt{\frac{\mu \varepsilon}{2 + \sqrt{\frac{1}{2} + \frac{1}{2(2\pi j)^2 \varepsilon \rho^2} + \frac{1}{2}}}}}$$  \hspace{1cm} (12)$$

where $\mu$ is the soil permeability, $\rho$ is the soil resistivity, and $f$ is the maximum frequency component in the spectrum after the Fourier transform of the lightning current.

For horizontal and vertical ground electrodes, the self-inductance $L_i$ is [22–23]

$$L_i = \frac{\mu_0 \Delta l_i}{2\pi} \left[ \ln \left( \frac{l}{r_c} \right) + \ln \left( \frac{f}{2b} \right) \right]$$  \hspace{1cm} (13)$$

$$L_h = \frac{\mu_0 \Delta l_i}{2\pi} \left[ \ln \left( \frac{4l}{r_c} \right) - 1 \right]$$  \hspace{1cm} (14)$$

where $\mu_0$ is the permeability of soil; $l$ is the length of the conductor; $b$ is the depth of the horizontal electrode; $r_c$ is the radius of the electrode.

The number and arrangement of the grounding electrodes will lead to the mutual inductance between different conductors. According to the theory of electromagnetic induction and Neumann’s formula [24–25], mutual inductance exists between non-vertical conductors, which can be expressed as (15):

$$M_{ji} = M_{ij} = \frac{\mu_0}{4\pi} \int_{\Delta l_i} \int_{\Delta l_j} \frac{\cos \vartheta}{Q_{ij}} d\Delta l_i d\Delta l_j$$  \hspace{1cm} (15)$$

where $\vartheta$ is the angle between $d\Delta l_i$ and $d\Delta l_j$, $Q_{ij}$ is the distance between $d\Delta l_i$ and $d\Delta l_j$.

When the two conductors are parallel to each other, as shown in Figure 3, the mutual inductance can be expressed as (16):

$$M_{ij} = M_{ji} = \frac{\mu_0}{2\pi} \left( \Delta L \ln \frac{\Delta L + \sqrt{\Delta L^2 + D^2}}{D} - \sqrt{\Delta L^2 + D^2} + D \right)$$  \hspace{1cm} (16)$$

where $D$ is the distance between two parallel conductors.

### 2.3 Study on soil nonlinear effect

When the lightning current flows in the soil around the grounding conductor, it meets

$$E = \rho J$$  \hspace{1cm} (17)$$

where $E$ is the electric field intensity, $\rho$ is the soil resistivity. Due to the influence of the nonlinear characteristics of the soil, the relationship between the current density $J$ and electric field intensity $E$ in the soil appears nonlinear. To better simulate the nonlinear characteristics of the soil, the function $\rho = f(E)$ is obtained through field experiments before the soil breakdown. In addition, the soil resistivity after a breakdown is set as the initial soil resistivity 7% [26]. Subsequently, the function is integrated into the finite element software, where the soil resistivity is set as a function of electric field intensity to deal with the simulation of the soil nonlinear characteristic. Finally, the nonlinear equation of the current dispersion process in the soil around the grounding conductor is solved by using the nonlinear method in the finite element software.
Therefore, this paper builds an experimental device and an experimental test platform based on parallel plate electrodes, as shown in Figure 4. In the experiment, an acrylic box with an opening at the top is used to insulate and hold soil samples. In addition, the test electrode and the common electrode are rectangular copper plates of 25 cm × 25 cm, respectively. The distance between the two electrode plates is 15 cm.

The electric field between two parallel plates can be regarded as an almost uniform electric field, and some non-uniform electric fields may be generated near the edge tip. The length of the customized parallel plate electrode shares the same length as that of the experimental container. During the test, the height of the soil keeps the same as that of the parallel plate. Therefore, the too-large electric field intensity only exists at the small edge of the parallel plate. Besides, the distance between the test electrode and the common electrode is relatively large. It can be considered that the electric field intensity distortion at the edge of the electrode will not affect the overall field intensity distribution in the experimental device. Consequently, it has little effect on the overall test results. To illustrate this point, a finite element model of the parallel plate electrode experimental device is built. It can be seen from Figure 5 that the electric field distortion mainly occurs in the outer part of the soil, and has little effect on the electric field in the soil. The electric field intensity in the soil can almost be regarded as a uniform electric field.

