Research on Concrete Installation Grounding Scattering Characteristics and External Application Resistance Reduction Strategy

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Abstract In order to research the problems of grounding dispersion characteristics and resistance reduction efficiency of concrete foundation for wind turbine, this study uses COMSOL Multiphysics simulation software to build a model of concrete foundation for wind turbine, to study the effects of concrete resistivity and soil conditions on the dispersion characteristics of concrete foundation and spark breakdown characteristics of soil, and to propose structural optimization measures for external application of flexible graphite composite electrical grounding material. The results show that: the concrete foundation grounding resistance increases with the increase of concrete (soil) resistivity; the influence of soil resistivity on the concrete foundation dispersion characteristics is more obvious than that of concrete resistivity; the spark breakdown volume of the soil around the concrete foundation increases with the increase of concrete (soil) resistivity, while the soil resistivity has a greater effect on it; the external flexible graphite composite electrical grounding material can influence the concrete foundation dissipation characteristics and increase the spark breakdown volume of the soil around it. The results of the study can provide a reference for the design of concrete pile foundations for actual wind turbines.

Keywords Wind turbine · Concrete foundation · Grounding dispersion characteristic · Spark breakthrough · Flexible graphite composite electrical grounding material

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1 Introduction

Wind turbines are towering and mostly deployed in open areas such as plains and hills, which are vulnerable to lightning strikes [1]. When the lightning current is transmitted to the incoming ground, its dissipation will be hindered by the influence of the surrounding complex soil conditions, resulting in a sharp increase in the ground and wind turbine potential, which endangers the safety of the insulation of the turbine equipment [2]. Therefore, it is crucial to maintain the reliable operation of turbines by minimizing the grounding resistance of wind turbines under the limited grounding construction area and thus achieving rapid dissipation to the soil after lightning strikes the blades [3].

Numerous studies have been conducted by experts and scholars to the research of lightning protection and grounding of wind turbines. Deng et al. [4] conducted impact characteristic simulation tests on the typical wind turbine grounding device for different soil conditions. To solve the problem of insufficient safety of the wind farm grounding system during lightning strikes, the literature [5] interconnected the wind turbine grounding network. Sima et al. [6] proposed a new method for frequency domain analysis of impact characteristics. In the literature [7], the effect of the natural grounding grid structure of wind turbines on the lightning strike transient process was analyzed by establishing a lightning strike transient model. In addition, the literature [8] used CDEGS simulation software to build an offshore wind turbine grounding model. Furthermore, the use of flexible graphite composite electrical grounding materials has emerged as a new hotspot [9, 10]. However, most of the existing studies on the grounding device of wind turbine have not considered the influence of concrete foundation.

This paper simulates the grounding dissipation characteristics of a wind turbine's concrete foundation during a lightning strike and optimizes the structure. Firstly, the formula for calculating the grounding resistance of wind turbine concrete foundation is explained; then the model of wind turbine concrete foundation is built, and the effects of different factors on the grounding resistance and current dissipation characteristics of wind turbine concrete foundation are analyzed, and the soil breakdown field strength around it is also calculated; finally, the flexible graphite composite electrical grounding material is applied to the concrete foundation of wind turbine.

2 Model Construction and Simplification

2.1 The Dispersion Calculation of Vertical Grounding Grid

The main research of this paper is about the grounding characteristics of concrete pile foundation when lightning strikes wind turbine. Among them, the calculation of the grounding resistance of the concrete foundation of wind turbine can be referred to the vertical grounding pole. Then the grounding resistance of concrete base when laid in concrete and soil is:

$$R_{\mathrm{DM}} = F(\rho, S_1, G) - F(\rho_c, S_1, G) \tag{1}$$

where S_1 is the intersection area of concrete and soil, m^2; G is the geometric factor considering the shape of electrode; ρ_{C} is the concrete resistivity; ρ is the soil resistivity. Equation (1) can be used to calculate the resistance value of the grounding resistance when the electrode wrapped outsourced concrete is in the soil.

