Research on calculation model of Tower Impulse resistance based on EMTP

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Abstract. Accurate determination of impulse grounding resistance of tower grounding body is the premise to improve the lightning withstand level of transmission line. The current research mostly ignores the nonlinear effect of soil spark discharge. Based on the analysis of the idea and conception of the equivalent model of grounding body considering spark discharge effect, two simulation models based on EMTP are proposed. The two simulation models can well simulate the inductance effect and spark discharge effect when lightning current flows through grounding body, and improve the grounding body model under impulse condition. The comparison results show that the simulation results are in good agreement with the field measurement results.

1. Introduction

With the development of power grid, the construction of various power facilities is increasing year by year. China has a vast territory, especially the construction of UHV power grid in recent years. Large transmission lines span a wide range of regions. There are many lightning intensive regions in China, especially in the south. At the same time, the south is also China's industrial intensive region, with large electricity sales, which requires the safety and reliability of the power grid. Therefore, it also increases the requirements for its lightning protection level. "Lightning protection lies in grounding". Therefore, ensuring the reliable grounding of transmission line is the fundamental guarantee and important measure to maintain the safe and reliable operation of power system and the safety of electrical equipment and operators [1,2].

The definition of grounding is to make electrical connection between some parts of electrical equipment and the ground, so that the potential difference between the electrical equipment and the ground is within the acceptable range in case of lightning strike and other accidents, so as to avoid accidents. The main role of grounding is to avoid damage to electrical equipment, prevent fire, and maintain safe and reliable operation of power system [3]. In essence, the occurrence process of lightning is simplified as an impulse current source, and the corresponding amplitude and waveform impulse current is injected into the electrical equipment. The voltage drop of the current on the grounding resistance makes the potential of the electrical equipment rise. The key is to maintain the allowable grounding potential of the equipment. Therefore, a good grounding with low resistance is to improve the lightning resistance of the transmission line in the design and transformation of the transmission line. It's an important reference index of the level of education.

Reducing the impulse grounding resistance of tower grounding body is an important measure to improve the lightning withstand level of transmission line and ensure the safe operation of the system. Accurate determination of impulse grounding resistance of tower grounding body is the basis of this
measure. Simulation is an important means to study the impulse grounding characteristics of transmission line tower. The simulation model should reflect the characteristics of tower grounding body under lightning impulse as much as possible, that is, the inductance effect and spark discharge effect of grounding body under lightning current. Up to now, the nonlinear effect of soil spark discharge has been ignored, and the inductance effect has been mainly considered. On this basis, the impulse grounding resistance has a certain deviation from the actual situation.

In this paper, the equivalent model of grounding body considering spark discharge effect is analyzed. The model can simulate the inductance effect and spark discharge effect of grounding body under lightning current. On the basis of this equivalent model, two simulation models based on EMTP are established. These two simulation models improve the grounding body model under impulse condition and make the impulse grounding resistance calculated by simulation more accurate.

2. Equivalent model of grounding electrode considering spark discharge effect
When lightning strikes the tower or lightning rod, the lightning flows through the tower or lightning rod and then spreads to the earth through the grounding device. Under the action of impulse current, the time-varying electromagnetic field is generated in the soil around the grounding body, and its field strength is shown in formula (1).

$$E = \rho J$$

(1)

Where $j$ is the current density and $\rho$ is the resistivity of the soil.

With the increase of the impact current amplitude, the electric field strength in the soil increases continuously. If it exceeds the critical breakdown field strength $E_C$ of the soil, spark discharge will be generated in the soil close to the grounding body, and the soil will be broken down. At this time, the field strength in the spark discharge area will be greatly reduced, and the soil resistivity will be greatly reduced. In the calculation of impulse grounding resistance of grounding body, the voltage drop in spark discharge area is usually omitted, that is, the soil in spark discharge area is equivalent to grounding body. The radius of the soil spark discharge area around the grounding body is considered to be the equivalent radius of the grounding body in the lightning impulse transient process [2-3].