The impulse power source keeps imposing voltage to the soil sample successively until it breaks down. Record the voltage across the soil sample and the current flowing through the soil sample. The resistivity of the soil sample $\rho$ and the electric field intensity $E$ can be obtained by the following formula:

$$\begin{align*}
\rho &= \frac{US}{IL} \\
E &= \frac{U}{L}
\end{align*}$$

where $S$ is the area of the test electrode, $L$ is the distance between the plates, $U$ and $I$ are the voltage across the soil sample and the current flowing through the soil sample, respectively. Moreover, $U$ and $I$ are the peak values of the impulse.

In this paper, five typical soils in Guangdong are selected for impulse characteristics. The water content and soil resistivity of the five soil samples are shown in Table 1. First, red soil is selected as the experimental soil sample. Its soil resistivity $\rho$ is $1893 \, \text{Ω} \cdot \text{m}$, and the soil water content is 5.75%. The impulse voltage is applied to the soil and keeps being increased successively until the soil is broken down. Additionally, the increment of the voltage is reduced when the soil is about to be broken down. By this means, the measured critical breakdown field intensity can be more accurate. Combined with the results of multiple tests and relevant studies, the characteristic phenomenon of soil breakdown can be described as the rapid change of waveform of voltage and current as well as the value of their sharp drop. Record the voltage waveform at both ends of the soil sample and the current waveform flowing through the sample, and calculate the impulse resistivity of the soil sample. The relationship between the impulse resistivity of five soil samples and the voltage across them is shown in Figure 6.

It can be seen from Figure 6 that the impulse test using the parallel plate electrode as the test electrode can fully simulate the change of the soil conductivity in the nonlinear region and that the impulse resistivity decreases with the increase of the amplitude of the impulse voltage. Moreover, the nonlinear characteristics of different types of soils vary greatly. The nonlinear changes in resistivity of red and yellow soils are obvious, while the nonlinear changes of fine sand and arenosol are little. Through the test results, a typical relation function between soil resistivity and electric field intensity in Guangdong can be

| Soil type           | Water content (%) | Soil resistivity (Ω·m) |
|---------------------|-------------------|------------------------|
| Red soil            | 5.75              | 1893                   |
| Yellow soil         | 7.5               | 1486                   |
| Yellow brown earth  | 6.31              | 700                    |
| Fine sand           | 6.25              | 467.7                  |
| Arenosol            | 7.06              | 238.9                  |
obtained, and the finite element software can be used to realize the accurate characterization of soil nonlinear characteristics.

The red soil is taken as an example. According to Equation (18), calculate the electric field intensity $E$ corresponding to the soil resistivity $\rho$, then fit the data to obtain the relation curve between $\rho$ and $E$, which is shown in Figure 7. In the figure, the abscissa of the right end of the curve is the critical breakdown field intensity of red soil, which is 421 kV/m. When the electric field intensity in the soil is less than the critical breakdown field intensity of the soil, the relationship between $\rho$ and $E$ is nonlinear. In addition, with the increase of $E$, soil resistivity decreases continuously.

2.4 Verification of soil nonlinear effects

To verify the correctness of the model to simulate the nonlinear effect of soil, a concentric hemispherical model is constructed in the finite element software to calculate the impulse impedance of the concentric hemispherical device under different voltage amplitudes. Construct a hemispherical metal container with a recirculation electrode radius of 10 cm, embed a metal ball with a radius of 1 cm at the centre of the hemispherical container, and bury the lower part of the ball in the soil as a high-pressure electrode. Since the inductance of the metal ball is extremely small and can be ignored, the inductance is not considered in the simulation model. The impulse power supply is set to be an $8/20\mu$s standard lightning wave. The soil resistivity is set to the relation function between the resistivity of red soil and the electric field intensity. In other researches, the permittivity of soil is usually set as 1, 4, 5, 8 and 9 [2, 5, 14, 27]. In the research process of this paper, the permittivity of red soil is set to 8, which is within the experimental measurement range of 7.8–8.3. The distribution of the electric field intensity in the soil under the typical impulse voltage is shown in Figure 8.

As shown in Figure 8, the scattered lightning current in the soil around the metal ball will give rise to the formation of a dynamic ionization region with an inhomogeneous distribution. To be precise, the electric field intensity and the soil ionization increase with the decreasing distance between the soil area and the ball. Conversely, the expansion of the distance can weaken both electric field intensity and soil ionization. In addition, the higher the amplitude of the applied voltage, the greater the electric field intensity corresponding to the soil area, and the larger the area where the spark effect occurs.