According to the formula proposed by E. J. Fagan and R. H. Lee for calculating the grounding resistance of outsourced concrete, the grounding resistance R_{C} of electrodes in concrete can be calculated using the following equation:

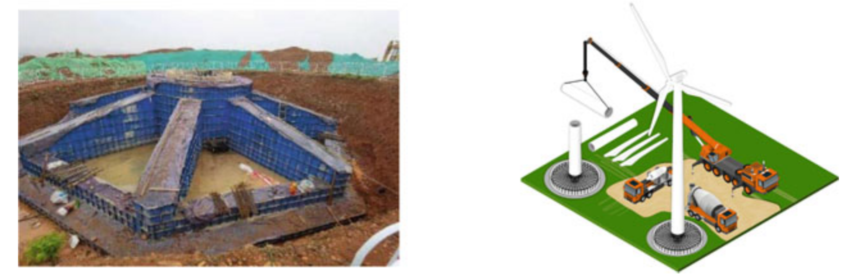
$$R_{\mathrm{C}} = (1/2\pi L_{\mathrm{r}})\{\rho_{\mathrm{C}} \ln(D/d) + \rho[\ln(8L_{\mathrm{r}}/D) - 1]\} \tag{2}$$

where L_{r} is the total length of the reinforcement in the concrete foundation, m; D is the diameter of the concrete shell with outsourced reinforcement, m; d is the diameter of the reinforcement, m. In addition, considering the discontinuity of the steel skeleton in the concrete foundation, the resistivity correction factor K_1 and the discontinuity correction factor K_2 are introduced, Where, $K_1 = 1.1$ and $K_2 = 1.05$:

$$R = (K_1 K_2 \rho/2\pi L_{\mathrm{r}})\ln(4L_{\mathrm{r}}/d) \tag{3}$$

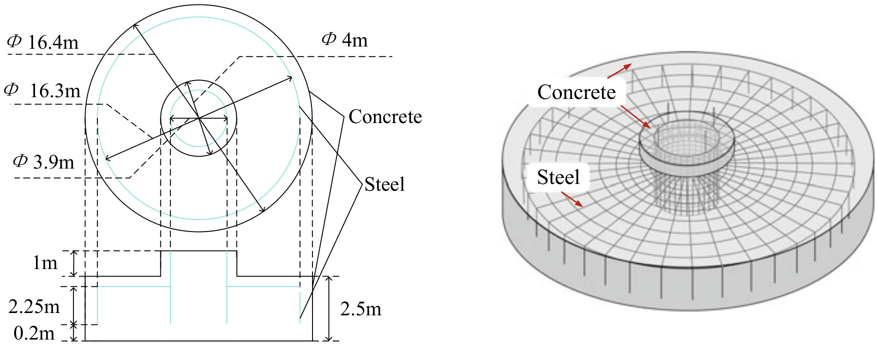
2.2 Modeling and Parameters of the Simulation

Diagram of concrete foundation construction of wind turbine can be seen as Figs. 1, and 2 shows the Model of wind turbine concrete foundation. The steel reinforcement material was selected as Φ16 mm galvanized round steel with resistivity of $1.92 \times 10^{-6}\,\Omega/\mathrm{m}$ and relative magnetic permeability of 636. The concrete thickness is 50 mm, the concrete is 200 mm from the bottom rebar, and the relative magnetic permeability is 1.



(a) Actual construction drawing (b) Diagram of concrete foundation

Fig. 1 Diagram of concrete foundation construction of wind turbine



(a) Form of concrete foundation (b) simulation specific model

Fig. 2 Model of wind turbine concrete foundation

3 Dispersion Characteristic of Wind Turbine Concrete Foundation

3.1 Effect of Concrete Resistivity on Dispersion Characteristics

The soil resistivity ρ is fixed at 500 Ω·m and the concrete resistivity ρ_C is changed. The grounding resistance values of wind turbine concrete pile foundation under different concrete resistivity conditions are shown in Table 1.

