Structure Optimization and Preparation of Power System Grounding Grid Based on Similarity Data Analysis Algorithm

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Structure Optimization and Preparation of Power System Grounding Grid Based on Similarity Data Analysis Algorithm

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Abstract

The grounding grid of power equipment is the most basic overvoltage protection device for the power system. Before the design and construction of the power grounding grid, the power system generally uses a scaled-down model to verify the characteristics of the grounding grid. As the types and structures of grounding materials become more and more complex, there are one or more similar items in the grounding simulation test that cannot be scaled down. This paper takes the similarity test of a new type of grounding material-flexible graphite composite grounding material as an example. Firstly, the complete similarity theory of grounding simulation test is deduced. Secondly, the source of similar distortion items is analyzed. Then, the distortion error of different similar items is analyzed. Finally, the distortion similarity test of the flexible graphite composite grounding material is taken as an example to verify the test error influence of the distortion similarity item of the grounding simulation. The research results of this paper can provide reference for grounding simulation test, and at the same time, it can be applied to similar tests in other fields.

Keywords: Similarity data analysis, Distortion similarity model, Grounding grid, Structure optimization, Flexible graphite composite grounding material (FGCGM)

1 Introduction

With the improving requirements for lightning protection of power transmission lines, the grounding characteristics of tower grounding grid have been paid more attention [1]. The tower grounding grid adopts metal grounding materials such as steel, galvanized steel and copper clad steel. They often have problems such as high corrosion rate, large soil gap, strong inductance effect, difficult construction and high production cost [2,3]. Flexible graphite composite grounding material (acronym as GCMG or FGCGM) is a new non-metallic grounding material made of high conductive graphite and synthetic fiber, effectively avoiding many advantages of metal grounding materials. It has been applied in tower grounding engineering of AC transmission lines with multiple voltage levels, and achieved good application results [4,5].

Grounding simulation tests based on the similarity theory can study the actual grounding characteristics of grounding materials. According to grounding grid prototype, a small grounding grid model is constructed, and the measurement data of small grounding grid is used to infer the parameters of grounding grid prototype. It can conveniently change the topological structure of grounding grid and accurately control the test parameters; therefore, grounding simulation tests have received extensive attention in grounding research field [6]. Around the 1940s, the modeling method based on similarity theory was widely used in natural science fields such as aviation, water transport, solid mechanics, electromagnetics and meteorology, providing a reliable and effective theoretical analysis method for engineering research. When using similarity theory to conduct the model test, the key point is to obtain similarity criterion of the phenomenon. According to the model test data, the physical quantity related to the similarity criterion is measured to obtain specific value in the simulated phenomenon. By finding out the proportional relationship between the physical quantities of simulation system and prototype system, the model test data are extrapolated to prototype system.

The diameter of flexible graphite composite grounding material is generally between 22mm and 40mm. Larger grounding electrode diameter can increase the effective current dissipation area [7]. However, when using the complete similarity theory to conduct the grounding simulation test of grounding material, the similarity terms of grounding electrode diameter and grounding electrode resistivity cannot be scaled down completely. The unconventional grounding materials such as copper clad steel, angle steel, flat grounding electrode and tubular grounding electrode often face the same problem during the grounding test [8]. These distortion similarity terms cause great test errors in grounding simulation test, which limits the application of similarity theory in grounding industry. In this paper, the distortion similarity model of grounding simulation test is proposed. By analyzing the error sources of distortion similarity terms, the applicable scope of distortion similarity model is determined.

2 Complete similar model based on dimensional analysis method

Grounding system simulation test is divided into power frequency grounding simulation test and impulse grounding simulation test. The grounding system adopts the power frequency grounding resistance value as the standard when designing, but the spark discharge effect caused by impulse current and the inductance and capacitance effects of grounding electrode are ignored. Impulse grounding simulation test can further simulate grounding resistance of grounding grid under lightning impulse current or short-circuit fault current, which is closer to the actual situation. The disadvantage is that it is difficult to achieve the scaled model of impulse test platform, especially the rising edge time variable of impulse current [9, 10].

2.1 Non-metallic grounding material and its preparation process

Unlike traditional metal grounding materials, flexible graphite composite grounding material (FGCGM) is conductor which made of graphite. As shown in Figure 1, the preparation of FGCGM involves the following processes:(1) crystalline flake graphite (material mesh 80, carbon content of 95%) through oxidation (potassium permanganate and hydrogen peroxide solution) to prepare expansible graphite. After heating at 900 ℃for 5 to 8 seconds to get vermicular graphite, the volume of vermicular graphite was tens of times larger than that of flake graphite, its shape is fluffy and can be compressed by pressure. (2) The vermicular graphite was pressed into a single layer of graphite paper, and the glass fiber was placed between the upper and lower layers of graphite paper. The surface of the glass fiber was soaked with adhesive (water-soluble ethyl acrylate, ratio 1:1). The moisture of the adhesive was removed by heating for 10 seconds at 60-80℃, and then the sandwich graphite paper is obtained by the second roll pressing. (3) The sandwich graphite paper is cut into narrow strips, and the graphite wire is made by twisting, with a diameter of about 2-2.5mm. (4) 44 graphite wires were used as the inner core layer, and the outer braided layer was 24 graphite wires. A graphite composite grounding with a diameter of about 28mm was obtained by braiding.