To justify the model simulation results, an experimental verification is carried out. At different voltages, an impulse experiment is conducted on a concentric hemispherical experimental device. The experimental circuit is shown in Figure 9. On this basis, the impulse impedance value under different voltages is acquired and followed by the next comparative analysis with the simulation calculation results.

It can be seen from Figure 10 that the simulation calculation results of the impulse impedance are consistent with the field
measurement results. The average relative error is 4.2%. Moreover, as the amplitude of impulse voltage increases, the impulse grounding resistance decreases gradually. The phenomenon is in accordance with the law of nonlinear effect on impulse impedance. Therefore, the relation function curve of $\rho$ and $E$ obtained through the parallel plate experiment can be used to effectively simulate the nonlinear effect of soil.

3 | MODEL VALIDATION

3.1 | Analysis of harmonic grounding impedance and verification of inductance effect based on CFEM

Harmonic grounding impedance $Z(\omega)$ is a particularly important parameter to study grounding devices. $Z(\omega)$ is defined as the ratio of the ground potential rise and the injected current for a certain frequency $f$, where $\omega = 2\pi f$ is the angular velocity. To verify the correctness of the CFEM model considering the inductance effect, a simulation model of a box-shaped grounding device with a side length of 10 m $\times$ 10 m is established. The conductor material belongs to galvanized copper with a radius of 7 mm. The grounding device is buried 0.8 m below the ground, where the uniform soil is with a resistivity of 100 $\Omega \cdot m$. Then the impulse impedance including the impedance modulus and impedance angle is gained and compared with an international authoritative electromagnetic simulation software (CDEGS).

The comparative results are shown in Figure 11. It can be known that the numerical error of modulus and angle obtained from the proposed model and CDEGS keeps within 5%. In addition, under the frequency of 1 kHz, the harmonic grounding impedance is almost unchanged with the frequency increase of the injected current. But when the frequency exceeds 1 kHz, the harmonic grounding impedance gradually increases, and the impedance angle increases significantly. Therefore, conclusions can be derived that the CFEM established in this paper can accurately reflect the high-frequency inductance effect of the grounding system.

3.2 | Field experiment verification

For further model verification, a field experiment is conducted in the hemispherical copper simulated impulse sand pond, authorized by the Guangdong Power Grid Corporation Grounding Technology and Engineering Laboratory. The experimental sand pond is composed of a copper hemisphere with a diameter of 5 m and a depth of 3 m. The surge power source is a 900 kV/30 kA mobile high-power generator, which can generate standard $8/20\mu s$ lightning waves. The experiment site connection and test are shown in Figure 12.

In this paper, a single horizontal grounding conductor is used for the surge simulation test. The length and the radius of the conductor are 1.2 m and 3 mm, respectively. Its material is round steel. The conductor is buried 0.1 m below the ground. Besides, the hemispherical copper sand pond is filled with soil with the resistivity of 290 $\Omega \cdot m$. Figure 13 shows the comparison between the measured value and the calculated value of the model. The results indicate that the maximum relative error
Finally, through the comparison between CDEGS and the on-site experimental results, the correctness of this model is jointly verified.

3.3 Comparison and verification between models

The correctness of the inductance effect and soil nonlinear characteristics of the CFEM model are verified by CDEGS and field experiments respectively. In addition, it is more meaningful to compare the proposed model with other models. Therefore, this paper has conducted a comparative study with other models [28]. The simulation conditions are consistent with Section 3.2. The comparison results show that the proposed model follows well with the results of measurements and the calculation results of Garbagnati et al. [28]. As the injected current increases, the degree of soil ionization also increases, and the impulse impedance gradually decreases.

The root mean square error (RMSE) and mean absolute error (MAE) between the measured value and the calculated value of Garbagnati et al. are 18.38 and 16.38, which is larger than the proposed model. In addition, compared with the model of Garbagnati et al., the calculation of the proposed model is carried out in finite element software, where the data post-processing is more convenient and abundant. Another advantage is that it is very easy to obtain the potential and current distribution of the grounding device and various positions of the soil under different lightning current waveform and amplitude. These data can further evaluate the safety of personnel and equipment. Therefore, the proposed model not only enables to gain more accurate results, but also satisfies the needs of obtaining various effective data. The specific comparison results are shown in Figure 13 and Table 2.