As can be seen from Table 1, the grounding resistance of wind turbine concrete foundation increases with the increase of concrete resistivity ρ_C under the condition of constant soil resistivity ρ. To illustrate this phenomenon, setting $\rho = 500$ Ω·m, $\rho_C = 10{,}000$ Ω·m, and observation surfaces of current density were constructed at 0.1 m above (in concrete) and 0.1 m below (in soil) from the bottom of the concrete base of wind turbine, respectively, as shown in Fig. 3.

Table 1 Grounding resistance of wind turbine foundation under different concrete resistivity

Soil resistivity ρ (Ω·m)	Concrete resistivity ρ_C (Ω·m)	Grounding resistance R_n (Ω)
500	5000	12.84
	8000	13.08
	10,000	13.17
	20,000	13.35
	50,000	13.47

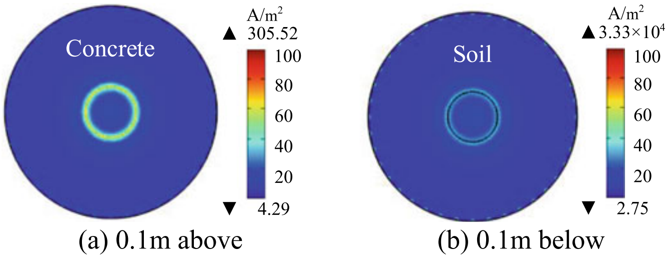


Fig. 3 Current density at two different positions

According to the current density at different observation surfaces shown in Fig. 3, it is known that: when the observation surface is located in concrete, the solution can be obtained the maximum leakage current density is 305.52 A/m^2, and when the observation surface When the observation surface is located in the soil, the maximum leakage current density is 3.33 × 104 A/m^2, which means that under the action of high-frequency impressed lightning current, the current tends to drain through the steel reinforcement to the soil around the concrete foundation with less resistivity, while the concrete has a higher resistivity and smaller thickness, so the effect on the dispersed current of the concrete foundation of wind turbine is not obvious.

3.2 Effect of Concrete Resistivity on Dispersion Characteristics

The concrete resistivity ρ_C is fixed at 1000 Ω·m, and the soil resistivity ρ is changed to obtain the grounding resistance of wind turbine concrete pile foundation under different soil resistivities as shown in Table 2.

As can be seen from Table 2, with the increase of soil resistivity ρ, the concrete pile foundation grounding resistance of wind turbine increases under the condition that the concrete resistivity ρ_C of wind turbine grounding device remains unchanged. In addition, compared with the concrete resistivity, the soil resistivity has a greater influence on the grounding resistance of the concrete foundation of wind turbine. This is due to the effect of lightning inrush current, the current tends to drain to the

Table 2 Grounding resistance of wind turbine foundation under different soil resistivity

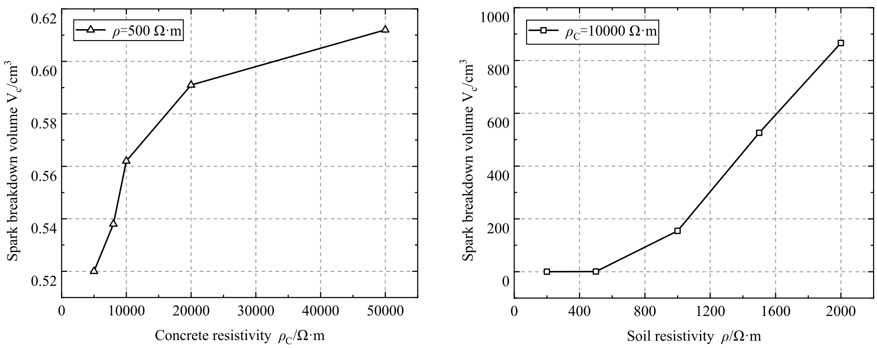
Concrete resistivity ρ_C (Ω·m)	Soil resistivity ρ (Ω·m)	Grounding resistance R_n (Ω)
10,000	200	6.99
	500	13.17
	1000	20.37
	1500	24.86
	2000	27.71

lower resistivity of the soil, when the soil resistivity increases, the current is more difficult to drain to the surrounding soil.