The transient performance of grounding device under the action of impulse current is very different from that under power frequency, which is mainly due to the high frequency of impulse current. Compared with resistance, the inductance effect of grounding body itself will be very obvious. The inductance will prevent the impulse current from flowing to the far end of the grounding body, which makes the scattered current of each point of the grounding body extremely unbalanced. The closer to the current injection point, the more current the grounding body dissipates, the greater the current density and the greater the breakdown area of the soil, that is, the greater the equivalent radius. Therefore, the breakdown area of the soil around the grounding electrode is conical [2-3], as shown in Figure 1. However, in order to simplify the simulation calculation, the grounding body is divided into several sections, and each conductor section is calculated with a cylindrical model [4-5]. The more the number of segments, the closer to the actual situation, but the more complex the calculation. In this paper, 5m is taken as one segment. Figure 2 shows the equivalent radius model of each section of the grounding body when the soil breaks down. In the figure, $a$ is the radius of the grounding body itself, and $R_I$ is the equivalent radius of the I section.

Fig. 1 Shape of spark discharge area
Fig. 2 Equivalent radius model of grounding electrode in each section during soil breakdown

Under the action of impulse current, the horizontal grounding body can be regarded as a \( \pi \) type equivalent circuit composed of inductance, capacitance, conductivity and resistance [6], in which each section of grounding body is simulated by a \( \pi \) type equivalent circuit, as shown in Figure 3. In Figure 3, \( R_i \) and \( L_i \) represent the resistance and inductance of each grounding body, \( C_i \) and \( G_i \) represent the capacitance to ground and leakage conductance of each grounding body.

When calculating impulse grounding resistance of horizontal grounding body, it is usually taken as a constant. In this paper, the resistance of grounding body per unit length is 0.05 \( \Omega / \text{m} \).

Considering the magnetic saturation in the steel grounding body during lightning stroke and ignoring the self-inductance in the grounding body, the formula of inductance per unit length [7] is simplified as:

\[
L_i = \frac{\mu_0}{2\pi} \ln \left( \frac{2l_i}{a} - 1 \right)
\]

Where: \( \mu_0 \) is the permeability coefficient of vacuum, which can be taken as \( \mu_0 = 4\pi \times 10^{-7} \) in practical range, \( a \) is the radius of grounding body, and \( l \) is the length of grounding body.

The formula of ground conductance per unit length of extended grounding body [7] is as follows.

\[
G_{i0} = \frac{2\pi}{\rho} \ln \left( \frac{l_i}{2hr_i} - 0.61 \right)
\]

In the formula: \( G_{i0} \) is the electrical conductance per unit length of the i-th elongated body; \( l_i \) is the length of the i-th section of the grounding body; \( \rho \) is the soil resistivity; \( h \) is the buried depth of the grounding body. The capacitance per unit length of each section of the grounding body to the zero plane at infinity [7] is.

\[
C_{i0} = \varepsilon \rho G_{i0}
\]

Where: \( \varepsilon \) is the dielectric coefficient of the soil, in the practical range \( \varepsilon = 9 \times 8.86 \times 10^{-12} \).

Since the electric field strength at the boundary of the spark area is the critical breakdown field strength of the soil, the equivalent radius of each segment of the conductor after the spark discharge is considered can be obtained by formula (6).

\[
J_i = \frac{E_c}{\rho} = \frac{\Delta I_i}{2\pi r_i \Delta l}
\]

Where: \( J_i \) is the current density flowing through the i-th conductor; \( \Delta I_i \) is the current flowing to the ground through the i-th conductor; \( \Delta l \) is the length of each conductor; \( \rho \) is the soil resistivity; \( E_c \) is the critical soil breakdown Field strength, when \( \rho = 1000 \Omega \cdot \text{m} \), \( E_c = 850 \text{kV/m} \).
3. Simulation Modeling

3.1. Model 1
Taking a 20m horizontal grounding body as an example, a simulation model based on ATP-EMTP is established, an ideal current source is used to simulate the lightning current, and a π-type equivalent circuit is used to simulate the grounding body. The simulation model is shown in Figure 4.