3.4 The influence of CFEM on lightning performance study

The lightning current flowing from the tower grounding device to the surrounding soil will form a ground potential rise (GPR). And the value of GPR should also be the safety requirements of personnel and equipment. To show the influence of the CFEM model on the lighting performance study, this paper compares the ground potential rise simulation results of the CFEM model and the model without considering soil ionization. Taking the typical box and ray grounding device in mountainous areas as an example, simulation modelling is carried out. The injection current amplitude is 10 kA, and the waveform is a standard lightning current wave of 8/20 μs [29]. The GPR curve of the grounding device is shown in Figure 14.
It can be seen that the GPR of the proposed model is lower than that of the model without soil ionization. The soil ionization can be viewed as increasing the equivalent radius of the grounding conductor, which results in a decrease in the impulse impedance and a drop in the GPR. In addition, as the soil resistivity rises, the ionization degree of the soil also increases, and the spark effect becomes more obvious. Therefore, the proposed model can simulate the nonlinear effect of soil, calculate the impulse impedance, and estimate the GPR.

4 | RESEARCH ON THE METHOD OF IMPEDANCE-REDUCING FOR THE GROUNDING DEVICE IN MOUNTAINOUS AREAS WITH UNDERGROUND ROCK LAYERS

In China, abundant power transmission towers are built on mountains. The harsh surroundings around the mountain towers enlarge the difficulty of construction. On the one hand, the construction area of the grounding device is extremely limited. On the other hand, rock layers are distributed under the surface of almost all mountains. The large density and the resistivity of the rock layer greatly affect the lightning strike dispersion effect of the grounding device and cause too large impulse impedance. The rock layer distributes at a few meters to several tens of meters below the surface. Besides, the lightning stray flow of the rock layer at different depths is quite different. In this paper, the distribution of the rock layer is considered to be 2 meters below the grounding device and 10 meters below the ground device. In addition, the lightning current simulated in this paper is a standard lightning wave of 8/20 μs with a peak value of 50 kA.

4.1 | The grounding device below 2 m is a rock layer

Welding four external horizontal grounding electrodes (EHGE) on the corresponding corners of the grounding device is a traditional method of impedance-reducing. As proved in existing research, the impedance-reducing performs best when the angle between EHGE and the original edge of the corners is 135°. Due to the shielding effect between conductors, the increase of the current and the decrease of the conductor distance jointly strengthen the shielding effect. In addition, the tree-shaped EHGE can be effectively constructed to adapt to the limited construction area around the tower. The sketch map of EHGE is shown in Figure 15.

Mountainous areas generally have high electrical resistivity, which needs long enough EHGE to achieve impedance-reducing. However, the harsh mountainous environment makes it difficult to achieve the construction of EHGE. To better accomplish impedance-reducing in the limited construction space, metal short conductors (MSC) is added to each EHGE, as shown in Figure 16.

Due to the influence of the shielding effect of the ground electrode and the end effect, the number, length and arrangement of the MSC will have an impact on the overall impedance-reducing effect. Define the impedance-reducing rate of MSC per unit length as:

$$\eta = \frac{R_i - R_o}{L_M} \quad (19)$$

where $R_i$ is the impulse impedance before optimization; $R_o$ is the optimized impulse impedance; $L_M$ is the total length of the MSC material used. Assemble 10-m-long EHGE at the four corners of the 10 m × 10 m box-shaped grounding device, and weld the MSC at equal intervals on the EHGE.

When lightning current flows through the grounding device, the stronger the shielding effect among the conductors, the greater the difficulty of the scattered current. As can be seen from Figure 17, the rise of the MSC length brings about the drop of the impedance-reducing rate of MSC within per unit length. Specifically, when the length is about 0.5 m, the impedance-reducing rate of MSC within per unit length reaches the maximum. In other words, the 10 m length of a single EHGE, the same total length of the MSC material and the 0.5 m length of MSC jointly perform the optimal impedance-reducing effect. Changing the spacing of the MSC on the EHGE, the impedance-reducing rate of MSC within per unit length is shown in Figure 18.

Obviously, with the increase of MSC spacing, the impedance-reducing rate of MSC within per unit length shows an upward trend. But when the MSC spacing is too large, the number of MSC is inevitably reduced, and then the impulse impedance of the entire grounding device is difficult to reduce to an appropriate value. Therefore, the impedance-reducing rate of MSC
within per unit length performs well when the space of MSC is about 1 m and the number of MSC is sufficient.

