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An EMTP Comprehensive Model of Tower Grounding and its Simulation Analysis

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Abstract. For the purpose of designing the grounding device of the poles and towers an improved EMTP model is put forward in this paper. The impulse characteristics of the tower grounding under impulse currents are simulated and analysed based on circuit theory. Only the non-linear effects caused by soil ionization are considered in the current studies. And the interactions deriving from the coexistence of segmented grounding electrodes have been neglected. Consequently, the calculated results of the impulse grounding resistance of the complex grounding device such as the tower grounding are not enough accurate using the traditional models. The soil ionization effects are simulated through the non-linear resistance. The current-controlled voltage sources are introduced in the model to take into account the interactions of the segmented grounding electrodes. Then the comprehensive model of the tower grounding is established. Comparison of simulation results with experimental data implies that the tower grounding model proposed in this paper is more accurate and effective than the traditional model.

1. Introduction

During the lighting protection design of the overhead transmission lines, the lightning protection calculation result is affected by the impulse grounding resistance of the tower grounding directly. Therefore, it is of great importance in studying the modelling and simulation method of tower grounding device (TGD). At present, the simulation calculation methods of tower grounding mainly includes: circuit analysis method [1] and electromagnetic theory [2]. The electromagnetic theory method has an advantage of high computational accuracy. But the computational efficiency of the complex grounding device is low. And for the simulation of soil ionization the electromagnetic theory method is not accurate enough. Hence, the effect of the soil ionization is usually ignored when using this method. The difference is that the dynamic process of the soil ionization can be simulated using nonlinear resistance in the circuit method [3]. In addition, the grounding device model based on the circuit method can integrate with other complex system models easily and the collaborative simulation can be achieved [4].

However, in the literatures based on circuit theory until now only the soil ionization is taken into account. The interactions deriving from the coexistence of segmented grounding electrodes have been neglected. Aiming at this, an EMTP comprehensive model of tower grounding is proposed in this paper. Where, the soil ionization effects are simulated through the non-linear resistance. The current-controlled voltage sources (CCVS) are introduced in the model to take into account the interactions of the segmented grounding electrodes.

2. Lumped parameter model of the grounding electrode considering the soil ionization

2.1. Calculation of the RLCG parameters in per unit length

Under the action of impact current, the grounding electrode can be considered as an π equivalent circuit consisting of inductance, capacitance, conductance and resistance [5]. And the RLCG parameters can be calculated using equation (1) [6].

$$\begin{cases} L \approx \mu_0 \cdot \left(\ln \frac{2l}{r} - 1 \right) \Big/ l \\ C = \pi \cdot \varepsilon \cdot l \Big/ \left[\ln(2l/\sqrt{2 \cdot r \cdot h}) - 1 \right] \\ G = \pi \cdot l \Big/ \left[\rho \cdot \ln\left(2l/\sqrt{2rh}\right) - \rho \right] \end{cases} \tag{1}$$

where, $\mu_0 = 4\pi \times 10^{-7}$ is the vacuum permeability. $\varepsilon_0 = 8.859 \times 10^{-12}$ F/m is the vacuum permittivity. l, r, h is the length, radius, buried depth of the grounding electrode respectively. ρ is the earth resistivity. And $R = 0.05\Omega$/m is used in this paper [5].

2.2. Simulation of the soil nonlinear effect

When the impulse current flows into earth the soil around the grounding electrode may be penetrated due to the strong electrical field. Then the ground resistance will temporarily decrease and it can be equivalent to the increase of the grounding electrode radius [7]. In fact, the soil penetration region around the grounding electrode casts a cone shape [8]. Nevertheless, considering the computational complexity the grounding electrode is divided into several sections in this paper. And each section is simulated using cylindrical model which is shown in figure 1.

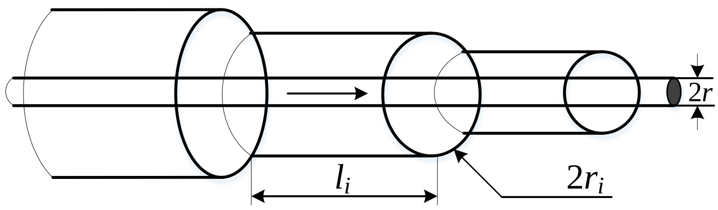


Figure 1. Equivalent radius model of a horizontal grounding electrode considering soil ionization.