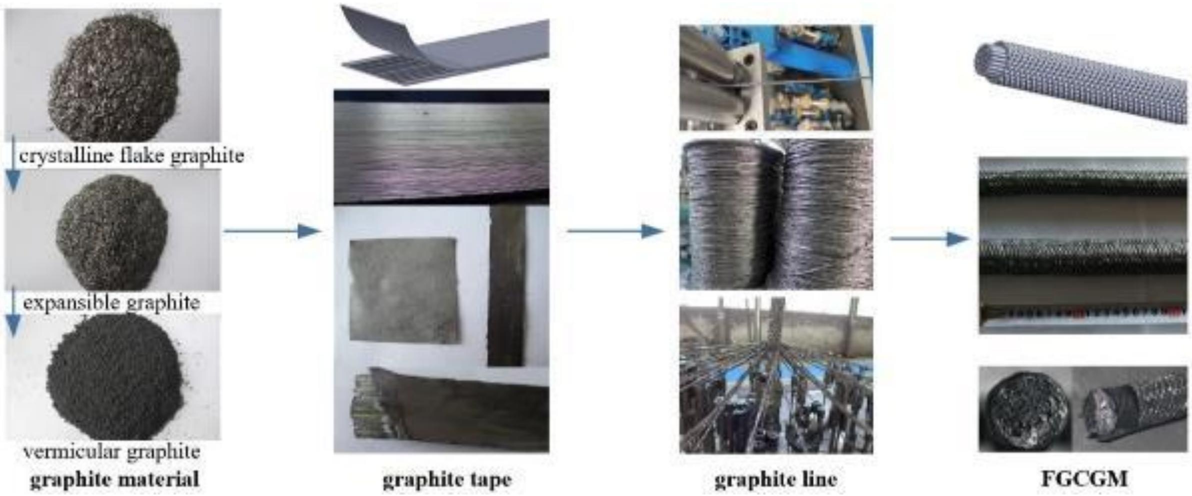

Fig. 1 Preparation processes of flexible graphite composite electrical grounding material (FGCGM)

Due to the difference between the preparation process of FGCGM and the metallurgical process of traditional metal, the diameter of FGCGM should not be too small. On the one hand, the power system requires the conductor cross-sectional area of grounding material, on the other hand, the preparation of FGCGM mainly adopts the weaving process, which causes that the similarity variable analysis method cannot adopt the complete similarity model.

2.2 Power frequency grounding complete similar model

The power frequency grounding simulation test is based on the similarity three theorems deduced by the Laplace equation [6]. This method takes the structural size of grounding electrode as the unified variables. In order to analyze the influence of length, diameter and cross-section shape of the graphite composite grounding electrode on the similarity criterion of the simulation test, this paper adopts the dimensional analysis method to derive the similarity criterion of the power frequency grounding simulation test.

According to the second similarity theorem, the criterion relationship or π relationship is shown in Eq.1 [11,12].

$$f(\pi_1, \pi_2, \cdots, \pi_{n-k}) = 0 \tag{1}$$

According to the first similarity theorem, the similarity criterion corresponding to similarity phenomenon at the same moment and same point is equal, as shown in Eq.2.

$$\begin{cases} \pi_{1m} = \pi_{1p} \\ \pi_{2m} = \pi_{2p} \\ \vdots \\ \pi_{(n-k)m} = \pi_{(n-k)p} \end{cases} \tag{2}$$

Where the p represents the parameter of full-scale test; the m represents the parameter of simulation test. The simplified formula is shown in Eq.3.

$$\begin{cases} f(\pi_{1m}, \pi_{2m}, \cdots, \pi_{(n-k)m}) = 0 \\ f(\pi_{1p}, \pi_{2p}, \cdots, \pi_{(n-k)p}) = 0 \end{cases} \tag{3}$$

In the model test, the π is divided into dependent variable π and independent variable π. If π_1 in Eq.1 is the dependent variable π of simulation system, Eq.2 can be converted to Eq.4.

$$\pi_1 = f_1(\pi_2, \pi_3, \cdots, \pi_{n-k}) \tag{4}$$

Eq.4 is the general expression of π relation equation between dependent variable and independent variable. If there are more than one dependent variables π, they can be moved to the left of equal sign.

According to the third similarity theorem, each single-valued variable of graphite composite grounding simulation test system is determined, such as grounding electrode length L, grounding electrode section diameter D, grounding electrode resistivity ρ_0, soil resistivity ρ_1, grounding electrode buried depth h, current source excitation amplitude I, time t, grounding electrode resistance R and grounding grid potential U. It should be noted that the reference variable D is for solid graphite composite grounding electrode, and the equivalent diameter should be considered for expanded-diameter graphite composite grounding material or other cross-section shape of grounding electrode. In addition, when the grounding electrode is in a layered soil structure, the similarity criterion of soil resistivity ρ_1 should be extrapolated to the soil resistivity ρ_{11}, ρ_{12}, ..., ρ_{1n} of each layer. The SI dimensions of the above physical quantities are shown in Table 1.

Table 1 SI dimension of each physical quantity of power frequency grounding simulation test

Physical quantity	l	D	h	I	t
SI dimension	L	L	L	I	T
Physical quantity	ρ_0	ρ_1	U	R	
SI dimension	$L^3MT^{-3}I^{-2}$	$L^3MT^{-3}I^{-2}$	$L^2MT^{-3}I^{-1}$	$L^2MT^{-3}I^{-2}$	

The basic physical quantities of the simulation system are selected as l, I, t, and ρ_1. Other physical quantities D, h, ρ_0, R, and U are regarded as functions of the basic physical quantities. The dimensional relationship between them is shown in Eq.5.

$$\left[R, U, D, h, \rho_0\right] = \left[l\right]^{x_1}\left[I\right]^{x_2}\left[t\right]^{x_3}\left[\rho_1\right]^{x_4} \tag{5}$$

Where x_1, x_2, x_3 and x_4 are the power indexes of each basic dimension, respectively. According to the dimensional homogeneous theorem, the five π terms of system are:

$$\pi_1 = \frac{Rl}{\rho_1},\quad \pi_2 = \frac{Ul}{I\rho_1},\quad \pi_3 = \frac{D}{l},\quad \pi_4 = \frac{h}{l},\quad \pi_5 = \frac{\rho_0}{\rho_1} \tag{6}$$

