Simulation Research on the Ground Resistance Measurement of the Tower with Clamp Meter Considering the Influence of the Tower Foundation

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Abstract. The grounding resistance of the tower is the main parameter to measure the grounding safety performance of the tower. As a commonly used method of measuring the grounding resistance of the tower, the clamp meter method has certain errors in the measurement principle. Based on the measurement principle of the clamp meter method, the artificial grounding device, tower foundation, transmission line tower and lightning protection wire are modeled and simulated, and the influence of different factors on the error of the clamp meter method measurement of the ground resistance of the tower is studied. The calculation results show that the change of soil resistivity has the most obvious influence on the calculation results. The higher the soil resistivity is, the coefficient of transformation between the measurement results of clamp tab. Method and the actual value gradually decreases. In the case of multi base tower grounding, the measured transformation ratio coefficient will be smaller than that in the case of single base tower grounding due to the shunt of tower lightning line parallel branch; The shorter the span between towers or the lower the height of towers, the smaller the parallel equivalent impedance of tower lightning line branches and the smaller the transformation ratio coefficient.

Keywords: Clamp meter method · Tower foundation · p ground resistance

1 Introduction

The grounding safety performance of transmission line towers is an important factor affecting the reliability of power system operation. Therefore, it is necessary to accurately measure its grounding resistance to judge whether it meets the requirements of the regulations [1, 2]. The traditional three pole method used for tower grounding resistance measurement is time-consuming and laborious, while the clamp meter method does not

H. Yang et al. (Eds.): SmartGIFT 2022, LNICST 483, pp. 439–451, 2023.
https://doi.org/10.1007/978-3-031-31733-0_38

need to arrange auxiliary electrodes, which greatly reduces the working intensity of the measuring personnel [3–5].

However, the clamp meter method actually measures the total loop impedance of the current flow path [6, 7]. Previous studies [8–11] usually only considered the current flow circuit formed by the parallel grounding of multi base towers. However, the grounding system of each base tower includes two parts: artificial grounding device and natural grounding electrode of the tower foundation, which can also form a series circuit [12, 13]. Even if the tower is grounded on multiple bases, the tower foundation will still have a certain shunt.

Therefore, it is necessary to build a tower grounding model considering both tower foundation and artificial grounding device, calculate and analyze to find out the influence law of relevant factors on the measurement error of clamp meter method.

2 Measuring Principle of Clamp Method

When the clamp meter method is used to measure the tower grounding resistance, the clamp meter is clamped around the grounding downlead, and the measurement result is the total impedance value of the circuit where the grounding downlead is located. The measuring circuit formed can be divided into two parts: the first part of the current flows through the path formed by the measuring tower artificial grounding device, grounding downlead, tower foot main materials, foundation bolts, tower foundation and soil; The second part of the current flows through the artificial grounding device of the measuring tower, the grounding downlead, the measuring tower body, the lightning wire, the tower body and grounding body near the multi base, and the path formed by the soil, as shown in Fig. 1. For single base towers without lightning wires, the measuring circuit will only include the first part.

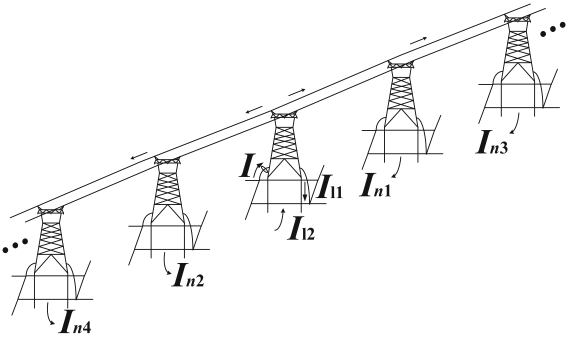

Fig. 1. Schematic diagram of tower grounding resistance measurement by clamp meter method.

2.1 Theoretical Calculation Principle of Tower Grounding Resistance

The tower grounding body includes two parts: artificial grounding device and tower foundation. When the current flows into the ground through two parts of the grounding body, the corresponding potential and current relationship [14, 15] on the two parts of the grounding body are:

$$\begin{cases} V_1 = R_{11}I_1 + R_{12}I_2 \\ V_2 = R_{21}I_1 + R_{22}I_2 \end{cases} \tag{1}$$

where, V_1 and V_2 are the potentials of the artificial grounding device and the basic grounding body respectively, I_1 and I_2 are the potentials of the artificial grounding device and the basic grounding body respectively, R_{11} and R_{22} are the potentials of the artificial grounding device and the basic grounding body respectively, and R_{12} and R_{21} are the potentials of the artificial grounding device and the basic grounding body respectively.

