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Fitting algorithm of transmission tower grounding resistance in vertically layered soil models

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ABSTRACT

It could be quite complicate to calculate the accurate grounding resistance of transmission line towers in an vertically layered soil model, which could bring excessive time consumption and computation load to many engineering applications. In order to calculate the resistance fast and conveniently while keeping necessary accuracy, we propose an algorithm that uses the least squares curve fitting method and hyperbolic fitting functions to fit the resistivity and grounding resistance of layered soil model. An expression of the fitting function and the fitting formula of tower grounding resistance are derived theoretically according to application demands. We applied the algorithm to calculate a practical case and the result has error less than 10%.

1. Introduction

The power network in China is developing quickly. Since the line corridors are limited, regions with high lightning trip-out rates are inevitably selected for new power lines, and this may bring increasing likelihood of lightning disasters to power networks and cause huge losses. Thus grounding resistance, as a key index parameter for grounding systems that greatly influences the efficacy and safety of transmission line systems, is getting more and more important in system designs [1].

In the designing process of a grounding system, earth is generally regarded as infinite uniform soil, while the anisotropy of soil resistivity and many other factors that are excessively complex for regular regulations are ignored in calculations. However, uniform soil is only an ideal case that almost non-practical. To this end, Nahman et al. developed non-uniform soil models and based on modifying Schwarz's formula they proposed a theoretical formula of grounding resistance for double-layer soil models, which is considerably complicated [2]. To calculate grounding resistance of grounding body in layered soil models intuitively and quickly, Dawalibi proposed a graphical method, which is still not convenient enough since it involves a large amount of complex drawing works.

With the development of computers and numerical electromagnetic field simulation techniques, the complex image method [3,4] and the base image method [5,6], both based on Green's function, are widely used in the parameter calculations of grounding systems. However, these two methods have high demands for computer resources that scales up quickly with the increase of complexity of soil structure, and due to their complexity, they could are not friendly to average engineers.

Hence, we developed a relatively easy but still accurate enough method to calculate grounding resistance for common engineering applications. Taking circular compound grounding device with horizontal rays (which is presently the most commonly used in transmission line towers) for example, we used the least squares curve fitting method to fit exact theoretical values into a complex soil model, and acquired a fitting formula of tower grounding resistance for soil models of two vertical layers.

2. Conventional algorithm of tower grounding resistance calculation

2.1. Conventional algorithm of grounding resistance calculation in transmission line designing

The calculation methods of power-frequency grounding resistance are classified according to the types of grounding bodies. Formulas recommended in variety of standards [7–9] are used to calculate grounding resistance for simple grounding bodies such as

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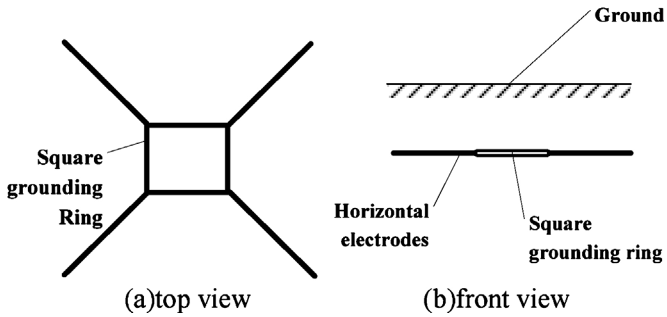

Fig. 1. Tower grounding device.

vertical grounding bodies, horizontal grounding bodies and circular grounding bodies, and the coefficient method or the resistance coefficient method for complex grounding bodies made up of simple artificial objects including tubes, belts and ring grounding bodies.

2.1.1. Coefficient of utilization method

The basic idea of coefficient method is that comprehensive power-frequency grounding resistance could be obtained by combining a number of parallel resistances, which is calculated using utilization coefficients that reflect the mutual shielding influences between grounding bodies.

Ref. [10] listed the formulas of power-frequency grounding resistance for five types of artificial grounding bodies, including compound grounding devices with n horizontal rays, compound grounding devices with grounding rings and deeply-buried lead wires, compound grounding devices with deeply-buried rings and horizontal rays, compound grounding devices with vertical electrodes, and compound grounding devices with horizontal electrodes.