3.3 Soil Spark Breakdown Calculation in the Vicinity of the Foundation

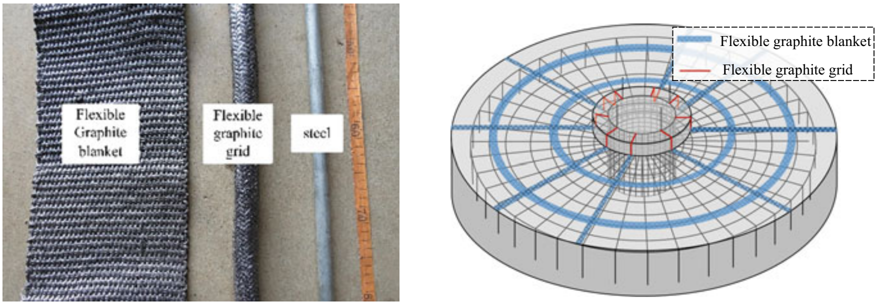
To study the spark breakdown characteristics of the soil near the concrete foundation of wind turbine under the action of high amplitude impact lightning current, the critical soil breakdown field strength E_c was set to 100 kV/m [11], and the spark breakdown volume of the soil around the concrete pile foundation of wind turbine under different concrete resistivity and different soil resistivity was shown in Fig. 4.

According to Fig. 4, it can be seen that the spark breakdown volume of soil around the concrete pile foundation of wind turbine gradually increases as the concrete resistivity (soil resistivity) increases. This is due to the fact that as the soil resistivity increases, the electric field strength in the soil around the concrete foundation increases after applying the impact lightning current amplitude, and the volume of



(a) Influence of soil resistivity (b) Influence of concrete resistivity

Fig. 4 Spark breakdown volume of soil around the foundation under different conditions



(a) (b)

Fig. 5 External flexible graphite composite electrical grounding material for foundation

the area in the soil that can reach the critical breakdown field strength E_c is larger. The optimization of wind turbine concrete foundation grounding dispersion structure.

3.4 External Structure of Wind Turbine Concrete Foundation

The traditional resistance reduction scheme with long outreach may not achieve the expected resistance reduction effect due to construction problems. To solve this problem, this paper uses flexible graphite composite grounding material externally applied to the concrete pile foundation of wind turbine, as shown in Fig. 5.

3.5 Effect of External Materials on the Dispersion in Concrete Foundations

In order to analyze the effect of the flexible graphite composite grounding material on the grounding resistance of wind turbine concrete foundation after its external application, the resistance reduction efficiency μ is introduced, defined as:

$$\mu = (R_n - R_g/R_n) \times 100\% \tag{4}$$

where R_n is the natural grounding resistance of pile foundation before applying flexible graphite composite grounding material, Ω; R_g is the grounding resistance of pile foundation after applying flexible graphite composite grounding material, Ω. The resistance value and resistance reduction efficiency of concrete pile foundation of wind turbine after applying flexible graphite composite grounding material under different soil resistivity are shown in Fig. 6.

