Analysis of Electrothermal Characteristics of Conductive Concrete Foundation of Power Tower

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Abstract. Conductive concrete has a good application prospect in transmission line tower grounding. The electrothermal effect and thermal stress distribution under lightning current impulse have an important influence on the design, application and maintenance of conductive concrete foundations. Based on the principle of thermoelectric coupling, the lightning current impulse model of conductive concrete foundation under electric-thermal-mechanical coupling is established by using COMSOL Multiphysics. The electric potential distribution, heat distribution and thermal stress distribution of the conductive concrete foundation are simulated and analyzed, and compared with conventional transmission line tower foundation. The simulation results show the conductive concrete foundation, as a natural grounding body, has a better grounding dispersion effect when it is impacted by lightning current, the internal temperature is lower, the thermal stress is smaller, and it has better electrothermal characteristics, which is more suitable for the field of power system grounding engineering without laying grounding body.

1. Introduction

With the development of the economy and the continuous expansion of power grid scale, the range of options for transmission corridors is becoming more and more narrow, and the conditions are getting worse. Due to the excessive tension of land resources, more transmission lines have to avoid areas suitable for human activities. Sites are selected in barren areas with poor soil conditions, more rocks, and high resistivity. At the same time, the construction conditions in the area are often poor, and flat sections are few, so the scope of construction is limited[1-2]. As a result, the requirements of grounding standards for transmission lines in such areas are difficult to be met, which poses a new challenge to the construction of transmission line grounding projects.

Resistance reduction measures commonly used in engineering, such as increasing the area of the grounding network and introducing external grounding, are difficult to achieve in such areas. Although chemical resistance reduction has a certain effect in the short term, it has a strong corrosion effect on the grounding conductor[3-6]. Therefore, it is necessary to design a grounding method that is easy to construct and has a better resistance reduction effect.

The foundation of the transmission line tower is the link between the tower and the earth. It is buried in the ground and is part of the grounding of the transmission line tower. However, due to the high resistivity and poor conductivity of the common concrete foundation, the grounding effect of the
tower cannot be improved. As a new type of material, conductive concrete has good conductivity and corrosion resistance, and has a good application prospect in the field of transmission line tower grounding engineering. In addition, References [7-11] show the preparation technology of conductive concrete has been relatively mature. In the power system, a small number of applications have tried to use conductive concrete to improve the grounding effect [12-14]. Therefore, this paper proposes to use conductive concrete pouring to form the tower foundation to improve the grounding effect.

As a conductive concrete foundation with high conductivity, when lightning strikes the transmission line, the conductive concrete foundation can release the huge lightning current into the earth. At the same time, huge heat is generated inside the conductive concrete foundation, and the distribution of heat leads to gradient thermal stress inside the conductive concrete foundation, reducing the work efficiency of the tower foundation and shortening the life cycle. Thus, a clear understanding of the electric potential distribution, heat distribution, and thermal stress distribution is of great significance to the design and construction of the conductive concrete foundation.

During the discharge of lightning current, the conductive concrete foundation has strong electro-thermal coupling characteristics. Based on the principle of thermoelectric coupling, the lightning current impulse model of conductive concrete foundation under electric-thermal-mechanical coupling is established by using the simulation software COMSOL Multiphysics. The characteristics of electric field distribution, temperature field distribution and stress distribution inside the conductive concrete foundation under lightning strike are analyzed, and compared with conventional transmission line tower foundation.

2. Electro-thermal coupling analysis of conductive concrete foundation of tower

The conductive concrete foundation is equipped with numerous steel bars. When the lightning current flows into the conductive concrete along the dense steel bars distributed inside the conductive concrete foundation, considering the existence of the internal resistance of the conductive concrete, part of the lightning energy is converted into heat energy, and electrothermal conversion occurs, resulting in Joule heat effect.

