Simulation Analysis of Impulse Characteristics of Grounding Electrode in High Altitude Area

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ABSTRACT: In order to study the effect of the structure and material of the grounding electrode on the impulse grounding resistance in the soil condition of high altitude area, the soil model of a high altitude area was measured on site, and the influence of the structure and material of the grounding electrode on the impulse characteristics of the grounding electrode was studied by simulation analysis method. The results show that the impulse grounding resistance is the lowest when the Angle of ray is 45°. With the increase of the total length of the grounding electrode, the impulse grounding resistance decreases with the increase of the number of ray roots, and the effective impulse length exists. The graphite type grounding electrode has better performance than the traditional metal grounding electrode, and the graphite based flexible grounding electrode can be preferred in the area of high soil resistivity. The addition of vertical grounding electrode can effectively reduce the impulse grounding resistance of horizontal grounding electrode, and the highest resistance reduction rate can reach 31.73%. The research results can provide some guidance for the design of grounding electrode in high altitude area.

INDEX TERMS grounding electrode; CDEGS; impulse grounding resistance; resistance reducing

I. INTRODUCTION

Among the many factors that affect the safe and stable operation of overhead transmission lines, the grounding electrode of transmission tower plays an extremely important role. It is the key channel of lightning current and fault current scattering, which directly relates to the lightning protection level and grounding performance of the line[1-3]. In view of the fact that high-voltage lines often need to pass through areas with high soil resistivity such as plateau frozen soil, these areas not only have high impulse grounding resistance, but also frequently encounter lightning attacks, which greatly increases the risk of the line suffering from counterattack overvoltage and tripping, posing a serious challenge to the safety of the power system[4].

In recent years, the research on the use of CDEGS software to optimize grounding design is increasingly rich[5-10]. In particular, the in-depth analysis of lightning impulse characteristics is focused. Karol et al. verified the reliability of CDEGS frequency domain calculation by comparing the variation of electromagnetic field of the ground device under simulated lightning flow with seven different programs, including CDEGS[11]. Wu Hao specifically discussed the influence of soil resistivity, grounding electrode size and other parameters on the lightning flow effect of the tower grounding device[12]. Zhu Zewei's team calculated the grounding potential distribution by CDEGS, providing a scientific basis for preventing lightning strikes[13]. Ma Yutang et al. verified the consistency of CDEGS and Matlab algorithms in the calculation of impulse response voltage under discrete lightning current conditions[14].Considering the frequency variation characteristics of soil under lightning impulse, Daniel et al. proposed a formula based on one-dimensional transmission line model to calculate the surface potential rise caused by the grounding body current, and applied it to the horizontal grounding electrode. CDEGS verified that the calculation accuracy of the formula was good[15]. Li Jingli et al. further modeled and simulated the influence law of soil resistivity, impulse current waveform and other factors on the impulse coefficient of the grounding device when considering soil frequency variability[16]. Literature [17-19] compared the impulse grounding performance of graphite-based flexible grounding electrode with traditional metal grounding electrode, and analyzed the feasibility of practical engineering application of graphite-based flexible grounding electrode in high soil resistivity area. Liu Xinghua et al. verified by CDEGS simulation that the additional vertical grounding electrode has a certain resistance reduction effect on the tower grounding network[20].

In summary, the impulse characteristics of various types of grounding electrode are comprehensively analyzed in the present research, which provides a good reference for practical engineering applications. On this basis, in view of the soil conditions in the high altitude area, this paper adopts the simulation analysis method to discuss in detail the structural parameters and material selection of the grounding electrode with the beam line in the box, and evaluates the resistance reduction efficiency of the additional vertical grounding electrode, aiming to provide strong support for the grounding electrode selection and resistance reduction strategy in practical engineering.