Similarly, the above studies are carried out for EHGE of different lengths under different soil resistivity. The results show that, for the area with a rock layer 2 m below the surface, the grounding device will have the best impedance-reducing effect by controlling the length of a single MSC to be 4–6% of the single EHGE and the spacing between MSC to be 10–12% of the single EHGE. And this is built on the premise that the grounding material is constant.

Finally, this paper conducts a comparative study on the impedance-reducing effects of different grounding types in mountainous areas with rock layers 2 m below the surface. It is assumed that the total length of the added grounding materials is 64 m. The results are shown in Figure 19. The comparison shows that the difference between the impedance-reducing effects of the three methods is little when the total length of the added material is the same. Although the impedance-reduction of regular EHGE and Tree-shaped EHGE is relatively better, the method of EHGE combined with MSC is more suitable for the rock layer area 2 m below the surface, considering the limited extendable area or the construction area.

5 | THE GROUNDING DEVICE BELOW 10 METRE IS A ROCK LAYER

5.1 | EHGE with MSC

Similarly, the application of EHGE can effectively reduce impulse impedance. If the construction area is limited, the combination of EHGE and MSC can be given into consideration. Assemble 10 m EHGE at the four corners of the 10 m × 10 m box-shaped grounding device and weld MSC at equal intervals on the EHGE. The effects of the length and spacing of the MSC on the impedance-reducing rate are shown in Figures 20 and 21, respectively.

It can be seen from Figure 20 that the length of MSC is negatively correlated with the impedance-reducing rate of MSC.
within per unit length. When the total length of the MSC materials is the same, MSC with the length of 0.3 m has the best impedance-reducing effect. Additionally, it can be seen from the analysis in Figure 21 and Section 4.1 that in the area where there is rock 10 m below the surface, the optimal spacing arrangement between MSC is at about 1.1 m when the single EHGE of the grounding device is 10 m.

Furthermore, many simulation analyses are conducted for different lengths of EHGE under different soil resistivity. According to the research results, for the area with rock layers 10 m below the surface, the grounding device will perform the optimal impedance-reducing effect by controlling the single MSC length to be 3–5% of the single EHGE length and the spacing between the MSC to be 10–14% of the single EHGE. And this is built on the premise that the grounding material is constant.

5.1.1 EHGE with vertical grounding electrode

When multiple vertical grounding electrodes (VGE) are adopted, the shielding effect between them is usually large because each vertical grounding pole is parallel to the other. To effectively utilize them, four VGE are first arranged at the junction of EHGE and the frame. Then equidistantly arrange outward along the EHGE direction, as shown in Figure 22. To be more specific, Figure 23 shows the value variation of the impulse impedance with the position of VGE.

It can be known from Figures 22 and 23 that the overall impulse impedance tends to decline as the VGE layout moves outward. In other words, the overall impedance-reducing effect of the grounding device is the best when the vertical grounding pole layout is at the end of EHGE. To further explore this rule, keep the total length of the grounding material unchanged and compare two typical layout schemes. In the first arrangement, the VGE are placed at the end of the EHGE as well as the connection point between the EHGE and the frame (i.e. point 5 and point 1), respectively. In the second arrangement, the VGE are fixed at the end of the EHGE and in the middle of the EHGE (i.e. point 5 and point 1), respectively. Table 3 shows the impulse impedance when the length of VGE changes in the two layout schemes.

It can be seen from Table 3 that only four VGE arranged at the end of four EHGE have the best impedance-reducing optimization effect when the total length of the VGE is constant. And this point can still be verified by changing different lightning current amplitude and soil resistivity in the simulation.

5.1.2 Comparison of impedance-reducing effects of various optimization methods

When the total length of the added impedance-reducing material is the same, the impedance-reducing effect of various optimization measures is compared as shown in Figure 24.
TABLE 3  Impulse impedance when the length of the VGE change in the two layout schemes

| Layout schemes          | Length of VGE in point 1 or point 3 (m) | Length of VGE in point 5 (m) | Impedance (Ω) |
|------------------------|----------------------------------------|------------------------------|---------------|
| First arrangement      | 9                                      | 1                            | 43.27         |
|                        | 7                                      | 3                            | 43.25         |
|                        | 5                                      | 5                            | 42.79         |
|                        | 3                                      | 7                            | 41.64         |
|                        | 1                                      | 9                            | 40.02         |
|                        | 0                                      | 10                           | 38.12         |
| Second arrangement     | 9                                      | 1                            | 41.60         |
|                        | 7                                      | 3                            | 41.20         |
|                        | 5                                      | 5                            | 40.59         |
|                        | 3                                      | 7                            | 39.32         |
|                        | 1                                      | 9                            | 38.78         |
|                        | 0                                      | 10                           | 38.12         |