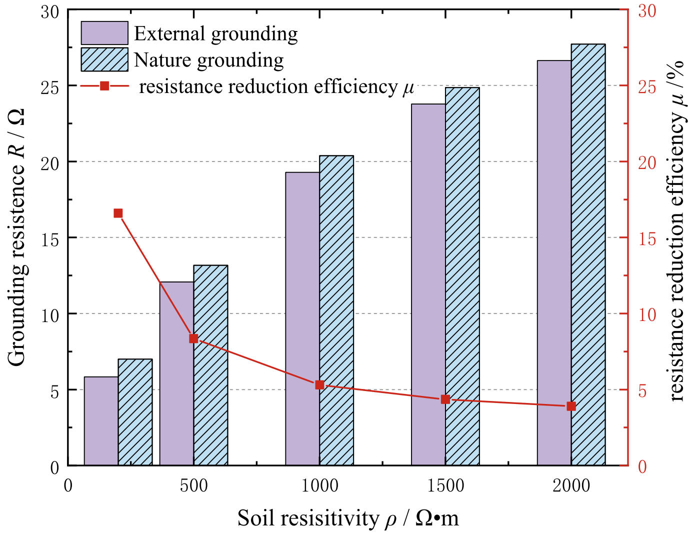


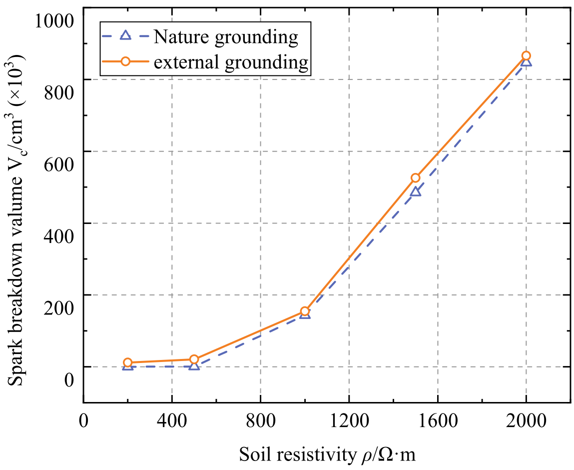
Fig. 6 Grounding resistance and resistance reduction efficiency of concrete foundation after external laying

As can be seen from Fig. 6, compared with natural grounding, the wind turbine concrete pile foundation with external flexible graphite composite grounding material grounding can better reduce grounding resistance and has higher resistance reduction efficiency. In addition, with the increase of soil resistivity around the concrete foundation of wind turbine, the more difficult it is for the current to drain into the surrounding soil, so the more difficult it is for the pile foundation to reduce resistance, and the resistance reduction efficiency decreases. This is because part of the injected current will be diverted along the flexible graphite cable body and the flexible graphite blanket material, the external material can effectively reduce the internal reinforcement of the wind turbine concrete pile foundation dissipation component, more current through the external material discharge to the soil. It can be seen that the external flexible graphite composite grounding material can effectively assist the concrete pile foundation of wind turbine to drain current into the surrounding soil while reducing its grounding resistance.

3.6 Effect of External Material on Soil Breakdown Area

In order to study the effect of external flexible graphite composite grounding material on the soil breakdown area near the concrete base of wind turbine, the critical breakdown field strength E_c of soil is set to 100 kV/m, and the spark breakdown volume of soil around the soil pile base under different soil resistivity is shown in Fig. 7.

Fig. 7 Spark breakdown volume of soil around concrete foundation after external flexible graphite composite electrical grounding material



Compared with the natural grounding, the external grounding of the concrete foundation with flexible graphite composite grounding material will increase the spark breakdown volume of the soil around it, which is due to the action of the impact lightning current, part of the current component will drain along the flexible graphite composite grounding material to the soil, making the pile foundation to the surrounding soil leakage current increased, the electric field strength generated in the soil is more likely to reach the soil critical breakdown field strength E_c (100 kV/m), which makes the spark breakdown volume in the surrounding soil increase, more conducive to the dissipation of the wind turbine concrete pile foundation and resistance reduction.

4 Conclusion

(1) the grounding resistance of pile foundation increases with the increase of soil (concrete) resistivity, but the effect of soil resistivity is more obvious.
(2) As the soil resistivity increases, the spark breakdown volume of the soil (concrete) around the concrete foundation of wind turbine gradually increases, and when the soil resistivity increases to 500 Ω·m, the rate of increase of the spark breakdown volume of the soil around it tends to level off.
(3) When the flexible graphite composite electrical grounding material is applied to the concrete foundation of wind turbine, more current component is discharged to the soil through the external material, thus reducing the grounding resistance of the concrete foundation.

(4) The external flexible graphite electrical composite grounding material can increase the electric field strength of the soil around the concrete foundation of wind turbine and the spark breakdown volume, which is more conducive to the resistance reduction of the concrete foundation.

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