For the two connected grounding bodies, if the voltage drop on the connecting conductor between them is ignored, then the potential of the two is equal. If the total incoming current is I, then there are:

$$\begin{cases} V_1 = V_2 = V \\ I = I_1 + I_2 \\ R_{12} = R_{21} \end{cases} \tag{2}$$

The actual value of tower grounding resistance can be obtained by combining formula (1) and formula (2):

$$R = \frac{V}{I} = \frac{R_{11}R_{22} - R_{12}^2}{R_{11} + R_{22} - 2R_{12}} \tag{3}$$

2.2 Measurement Principle of Clamp Meter Method in the Case of Single Tower Grounding

When testing the single base grounding of the tower, the measured current will only flow through the artificial grounding device of the test tower and the circuit where the tower foundation is located. For the artificial grounding device and foundation grounding body in the series circuit, considering the induced potential E generated by the pincer meter on the grounding downlead, there are:

$$\begin{cases} V_1 = V_2 + E \\ I_1 = -I_2 = I' \\ R_{12} = R_{21} \end{cases} \tag{4}$$

where, $I'$is the current flowing on the grounding down lead.

Simultaneous Eqs. (1) and (4) can be used to obtain the actual grounding resistance measured by clamp meter method when a single tower is grounded:

$$R' = \frac{E}{I'} = R_{11} + R_{22} - 2R_{12} \tag{5}$$

With simultaneous Eqs. (3) and (5), the transformation coefficient between the measured value and the actual value of the clamp meter method at this time can be obtained η Is:

$$\eta = \frac{(R_{11} + R_{22} - 2R_{12})^2 + R_{12}^2 - R_{11}R_{22}}{R_{11}R_{22} - R_{12}^2} + 1 \tag{6}$$

From Eq. (6), it can be seen that the error increment between the measured value of clamp meter method and the actual value is related to the self resistance of the artificial device and the basic grounding body and the mutual resistance between them.

2.3 Measurement Principle of Clamp Meter Method in the Case of Multi Base Tower Grounding

When testing the multi base grounding of towers and using the clamp meter method to verify its grounding performance, it is equivalent to adding other towers and lightning wires on the basis of the single base tower grounding. For the current flowing into the ground through multiple grounding bodies, the corresponding potential and current relationship on the two grounding bodies of the test tower are as follows:

$$\begin{cases} V_1 = R_{11}I_1 + R_{12}I_2 + R_{13}I_3 + \cdots + R_{1n}I_n \\ V_2 = R_{21}I_1 + R_{22}I_2 + R_{23}I_3 + \cdots + R_{2n}I_n \end{cases} \tag{7}$$

where, $R_{12}, R_{13}, \ldots, R_{1n}$are the mutual resistance between the artificial grounding device of the test tower and other tower grounding bodies, andR_{22}, R_{23}, …, R_{2n} are the mutual resistance between the foundation grounding body of the test tower and other tower grounding bodies.

Since there is at least one span distance between the grounding body of other towers and the grounding body of the test tower, the mutual resistance between the grounding body and the grounding body of the test tower is very small and can be ignored, so formula (7) can be simplified to formula (8).

$$\begin{cases} V_1 = R_{11}I_1 + R_{12}I_2 = (R_{11} - R_{12})I_1 + R_{12}(I_1 + I_2) \\ V_2 = R_{12}I_1 + R_{22}I_2 = (R_{22} - R_{12})I_2 + R_{12}(I_1 + I_2) \end{cases} \tag{8}$$

Similarly, the grounding bodies of other connected towers can be converted into similar forms, so the equivalent circuit diagram of clamp meter method measurement in the case of multi base tower grounding is shown in Fig. 2.

