Study on innovative modified silicate composite grounding electrode

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Abstract: In view of the current corrosion of metal grounding materials and the low degree of soil adhesion, this paper proposes a modified silicate composite grounding body, which is coated with metal materials by modified silicate materials mainly adding carbon fibers and made by high pressure extrusion, the modified silicate material was analyzed for its micro-morphology and characteristics, and further introduces its structural design and calculation method of ground resistance. Given the typical box-ray grounding device for 220kV transmission line power and its ground resistance requirements under different soil resistivity, CDEGS is used for simulation calculation to get the number of grounding electrodes and ground resistance that meet the standard requirements. It was found that the modified silicate composite grounding is effective in grounding system for lightning protection.

1. Introduction

A lightning strike is one of the leading causes for tripping of transmission lines. According to the statistics, in 2016, about 52% of the tripping of transmission lines at 500kV and above was caused by lightning strikes, of which 91.7% was generated by shielding failure and 8.3% by inverse flashover. For many years, researchers and technical personnel have been dedicated to studies on lightning protection for transmission lines and have achieved many relevant results, such as the development of a new generation of lightning positioning system, the introduction of differential lightning protection, and a series of measures including reducing shielding angle of grounding wires, reducing the ground resistance of the tower, enhancing the insulation of transmission lines, using anti-shielding failure lightning rods, and installing lightning arresters on the line. These results are of practical significance to improving the lightning protection of transmission lines. The domestic and foreign operating experience and theoretical analysis show that reducing the ground resistance of the tower is the most effective measure to protect transmission lines against a lightning strike. Therefore, reliable and stable grounding is necessary for the safe and stable operation of transmission lines.

The early power system design techniques used in China learned from the experience of the Soviet Union. Zinc-galvanized flat steel and round steel were the common grounding materials. These materials get corroded easily, especially in soils with acidity, alkalinity, high salinity, and high moisture content. It usually takes 5-7 years to renovate or even replace the tower grounding grid [1]. The grounding materials buried underground increase the workload and cost of transmission line operation and maintenance. To prevent corrosion, copper and copper-plated steel are often used as grounding materials in foreign countries. Due to the high cost of copper materials, domestic researchers once introduced grounding materials such as copper-clad steel, zinc-clad steel, stainless steel, alloy cladding steel, and high-silicon chromium iron [2]. The use of copper-clad steel follows the different production process; zinc-clad steel is developed from the corrosion protection method of sacrificial anode. A thick zinc layer is coated on the surface of the steel in an extrusion cladding process to overcome the disadvantage of a thin coating of hot-dip galvanized steel and thus prevent corrosion. This material is not commonly used in practical engineering; stainless steel has excellent corrosion resistance in the atmosphere, but it is rarely used in grounding projects; the coating of alloy cladding steel is made from various
alloy materials, mainly represented by aluminum-magnesium alloy. It is made in a thermal spraying or a hot dip galvanizing process. Now the application of this technology stays in the research stage.

At present, the study on non-metallic grounding materials provides new ideas about anti-corrosion and resistance reduction of grounding materials. Non-metallic grounding materials, predominantly graphite-based and carbon fiber-based materials, are widely recognized by researchers because of their excellent conductivity, chemical stability, resistance to acid and alkali, and excellent oxidation resistance. Hu and Qiu [3] used highly pure crystalline flake graphite as the primary conductive material to make a flexible graphite composite grounding material with a Litz-layered structure. They tested its performance and considered that the flexible graphite composite grounding material has a stable structure, low skin effect and inductance effect, and a high degree of compatibility with soil. These features facilitate transportation and construction and guarantee a wide range of applications. Shao and Le [4] introduced the preparation and performance of JR nanocarbon anti-corrosion conductive coating and its use in grounding grid anti-corrosion. They argued that this coating could meet the ground resistance and thermal stability requirements of grounding grid while adequately protecting the grounding grid from being corroded in the damp soil environment. Zhou et al. [5] carried out the transient response characteristics and frequency-dependent grounding impedance analysis of the carbon grounding module. The results show that the carbon-based module can be effectively applied to the lightning protection grounding system and verify the correctness of the simulation technology. The applicability of the distributed parameter circuit model to the ground electrode.