According to Eq.4, the π relationship related to the dependent variables in the grounding simulation test is expressed as:

$$\begin{cases} \dfrac{Rl}{\rho_1} = f_R\left(\dfrac{D}{l}, \dfrac{h}{l}, \dfrac{\rho_0}{\rho_1}\right) \\ \dfrac{Ul}{I\rho_1} = f_U\left(\dfrac{D}{l}, \dfrac{h}{l}, \dfrac{\rho_0}{\rho_1}\right) \end{cases} \tag{7}$$

According to the second similarity theorem, in order to make the grounding grid model composed of graphite composite grounding electrode completely similar to the prototype, each π term of the independent variable must be equal, namely:

$$\frac{D_{\mathrm{p}}}{l_{\mathrm{p}}} = \frac{D_{\mathrm{m}}}{l_{\mathrm{m}}},\ \frac{h_{\mathrm{p}}}{l_{\mathrm{p}}} = \frac{h_{\mathrm{m}}}{l_{\mathrm{m}}},\ \frac{\rho_{0\mathrm{p}}}{\rho_{1\mathrm{p}}} = \frac{\rho_{0\mathrm{m}}}{\rho_{1\mathrm{m}}} \tag{8}$$

When the similarity condition of the above independent variables is satisfied, the dependent variable π terms are equal, namely:

$$\frac{R_{\mathrm{p}} l_{\mathrm{p}}}{\rho_{1\mathrm{p}}} = \frac{R_{\mathrm{m}} l_{\mathrm{m}}}{\rho_{1\mathrm{m}}} \tag{9}$$

$$\frac{U_p l_p}{I_p \rho_{1p}} = \frac{U_m l_m}{I_m \rho_{1m}} \tag{10}$$

Combined with Eq.7, there are:

$$\begin{cases} \dfrac{R_{\mathrm{p}} l_{\mathrm{p}}}{\rho_{1\mathrm{p}}} = \dfrac{R_{\mathrm{m}} l_{\mathrm{m}}}{\rho_{1\mathrm{m}}} = f_R\left(\dfrac{D_{\mathrm{m}}}{l_{\mathrm{m}}},\quad \dfrac{h_{\mathrm{m}}}{l_{\mathrm{m}}},\quad \dfrac{\rho_{0\mathrm{m}}}{\rho_{1\mathrm{m}}}\right) \\ \dfrac{U_{\mathrm{p}} l_{\mathrm{p}}}{I_{\mathrm{p}}\rho_{1\mathrm{p}}} = \dfrac{U_{\mathrm{m}} l_{\mathrm{m}}}{I_{\mathrm{m}}\rho_{1\mathrm{m}}} = f_U\left(\dfrac{D_{\mathrm{m}}}{l_{\mathrm{m}}},\quad \dfrac{h_{\mathrm{m}}}{l_{\mathrm{m}}},\quad \dfrac{\rho_{0\mathrm{m}}}{\rho_{1\mathrm{m}}}\right) \end{cases} \tag{11}$$

When establishing the grounding grid model of simulation test composed of graphite composite grounding electrode, the similarity relationship between the above similarity terms must be determined. Generally, based on the model size similarity ratio, the factors that are easy to control in the test are scaled down accordingly. The similarity ratio of grounding electrode length is:

$$\lambda_l = \frac{l_{\mathrm{p}}}{l_{\mathrm{m}}} \tag{12}$$

The similarity ratio of soil resistivity in the simulation test is:

$$\lambda_{\rho 1} = \frac{\rho_{1\mathrm{p}}}{\rho_{1\mathrm{m}}} \tag{13}$$

Then, the similarity ratio of the cross-sectional diameter of grounding electrode is solved according to Eq.8:

$$\lambda_D = \lambda_l \tag{14}$$

The distance between the axis of grounding electrode and horizontal plane, namely, the buried depth similarity ratio is:

$$\lambda_h = \lambda_l \tag{15}$$

The resistivity similarity ratio of simulation test grounding electrode should satisfy:

$$\lambda_{\rho_0} = \lambda_{\rho_1} \tag{16}$$

The similarity ratio of grounding resistance can be solved according to the Eq.9:

$$\lambda_R = \frac{\lambda_{\rho 1}}{\lambda_l} \tag{17}$$

The power frequency grounding test generally adopts power frequency voltage source or current source excitation. Taking the power frequency current source as an example, the similarity ratio of current excitation between full-scale test and model test is:

$$\lambda_I = \frac{I_{\mathrm{p}}}{I_{\mathrm{m}}} \tag{18}$$

According to the Eq.10, the similarity ratio of grounding grid potential is obtained as follows:

$$\lambda_U = \frac{\lambda_I \cdot \lambda_{\rho 1}}{\lambda_l} \tag{19}$$

Eq.12 to Eq.19 the similarity conditions of each variable in the completely similar simulation test of graphite composite grounding materials.