3 Simulation Calculation of Single Tower Grounding

3.1 Simulation Model

Because in the case of single base tower grounding, the self resistance and mutual resistance of the artificial device and tower foundation will have an error impact on the measurement results, so it is necessary to model the two parts of grounding body carefully. The international general Grounding Calculation Software CDEGS is used to build a single base tower grounding model, as shown in Fig. 3. The specific parameters of the model are as follows.

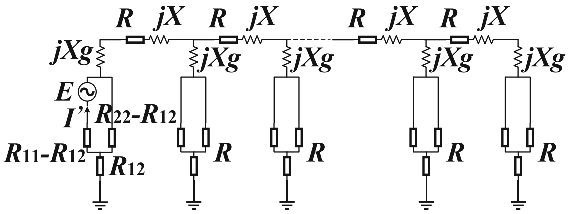

Fig. 2. Equivalent circuit diagram of tower grounding resistance measured by clamp meter method.

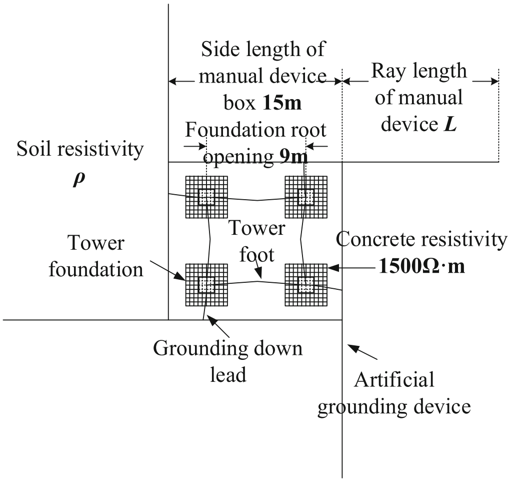

Fig. 3. Simulation model of single base tower grounding.

Tower Foundation Model. Straight column slab foundation is a commonly used type of tower foundation [16]. In this paper, straight column reinforced concrete slab foundation is used for modeling. There are 24 bars with a length of 3.8 m in the straight column φ 16 main bars and 16 pieces of 2.8 m long φ 8 hoops of steel bars, 48 steel bars with a length of 3.9 m for the plate type part φ 48 base plate reinforcement. The height of the foundation above the ground is 0.9 m. Each tower foundation is located in a concrete module with a wall thickness of 0.1 m, and the concrete resistivity is 1500 Ω m.

Artificial Grounding Device Model. The artificial grounding device adopts the form of closed box with rays, and the material is φ 12 round steel, the side length of the box is 15 m. The value of ray length *L* of artificial device under different soil resistivity of a project is shown in Table 1.

Tower Foot Connection Part Model. The grounding down lead is 50 mm × 5 mm flat steel, 75 mm main material of tower foot × 40 mm × 40 mm angle steel [14, 15]. Each foundation adopts 4 1.2 m long φ 42 anchor bolts.

Incentive Model. By applying current excitation, the theoretical value of tower grounding resistance, the self resistance of artificial device and tower foundation are calculated

Table 1. Corresponding ray length of artificial device under each soil resistivity.

Soil resistivity $\rho/\Omega\cdot\text{m}$	$100 \le \rho \le 500$	$500 < \rho \le 1000$	$1000 < \rho \le 1500$	$1500 < \rho \le 2000$
Ray length L/m	18	23	28	38

respectively. Apply voltage excitation to a certain section of the grounding down lead, and measure the axial current through the excitation conductor at the same time. The ratio of voltage to current is the measured value of clamp meter method.

3.2 Analysis of Simulation Results

The relevant factors affecting the self resistance and mutual resistance of grounding body are mainly soil resistivity and the size of grounding body. According to the calculation model, change the soil resistivity ρ from 100 $\Omega \cdot$ m to 2000 $\Omega\cdot$m, and the corresponding ray length of the artificial device will change. Calculate the theoretical value of the tower grounding resistance, the self resistance of the two parts of the grounding body, the mutual resistance between the two parts and the measured value of the clamp meter method under different input conditions, compare the errors, and analyze the sensitivity of each influencing factor. The relationship curves between various resistance values, transformation ratio coefficient η and soil resistivity ρ are shown in Fig. 4 and Fig. 5.