FIGURE 24  Comparison of impedance-reducing effects when the total length of the added impedance-reducing material is the same

Among them, the size of the mouth-shaped grounding device is 10 m × 10 m and the buried depth is 0.8 m. Besides, there is a rock layer 10 m below the grounding device. The total length of the added grounding material is 58 m. It can be seen from Figure 24 that the order of impedance-reducing effect (from advantage to disadvantage) is EHGE, EHGE + VGE, EHGE + MSC and EHGE + VGE + MSC. Therefore, considering the complexity of the mountainous terrain and the limitations of the construction area, it is more appropriate to reduce the impulse impedance by installing EHGE and welding VGE with an appropriate ratio at the end of the EHGE on the grounding device.

6  | CONCLUSION

In this paper, a function curve between soil resistivity and electric field intensity is obtained through experiments, and a CFEM considering soil nonlinear effects is established, and field test verification is carried out. In addition, aiming at the mountainous areas with rock layers under the earth surface, this paper proposes the optimization method of impedance-reducing and presents the optimal design method and layout type of transmission tower grounding device containing rock layer.

On the one hand, the variation curves of soil resistivity with an electric field intensity of five typical soils are obtained through the parallel plate test platform. The results showed that the nonlinear characteristics of different types of soil are greatly different. The degree of nonlinear change of resistivity of red soils and yellow soils is obvious, while that of fine sand and arenosol is little. By constructing a concentric hemispherical model with soil nonlinear effects and carrying out experimental research, the average relative error between the test results and the model calculation results is only 4.4%. On this basis, considering the inductance effect of the grounding device, the CFEM of the grounding system is established. Compared with the CDEGS software, the error is within 5%. Based on the high-current impulse generator, field tests are conducted on a single horizontal conductor. The MRE between the proposed model and the actual measurement was only 4.67%, which verified the accuracy of the model.

On the other hand, based on the established CFEM, this paper conducts the impedance-reducing optimization method study on the grounding device with rock layers 2 m and 10 m below the grounding device in mountainous areas. The research results are as follows:

1. For the area where there is a rock layer 2 m below the grounding device, the effect of impedance-reducing is best when the MSC length is 3%-5% of the EHGE and the MSC spacing is 10%-12% of the EHGE.
2. For the area where there is a rock layer 10 m below the grounding device, the impedance-reducing effect is best when the MSC length is 4%-6% of the EHGE and the MSC spacing is 10%-14% of the EHGE.
3. When a VGE is used, the impedance-reducing effect is best when the VGE is placed at the end of the EHGE.
4. When there is a rock layer 2 m below the grounding device, the effects of various impedance-reduction methods are similar. However, considering the limited extendable area or construction area of the area, it is recommended to use the method of EHGE combined with MSC.
5. When there are rocks 10 m below the grounding device, the combination of EHGE + VGE has a better impedance-reducing effect.

The research results can provide a reference for the design transformation and protection optimization of the transmission tower grounding device in mountainous areas.