2.3 Impulse grounding completely similar model

According to the physical quantities shown in Table 1, the impulse grounding simulation test should also consider the electric field strength *E* (dimension [LMT^{-3}I^{-1}]), the inrush current head time *τ* (dimension [T]), and the propagation velocity *v* of inrush current in the soil (dimension [LT^{-1}]). The basic physical quantities of the impulse grounding simulation test are selected as *l*, *I*,

τ, and ρ_1. Other physical quantities D, h, ρ_0, E, v, R and U are expressed by the basic physical quantities. The π relation of the impulse grounding simulation test is:

$$\begin{cases} \dfrac{Rl}{\rho_1} = f_{\mathrm{ch}R}\left(\dfrac{D}{l}, \dfrac{h}{l}, \dfrac{\rho_0}{\rho_1}, \dfrac{El^2}{I\rho_1}, \dfrac{vl}{\tau}\right) \\ \dfrac{Ul}{I\rho_1} = f_{\mathrm{ch}U}\left(\dfrac{D}{l}, \dfrac{h}{l}, \dfrac{\rho_0}{\rho_1}, \dfrac{El^2}{I\rho_1}, \dfrac{vl}{\tau}\right) \end{cases} \tag{20}$$

Similarly, the similarity conditions for solving the impulse grounding simulation test should satisfy:

$$\lambda_D = \lambda_l \text{, } \lambda_h = \lambda_l \text{, } \lambda_{\rho_0} = \lambda_{\rho_1} \text{, } \lambda_E = \frac{\lambda_I \lambda_{\rho_1}}{\lambda_l^{\ 2}} \text{, } \lambda_v = \frac{\lambda_l}{\lambda_\tau} \tag{21}$$

The impulse grounding simulation test and full-scale test need to ensure that the grounding electrode resistivity and soil resistivity are consistent, the electric field strength is consistent, and the lightning current wave velocity is consistent, therefore, Eq.21 has the following relation under theoretical conditions: $\lambda_{\rho_0} = \lambda_{\rho_1} = 1$, $\lambda_E = 1$, $\lambda_v = 1$.

The simplified similarity conditions for impulse grounding simulation test based on the dimensional analysis method are as follows:

$$\lambda_D = \lambda_l \text{, } \lambda_h = \lambda_l \text{, } \lambda_{\rho 0} = \lambda_{\rho 1} = 1 \text{, } \lambda_I = \lambda_l^{\ 2} \text{, } \lambda_\tau = \lambda_l \tag{22}$$

According to this similarity conditions, the similar relationship between impulse grounding simulation test result and the full-scale test is as follows:

$$\begin{cases} \lambda_{chR} = \lambda_l^{\ -1} \\ \lambda_{chU} = \lambda_l \end{cases} \tag{23}$$

In addition, according to the definition that the impulse coefficient of grounding resistance is the ratio of impulse grounding resistance to power frequency grounding resistance, the similarity relationship of impulse coefficient obtained by combining Eq.17 and Eq.23 is:

$$\lambda_\alpha = \frac{\alpha_{\mathrm{p}}}{\alpha_{\mathrm{m}}} = 1 \tag{24}$$

Eq.12~19 are the complete similarity conditions and prediction relationships of impulse test of graphite composite grounding electrode.

It should be noted that: (1) Since the full-scale grounding grid and simulation test adopt the same graphite composite grounding material, the Eq.16: $\lambda_{\rho 0}$=1. In order to theoretically make the model completely similar to the prototype, the simulation test should use the same soil as the full-scale test. (2) Power frequency grounding simulation test is generally used to solve the power frequency grounding resistance. Considering that the test current amplitude is not high, the potential rise of grounding grid is solved only in impulse grounding simulation test.

3 Simulation Verification of Completely Similar Model Based on Dimensional Analysis

In order to verify the accuracy of similarity theory of grounding simulation test based on dimensional analysis method, a full-scale grounding grid and a scaled grounding grid according to similarity criterion are established. The similarity criterion derived from Eq.12~19 is used to analyze the error between the prototype grounding grid and the actual grounding grid.

The prototype grounding grid composed of graphite composite grounding electrode is the 500kV transmission tower grounding grid [13], and the grounding grid model is FK20/50 (box extension type, grounding grid side length is 20m, extension grounding electrode of 4 corners is 50m). According to the completely similar model, the grounding grid prototype is reduced to small grounding grid model in different proportions. The grounding grid prototype and model parameters are shown in Table 2.

3.1 Prediction of power frequency grounding simulation test

The completely similar model of grounding grid power frequency grounding simulation test is verified. According to Eq.17 and Eq.19, the grounding resistance and conductor potential of the grounding grid prototype are predicted, and compared with the actual value of prototype.

Table 2 Prototype and Model Simulation Test of Graphite Composite Grounding Grid

Test parameters	Grounding grid prototype	λ_l=20 model	λ_l=10 model
Box length l_1 (m)	20	1	2
Ray length l_2 (m)	50	2.5	5
Buried depth h (m)	1	0.05	0.1
Grounding body resistivity ρ_0 (Ω·m)	3.25×10^{-5}	3.25×10^{-5}	3.25×10^{-5}
Grounding body relative permeability μ_r	1	1	1
Grounding body diameter D (mm)	28	1.4	2.8
Soil resistivity ρ_1 (Ω·m)	200	200	200
Power frequency current I (A)	20	5	10
Model power frequency grounding resistance R_m (Ω)	/	42.256	21.058
Prototype power frequency grounding resistance R_P (Ω)	2.010	2.113	2.106
Model conductor potential R_m (V)	/	211.279	210.578
Prototype conductor potential R_P (V)	40.7945	42.256	42.116

According to the calculation data in Table 2, compared with the grounding grid prototype, the prediction errors of power frequency grounding resistance of grounding grid models with λ_l=20 and λ_l=10 are 5.12 % and 4.78 %, and the prediction errors of conductor potential rise are 3.58 % and 3.12 %, respectively. The simulation results show that the model extrapolation results are consistent with the similarity relationship deduced by Eq.17 and Eq.19. According to the complete similarity condition based on dimensional analysis method, the prototype parameters of graphite composite grounding grid can be accurately predicted. The grounding grid model with a smaller similarity ratio λ_l=10 is closer to the test prototype.