![Fig.4 Simulation model 1](image)

The lightning current waveform is represented by the Heidler function model, and the specific expression is as follows.

\[
i(t) = I_0 \frac{\left(\frac{t}{\tau_1}\right)^\nu}{1 + \left(\frac{t}{\tau_1}\right)^\nu} e^{-\eta \tau_1} \quad (7)
\]

Where: I0 is the lightning current peak value; \( \tau_1 \) and \( \tau_2 \) are the wave head and wave tail time constants respectively, and \( \frac{2.6}{50} \mu s \) are the current steepness factors, taking 10. The lightning current waveform is taken, and the equivalent wave impedance of the lightning channel is selected according to relevant specifications.

![Fig.5 Lightning current waveform](image)

The calculation adopts successive approximation algorithm. First of all, without considering the effect of spark discharge, that is, the radius of the extended grounding body is considered to be \( a \), and the parameters \( L_i, G_i, C_i \) and \( R_i \) at this time are calculated by formulas (2)–(4), and the parameters in the ATP-EMTP model are set and run Model, get the current value \( \Delta I_i \) discharged by each section of the conductor, and the simulation result is shown in Figure 6.

Bring it into equation (6) to calculate the equivalent radius \( r_i \) of each conductor segment, and then bring \( r_i \) into equations (3) and (4) to obtain \( G_i' \) and \( C_i' \) at this time. Due to the existence of inductance in the model, it prevents the high-frequency lightning current from dissipating to the far end. Therefore, the closer the current injection point is, the more current is discharged, the larger the equivalent radius \( r_i \), and the larger the calculated \( G_i' \) and \( C_i' \). \( G_i' \) and \( C_i' \) replace \( G_i \) and \( C_i \) in the original model. At this time, the model can be considered to take into account the effect of partial spark discharge, which is one step closer to the real spark discharge effect, but it is not enough. Then run the model again to measure the current value \( \Delta I_i \) discharged by each segment of the conductor at that moment, repeat the above steps, each time it will be further from the real spark discharge effect, until the \( \Delta I_i \) measured twice continuously changes little. It can be approximated that the model at this time has considered the influence of spark discharge.
Fig. 6 The current waveform of the four-section grounding body loop under model 1

It can be seen from the figure 6 that the calculated equivalent conductance of the four-group segment grounding body is a fixed value under Model 1, and after conversion to the resistance value, the equivalent resistance of one segment is the largest, reaching 414.94Ω, and the four-group is the smallest, 181.94Ω. Therefore, the current difference between the four groups of equivalent grounding bodies is obvious, the four groups have the largest current, reaching 72.66kA, and the minimum of one section is 32.01kA.

Finally, the voltage amplitude $U_m$ at the impulse current injection point is measured by the potentiometer, then the impulse grounding resistance $R_g$ is:

$$R_g = \frac{U_m}{I_m}$$  \hspace{1cm} (8)

3.2. Simulation model 2

Since the lightning current applied to the grounding body is time-varying, the spark discharge area around the grounding body also changes with the size of the lightning current, and the equivalent radius of each unit section of the grounding body also changes accordingly. In order to simulate non-linear spark discharge, the electrical parameters (including conductance to ground and capacitance to ground) closely related to each unit section of the grounding body and its radius should also be time-varying.

From formulas (3) to (6), it can be seen that $G_i$ and $C_i$ are functions of the discharge current $\Delta I_i$ of each section of the grounding body, that is, $G_i$ and $C_i$ change at all times with the change of $\Delta I_i$. Therefore, as long as the size of $\Delta I_i$ is collected in real time, inputted to the control module, after arithmetic processing, and continuously output signals to correspondingly control the size of $G_i$ and $C_i$, the spark discharge effect and the time-varying characteristics of lightning current parameters can be simulated. Since the effect of the conductance to ground is much greater than that of the capacitance to ground, this article still treats the capacitance to ground as an invariant.