II. SIMULATION MODEL CONSTRUCTION AND PARAMETER SELECTION

A. MEASUREMENT AND INVERSION OF SOIL RESISTIVITY

The terrain of Tibet is complex and diverse, with an average altitude of more than 4000m, low soil organic matter and water content, calcium accumulation and gypsum layer in the surface or subsurface layer, and even bare gravel, resulting in high soil resistivity and difficult resistance reduction in the grounding electrode. In this paper, a typical area with an altitude of 4300m in Tibet was selected to measure the soil resistivity by using the Wenner quadrupole method. The Weinner quadrupole method is the most commonly used method to measure the soil resistivity of layered structure, and the principle diagram of soil resistivity measurement by this method is shown in Figure 1.

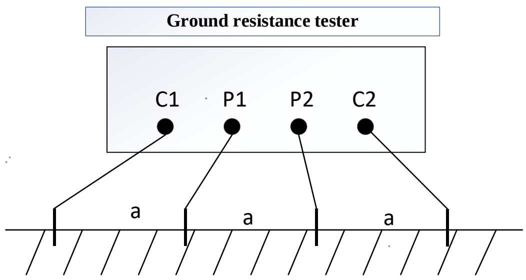

FIGURE 1. Schematic diagram of soil resistivity test

The four electrodes are buried in the ground along a straight line with equal spacing A, and the test current forms a loop from the current poles C1 and C2 through the ground. The grounding resistance tester measures the potential difference through the potential poles P1 and P2, and calculates the grounding resistance R. After the ground resistance R is measured, the soil resistivity ρ=2πaR. Change the pole spacing a and measure R several times to ensure the accuracy of the measurement results. Due to the complex soil structure in Tibet, a three-layer model is adopted in this paper[21]. Using the RESAP module of the grounding analysis software CDEGS, the actual hierarchical structure model of soil was obtained by inversion, as shown in Table 1. It can be seen from Table 1 that the resistivity of soil in this area is higher than that of ordinary soil, especially the resistivity of soil in the middle layer is as high as 2390.59Ω·m, which brings certain difficulties to the design of the grounding electrode.

TABLE I

Inversion results of soil resistivity stratification parameters

soil layer	thickness (m)	soil resistivity (Ω·m)
surface layer	1.14	553.33
intermediate layer	9.27	2390.59
bottom layer	∞	347.27

B. PARAMETER SELECTION OF TOWER GROUNDING ELECTRODE

The grounding device of the tower is usually based on the box type. In this paper, the impulse grounding resistance of different grounding devices is studied by adding horizontal rays on the basis of the box type grounding device, and by changing the material and structure of the grounding device.

In this paper, 3 types of box belt with 4 rays, box belt with 8 rays and box belt with 12 rays are adopted, which are respectively represented by type 1, type 2 and type 3. Simulation modeling is carried out by HIFREQ and FFTSES modules of grounding analysis software CDEGS. The models of 3 types are shown in Figure 2. In the model shown in Figure 2, the length of the square edges is 20m, the radius r of all conductors is 0.01m, the buried depth of all horizontal grounding electrodes is 0.8m, and the materials are galvanized steel. The Angle of the ray in the model of type 1 is 45° with the extension line of the side of the box, the Angle of the ray in the model of type 2 is coincided with the extension line of the box, and the ray in the model of type 3 is the combination of the rays in type 1 and type 2. The soil model in this paper adopts the layered structure model of soil resistivity measured in Section 2.1. The inrush current is injected into the four vertices of the box. The inrush current injected is the standard lightning current with amplitude of 10kA and waveform of 2.6/50μs. The FFTSES module of CDEGS software is used to perform Fourier transform on the impulse current, and the impulse is decomposed into the superposition of multiple sinusoidal currents. The frequency response of the grounding electrode in each sinusoidal current is calculated in the HIFREQ module, and then the time domain response of the grounding electrode is obtained by the inverse Fourier transform in the FFTSES module. Finally, the impulse characteristics of the grounding electrode under the impulse current are obtained by superimposing the calculated results.

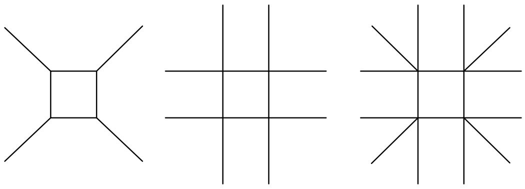

FIGURE 2. Simulation model of grounding device

The commonly used grounding materials are galvanized steel, stainless steel, graphite, etc. In this paper, the above three materials are selected as the research object to compare the impulse characteristics of the grounding electrode of different materials. The relevant simulation parameters of the three materials are shown in Table 2.