It should be noted that the diameter of graphite composite grounding electrode of grounding grid model with λ_l=20 and λ_l=10 used in the simulation strictly follows the complete similarity criterion. This is because the small diameter grounding electrode in the actual grounding simulation test does not meet the material forming conditions, which involves the implementation and trade-off of some similar conditions in the grounding simulation test. In addition, the resistivity ρ_0 of graphite composite grounding electrode is not scaled down according to the complete similarity criterion. The lack of this similarity term is the main reason for the prediction error, but the error is still within the acceptable range.

3.2 Prediction of impulse grounding simulation test

The simulation test parameters of graphite composite grounding electrode are similar to table 2, and the grounding grid prototype adopts a standard lightning current waveform of 8/20μs. According to the actual measured value of lightning current of transmission line, the amplitude of lightning current of tower is 135kA [14]. In fact, when the impulse current amplitude exceeds the saturation current of soil, the simulation of impulse characteristics of grounding grid is basically guaranteed [15]. According to the complete similarity conditions of impulse grounding simulation test of Eq.22~Eq.24, the graphite grounding material grounding grid prototype in Table 2 is subjected to impulse grounding simulation tests with different similarity ratios. The calculation results are shown in Table 3.

Table 3 Impact grounding simulation test completely similar model

Parameter	Grounding grid prototype	λ_l=20 model	λ_l=10 model
Model impact grounding resistance R_{chm} (Ω)	/	163.699	81.986
Prototype impact grounding resistance R_{chp} (Ω)	11.914	8.185	8.199
Model conductor potential U_{chm} (kV)	/	55.248	1.107×10^{2}
Prototype conductor potential U_{chp} (kV)	1.610×10^{3}	1.105×10^{3}	1.107×10^{3}

It should be noted that since the inductance effect of the grounding electrode is considered only in the simulation calculation and the spark discharge effect [16] is neglected, the impulse grounding impedance value and the grounding potential rise in Table 3 are much larger than those in Table 2. Thus, the impulse grounding characteristics calculated by simulation have deviations from the actual physical process. More accurate test results can be obtained through the true impact grounding test.

4 Distortion similarity terms and distortion similarity model of grounding simulation test

4.1 Distortion similarity terms

When all the dependent variable π terms satisfy $\pi_p=\pi_m$ in the grounding simulation test, the model used in the simulation test can theoretically correspond to the full-scale test. However, not all test conditions can satisfy the correspondence of $\pi_p=\pi_m$ in fact. When the phenomenon is more complicated and the test conditions are limited, several dependent variable π terms cannot satisfy the second similarity theorem. The model with one or more π terms that cannot be satisfied is called incomplete similarity model or distortion model. The π term of one or more dependent variables that do not satisfy the second similarity theorem in the model is called incomplete similarity term or distortion term [17] (The following are collectively referred to distortion similarity term). When there is an incompletely similar π term in the simulation test, the predicted prototype results deviate from the actual values.

The solid and expanded graphite composite grounding materials shown in Fig.1 are all over 28mm in diameter. In grounding simulation tests of galvanized steel and round steel, steel wires or rods with different diameters are often used to achieve the scaling of grounding electrode diameter. However, the graphite composite grounding material is limited by the molding method and cannot be scaled in diameter. When the size of grounding electrode can be compared with the length of grounding body, the lack of this similarity will bring considerable error to the simulation test, which further limits the application of similarity theory in grounding simulation test.

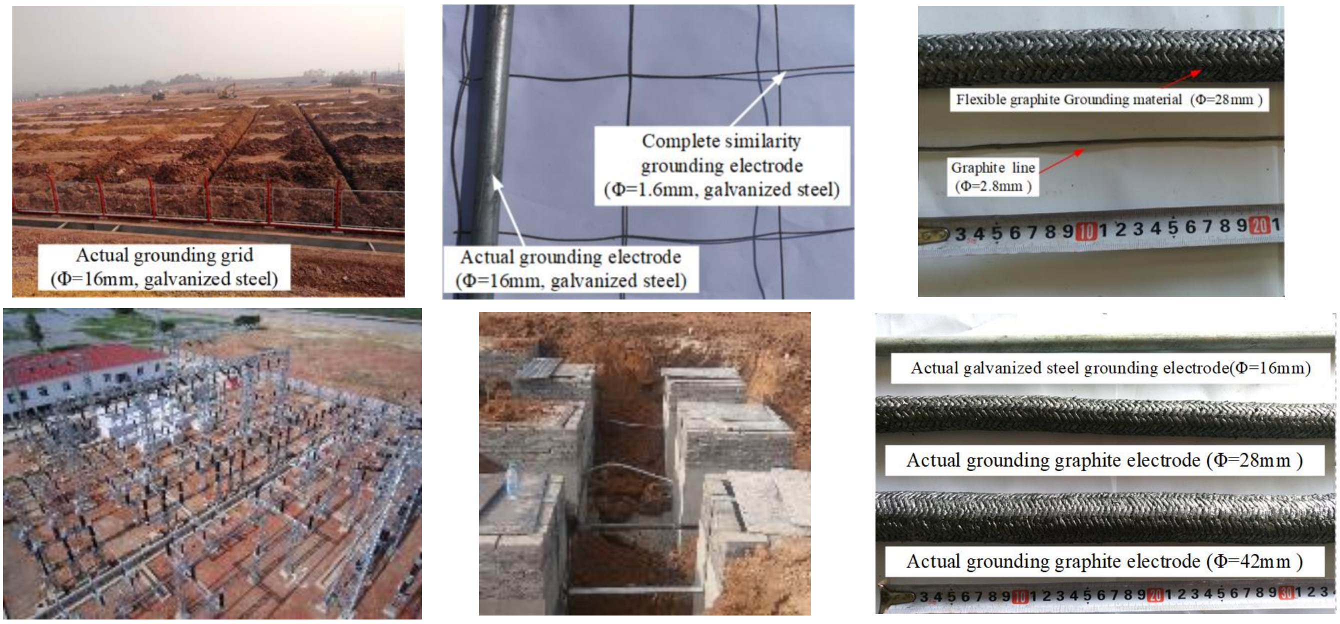

Fig. 2 Actual grounding grid and simulation test model (galvanized steel and GCGM)