Simulation model 2 based on ATP-EMTP is improved on the basis of model 1. The conductance to ground in model 1 is replaced by a variable resistance, and a control module is added to control the size of the variable resistance, as shown in Figure 6.
The control module collects the current $\Delta I_i$ in real time, brings it into equation (6) to calculate the equivalent radius $r_i$, and then brings $r_i$ into equation (3) to obtain the conductance $G_i$ to ground, and then converts it into resistance, which is the size of $R(t)$.

![Fig.8 The current waveform of the four-section grounding body loop under model 2](image)

The overvoltage amplitude $U_m$ at the impulse current injection point is measured by the potentiometer, and the impulse grounding resistance can be directly obtained by equation (8). The simulation model 2 collects the magnitude of $\Delta I_i$ in real time through the control module, and accordingly changes the magnitude of the conductance to the ground, approximately simulating the spark discharge effect and the time-varying characteristics of lightning current parameters under lightning impulse conditions, and simplifies the calculation process.

The four groups of loop current waveforms in the simulation results are shown in Figure 8. It can be seen from Figure 8 that the current gap in the four-stage grounding body under Model 2 is relatively small. This is because the equivalent conductance of the four-stage grounding body changes in real time according to the current flowing in the loop. From the simulation data, the resistance value converted by equivalent conductance of the grounding body at the maximum time can reach 54kΩ, which is 130 times the resistance value in Model 1, and is also 10 times the normal value at most times. At the same time, the difference between the equivalent resistance values of the four sections is small. Therefore, the current values flowing through the four equivalent ground bodies are very close.

4. Model comparison

Using the above two models can easily calculate the impulse ground resistance of the grounding device. Taking a 20m long horizontal grounding body as an example, when the soil resistivity is 1000Ω·m, the results obtained by the method described in this article are compared with the field test results [8], and the simulation test results in the literature [9] are also compared. For comparison, as shown in Table 1 and Figure 8.

| $\Delta I_1$ | References [8] | References [9] | Model 1 simulation data | Model 2 simulation data |
|-------------|----------------|----------------|------------------------|------------------------|
| $\Delta I_2$ | 0.68            | 0.63           | 0.67                   | 0.64                   |
| $\Delta I_3$ | 0.59            | 0.59           | 0.60                   | 0.58                   |
| $\Delta I_4$ | 0.55            | 0.57           | 0.56                   | 0.54                   |

It can be seen from Table 1 that the results of the simulation model calculation in this paper are basically consistent with the results of the field test, especially between 4kA and 8kA, and the three
curves are almost parallel. When the amplitude of the impulse current is small, the spark discharge effect is weak. The increase of the impulse current will greatly enhance the spark discharge effect in the soil [10]. Therefore, the discharge capacity of the grounding body is greatly enhanced, so that the grounding body impacts the ground resistance and the impact coefficient Decline faster. However, with the further increase of the inrush current, the discharge capacity of the grounding body gradually tends to be saturated, so that the speed of the grounding body's impact grounding resistance and the impact coefficient decreasing with the increase of the inrush current amplitude gradually slows down. It can also be seen from Table 1 that the results of the simulation model calculation are more consistent with the results of the field test, and the error is within ±2% in most cases. Therefore, the two simulation models in this paper can more realistically simulate the characteristics of the tower grounding body under the impact of lightning, and accurately calculate the impact grounding resistance of the tower grounding body.

5. Conclusion
This article takes the calculation model of the tower impulse resistance as the research object, and draws the following conclusions through the comparative analysis of the two simulation models.

(1) The paper analyzed the ideas and ideas of the equivalent model of the grounding body when considering the spark effect, and proposed a modeling scheme, so that the simulation calculation model can better simulate the inductance effect and spark discharge effect of the grounding body under lightning current.

(2) Based on the above ideas and ideas, two simulation calculation models based on ATP-EMTP are proposed: Model 1 uses \( \pi \)-type equivalent circuit combined with successive approximation algorithms; Model 2 uses \( \pi \)-type equivalent circuit combined with control Module. Both simulation models can simulate the inductance effect and spark discharge effect when the lightning current flows through the grounding body, perfecting the grounding body model under impact conditions.

(3) The comparison results show that the results calculated by the simulation model in this paper are basically consistent with the changes in the field measured results, and the values are more consistent.

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