It can be seen from Fig. 4 and Fig. 5 that when the soil resistivity is low, the measured value of the clamp meter method is significantly greater than the actual value. With the increase of soil resistivity, the increase rate of the measured value by clamp meter method is less than the actual value, and the transformation coefficient will gradually decrease.

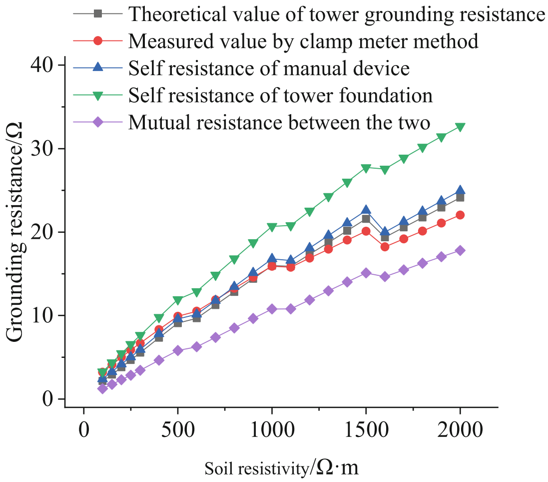

Fig. 4. Various resistance values under different soil resistivity.

From the comparison of curve size relationship in Fig. 4, it can be seen that the reason for this trend is: the existence of high resistivity concrete module makes the self resistance R_{22} of tower foundation much larger than the self resistance R_{11} of artificial device and the mutual resistance R_{12} between them under the condition of low soil resistivity, which makes the transformation coefficient η In formula (6), the first term $(R_{11} + R_{22} - 2R_{12})^2$ of the error increment numerator is much larger than the third term $R_{11}R_{22}$, so the error increment part is also positive. Therefore, in the range of low soil resistivity, the simulation value of clamp meter method is higher than the actual value. The self resistance of tower foundation and artificial device increases faster with the increase of soil resistivity than that of mutual resistance and clamp meter method. Therefore, with the increase of soil resistivity, the error increment changes from positive to negative. In general, the impact of the increase in soil resistivity plays a leading role.

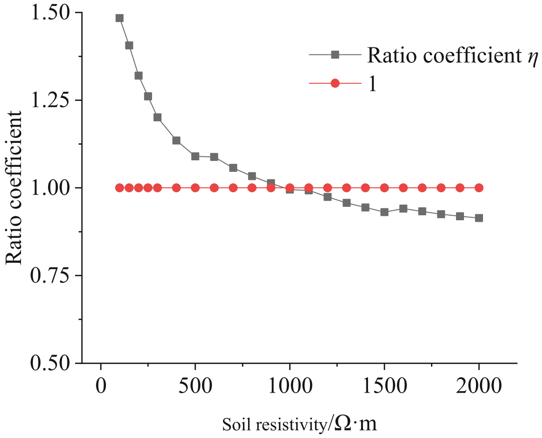

Fig. 5. Transformation coefficient under different soil resistivity.

4 Simulation Calculation of Multi Base Tower Grounding

4.1 Simulation Model

For the measurement under the condition of multi base tower grounding, compared with the measurement of single base tower, the test tower body, lightning wire, and the parallel branches of other towers and their grounding bodies are added. Therefore, it is necessary to model the adjacent towers and lines. The tower grounding resistance model is equivalent according to the equivalent circuit diagram in Fig. 2 and the calculation results under the condition of single base tower grounding. The specific parameters are as follows.

Line and Tower Model. The transmission line adopts Jmarti model, the DC resistance of lightning conductor is 2.86 Ω/km, the height of tower is 45 m, and the span of tower is 200 m. The tower model is simulated by using the segmented wave impedance model

[17–20], which is divided into main materials, inclined materials and cross arms. The wave impedance of each section is taken as the conventional value, in which the wave impedance $Z_{\mathrm{T}k}$ of the main material is taken as 150 Ω; The wave impedance of the inclined material $Z_{\mathrm{L}k} = 9Z_{\mathrm{T}k} = 1350\ \Omega$, and the length of the inclined material is set to 1.5 times the length of the corresponding main material; The cross arm wave impedance $Z_{\mathrm{A}k}$ is taken as 200 Ω; The propagation speed of shock wave in the tower is 0.85 times the speed of light, that is2.55×10^8 m/s.