4.2 Distortion similarity model

When there is a distortion similarity term in the grounding simulation test, the predicted prototype results deviate from the actual values. This paper defines the similarity test model with distortion similarity terms as incomplete similarity model or distortion similarity model (The following are collectively referred to distortion similarity model). When there is a π term in the grounding simulation test that cannot satisfy the corresponding relationship of $\pi p=\pi m$, the π term is called the single distortion term, and the grounding simulation test model is called the single distortion model. When more than one π term cannot be satisfied in the grounding simulation test, the grounding simulation test model is called a multi distortion model.

In order to further describe the mathematical expression of grounding simulation test distortion similarity model, this paper assumes that the π term related to the dependent variable is π_1. There are two independent variables π terms, namely π_j and π_k, which cannot be satisfied. The distortion coefficients φ and ω are defined as follows:

$$\varphi = \frac{\pi_{jm}}{\pi_{jp}} \tag{25}$$

$$\omega = \frac{\pi_{km}}{\pi_{kp}} \tag{26}$$

The physical meaning of distortion coefficient is the distortion degree of dependent variable π term in the model. When other π terms satisfy similarity conditions, the test conditions followed by the distortion model are:

$$\begin{cases} \pi_{2m} = \pi_{2p} \\ \pi_{3m} = \pi_{3p} \\ \quad \cdots \\ \pi_{jm} = \varphi \cdot \pi_{jp} \\ \pi_{km} = \omega \cdot \pi_{kp} \\ \quad \cdots \\ \pi_{nm} = \pi_{np} \end{cases} \tag{27}$$

According to Eq.4, the dependent variable π term can be expressed as a function of the independent variable π term. Assuming that the relationship between the dependent variable $\pi 1$ and the independent variable for the full-scale test is:

$$\begin{cases} \pi_{1p} = f\left(\pi_{2p}, \cdots, \pi_{jp}, \pi_{kp}, \cdots, \pi_{np}\right) \\ \pi_{1m} = f\left(\pi_{2m}, \cdots, \pi_{jm}, \pi_{km}, \cdots, \pi_{nm}\right) \end{cases} \tag{28}$$

Eq.25~ Eq.28 are the mathematical representations of distortion similarity model in the grounding simulation test.

5 Distortion similar grounding simulation test example

In order to further illustrate the effect of distortion similarity terms on the grounding simulation test of graphite composite grounding materials, the comparison test of complete similarity model and distortion similarity model is carried out on the grounding simulation test platform. The grounding simulation test platform adopts a hemispherical metal simulation tank with a radius of 4m, and the reflux electrode of the simulated tank shell adopts a flat copper strip with longitude and latitude distribution, which is connected to the outdoor grounding grid [18]. The soil type in the simulated tank is double-layer simulated soil. The upper simulated soil adopts fine sand with a thickness of 0.35m, its soil resistivity can be adjusted by the water content of the sand. The soil resistivity of lower red loam is about 167 Ω·m. Before the test, the soil resistivity of upper sand was reduced by adjusting the water content. After the water was uniformly dispersed, the soil resistivity of the upper sand is about 540 Ω·m measured repeatedly by the soil resistivity test tank.

5.1 The measurement results of distortion similarity model

The graphite composite grounding electrode with diameter of 28 mm is selected to form the diameter distortion similarity grounding grid model, and the steel wire with diameter of 2.6 mm (which is replaced the composite grounding electrode with diameter of 2.8 mm) is selected to form the completely similarity grounding grid model. The size of prototype grounding grid is FK15/8m, and the buried depth is 1m. The size of grounding grid model is FK1.5/0.8m, and the buried depth is 0.1m. Taking the graphite composite grounding grid model as an example, the model of distortion similarity grounding grid is shown in Fig.2:

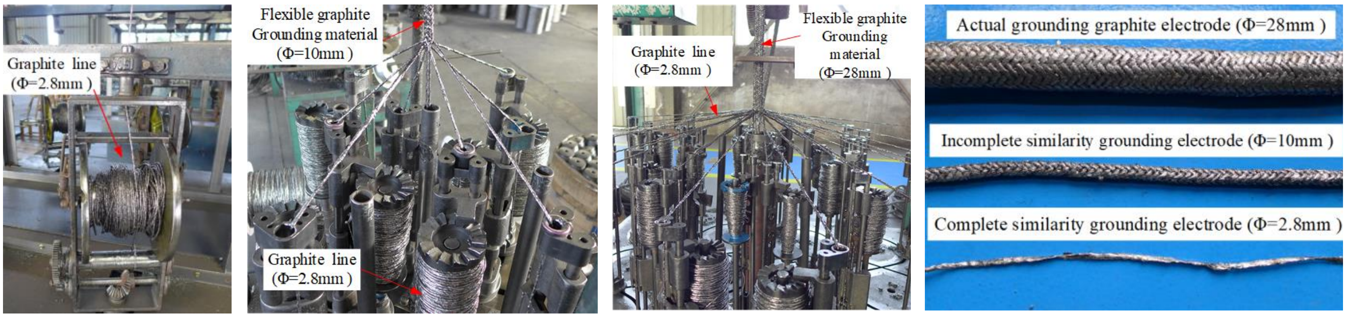

Fig. 3 Distortion similarity model grounding simulation test

The grounding resistance of grounding grid model is measured by the power frequency injection method for the 1# and 2# grounding down conductors of the near-ground and remote ends respectively. The measurement results are shown in Table 4.