TABLE II

Calculation parameters of grounding materials

grounding material type	relative (copper) resistivity	relative (copper) permeability
galvanized steel	10	636
stainless steel	40	636
graphite	1828	1

III.ANALYSIS OF SIMULATION RESULTS

A. INFLUENCE OF GROUNDING ELECTRODE RAY ANGLE

In order to study the effect of the horizontal ray Angle on the earth pole impulse grounding resistance, the Type 1 model is selected for simulation analysis. Type 1 grounding electrode parameters are selected as follows. The box side length is 20m, the ray length is 50m, the conductor radius is 0.01m, the burial depth is 0.8m, and the material is galvanized steel. It is considered that the ray arrangement as shown in FIG. 3 (a) means that the ray Angle is 0°, the ray arrangement as shown in FIG. 3 (b) means that the ray Angle is 45°, and the ray arrangement as shown in FIG. 3 (c) means that the ray Angle is 90°, and the ray Angle varies from 0 to 90°. The simulation results are shown in Figure 4.

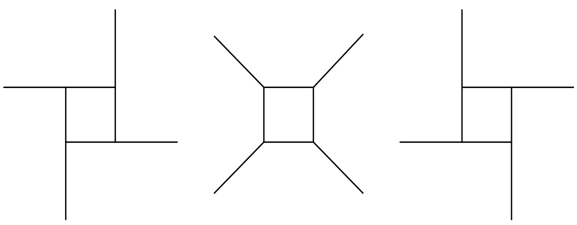

FIGURE 3. Schematic diagram of Type 1 grounding electrode ray Angle

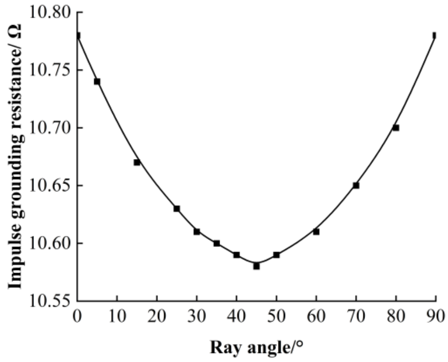

FIGURE 4. Comparison of impulse grounding resistance of type 1 at different ray angles

It can be seen from Figure 4 that the ray Angle has a certain influence on the impulse grounding resistance of type 1: When the ray Angle is 45°, the shielding effect between the grounding rays is the smallest, and the impulse grounding resistance of the grounding electrode of type 1 is the smallest, which is 10.59Ω. Overall, the impulse of the ray Angle is not significant, and the impulse grounding resistance at a ray Angle of 45° is only 2.03% lower than that at a ray Angle of 0° (90°). To sum up, when the Type 1 grounding electrode is designed in this area, it is recommended that the ray Angle be arranged between 45° in order to reduce the impulse grounding resistance.

B. INFLUENCE OF THE NUMBER OF GROUNDING ELECTRODE RAYS

The number of ray roots in the grounding electrode directly affects the number of impulse current diffusing in the soil, thus affecting the impulse grounding resistance of the grounding electrode. In order to analyze the above effects, three kinds of box models with 4 rays (type 1), 8 rays (type 2) and 12 rays (type 3) were selected for simulation analysis. Under the condition that the total length of the grounding electrode is unchanged, the influence of different number of roots on the impulse grounding resistance of the grounding electrode is compared, and the total length of the grounding electrode is 140m, 200m, 260m, 320m, 380m and 440m. The box side length of the three models is 20m, and the length of each ray of each model is the same under different total lengths. The specific length of each ray is shown in Table 3. The conductor radius is 0.01m, the buried depth is 0.8m, and the material is galvanized steel.