Fig. 1 shows a comprehensive grounding device comprised of grounding rings and horizontal rays. To calculate its grounding resistance in designing, it can be divided into a compound grounding device with n horizontal rays and a grounding device with square grounding rings by unit, like the simple artificial grounding bodies given by standards [8–10]. The device with n horizontal rays can be further divided into a number of single horizontal grounding bodies. Then the final calculation formula of grounding resistance is obtained as Eq. (1).

$$R_4 = \frac{R_3 \times \frac{R_1}{n_1} \times \frac{R_2}{n_2}}{R_3 \times \frac{R_1}{n_1} + \frac{R_2}{n_2}\left(R_3 + \frac{R_1}{n_1}\right)} \times \frac{1}{\eta} \tag{1}$$

where, R_1 is the grounding resistance of a single ray; R_2 is the grounding resistance of grounding ring; R_3 is the grounding resistance of compound grounding device in Fig. 1; n_1 is the number of horizontal electrodes, here $n_1 = 4$; η is utilization coefficient.

2.1.2. Resistivity method

Considering the similarity between current field and electrostatic field under the ground, potential equations of each grounding body can be obtained as follows:

$$\begin{aligned} \varphi_1 &= R_{11}I_1 + R_{12}I_2 + \cdots + R_{1n}I_n \\ \varphi_2 &= R_{21}I_1 + R_{22}I_2 + \cdots + R_{2n}I_n \\ &\cdots \\ \varphi_n &= R_{n1}I_1 + R_{n2}I_2 + \cdots + R_{nn}I_n \end{aligned} \tag{2}$$

where $I_1, I_2, \ldots, I_n$ are conduction currents of each grounding body, $\varphi_1, \varphi_2, \ldots, \varphi_n$ are potentials of each grounding body, R_{ik} is mutual resistance coefficient between body i and body k, and R_{kk} is self-resistance coefficient of body k.

Since the grounding bodies are set in parallel, the boundary condition is

$$\begin{aligned} &\varphi_1 = \varphi_2 = \cdots = \varphi_n = \varphi \\ &I_1 = I_2 = \cdots = I_n = I \\ &R_{ij} = R_{ji} \end{aligned} \tag{3}$$

Combining Eqs. (2) and (3), grounding resistance of the grounding device can be solved based on Ohm's law.

2.2. Accurate algorithm based on Green's functions

Green's function is a potential function that is deduced based on unit current sources. To calculate grounding resistance accurately, a grounding electrode is divided into n infinitesimal elements, and at any point P the potential generated by each tiny section's charge density is

$$V_P = \iint_S G(P, Q)J(Q)dS \tag{4}$$

where, $J(Q)$ is the leakage current density of point Q on the electrode surface S, and $G(P,Q)$ is the Green's function of point P [12].

Divide the electrode into n tiny sections based on the constant current field theory and define the length, leakage current and center coordination of the jth section as L_j, I_j and O_j respectively, then there is

$$L = \sum_{j=1}^{n} L_j \tag{5}$$

$$I = \sum_{j=1}^{n} I_j \tag{6}$$

The potential at point P, generated by the leakage current in length L, can be calculated according to the superposition theorem.

$$V_P = \sum_{j=1}^{n} G(P, O_j)I_j \tag{7}$$

In order to obtain the current distribution of each tiny section, place the target point P at the ith tiny section, then $G(P,O_j)$ represents the voltage of the ith section when applying unit current source on the jth section.

We use Eq. (8) to calculate the current distributions of each element.

$$V_P = \sum_{j-1}^{n} R_{ij}I_j \tag{8}$$

where, R_{ij} is mutual resistance between sections i and j; when $i = j$, R_{ij} is the self-resistance.

After R_{ij} is solved according to the boundary conditions, the grounding device's grounding resistance can be obtained.

2.3. Comparison between calculation methods

Although calculation methods for tower grounding resistance have been developed fairly well, they are facing obstacles in practical uses. As proposed in reference [12], grounding resistance is calculated conveniently by the regulation method that adopted infinite even soil model, but the results are generally larger than actual values and lead to excessive sizes of grounding systems. Ref. [13,14] indicates that it takes a large amount of time to calculate grounding resistance using Green's functions; these functions could