The influence of coke aging on electrical performance of double rings DC grounding electrode

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Abstract. The long-time work of the HVDC grounding electrode leads to the degradation of electrical performance, which not only affects the normal operation of the grounding electrode, but also may affect the safe and stable operation of the HVDC system. It is an important task to study the effect of the aging of coke bed and the corrosion of grounding electrode for the operation and maintenance of grounding electrode. Aiming at Xintian grounding electrode of Tianguang HVDC project, which has been running for 17 years, this paper analyzes the structure of double rings grounding electrode and the mechanism of aging of the coke, derived the algorithm with the consideration of coke bed to calculate the electrical performance indexes of ring grounding electrode, then use the design date of Xintian grounding electrode to verify it, finally, analyze the effect on the electrical performance of double rings grounding electrode which contributed by the aging of coke. The research results and conclusions can be used as reference for maintenance and overhaul of double rings grounding electrodes.

Keywords: HVDC, grounding electrode, coke aging, electrical performance.

1. Introduction
The monopole ground return operation mode is one of the operating modes of the HVDC system. The electrical performance of the grounding electrode is very important to the normal and safe operation of the HVDC system. With the increase of HVDC and UHVDC power transmission projects, and some grounding electrode that has been put into operation has been running for 20-30 years, and there is a problem of corrosion and aging, the maintenance of DC grounding electrodes has become a matter of concern and research. At present, coke is the only filling material used in the grounding electrode project. The performance of coke is closely related to the electrical performance and service life of the grounding electrode. Coke bed increases the cross-section area of the electrode, reduces the grounding resistance, reduces the current density at the junction of ground electrode and soil, improves the heating and electrical permeability problems, slows down the corrosion rate and prolongs the service life of the grounding electrode. But thousands of currents flow through the coke, causing coke to heat up and gradually aging, both the chemical and physical properties of coke will change. which will affect the electrical performance of the grounding electrode, and even affect the safe operation of the grounding electrode.
At present, the commonly used methods for calculating about grounding electrode include the finite element method [2-3], the boundary element method [4-5], the moment method [6], and so on. But most of the calculation of the grounding electrode did not consider the influence of the coke bed on the ground electrode. Reference [7] derives the distribution of the spilled current density of ring grounding electrode, and [8-9] uses the image method to derive the algorithm of grounding resistance. Reference [10-11] study the influence of coke bed on leakage current distribution by combining the moment method with the boundary element method. [12] regards the coke as the resistance between the grounding electrode and the soil by numerical method to study the influence of coke on the electrical performance. Reference [13] uses the finite element software ANSYS simulating to analyze the influence of coke bed on the ground resistance and the temperature rise characteristics of the grounding electrode. [14-18] take ring grounding electrode as an example, analyze the influence of conductivity anomaly on earth surface potential distribution by using finite difference method. These references show that there are few studies on the operation and maintenance of grounding electrodes. This paper study the influence of coke aging on the electrical performance of the grounding electrode to provides the basis for the operation and maintenance of the grounding electrode.

2. Double rings grounding electrode and the aging mechanism of coke

2.1. Introduction of double rings grounding electrode.

The typical structure of the double ring grounding electrode is shown in Figure 1(a). The grounding pole leads are connected to the central tower, then central tower is connected to the branch towers through the diversion cable, and then cables are connected with the feeding bars for current dividing. The feeding bars are embedded in the coke bed, and the cross-section diagram is shown as Figure 1(b). The inner ring radius R1 is generally between 100~500m, and the outer ring radius R2 is generally between 200~700m. The ratio of the radius of the rings is closely related to the diversion of current between the rings. When R1/R2=0.65~0.75, the comprehensive index of the grounding electrode is superior. The feed bar material is mostly round steel or high silicon ferrochrome, and the diameter is between 30~80mm. Generally, the diameter of the inner fed bar is slightly larger than that of the outer loop. Although increasing buried depth(h) helps to improve the performance of grounding electrodes, the increase in h will increase the cost, and is not conducive to exhaust, construction and maintenance, so the h is generally 2~7m. The length of the coke bed cross section (d) is generally between 0.4~1.5m, d should meet the current density requirement show as formula (1). Usually, the leakage current density of outer ring is larger, so it is generally d2> d1.

\[
d \geq \frac{J}{4} \sqrt{\frac{\rho T_0}{\theta_{\text{max}} - \theta_c}}
\]

In formula: J is the leakage current density of unit length; T0 is the continuous running time at normal rated current.
2.2. The aging mechanism of coke.