TABLE III

Ray lengths of each model with different total lengths

Model	Total length					
	140	200	260	320	380	440
Type 1	15	30	45	60	75	90
Type 2	7.5	15	22.5	30	37.5	45
Type 3	5	10	15	20	25	30

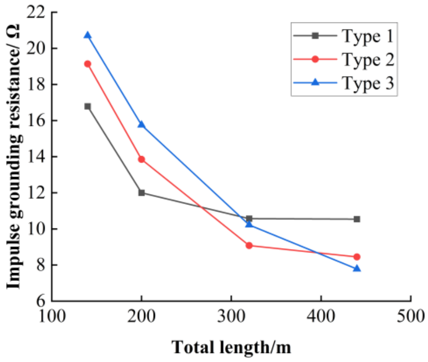

FIGURE 5. Comparison of impulse grounding resistance with different number of ray roots in the grounding electrode

As can be seen from Figure 5, when the total length of the grounding electrode is short, that is, the length of the ray is short, the impulse grounding resistance of the grounding electrode is type 3, type 2, and type 1 in order from large to small. With the increase of the total length of the grounding electrode, the impulse grounding resistance of the grounding electrode is type 3, type 1 and type 2 from large to small. The total length of the grounding electrode continues to increase, and the impulse grounding resistance of the grounding electrode is type 1, type 3, and type 2 from large to small. When the total length of the grounding electrode is increased to a certain length, the impulse grounding resistance of the grounding electrode is type 1, type 2 and type 3 from large to small. When the ray length is short, the type 1 grounding electrode should be given priority. When the ray length is long, the optimal grounding electrode is type 3. With the increase of ray length, the impulse grounding resistance of the three types of grounding electrode decreases, and the overall impulse grounding resistance decreases gradually, and then remains basically unchanged. The impulse grounding resistance of the grounding electrode does not decrease continuously with the increase of the ray length. When the ray length increases to a certain value, the impulse grounding resistance gradually tends to a constant value, which is the effective impulse length of the grounding electrode.

In summary, when the total length of the grounding electrode of the beam line is low, the impulse grounding resistance of type 1 is the smallest. With the increase of the total length, the length of the grounding electrode ray of type 1 first reaches the effective length, then the grounding electrode ray of type 2 reaches the effective length, and the grounding electrode ray of type 3 finally reaches the effective length. The increase in the number of ray roots is mainly to increase the current drain channel, thereby reducing the impulse grounding resistance of the grounding electrode. However, there is a certain mutual shielding effect between the conductors buried in the soil. With the increase in the number of ray roots, this shielding effect will be more obvious, affecting the impulse characteristics of the grounding electrode. In areas with high soil resistivity, the impulse current is difficult to diffuse in the soil, and can only diffuse to the end of the horizontal ray at the grounding electrode, the more fully used the ray, the longer the effective length of the ray impulse. Therefore, when designing the grounding electrode of the tower in this area, the length and number of rays can be appropriately increased according to the actual situation of the project, but considering the shielding effect between rays and the effect of the effective length of rays, The number of rays should not be too large and the length of rays should not be too long.

C.IMPULSE OF DIFFERENT GROUNDING MATERIALS

Different grounding materials have different characteristics. Galvanized steel is the most commonly used grounding electrode material in our country because of its low price, but the corrosion resistance of galvanized steel is poor; Compared with galvanized steel, stainless steel has better corrosion resistance, but the price is more expensive and the electrical conductivity of stainless steel is poor; The conductive effect of graphite is mainly achieved by the movement of electrons between carbon atoms, the material itself does not exist electrolytic corrosion, so graphite has good electrical conductivity and corrosion resistance, but the structure of graphite is looser than that of metal and more vulnerable to damage.

In this section, Type 3 model is selected to simulate and analyze the effect of grounding electrode of galvanized steel, stainless steel and graphite on impulse grounding resistance. The research only considers the resistivity and permeability of the three materials, without considering other properties of the materials. The relevant calculation parameters of the three materials are shown in Table 2. Type 3 grounding electrode box side length is 20m, ray length is 20m, 40m, 60m, 80m, 100m, buried depth is 0.8m. The calculation results are shown in Figure 6.