Table 4 Distortion similarity model measurement of GCGM (power frequency current injection method)

1# down the line	Measuring voltage (V)	128.7	156.2	178.6	197.4	218.6
	Measuring current (A)	1.92	2.333	2.669	2.954	3.279
	Power frequency grounding resistance (Ω)	67.06	67.03	66.95	66.92	66.83
2# down the line	Measuring voltage (V)	117.5	143.6	170.4	195.1	219.1
	Measuring current (A)	1.756	2.148	2.551	2.926	3.29
	Power frequency grounding resistance (Ω)	66.91	66.85	66.80	66.68	66.60

It can be seen from Table 4 that with increasing measured current, the measured values of power frequency grounding resistance of different down conductors are basically stable. In order to verify the accuracy of measurement, the C.A 6423 grounding resistance tester is used to measure the power frequency grounding resistance, as shown in Table 5.

Table 5 Distortion similarity model measurement of GCGM (three-electrode method)

Measurement direction	Direction 1	Direction 2	Direction 3	Direction 4	Mean value
Power frequency grounding resistance (Ω)	66.6	65.9	66.4	64.0	65.73

Combining the measurement results in Table 4 and Table 5, the power frequency injection method is very close to the three-electrode method. Since the grounding grid test model is small, the measured values of the near-ground line end and the remote end line are not much different. In this paper, the mean value of 66.72 Ω is taken as power frequency grounding resistance of distortion similarity grounding grid model. According to Eq.17, the grounding resistance of prototype grounding grid with FK15/8m should be 6.672Ω.

It should be noted that the above test not only has the distortion term of grounding electrode diameter, the similarity test but also has the distortion term of grounding electrode resistivity according to Eq.6 and Eq.16. For the latter, this paper can consider that the soil resistivity in the grounding simulation tank is consistent with the soil resistivity in the actual grounding grid prototype, so this distortion term is ignored, and only the influence of grounding electrode diameter distortion on the prediction result is considered.

5.2 The measurement results of completely similar model

After the distortion similar grounding simulation test, in order to prevent the change of soil resistivity in the grounding tank, the completely similar model grounding grid constructed with 2.6mm steel wire is immediately replaced by the distortion similar grounding grid. The size of grounding grid model is FK1.5/0.8m, and the buried depth is 0.1m. The power frequency current is applied to the grounding grid model by a single-injection down-flow method. The measured values under different current amplitudes are shown in Table 6.

Table 6 Completely similar model measurement of galvanized steel (power frequency current injection method)

Measuring voltage (V)	79.61	94.20	110.2	121.9	139.4
Measuring current (A)	0.72	0.854	1.002	1.108	1.269
Power frequency grounding resistance (Ω)	110.56	110.30	109.98	110.02	109.85
Measuring voltage (V)	154.3	169.1	186.8	206	217.3

Measuring current (A)	1.406	1.544	1.708	1.886	1.993
Power frequency grounding resistance (Ω)	109.74	109.52	109.37	109.23	109.03

It can be seen from Table 6 that the stable value of the power frequency grounding resistance of the round steel completely similar grounding grid model is about 109.03 Ω, and the grounding resistance of the prototype grounding grid with the size of FK15/8m should be 10.903Ω. Comparing this value, it can be found that due to the existence of distortion term of grounding electrode diameter, the predicted value of distortion similarity model extrapolated to grounding grid prototype is 6.672Ω, which is smaller than the predicted value of 10.903Ω for completely similar grounding grid This shows that on the small-sized grounding simulation test platform, the deviation caused by the existence of the grounding electrode diameter distortion term has affected the predicted results of the grounding simulation test.

5.3 Comparison verification

The simulation calculation software is used to repeat the above grounding simulation test, and the test parameters are set according to the actual test parameters of grounding simulation test platform. The power frequency grounding resistance of prototype grounding grid with the size of FK15/8m and buried depth of 1m is about 9.07Ω, which is close to the predicted value of completely similar model constructed by the steel wire grounding grid. On the grounding simulation test platform, the prediction error of grounding grid predicted by completely similar condition is small, the prediction result of distortion similarity model is quite different from the actual value. It is necessary to correct the error of the prediction results of the distortion model.

When the graphite composite grounding material, the copper-clad steel grounding material and non-circular grounding electrode are used for the grounding simulation test, the structure size of grounding electrode cannot be scaled according to the similar conditions, resulting in one or more distortion similarity terms. The above error is the main source of prediction error in grounding simulation test.

6 Conclusion

This paper starts from the practical problem that some similarity te π rms in the grounding simulation test cannot meet the similarity conditions. Through theoretical analysis and test verification, the main conclusions are as follows:

(1) The grounding simulation test is mainly based on the complete similarity theory derived by equation analysis method in Ref [1]. When the three-dimensional size and material parameters of the grounding electrode in the grounding simulation test influence the simulation test results, the prediction error caused by these similarity terms needs to be considered.

(2) Based on dimensional analysis method, a completely similar model of grounding simulation test considering the similarity terms of three-dimensional size and material parameters of grounding electrode is proposed. The correctness of the similarity criterion was verified by simulation tests.

(3) The concepts of distortion similarity terms, distortion coefficient, single distortion similarity model and multi distortion similarity model in grounding simulation test are proposed. The mathematical representation of distortion similarity model is given. The source of distortion similarity terms in the grounding simulation test is clarified.

(4) Through the grounding simulation test platform, the distortion similarity model and complete similarity model are built. The measurement results and simulation verifications show that the prediction error of distortion similarity model in the grounding simulation test.