The constituent elements of coke are mainly carbon, but also contain a small amount of hydrogen, nitrogen, sulfur, oxygen and some metal elements. When the carbon, hydrogen, nitrogen and other organic elements in metallic salt compound in coke form $\text{CO}_2$, $\text{H}_2\text{O}$, $\text{N}_2$ and spill over, the metal oxides are left. These metal oxides are ash and ash is non-conductive material.

When the grounding electrode is running in monopole ground return mode, thousands of currents flow through the coke, causing the coke to heat up and some coke to burn out. In particular, coke granular contact is a point contact. The heat coke at the point contact is first oxidized to ash. When the carbon content of coke decreases and ash content increases, resistivity increases sharply. Experiments showed that when the carbon content decreased from 97.5% to 94.5% and ash content increased from 0.76% to 3.7%, the resistivity of coke increased from $8.3\Omega\cdot\text{m}$ to $55\Omega\cdot\text{m}$[19].

3. Electrical performance indexes and their algorithm

3.1. Electrical performance indexes.

a. grounding resistance

When grounding electrode's rated current duration is greater than its thermal time constant, the temperature rise of the grounding electrode is usually controlled by the grounding resistance. Therefore, in order to ensure the safe operation of the grounding electrode, The technical guidelines for HVDC grounding electrodes require that the grounding resistance meet the requirements of thermal stability, that is, the following formula should be satisfied [20].

$$R_e \leq R_0 = \sqrt{2\lambda \rho (\theta_{\text{max}} - \theta_c)} / I_d$$

In formula: $R_e$ is grounding resistance; $R_0$ critical grounding resistance; $\lambda$ is soil thermal conductivity; $\rho$ is soil resistivity; $\theta_{\text{max}}$ is grounding electrode's design-permissible maximum temperature; $\theta_c$ is ambient temperature.

b. leakage current density

To prevent electroosmosis, the latest DL/T5224-2014 specification stipulates that the maximum current density at the contact surface of the coke and the soil should be limited for the grounding
electrode operating as an anode for a long time. For the anode ground electrode with long-term monopole operation or less soil moisture content, the maximum surface current density should not exceed 1A/m² at rated current.

c. step voltage

According to The technical guidelines for HVDC grounding electrodes, the maximum allowable step voltage should be satisfied with the following formula:

\[ E_a = 7.42 + 0.0318\rho_s \]  

(3)

In formula: \( E_a \) is maximum allowable step voltage; \( \rho_s \) is surface soil resistivity.

3.2. The algorithm of electrical performance indexes.

a. grounding resistance

The grounding electrode can be regarded as an equipotential body in operation, so the grounding resistance can be calculated as long as the potential at the grounding electrode is calculated, \( R_c = \frac{\Phi}{I_d} \).

b. leakage current

The grounding electrode is dispersed into \( n \) points, and the current at each point is expressed by \( I_1, I_2, \ldots, I_n \). The potential of any point on the grounding electrode can be expressed as the following formula:

\[ \Phi_i = \alpha_{11}I_1 + \alpha_{12}I_2 + \cdots + \alpha_{1n}I_n \]  

(4)

In formula: \( \alpha_{ij} \) is potential coefficient

According to formula (4), the potential expression of each discrete point can be written. Because the potential of each point on the ground electrode is equal, and the discrete point current satisfies the constraint condition: \( I_1 + I_2 + \cdots + I_n = I_d \), the equations in matrix form can be obtained as follows:

\[
\begin{bmatrix}
\alpha \\
1
\end{bmatrix}
\begin{bmatrix}
I
\end{bmatrix} =
\begin{bmatrix}
\Phi \\
I_d
\end{bmatrix}
\]