The equivalence radius of each section considering soil ionization can be calculated using:

$$r_i = \frac{\rho \cdot \Delta I_i}{2\pi l_i E_c} \tag{2}$$

where, ΔI_i is the current flows into earth through the i^{th} segmented grounding electrode. l_i is the length of the i^{th} section. E_c is the critical value of soil penetration which can be given by $E_c = 241\rho^{0.215}$ kV/m.

Then the equation (1) can be rewritten as:

$$G_i = 1 \big/ \left(\beta - \alpha \ln \Delta I_i \right) \tag{3}$$

where,

$$\begin{cases} \beta = \dfrac{\rho}{\pi \cdot l_i} \ln \dfrac{2l_i \cdot \sqrt{\pi l_i E_c}}{\sqrt{\rho h}} - \dfrac{\rho}{\pi \cdot l_i} \\ \alpha = \dfrac{\rho}{2\pi \cdot l_i} \end{cases} \tag{4}$$

3. Comprehensive model of tower grounding device

The computing method of the RLCG parameters in per unit length for grounding electrode has been proposed in section 2.1. But this method is not accurate enough for complex grounding devices. Because the interactions with other segmented grounding electrodes have not been considered. When the impulse current is injected to the earth, each electrode will alter the earth potential around it and reduce the efficiency of the surrounding electrodes. In other words, the grounding resistance is higher than the one obtained by considering isolated with other electrodes [9]. The interactions with other segmented grounding electrodes are simulated in this paper through introducing two CCVS in the π equivalent circuit model of the grounding device. The equivalent circuit model of a simplified grounding device is shown in figure 2.

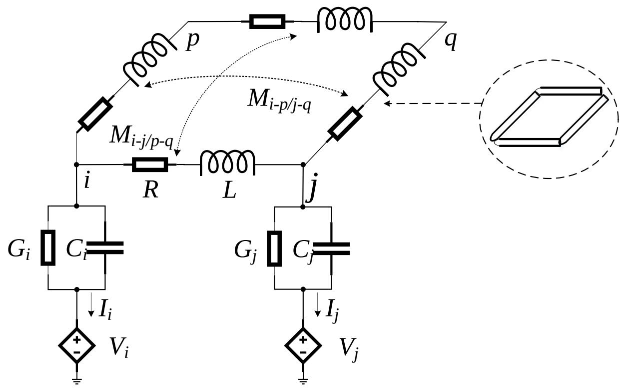


Figure 2. Equivalent model of a simplified grounding device considering the interactions of the segmented grounding electrodes.

In figure 2 the voltage of the CCVS can be calculated using equation (5).

$$V_i = \sum_{j \neq i} A_{ij} \cdot I_j \tag{5}$$

where, I_j is the impulse current flows into earth through j-node. A_{ij} is the coupling coefficient which depends on the geometric arrangement of the TGD and the resistivity of the soil.

The voltage calculation principle of CCVS at point j-node is shown in figure 3.

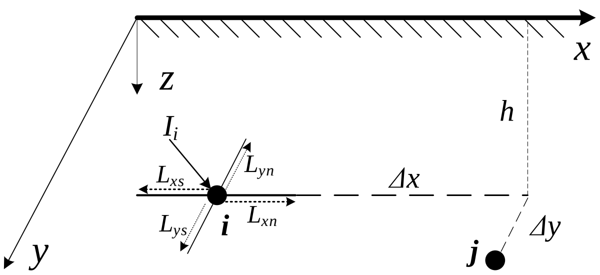


Figure 3. Calculation principle of the CCVS voltage.