The lightning impulse the conductive concrete foundation model is shown in Fig. 1. When the lightning current discharges along the steel bars to the conductive concrete material inside the concrete foundation, Maxwell's law of charge conservation is followed:

\[
\int_S J \cdot ndS = \int_V r_c dV
\]  

Where: \( J \) is the current density of lightning current dissipating to the conductive concrete foundation, \( S \) is the surface area of the conductive concrete foundation unit volume \( V \), \( n \) is the outer normal direction vector of \( S \), and \( r_c \) is the current source of unit volume \( V \) in conductive concrete foundation.

![Fig. 1 conductive concrete foundation model](image1)

![Fig. 2 Mesh mass distribution](image2)

When lightning current flows through the conductive concrete foundation, charge conservation is always followed at any position. At the same time, after the conductive concrete foundation is
electrified, the consumed lightning energy $Q_{ec}$ is converted into heat energy due to the effect of heating power:

$$Q_{ec} = E \cdot J$$

(2)

According to Ohm's Law:

$$J = \sigma \cdot E$$

(3)

Where: $E$ is the electric field strength and $\sigma$ is the conductivity.

Transient heat conduction equation:

$$\rho c_e \frac{\partial T}{\partial t} = \lambda \cdot \nabla^2 T + Q_{ec} = \lambda \cdot \nabla^2 T + \sigma E^2$$

(4)

Where: $\rho$ is the density, $c_e$ is the specific heat capacity, and $\lambda$ is the thermal conductivity of the conductive concrete material. Besides, $T$ is the temperature, and $t$ is the time.

Therefore, the thermal energy released by the lightning current in the conductive concrete foundation is related to the electric field distribution in the conductive concrete and the characteristics of the conductive concrete material. A large amount of lightning current charges move in the conductive concrete materials, generating huge high-temperature resistance heat, causing the temperature of the foundation to rise and spreading the heat around.

3. Multi-physics field coupling simulation model of tower foundation

When lightning strikes the transmission line, the electric field and thermal field of the conductive concrete material poured in the foundation affect each other. In order to accurately simulate the electric potential distribution and heat distribution inside the natural grounding of the conductive concrete foundation during the lightning current impact, COMSOL Multiphysics is used to simulate the real situation. As a comparison, a simulation model of lightning current impact of common concrete foundations is also established.

Combined with the engineering practice, the bottom plate size is 6300 mm * 6300 mm * 500 mm, the step size is 3800 mm * 3800 mm * 600 mm, and the main column size is 1200 mm * 1200 mm * 2300 mm. Due to the large size of the foundation model, dense internal steel bars and small size, the amount of memory required for the geometric model is large, which easily exceeds the limit of computer memory. Thus, the conductive concrete foundation model is simplified. Considering the accuracy and running time of the solution, the mesh is set as 1281646 elements, the minimum element mass is set as 0.06175, and the average element mass is set as 0.6284. The mesh generation model is shown in Fig. 2. The closer the quality of the mesh element is to 1, the better. Fig. 2 shows the mesh division meets the solution requirements.

To analyze the electric field and temperature field distribution characteristics of the conductive concrete foundation, the key is to determine the initial conditions of the electrical and thermal boundaries. Considering that the conductive concrete foundation is buried in the earth in the actual project, the bottom surface of the cushion layer of the foundation can be grounded, and the electric potential of all sides of the cushion, bottom plate, step and main column of the foundation is 0V as the electric boundary condition. The thermal radiation, transient heat transfer on the surface of the foundation and the transient heat transfer of the steel bars inside are used as thermal boundary conditions. The lightning strike point and the infinity of the earth are always at an environment temperature of 20°C.

4. Analysis of electrothermal characteristics of tower foundation

4.1. Electric field distribution of the tower foundation

The simulation time step was set to rang(0,0.1,30)us. The impulse current peak value of 100kA and the
waveform of 8/20us were used. The electric potential distribution of the tower foundation is shown in Fig. 6.