This paper presents a modified silicate composite grounding electrode and discusses its composition and electrical conductivity principle. It also analyzes its microscopic morphology and characteristics and introduces its structural design and calculation method of ground resistance. The findings of this study can serve as reference and guidance for the application of composite grounding materials of modified silicate in engineering grounding.

2. The composition of modified silicate composite grounding electrode
The modified silicate composite grounding electrode is mainly composed of modified silicate and conductive core. The modified silicate (commonly known as electrical conductive concrete) is made from Portland cement, bentonite, fly ash, silicon powder, polyacrylonitrile-based (PAN-based) carbon fiber, stainless steel fiber, and moisturizer mixed in a certain proportion. The conductive part mainly comes from PAN-based carbon fiber uniformly mixed in the mortar.

Bentonite, known as "universal soil", is a natural clay containing montmorillonite (which takes up 85-90%). It is non-corrosive and stable and has a resistivity of 2.5Ω•m when the moisture content reaches 300%. The concrete that is mixed with soil-like materials such as bentonite has better crack resistance, impermeability and cohesiveness to maintain close contact with the conductive core and the ground layer, thereby eliminating the contact resistance between the grounding electrode and the soil. Thus it has good compatibility with soil. Fly ash can improve the water impermeability, gas impermeability, sulfate resistance and chemical corrosion resistance of concrete, reduce the heat of hydration, improve the high temperature resistance of concrete, reduce particle separation and precipitation, reduce shrinkage and cracking of concrete, suppress stray current corrosion of the metal part of the concrete. Silica powder, whose scientific name is “silica fume”, can reduce Ca(OH)_2 content, increase concrete compactness, and effectively improve the weak acid corrosion ability. Besides, silica powder concrete is denser, and its pore structure is refined to lower the transmission rate of harmful ion and reduce the formation of soluble Ca (OH)_2 and ettringite, making it also resistant to salt corrosion, especially to chloride salt and sulfate. In particular, in harsh environments such as with chloride salt...
pollution, sulfate erosion and high humidity, the durability of concrete can be doubled or increased by several times. Adding an appropriate amount of stainless steel fiber in concrete can significantly improve the tensile, fracture, bending, shear, and splitting resistance and other mechanical properties of the concrete.

Carbon fiber has a variety of carbon properties, the fiber characteristics, excellent conductivity and wear resistance [6]. Compared with graphite, carbon fiber has the following features: conductive fiber is more likely to form a conductive network than a conductive particle. The finer the fiber, the smaller the diameter. With the same volume content, more fibers will have a higher total length, and they are more easily overlapped to form a network of interconnected conductive fibers; the longer the fibers, the easier the overlapping.

Compared with other non-metallic grounding materials, the modified silicate composite grounding material is composed of electrical conductive concrete and stainless steel core which has excellent conductivity. This material has a stable structure and thus shows clear advantages in soil compatibility, mechanical strength and stability. Its application in tower grounding is of practical significance.

3. Microscopic morphology of modified silicate composite grounding electrode

Carbon fiber is a micro-crystalline graphite material produced after carbonization and graphitization of organic fibers. The microscopic morphology of carbon fibers extends along the axial direction of the fibers, as shown in Figure 1. Carbon fiber has good self-lubrication and electrical conductivity, and reinforced concrete mixed with carbon fibers has high compressive strength and tensile strength. Due to its properties, carbon fiber can significantly increase the strength of concrete. Because of its excellent resistance to air oxidation, it has been widely studied in recent years. In general, the higher the carbon fiber content, the better the electrical conductivity of the concrete. With the same carbon fiber content, the better the dispersion of the carbon fiber is, the easier it is to form a complete conductive network. The resistivity of carbon fiber concrete is affected by temperature. The higher the temperature is, the lower the concrete resistivity is, and vice versa.

Figure 2 shows that the modified silicate hydrates are tightly bonded with few gaps. After incorporation of carbon fibers, the carbon fibers are evenly distributed, and tight bonding between the carbon fibers and the modified silicate hydration products can be observed clearly. The hydration products can fill into the gaps between the carbon fibers to form a dense microstructure, thereby improving the mechanical properties of the modified silicate hydration products. With higher carbon fiber content, as the external load to destroy the bonding force between the modified silicate hydration products and carbon fibers and to break the fibers increases, the compressive strength of the modified silicate concrete and its cohesion with the inner stainless steel core material will be enhanced.