The grounding voltage of the j-node due to the impulse current flowing in the i-node is given by:

$$\Delta V_{ji} = \frac{\rho}{2\pi} \cdot \left(\frac{I_x}{L_{xs} + L_{xn}} \cdot A_1 + \frac{I_y}{L_{ys} + L_{yn}} \cdot A_2 \right) \tag{6}$$

where, L_{ij} are the half-length of the segments converging to the node i. The coefficients A_1 and A_2 can be evaluated with equation (7).

$$\begin{cases} A_1 = \int_{-L_{xs}}^{L_{xn}} \left(dx \Big/ \sqrt{r^2 + \Delta y^2 + (x - \Delta x)^2} \right) + \int_{-L_{xs}}^{L_{xn}} \left(dx \Big/ \sqrt{4h^2 + \Delta y^2 + (x - \Delta x)^2} \right) \\ A_2 = \int_{-L_{ys}}^{L_{yn}} \left(dy \Big/ \sqrt{r^2 + \Delta x^2 + (y - \Delta y)^2} \right) + \int_{-L_{ys}}^{L_{yn}} \left(dy \Big/ \sqrt{4h^2 + \Delta x^2 + (y - \Delta y)^2} \right) \end{cases} \tag{7}$$

By assuming $I_x + I_y = I_i$ and $I_x/(L_{xs} + L_{xd}) = I_y/(L_{ys} + L_{yd})$ equation (6) can be rewritten as:

$$\Delta V_{ji} = \frac{\rho}{2\pi} \cdot \frac{I_i}{L_{xs} + L_{xn} + L_{ys} + L_{yn}} \cdot (A_1 + A_2) \tag{8}$$

Then introducing the coefficients C_1, C_2, C_3, and C_4 after solving the integrals in equation (7):

$$\begin{cases} C_1 = \dfrac{\sqrt{L_{xn}^2 - 2L_{xn}\Delta x + \Delta x^2 + \Delta y^2 + r^2} + L_{xn} - \Delta x}{\sqrt{L_{xs}^2 + 2L_{xs}\Delta x + \Delta x^2 + \Delta y^2 + r^2} - L_{xs} - \Delta x} \\ C_2 = \dfrac{\sqrt{L_{ys}^2 - 2L_{ys}\Delta y + \Delta x^2 + \Delta y^2 + r^2} + L_{ys} - \Delta y}{\sqrt{L_{yn}^2 + 2L_{yn}\Delta x + \Delta x^2 + \Delta y^2 + r^2} - L_{yn} - \Delta y} \\ C_3 = \dfrac{\sqrt{L_{xn}^2 - 2L_{xn}\Delta x + \Delta x^2 + \Delta y^2 + 4h^2} + L_{xn} - \Delta x}{\sqrt{L_{xs}^2 + 2L_{xs}\Delta x + \Delta x^2 + \Delta y^2 + 4h^2} - L_{xs} - \Delta x} \\ C_4 = \dfrac{\sqrt{L_{ys}^2 - 2L_{ys}\Delta y + \Delta x^2 + \Delta y^2 + 4h^2} + L_{ys} - \Delta y}{\sqrt{L_{yn}^2 + 2L_{yn}\Delta x + \Delta x^2 + \Delta y^2 + 4h^2} - L_{yn} - \Delta y} \end{cases} \tag{9}$$

And the grounding voltage of the CCVS at j-node can be calculated by:

$$\Delta V_{ji} = \frac{\rho \cdot [\ln(F1) + \ln(F2)]}{2\pi (L_{xs} + L_{xn} + L_{ys} + L_{yn})} \cdot I_i \tag{10}$$

where, $F1 = C_1 \cdot C_2$,$F2 = C_3 \cdot C_4$.

4. Simulation analysis and verification

4.1. Simulation model of tower grounding based on ATP-EMTP

The comprehensive model of TGD proposed in this paper can be easily implemented on ATP-EMTP for electromagnetic transient studies. Due to the limited space the EMTP model of TGD is not given in this paper. Only the model of the simplified grounding device in figure 2 is given here. The ATP-EMTP simulation model is shown in figure 4.