The distortion similarity model described in this paper can provide theoretical reference for simulation tests of other grounded materials. Since distortion similarity terms widely exists in other power system scaling tests, the single distortion or multi distortion similarity model proposed can also provide reference for simulation tests in other fields.

CONFLICT OF INTEREST STATEMENT

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

AUTHOR CONTRIBUTIONS

Yuanchao Hu: software and grounding test; Tao Huang: simulation and grounding test; Seunggil Jeon: Manufacturing equipment development and debugging, control equipment installation; Changqing DU: grounding test; Yunzhu An: project administration and data arrangement; Shangmao Hu: supervision, supervision and proofreading.

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DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

References

[1] Chen, H., & Du, Y. (2018). Lightning grounding grid model considering both the frequency-dependent behavior and ionization phenomenon. IEEE Transactions on Electromagnetic Compatibility, 61(1), 157-165. doi:10.1109/TEMC.2017.2789210.

[2] Nazari, M., Moini, R., Fortin, S., Dawalibi, F. P., & Rachidi, F. (2020). Impact of Frequency-Dependent Soil Models on Grounding System Performance for Direct and Indirect Lightning Strikes. IEEE Transactions on Electromagnetic Compatibility, 1–11. doi:10.1109/temc.2020.2986646

[3] Alipio, R., Conceição, D., De Conti, A., Yamamoto, K., Dias, R. N., & Visacro, S. (2019). A comprehensive analysis of the effect of frequency-dependent soil electrical parameters on the lightning response of wind-turbine grounding systems. Electric Power Systems Research, 175, 105927. doi:10.1016/j.epsr.2019.105927

[4] Sekioka, S. (2018). Frequency and Current-Dependent Grounding Resistance Model for Lightning Surge Analysis. IEEE Transactions on Electromagnetic Compatibility, 1–7. doi:10.1109/temc.2018.2829923.

[5] Batista, R., Louro, P. E. B. B., & Paulino, J. O. S. (2021). Lightning performance of a critical path from a 230-kV transmission line with grounding composed by deep vertical electrodes. Electric Power Systems Research, 195, 107165. doi:10.1016/j.epsr.2021.107165

[6] Ghania, S. M. (2019). Grounding systems under lightning surges with soil ionization for high voltage substations by using two layer capacitors (TLC) model. Electric Power Systems Research, 174, 105871. doi:10.1016/j.epsr.2019.105871

[7] Gazzana, D. S., Bretas, A. S., Dias, G. A. D., Telló, M., Thomas, D. W. P., & Christopoulos, C. (2014). A study of human safety against lightning considering the grounding system and the evaluation of the associated parameters. Electric Power Systems Research, 113, 88–94. doi:10.1016/j.epsr.2014.03.015

[8] Zhang, B., Patlolla, V. R., Chiao, D., Kalla, D. K., Misak, H., & Asmatulu, R. (2012). Galvanic corrosion of Al/Cu meshes with carbon fibers and graphene and ITO-based nanocomposite coatings as alternative approaches for lightning strikes. The International Journal of Advanced Manufacturing Technology, 67(5-8), 1317–1323. doi:10.1007/s00170-012-4568-3

[9] Li, Z.-X., Gao, K.-L., Yin, Y., & Ge, D. (2014). Transient lightning responses of grounding systems buried in horizontal multilayered earth with a hybrid method. Journal of Electrostatics, 72(5), 381–386. doi:10.1016/j.elstat.2014.06.009

[10] Salarieh, B., De Silva, H. M. J., & Kordi, B. (2020). Electromagnetic transient modeling of grounding electrodes buried in

frequency dependent soil with variable water content. Electric Power Systems Research, 189, 106595. doi:10.1016/j.epsr.2020.106595

[11] Caetano, C. E. F., Lima, A. B., Paulino, J. O. S., Boaventura, W. C., & Cardoso, E. N. (2018). A conductor arrangement that overcomes the effective length issue in transmission line grounding. Electric Power Systems Research, 159, 31–39. doi:10.1016/j.epsr.2017.09.022

[12] Androvitsaneas, V. P., Gonos, I. F., & Stathopulos, I. A. (2016). Experimental study on transient impedance of grounding rods encased in ground enhancing compounds. Electric Power Systems Research, 139, 109–115. doi:10.1016/j.epsr.2015.11.032

[13] Martins-Britto, A. G., Moraes, C. M., & Lopes, F. V. (2021). Transient electromagnetic interferences between a power line and a pipeline due to a lightning discharge: An EMTP-based approach. Electric Power Systems Research, 197, 107321. doi:10.1016/j.epsr.2021.107321

[14] Nassar, M. M. A., Arunachalam, R., & Alzebdeh, K. I. (2016). Machinability of natural fiber reinforced composites: a review. The International Journal of Advanced Manufacturing Technology, 88(9-12), 2985–3004. doi:10.1007/s00170-016-9010-9

[15] Wu, J., Zhang, B., He, J., & Zeng, R. (2014). Optimal design of tower footing device with combined vertical and horizontal grounding electrodes under lightning. Electric Power Systems Research, 113, 188–195. doi:10.1016/j.epsr.2014.03.021

[16] Taha, M. A., Li, L., & Wang, P. (2020). Estimation Performance of the Lightning Protection System in an Urban 110 kV Grounding Grid Substation. Results in Engineering, 100140. doi:10.1016/j.rineng.2020.100140

[17] Kuklin, D. (2016). Choosing configurations of transmission line tower grounding by back flashover probability value. Frontiers in Energy, 10(2), 213–226. doi:10.1007/s11708-016-0398-6.

[18] Grcev, L. (2009). Impulse Efficiency of Ground Electrodes. IEEE Transactions on Power Delivery, 24(1), 441–451. doi:10.1109/tpwrd.2008.923396