(5)

The leakage current distribution of discrete points can be obtained by solving the upper formula.

c. step voltage

The step voltage is the component of the surface electric field intensity in the direction of x and y, which can be expressed in the following formula:

\[
\begin{align*}
E_{sx} &= \frac{\rho_s}{4\pi} \sum_{i=1}^{n} I_i S_{xi} \\
E_{sy} &= \frac{\rho_s}{4\pi} \sum_{i=1}^{n} I_i S_{yi} \\
E_k &= \sqrt{E_{sx}^2 + E_{sy}^2}
\end{align*}
\]  

(6)
In formula: \( \rho_m \) is soil resistivity at the layer of the electrode; \( S_{ii}, S_{jj} \) is coefficient of electric field.

Using the above calculation method, ANSYS simulation software can be used for modeling calculation. Because the length of feeding bars is much larger than their diameter, a one-dimensional linear element LINK68 can be used to build the model of grounding electrode. The coke bed can be regarded as a conductivity anomaly in the soil, and in this case, the soil model is a three-dimensional model, so the coke and soil model of the pole address can be built by element SOLID69. Divide the grid automatically, and then allocate corresponding resistivity to the corresponding layer.

After the model is built, applied the current load, and the maximum instantaneous rated current is adopted to calculate the maximum step voltage. Finally, set the boundary conditions to calculate. The boundary conditions are as follows: (1) The boundary potential of the soil model is 0; (2) In the boundary between the soil model and the air: \( \frac{\partial U}{\partial n} = 0 \), \( n \) is outer normal direction, pointing to the air; (3) In the boundary inside the soil:

\[
\frac{1}{\rho_i} \frac{\partial U_i}{\partial n} = \frac{1}{\rho_j} \frac{\partial U_j}{\partial n} \quad i \text{ and } j \text{ represent different soil regions.}
\]

Thus, the potential of the grounding electrode can be solved, and then the grounding resistance, the leakage current and the step voltage can be solved.

4. Numerical example and result analysis

4.1. Model verification.

Use the model of Xintian grounding electrode as the simulation model. Xintian grounding electrode is a double ring grounding electrode, inner ring radius is 240m, outer ring radius is 345m, the buried depth is about 3m, the grounding pole material is 50mm round steel, and it is placed in the center of coke bed, The section size of the coke bed is 0.75m \( \times \) 0.75m square. The soli resistivity model uses a 4-tiering layered model, as shown in Table 1.

| Numble | resistivity \( \Omega \cdot m \) | Layer thickness m |
|--------|-------------------------------|-------------------|
| 1      | 120                           | 4                 |
| 2      | 180                           | 14                |
| 3      | 50                            | 175               |
| 4      | 255                           | 4120              |
| 5      | 360                           | infinite          |

The calculated grounding resistance is compared with the measured data and the result without considering the influence of coke bed, as shown in Table 2.

| Numble | The calculated value considering coke | The calculated value without considering coke | the measured value |
|--------|--------------------------------------|-----------------------------------------------|-------------------|
|        | 0.109Ω                               | 0.125Ω                                       | 0.111Ω            |

It can be seen that the error of the model considering the coke layer is smaller. The error sources may be the errors in the equivalent process of the soli resistivity model and the errors in the test.

In order to simplify the calculation, in the following analysis, the soil model of the pole address is simplified to a two-level soil model. The parameters are shown in Table 3.
Table 3. The simple earth resistivity model parameters

| Numble | resistivity | Layer thickness |
|--------|-------------|----------------|
| 1      | 540 Ω·m    | 193 m          |
| 2      | 360 Ω·m    | infinite       |

4.2. Effect of coke aging on grounding resistance.
Change the resistivity of the coke bed, calculate the grounding resistance, draw the above data into a diagram as shown in Fig. 2(a), it is seen that the grounding resistance increases linearly with the resistivity of the coke.