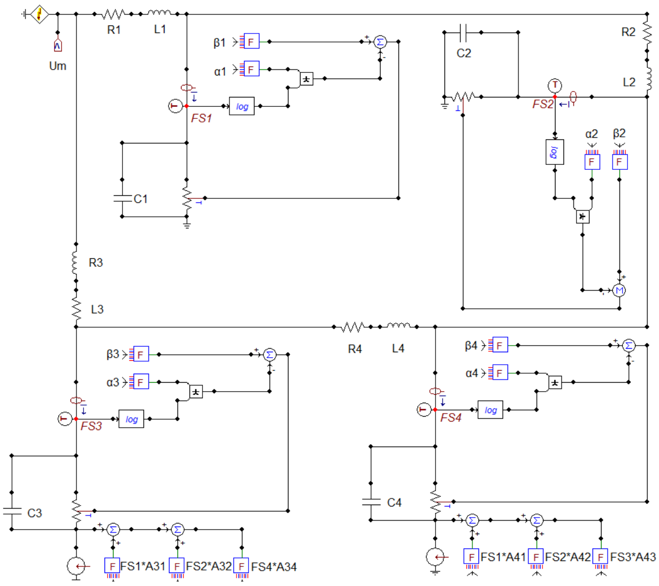


Figure 4. ATP-EMTP simulation model of the simplified grounding device.

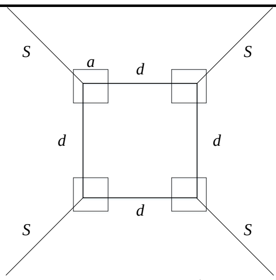
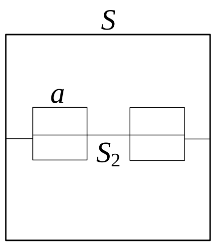
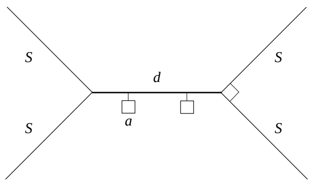
The LC parameters are calculated using equation (1). The soil ionization is simulated through the current acquisition module (CAM), control module (CM) and nonlinear resistance. CAM collects the current flowing into earth ΔI_i in real time and converts the circuit data into TACS data. CM handles the value of nonlinear resistance according to ΔI_i. α, β in equation (3) are constant when the condition is determined and they can be calculated using equation (4). The coupling coefficient A_{ij} calculated through equations (9-10) is multiplied by the corresponding current ΔI_i to control the output of "TACS Controlled Source". Then the simulation of the interactions with other segmented grounding electrodes has been realized. The impulse grounding resistance can be calculated by: $R_{ch} = U_M / I_M$.

4.2. Simulation and verification of the typical tower grounding devices

The structure and dimension of the common TGDs in China are shown in table 1 and the calculation formula of power frequency ground resistance is given as equation (11) [10].

$$R_l = \rho\left[\ln\left(D^2/2hr\right)\right]/2\pi D \tag{11}$$

Table 1. Structures and dimensions of the common tower grounding devices.

Type	I	II	III
Structure			
	$a = 4, S = 26, d = 10$	$a = 2.5, S = 10$	$a = 1.5, S = 26, d = 10$

The empirical equation of impulse coefficient determined by experiment can be expressed as [11]:

$$y = x_1\rho^{x_2}\left(x_3+\sqrt{S}\right)\left[x_4-\exp\left(x_5 I_M^{x_6}\right)\right] \tag{12}$$

where, D is the total length of the grounding electrode and the values of the x are shown in table 2.

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Table 2. Values of A and x in equations (11-12).

Type	x_1	x_2	x_3	x_4	x_5	x_6	A
I	0.74	-0.4	7.0	1.56	-3.0	-0.4	1.76
II	2.94	-0.5	6.0	1.23	-2.0	-0.3	1.0
III	1.36	-0.4	1.3	1.55	-4.0	-0.4	2.0

The above three kinds of the common TGDs are taken as examples to verify the accuracy of the comprehensive model. The radius of all grounding conductors is 0.01m and the burial depth is 0.8m. The single grounding electrode in the TGD is segmented every 2m. And the double exponential expression based lightning waveform is adopted. Firstly, compute the impulse ground resistance of the TGD through the comprehensive model. Secondly, compute the power frequency ground resistance with corresponding impulse current and soil resistivity. Finally, compare the impulse coefficients with the ones obtained by equation (12). The computed results of the TGDs are shown in figure 5. It should be emphasized, when calculating the impact on impulse coefficient caused by impulse current the soil resistivity is 500Ω·m. And during another calculation the current amplitude is 100kA.