Figure 1. SEM image of carbon fibers

Figure 2. Microscopic morphology of modified silicate concrete after incorporation of carbon fibers

Figure 3. SEM image of modified silicate hydrates
4. Grounding characteristics of modified silicate composite grounding electrode

The performance of the modified silicate composite grounding electrode should meet the requirements in GB/T 21698-2008 “Technical specifications of composite grounding device” and DL/T 380-2010 “Technical condition of material for reduced ground resistance”.

Grounding electrode test should be carried out under standard test atmospheric conditions [7]: temperature of 10-35°C, relative humidity of 50-80%, and air pressure of 86-106kPa. Three samples were used in each set of tests for the comparison purposes.

(1) Resistance test

Three modified silicate composite grounding electrodes were used, and both sides (outer sides) of each electrode were coated with silver paste in a concentric area of 15mm. The resistance of the grounding rods measured after 1 hour was 6.4-8.5Ω. The resistance test wiring is shown in figure 3.

![Figure 3. Schematic diagram of resistance test circuit (grounding electrode)](image)

Three samples of modified silicate material were tested. They were coated with silver paste on the entire left and right sides (40mm x 40mm). The resistance of the ground rods measured after 1h was 6.2-7.5Ω. The resistance test wiring was shown in figure 4.

![Figure 4. Schematic diagram of resistance test circuit (materials)](image)

(2) Test of resistance-reducing coefficient

Three modified silicate composite grounding electrodes and three metal rods were tested. An open space with soil resistivity of 500Ω·m or more was selected. The metal grounding electrodes with the same size as the grounding electrodes and the modified silicate composite grounding electrodes were buried in the soil. The three-electrode method was used to measure power frequency ground resistance and resistance reducing coefficient of the grounding electrodes and the metal grounding electrodes which was the power frequency ground resistance ratio of the grounding rods and the metal grounding electrodes. The ratio of the resistance-reducing the coefficient of the grounding rods measured after 720h was 0.8-0.85.

(3) Pulse current withstand test

Three modified silicate composite grounding electrodes were buried in the soil inside a metal barrel. Before the pulse current withstands test the measured power frequency current was 1A, and the determined resistance was U/I, according to the wiring diagram, as shown in figure 5.
Three modified silicate composite grounding electrodes were used and applied with impulse current of 8/20μs and 1kA for 20 times, each with a time interval of 60s. There was a longer interval of 30min between every five times of application. The resistance of samples under power frequency current of 1A was measured again after the test. The resistance of the grounding electrodes varied from -5.4 to 12.9%.

(5) Power frequency current withstand test

Three modified silicate composite grounding electrodes were applied with power frequency current of 10A 5 times, each for 10s. The time interval for every two application was 30min. The wiring diagram of the power frequency current withstand test after the test is shown in figure 6. The resistance-reducing coefficient varied between -34 and -25%.

5. Structure and ground resistance calculation of modified silicate composite grounding electrode

The shape of the grounding electrode is a factor that affects the ground resistance reduction of the tower. At present, common grounding module shapes include cylindrical, rectangular, plum-, and REX-shaped. To improve the grounding effect of electrical conductive concrete grounding module, the most common cylindrical and rectangular grounding electrodes were prepared, as shown in figure 7. The cylindrical grounding electrode was buried vertically while the rectangular grounding electrode was buried horizontally. The connecting wire between the grounding electrodes was copper wire-wrapped with an insulating material.
If the ground resistance of any shaped grounding device buried in a single medium was [8]:

\[ R_{SM} = F(\rho, S_0, G) \]  \tag{1}

\[ R_{DM} = F(\rho_c, S_0, G) + F(\rho, S_1, G) - F(\rho_c, S_1, G) \]  \tag{2}

where \( R_{SM} \) and \( R_{DM} \) are resistances of a single and dual dielectric electrodes, respectively (\( \Omega \)); \( S_0 \) is the electrode surface area (m\(^2\)); \( S_1 \) is the interface area (m\(^2\)); \( G \) is the geometric coefficient of a given electrode characterized by a special shape.