![Electric potential distribution of tower foundation under lightning current impulse](image)

**Fig. 3 The electric potential distribution of tower foundation under lightning current impulse**

Fig. 3 shows the electric potential weakens from the center of lightning strike point to the outside, and gradually decreases along the step, the bottom plate and the cushion. Compared with the common concrete foundation, the electric potential of the conductive concrete foundation is smaller, which is mainly due to the good conductivity of the conductive concrete.

4.2. **Temperature field distribution of the tower foundation**

During the lightning loading, the lightning current is conducted from the interface of the initially loaded steel bar along the steel bars in contact with each other inside the foundation, and is released to the earth from the steel bar boundary through the conductive concrete material. The simulation results of the temperature field distribution are shown in Fig. 4 and Fig. 5.
Fig. 4 shows the maximum temperature of conductive concrete foundation is lower than that of common concrete, which indicates that the internal heat of the common concrete foundation is higher, and the electric heating effect is significant. The highest temperature points of the two are located at different positions.

Fig. 5 shows the temperature at both ends of the main reinforcement near 45mm of the outer net protection layer is relatively high, and the heat released is diffused outwards centered on the main reinforcement, and the heat distribution is also the most obvious. When the pouring material is conductive concrete, the temperature distribution is relatively uniform, and the temperature change is small, basically maintained at the environment temperature of 20 ℃; while the pouring material is common concrete, the heat distribution around the steel bar is more obvious, and the temperature changes greatly, and the maximum temperature can reach 300 ℃. This is mainly due to the addition of two conductive phase materials, graphite and steel fiber, to conductive concrete, which has higher conductivity and reduces the resistance heat generated by high current. In addition, the high thermal conductivity of conductive concrete can quickly diffuse the resistance heat to the surroundings, which greatly reduces the heat accumulation caused by lightning. Therefore, the internal temperature of the conductive concrete foundation is lower. However, the poor conductivity and thermal conductivity of common concrete results in a large amount of high-temperature resistance heat to accumulate, and the internal temperature of conventional concrete foundation is higher. Thus, as a natural grounding body, the conductive concrete foundation has a better conductive dispersion effect.

4.3. Thermal stress distribution of the tower foundation
The distribution of electric field and temperature field of the foundation is obtained through the above electric thermal coupling analysis of the foundation. Considering that the temperature field during a lightning strike is the basis for thermal stress, the solid mechanics interface is added to COMSOL to couple the three physical fields of electricity, heat and force. In order to facilitate the view, one side of the column and the upper surface of the step and bottom plate are hidden. The results of thermal stress distribution are shown in Fig. 6.

![Fig. 6 Comparison of thermal stress distribution of tower foundation](image)

Fig. 6 shows the deformations of both are mainly located near the steel bars inside the foundation, especially at the main column and both ends of the steel bars are serious, which is consistent with the temperature field distribution of lightning strikes. The thermal stress cause expansion and deformation of the geometric structure. Compared with the common concrete foundation, conductive concrete foundation has less stress and less deformation. Therefore, the service life cycle of conductive concrete foundation is longer.

5. Conclusion
(1) The conductive concrete foundation has good electric heating characteristics, and its temperature distribution, electric potential distribution and thermal stress distribution are much better than that of common concrete foundation.
(2) Under lightning current impulse, the electric potential of the conductive concrete foundation is lower, which weakens from the center of the lightning strike point to the outside, and decreases along the step, the bottom plate and the cushion.

(3) Under the impact of 100kA lightning current for 30us, the temperature rise of the conductive concrete foundation is small, and the temperature distribution is relatively uniform, which basically maintains at the environment temperature of about 20℃; while the maximum temperature of the common concrete foundation reaches about 300℃.

(4) Compared with conventional transmission line tower foundation, the thermal stress and deformation of conductive concrete foundation are smaller.

(5) The results show the conductive concrete has a good application prospect in the tower foundation.

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