Tower Grounding Resistance Model. According to the calculation results of single base tower grounding, the self resistance and mutual resistance of the corresponding artificial grounding device and tower foundation grounding body under different soil resistivity can be obtained, and the tower grounding parameters in the simulation model can be set according to the equivalent circuit diagram in Fig. 2.

Power Model. The amplitude of excitation power supply is 10 V, and the frequency is 2400 Hz measured by Kyoritsu model 4200 clamp type grounding resistance tester.

Finally, the simulation model shown in Fig. 6 can be established.

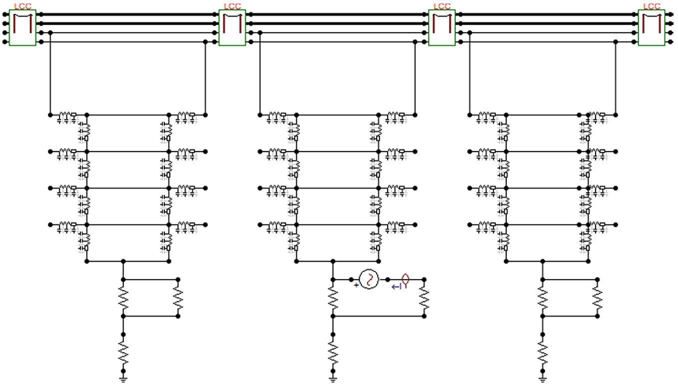

Fig. 6. Partial diagram of multi base tower clamp Table measurement simulation model.

4.2 Analysis of Simulation Results

The main factors affecting the impedance of this new parallel branch are the tower and lightning conductor. The effects of tower span, tower height, DC resistance of lightning conductor and soil resistivity on the measurement results are simulated.

Influence of the Number of Surrounding Parallel Towers. Firstly, the influence of the number of tower circuits on the measurement results is studied, and the number of towers on both sides of the measured tower is changed in the simulation model to study the change of the measurement results. In the simulation, various resistance values are set as the calculation data when the soil resistivity is 500 Ω·m. The grounding resistance of the tower artificial device is 9.587 Ω, the foundation grounding resistance is 11.929 Ω, the mutual resistance is 5.805 Ω, and the theoretical value is 9.089Ω. The relationship between the transformation ratio coefficient and the number of unilateral towers can be obtained by measuring the loop current, as shown in Table 2.

Table 2. Calculation results under different numbers of parallel towers.

Number of single pole and tower	Measuring current/A	Measured value by clamp meter method/Ω	Ratio coefficient η
1	1.284	7.788	0.857
2	1.299	7.698	0.847
3	1.312	7.622	0.839
4	1.318	7.587	0.835
5	1.319	7.582	0.834

According to the calculation results in Table 2, the more towers are connected in parallel, the more parallel circuits are formed, and the smaller the equivalent impedance is, the smaller the transformation ratio coefficient is. In addition, after the number of unilateral towers exceeds 4, the trend of reduction of transformation ratio coefficient tends to be saturated. It can be seen that the measuring current mainly forms a loop through the towers within 800 m from both sides of the measuring tower, and the influence of other towers at a longer distance on the resistance is negligible. Therefore, the later simulation research is slightly simplified, using the model of four towers on both sides, which helps to speed up the calculation speed, and has little impact on the results.

Influence of Tower Span. Within the range of 800 m from the measured tower, if the distance between the towers is changed, the number of towers will change, that is, the number of circuits formed by lightning wires is different. Since the circuits can be regarded as parallel relationship, the parallel equivalent resistance of circuit resistance will also change. The relationship between the ratio coefficient and the span of the tower can be obtained, as shown in Table 3.

Table 3. Calculation results under different tower spans.

Tower span/m	Measuring current/A	Measured value by clamp meter method/Ω	Ratio coefficient η
100	1.360	7.353	0.809
160	1.333	7.502	0.825
200	1.318	7.587	0.835
400	1.262	7.924	0.872

According to the calculation results in Table 3, the shorter the span between towers is, the more parallel circuits will be formed within a certain distance. Therefore, the smaller the parallel equivalent impedance of tower lightning line branch is, the smaller the measured loop impedance is and the smaller the transformation ratio coefficient is.