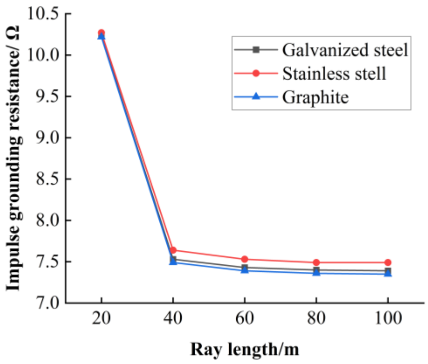

FIGURE 6. Comparison of impulse grounding resistance in different materials of grounding electrodes

As can be seen from Figure 6, when the ray length is 10m, the impulse grounding resistance of the grounding electrode of the three materials is 15.76Ω, and the impulse grounding resistance decreases with the increase of the ray length. When the ray length is 100m, the impulse grounding resistance of each material is 8.27Ω of stainless steel, 8.37Ω of galvanized steel, and 8.41Ω of graphite from small to large. The results show that the grounding performance of graphite is better than that of traditional metal materials from the perspective of impulse grounding resistance, but the thermal stability of traditional graphite grounding electrode is not as good as that of traditional metal materials because of the polymer adhesive. Therefore, the design of the grounding electrode in this area can adopt a new flexible graphite grounding material, which can make the graphite with good electrical conductivity soft reform, so that its electrical, physical and chemical properties can meet the requirements of engineering construction.

D. RESISTANCE REDUCTION ANALYSIS OFADDITIONAL VERTICAL GROUNDING ELECTRODER

When reducing resistance in high soil resistivity area, it is one of the common methods to consider installing a vertical grounding electrode. In order to further study the impulse of additional vertical grounding electrodes on the impulse characteristics of the original grounding electrode, 5m, 10m, 20m, 40m and 60m vertical grounding electrodes were installed on the injection points of model 1, model 2 and model 3, respectively. The models after the addition of vertical grounding electrodes are shown in Figure 7. Each model has a square frame length of 20m, a ray length of 50m, and a buried depth of 0.8m. The material is galvanized steel. Simulation analysis of the impulse grounding resistance of each model after installing 0m, 5m, 10m, 20m, 40m and 60m vertical grounding electrodes respectively. The calculation results are shown in Figure 8. After installing the vertical grounding electrode, the resistance reduction of each model is shown in Figure 9.

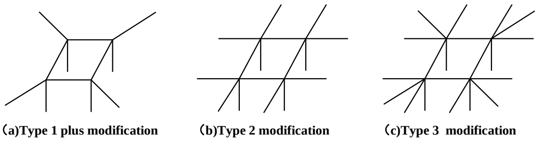

FIGURE 7. Schematic diagram of each model with vertical grounding electrode

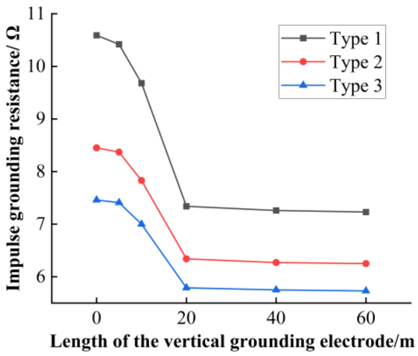

FIGURE 8. The impulse grounding resistance diagram of each grounding electrode with additional vertical grounding electrode

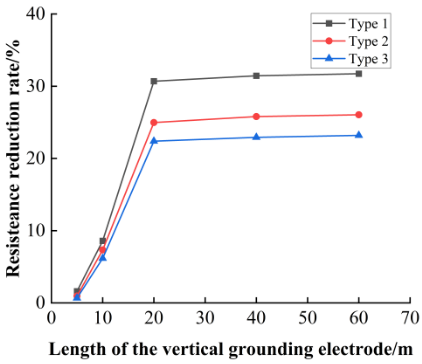

FIGURE 9. Resistance reduction rate of each grounding electrode with additional vertical grounding electrode