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**REFERENCES**

1. Christodoulou, C.A., et al.: Effect of the grounding resistance to the behaviour of high-voltage transmission lines’ impulse arresters. IET Sci. Meas. Tech. 8(6), 470–478 (2014)
2. Liu, Y.Q., et al.: An engineering model for transient analysis of grounding system under lightning strikes: Nonuniform transmission-line approach. IEEE Trans. Power Delivery 20(2), 722–730 (2005)
3. Gerti, A., et al.: Non-linear behaviour of ground electrodes under lightning impulse currents: Computer modelling and comparison with experimental results. IEEE Trans. Magn. 28(2), 1442–1445 (1992)
4. He, J., et al.: Effective length of counterpoise wire under lightning current. IEEE Trans. Power Delivery 20(2), 1585–1591 (2005)
5. Chiheb, S., et al.: Transient behaviour of grounding electrodes in uniform and in vertically stratified soil using state space representation. IET Sci. Meas. Tech. 12(4), 427–435 (2018)
6. Gerti, A.: Behaviour of grounding systems excited by high impulse currents: The model and its validation. IEEE Trans. Power Delivery 14(3), 1008–1017 (1999)
7. Gupta, B.R., Thapar, B.: Impulse Impedance of Grounding Grids. IEEE Trans. Power Appar Syst. PAS-99(6), 2357–2362 (1980)
8. Otero, A.F., et al.: Frequency-dependent grounding system calculation by means of a conventional nodal analysis technique. IEEE Trans. Power Delivery 14(3), 873–878 (1999)
9. Grecv, L.: Modeling of grounding electrodes under lightning currents. IEEE Trans. Electromagn. Compat. 51(3), 559–571 (2009)
10. Hajianic, A., Trlep, M.: The simulation of the soil ionization phenomenon around the grounding system by the finite element method. IEEE Trans. Magn. 42(4), 867–870 (2006)
11. Nekhoul, B., et al.: A finite element method for calculating the electromagnetic fields generated by substation grounding systems. IEEE Trans. Magn. 31(3), 2150–2153 (1995)
12. Grecv, L.: Impulse efficiency of ground electrodes. IEEE Trans. Power Delivery 24(1), 441–451 (2009)
13. Visacro, S., Alipio, R.: Frequency dependence of soil parameters: Experimental results, predicting formula and influence on the lightning response of grounding electrodes. IEEE Trans. Power Delivery 27(2), 927–935 (2012)
14. Liu, K., et al.: Estimation of critical electric field of soil ionisation based on tangential electric field method. IET Sci. Meas. Tech. 9(6), 758–764 (2015)
15. Nor, N.M., et al.: Determination of Threshold Electric Field of Practical Earthing Systems by FEM and Experimental Work. IEEE Trans. Power Delivery 28(4), 2180–2184 (2013)
16. Yunus, M., et al.: Performance of earthing systems for different earth electrode configurations. IEEE Trans. Ind. Appl. 51(6), 5335–5342 (2015)
17. Meng, Q., et al.: A new method to decrease ground resistances of substation grounding systems in high resistivity regions. IEEE Trans. Power Delivery 14(3), 911–916 (1999)
18. Yang, S., et al.: Factors affecting the impact characteristics of framed beam type grounding body. High Voltage Eng. 42(5), 1548–1555 (2016)
19. Yuan, T., et al.: Analysis of impulse earthing resistance reduction for grounding extreme diffusion efficiency. Trans. China Electrotechnical Soc. 27(11), 278–284 (2012)
20. Gong, R., et al.: Performance comparison between flexible graphite-copper composites grounding material and conventional grounding materials. In: 2016 IEEE International on High Voltage Engineering and Application, Chengdu, China, 19–22 September pp. 1–5 (2016)
21. Asadpourzamadchali, M., et al.: Hybrid continuous circuit-trapezoidal integration method analysis of multi-cross structure of grounding system. IET Sci. Meas. Tech. 14(5), 292–302 (2020)
22. Sunde, E.D.: Earth Conduction Effects in Transmission Systems, New York, NY, USA: In:Bell Telephone Laboratories Incorporated, (1968)
23. Grecv, L., Popov, M.: On high-frequency circuit equivalents of a vertical ground rod. IEEE Trans. Power Delivery 20(2), 1598–1603 (2005)
24. Terman, F.: Radio engineers handbook, NY: In:Mc Graw-Hill Book Company, (1943)
25. Rizk, M.E.M., et al.: Performance of large-scale grounding systems in thermal power plants against lightning strikes to nearby transmission towers. IEEE Trans. Electromagn. Compat. 61, 400–408 (2019)
26. Kherif, O., et al.: Time-domain modeling of grounding systems’ impulse response incorporating nonlinear and frequency-dependent aspects. IEEE Trans. Electromagn. Compat. 60(4), 907–916 (2018)
27. Zeng, R., et al.: Lightning Impulse Performances of Grounding Grids for Substations Considering Soil Ionization. IEEE Trans. Power Delery 23(2), 667–675 (2008)
28. Garbagnati, E., et al.: Non-linear behavior of ground electrodes under lightning surge currents: Computer modeling and comparison with experimental results. IEEE Trans. Magn. 28(2), 1442–1445 (1992)
29. IEC1312: Protection against lightning electromagnetic Impulse, (1995)

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