Influence of Tower Height. By changing the height of the tower and correspondingly changing the sectional wave impedance of the tower, the relationship between the transformation ratio coefficient and the height of the tower can be obtained, as shown in Table 4.

Table 4. Calculation results under different tower heights.

Tower height/m	Measuring current/A	Measured value by clamp meter method/Ω	Ratio coefficient η
35	1.328	7.530	0.828
45	1.318	7.587	0.835
55	1.307	7.651	0.842
65	1.304	7.669	0.844

According to the calculation results in Table 4, the lower the tower height is, the smaller the equivalent wave impedance is, the smaller the transformation ratio coefficient is. Because at this time, the smaller the tower impedance makes the reduction effect of parallel branches on the total loop impedance more obvious.

Influence of DC Resistance of Lightning Conductor. By changing the DC resistance of the lightning conductor, the relationship between the transformation ratio coefficient and the DC resistance of the lightning conductor can be obtained, as shown in Table 5.

Table 5. Calculation results under different DC resistance of lightning conductor.

DC resistance of lightning conductor/Ω	Measuring current/A	Measured value by clamp meter method/Ω	Ratio coefficient η
0.18	1.321	7.570	0.833
0.36	1.320	7.576	0.834
0.72	1.320	7.576	0.834
1.43	1.319	7.582	0.834
2.86	1.318	7.587	0.835

It can be seen from the calculation results in Table 5 that when using the lightning conductor with better conductivity and smaller outer diameter, the DC resistance of the lightning conductor is smaller, and the transformation ratio coefficient is smaller.

At this time, the smaller lightning conductor impedance makes the reduction effect of parallel branches on the total loop impedance more obvious. However, since the measured current propagation range is mainly within 800 m, the total DC resistance of the lightning conductor changes little when the distance is short, and the influence on the transformation ratio coefficient is small, which can be ignored.

Influence of Soil Resistivity. Various resistance values are taken according to the calculation results of different soil resistivity in Fig. 4. Changing various resistance values can obtain the relationship between transformation coefficient and soil resistivity, as shown in Table 6.

Table 6. Calculation results under different soil resistivity.

Soil resistivity/Ω·m	Theoretical value/Ω	Measuring current/A	Measured value by clamp meter method/Ω	Ratio coefficient η
100	2.163	3.557	2.811	1.300
150	2.924	2.900	3.448	1.179
200	3.803	2.444	4.092	1.076
250	4.665	2.138	4.677	1.003
300	5.566	1.906	5.247	0.943
400	7.329	1.528	6.545	0.893
500	9.089	1.318	7.587	0.835
800	12.830	1.001	9.990	0.779
1100	15.911	0.846	11.820	0.743
1400	20.169	0.697	14.347	0.711
1700	20.559	0.719	13.908	0.677
2000	24.124	0.621	16.103	0.668

According to the calculation results in Table 6, the transformation ratio coefficient will still decrease with the increase of soil resistivity in the case of multi base tower grounding, but due to the shunt of tower and lightning wire, the measurement result at this time is smaller than that in the case of single base tower grounding. When the soil resistivity is 100 Ω·m, the transformation ratio coefficient is 1.300. When the soil resistivity exceeds 300 Ω·m, the transformation coefficient will fall below 1.

5 Conclusion

In this paper, the following conclusions are obtained by establishing the simulation models of measuring the tower grounding resistance with clamp meter method under the conditions of single base tower grounding and multi base tower grounding respectively:

1) In the case of single tower grounding, when the soil resistivity is low, the measured value of clamp meter method is significantly greater than the actual value. With the increase of soil resistivity, the measured value of clamp meter method will show a trend of decreasing to a large extent, even smaller than the actual value.
2) In the case of multi base tower grounding, the measurement result of clamp meter method is smaller than that of single base tower grounding due to the shunt of tower and lightning wire.
3) The shorter the span between towers is, or the lower the height of towers is, the smaller the parallel equivalent impedance of tower lightning line branches is, the smaller the transformation ratio coefficient is.
4) In the measurement of tower grounding resistance, multiple error factors affect together, and different factors will play a leading role in different situations. Combined with the above simulation results and actual conditions, corresponding calculations can be carried out.

Acknowledgment. This work was financially supported by the science and technology project of State Grid Hunan Electric Power Company Limited (5216A5220005).

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