The calculation results show that the additional vertical grounding electrode has significant resistance reduction effect on type 1, type 2 and Type 3 grounding electrodes. When the vertical grounding electrode length is short, the impulse grounding resistance of each model grounding electrode decreases significantly with the increase of the vertical grounding electrode length. The resistance reduction rate of type 1 model with 60m vertical grounding electrode is the highest, which is 31.73%, and the impulse grounding resistance value of type 3 model with 60m vertical grounding electrode is the lowest, which is 5.73Ω. Due to the shielding effect between conductors and the effective length of conductor impulse, the length of the vertical grounding electrode increases linearly, and the decrease of the grounding resistance of the grounding electrode impulse is limited, and gradually tends to a constant value. The analysis shows that the additional vertical grounding electrode has a significant drag reduction effect, but with the increase of the length of the vertical grounding electrode, the drag reduction rate gradually tends to saturation. Therefore, when selecting the additional vertical grounding electrode to reduce the drag, the desired effect cannot be achieved by blindly increasing the length of the vertical grounding electrode. In practical engineering, it is necessary to choose the length of the vertical grounding electrode reasonably according to the engineering site to design the grounding electrode model that meets the engineering requirements.

IV. CONCLUSION

In summary, the impulse grounding resistance of the grounding electrode is affected by the structure of the grounding electrode (ray Angle, ray number, ray length) and the material of the grounding electrode. The main conclusions include the following aspects: Based on the soil resistivity data measured on site in typical areas of Tibet and through simulation analysis, this paper has certain guiding significance for the design and optimization of grounding electrodes in practical projects at high altitudes. The main conclusions are as follows:

1) in view of the box with 4 root level lines (type 1) grounding, ray Angle have influence on the impulse grounding resistance butt the ends of the earth, but the overall effect was not significant, when the ray Angle 45 ° with extension into the box for the optimal layout.

2) When the total length of the grounding electrode is long, the impulse grounding resistance of the type 3 grounding electrode is minimum, and the type 3 grounding electrode should be preferred in the actual project; When the total length of the grounding electrode is moderate, the impulse grounding resistance of the type 2 grounding electrode is minimum, and the type 2 grounding electrode should be preferred in practical engineering. When the total length of the grounding electrode is short, the impulse grounding resistance of the type 1 grounding electrode is the smallest, and the type 1 grounding electrode should be preferred in practical engineering.

3) The grounding performance of different material grounding electrodes is graphite, galvanized steel, stainless steel from high to high, but considering that the traditional graphite grounding electrode is usually bonded by polymer adhesive, its dynamic thermal stability is not as good as traditional metal materials, priority can be given to new flexible graphite grounding materials when choosing graphite grounding electrodes.

4) The addition of a vertical grounding electrode at the injection point has a certain resistance reduction effect, of which the resistance reduction of the type 1 grounding electrode is the largest, up to 31.73%, and the impulse grounding resistance of type 3 is the smallest, up to 5.73Ω. It is worth noting that the drag reduction effect tends to be saturated with the increase of the length of the vertical grounding electrode. Therefore, in practical engineering, when considering additional vertical grounding electrode to reduce resistance, the length of vertical grounding electrode should be scientifically planned to achieve maximum benefit.

In addition, because the CDEGS software neglects the soil spark effect in the simulation process, the calculated impulse grounding resistance value of the grounding electrode may be higher than the actual value in theory. Although the spark effect is not considered, the basic trend of the influence of the grounding electrode structure and material changes on its grounding performance is still clear, and it is still of guiding significance for practical engineering applications. Future studies can further focus on the soil spark effect to fully analyze its specific impulse on the grounding electrode impulse grounding resistance.

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[18] W. X. Xiao, D. C. Huang, J. J. Ruan, H. Wei, Q. H. Zhan, and Y. C. Hu, “Comparison of shock grounding performance between graphite-based flexible grounding bodies and metal Achievements at Three Gorges University. He has also been honored multiple times with titles such as Outstanding Teacher and Outstanding Party Worker at Three Gorges University. His current research focuses on new types of power system grounding and high voltage testing technology, power system grounding technology, consulting and operation & maintenance services for green power engineering construction, as well as the digital transformation of the energy industry and digital asset operations in the context of carbon neutrality.