It can be seen from figure 5 that the impulse coefficient of TGD reduces gradually with the increase of the impulse current I_M and the soil resistivity ρ. The earth potential rise caused by other segmented grounding electrodes has been neglected when only considering the soil ionization. So the calculation results of impulse resistance are much smaller than the ones calculated by the empirical formula. Besides, the calculation results based on the comprehensive model are in good agreement with the ones obtained by the empirical formula. It indicates that the model proposed in this paper can realistically simulate the impulse characteristic of TGD and it can accurately compute the impulse grounding resistance of TGD.

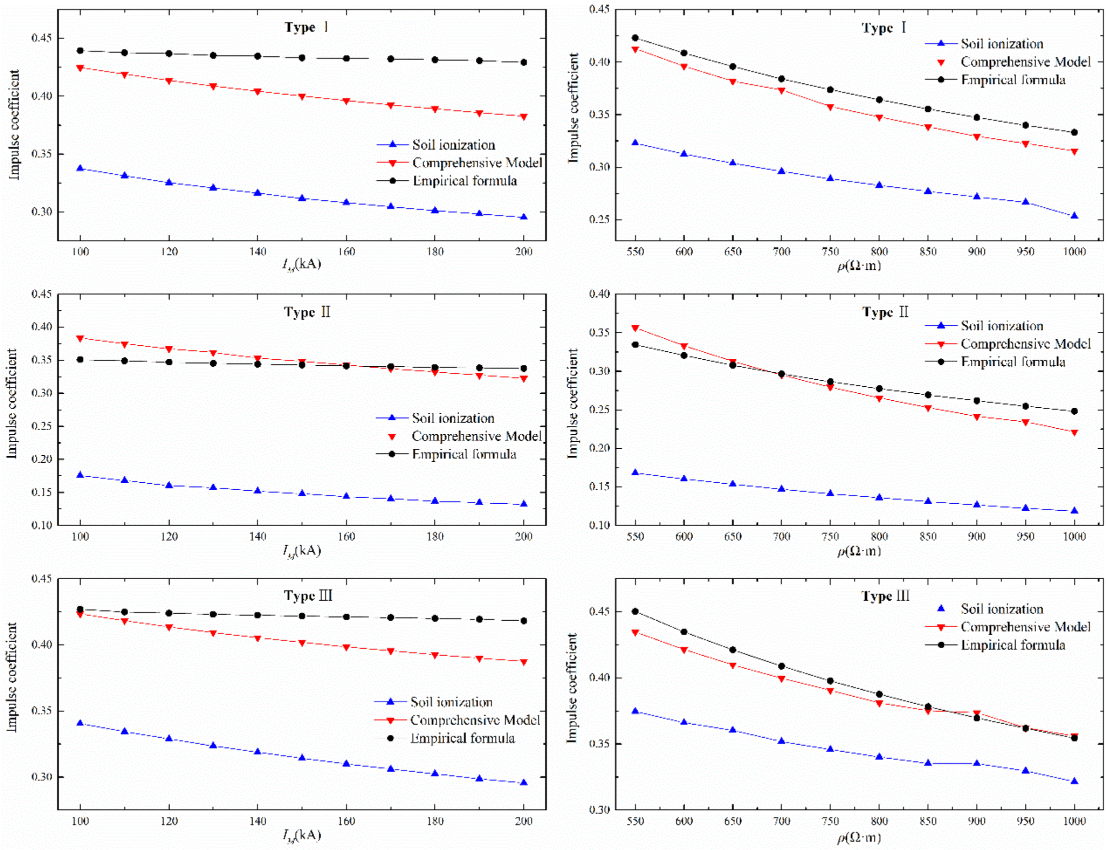

Figure 5. Calculation results and the comparison with experimental results.

5. Conclusion
A comprehensive model of TGD simultaneously considered the soil ionization and interactions of the segmented grounding electrodes was proposed in this paper. And the implementation scheme in ATP-EMTP was given too. The soil ionization effect was simulated through the non-linear resistance. The CCVS were introduced in the model to take into account the interactions of the segmented grounding electrodes. Three kinds of the common TGDs were simulated based on the comprehensive model. Comparison of simulation results with experimental data implied that the model proposed in this paper was more accurate and effective than the traditional model which only considered the soil ionization.

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