This equation can be used to analyze the ground resistance of a ground electrode of any shape buried in the soil and wrapped by another material with a different resistivity.

\[ R_e = \frac{1}{2\pi\rho_c} \left[ \rho_c \ln\left(\frac{\rho}{\rho_c}\right) + \rho \left[ \ln\left(\frac{L_e}{d}\right) - 1 \right] \right] \]  \tag{3}

where \( \rho \) and \( \rho_c \) are resistivities of soil and concrete, respectively (\( \Omega \cdot m \)); \( L_e \) is the length of the vertical grounding electrode (m); \( d \) is the grounding conductor diameter (m); \( D \) is the concrete shell diameter (m).

\[ R_s = \frac{\rho}{2\pi L_e} \left[ \ln\left(\frac{L_e}{d}\right) - 1 \right] \]  \tag{4}

\[ R_c = \frac{1}{2\pi\rho_c} \left[ \rho - \rho_c \right] \left[ \ln\left(\frac{L_c}{d}\right) - 1 \right] + \rho \left[ \ln\left(\frac{L_e}{d}\right) - 1 \right] \]  \tag{5}

The above two equations two values of ground resistance: that of the concrete-wrapped ground electrode and that of the concrete vertical grounding electrode with a diameter of \( D \), which is buried in the soil.

The ground resistance of the tower grounding device, for which the grounding plate is laid, is calculated similarly to the case of buried strip-shaped horizontal grounding electrode. The ground resistance \( R_C \) of the horizontal grounding electrode (grounding plate) of length \( A \) and width \( B \) can be calculated as follows:

\[ R_c = \frac{1}{2\pi\rho_c} \left[ \rho - \rho_c \right] \ln\left(\frac{A}{B}\right) + \rho_c \ln\left(\frac{A}{B}\right) \]  \tag{6}

where \( \rho \) and \( \rho_c \) are resistivities of soil and the modified silicate material, respectively (\( \Omega \cdot m \)); \( A \) and \( B \) are the length and width, respectively, of the wrapped grounding electrode (m).

Besides, the ground resistance of the concrete wrapped vertical ground electrode can also be calculated by the following equation:

\[ R_c = \frac{k_1 k_2 \rho}{2\pi L_c} \ln\frac{A}{d} \]  \tag{7}

Given the typical box-ray grounding device for 220kV transmission lines in regions with different soil resistivity, rectangular modified silicate composite grounding electrodes with a box side length (foot distance) of 10m were buried along the external extension line at an angle of 45° in the four corners. The rectangular modified silicate composite grounding electrode was 1m-long, 0.2m-wide, and 0.04m-thick. The relative resistivity of the composite grounding electrode (vs. annealed copper) was 45.6, and the relative permeability was 1 (vs. vacuum). The two grounding electrodes had a spacing of 1m and were connected by a special connection line. According to the GB50545-2010 “Design specification for 110-750kv overhead transmission
lines,” the CDEGS special grounding analysis software was used to simulate the composite grounding electrodes. The required number of grounding electrodes and ground resistance values are listed in table 1.

| Soil resistivity (Ω·m) | Upper limit of ground resistance (Ω) | Number of grounding electrodes (pieces) | Ground resistance (Ω) |
|------------------------|--------------------------------------|----------------------------------------|-----------------------|
| 100                    | 10                                   | 2                                      | 7.7                   |
| 500                    | 15                                   | 8                                      | 12.2                  |
| 1000                   | 20                                   | 11                                     | 18.9                  |
| 2000                   | 25                                   | 18                                     | 25                    |
| 2500                   | 30                                   | 19                                     | 30                    |

6. Conclusions
This paper introduces a modified silicate composite grounding electrode. It analyzes its microscopic morphology and characteristics and further proposes its structural design and calculation method of ground resistance. Given the typical box-ray grounding device for 220kV transmission line power and its ground resistance requirements under different soil resistivity, CDEGS is used for simulation calculation to get the number of grounding electrodes and ground resistance that meet the standard requirements. The finding of this study will guide the application of composite grounding materials of modified silicate in engineering grounding.

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