![Fig. 2 (a) Change of grounding resistance with the change of coke resistivity](image)

(b) Change of grounding resistance with the change of coke resistivity in different thickness of coke bed

Change the thickness of the coke bed, calculate to get the relationship between the coke aging and the grounding resistance is shown in Figure 2(b), it is seen that the thicker the coke layer is, the faster the grounding resistance increases with the increase of the resistivity of coke bed.

4.3. Effect of coke aging on the distribution of leakage current.
When the coke resistivity rises, the outer ring leakage current distribution changes as shown in Figure 3(a), the inner ring leakage current distribution changes as shown in as shown in Figure 3(b), the variation trend of the uniformity coefficient of the leakage current (= the maximum value / the minimum value) is shown in Figure 3(c), the variation trend of current split ratio(= the current flows to inner ring/the current flows to outer ring) is shown in Figure 3(d).

![Fig. 3 (a) Change of current distribution](image)

(b) Change of current distribution
Fig. 3 (a) Influence of coke aging on leakage current distribution of outer ring; (b) Influence of coke aging on leakage current distribution of inner ring; (c) Influence of coke aging on uniformity coefficient of the leakage current; (d) Influence of coke aging on current split ratio

It can be seen from Fig. 3, with the increase of coke resistivity, the distribution of the leakage current is gradually well-distributed, which is due to the weakening of the end effect with the increase of resistivity. The current split ratio is gradually increasing, that is to say, the current of inner ring is gradually increasing. So, the leakage current density increase, which may cause the coke bed size of inner ring designed according to the original current density may no longer meet the design requirements. Therefore it is necessary to recheck whether the size of coke section still meet the demand according to the aging degree of coke. Otherwise, coke should be replaced in time.

Change the resistivity of surface soil, obtain the change of current split ratio when the surface soil resistivity is 3 ohms and 300 ohms, shown in Figure 4.

It can be seen that the change of the current split ratio caused by the aging of coke is more obvious in the polar address which the surface soil is low resistivity. So the grounding electrode in the polar address which the surface soil is low resistivity is more required to prevent the increase of the inner ring leakage current density exceeding the limit.

Fig. 4 Influence of coke aging on current split ratio in different surface soil resistivity

4.4. Effect of coke aging on the surface potential distribution and the step voltage.
Considering the resistivity changes caused by the aging of coke, calculate the surface potential distribution and the step voltage, the results is shown in Figure 5. Although the surface potential rise as
the resistivity of coke increase, the thickness of coke bed is very thin to the soil model and ground potential distribution of the pole address is mainly determined by the soil resistivity model. Therefore, the effect of coke aging on the distribution of ground potential is very small. The step voltage will decrease due to the weakening of the end effect with the increase of coke's resistivity. But at the beginning of the design, the step voltage calculate considering the coke bed is larger than the result without considering the coke bed. Therefore, the influence of the coke bed should be taken into account in the design.

![Graphs showing change of surface potential and step voltage](image)

Fig. 5 (a) Change of surface potential caused by aging of coke; (b) Change of step voltage caused by aging of coke

5. Summary
Coke aging has a linear correlation with the grounding resistance, which is related to the coke thickness. The thicker the coke layer is, the greater the slope is, the more significant the impact is. Therefore, in practical engineering, we should consider the influence of coke aging on the ground resistance and verify whether the grounding resistance meets the requirements of thermal stability.

The influence of coke aging on leakage current of the grounding electrode is large. In the initial stage, the coke resistivity is very small and the end effect is serious. It is necessary to reduce the end effect by means of installing diffuser circles at the end or enlarging the size of the end feed bars. When the coke resistivity increase, the current of inner ring is gradually increasing, the coke bed size of inner ring designed according to the original current density may no longer meet the design requirements. This phenomenon is more significant in the area which the surface soil is low resistivity, and the maintenance of these areas should pay more attention to monitoring the increase of the leakage current in the inner ring, checking whether the size of coke section still meet the demand and replacing the coke in time.

The step voltage decreases due to the weakening of the end effect with the increase of coke's resistivity. But at the beginning of the design, the step voltage calculate considering the coke bed is larger than the result without considering the coke bed. Therefore, the influence of the coke bed should be considered in the design phase.

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