Distribution characteristics of circular grounding ground potential in HVDC transmission system

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Abstract. This paper presents a model of double-ring type grounding pole unequal depth embedding for high-voltage direct current (HVDC) transmission system; and introduces calculation formula of DC ground potential distribution when double-ring type grounding pole is unequal buried. Furthermore the ground potential distribution and stride voltage level around the grounding pole and influence of grounding depth and soil parameters on the current field are discussed in this paper. The electric field zoning model of the ring current source is established by using the power system grounding pole analysis software CDEGS to verify the feasibility of this method. As the model is able to make the grounding current overflow density and potential distribution as uniform as possible, there is no serious local current concentration.

1. Introduction
With the large-scale construction of HVDC transmission project, the operation of HVDC has certain specificity and complexity, and the operation of the earth loop is one of the important aspects. When the HVDC wiring is operated by the earth loop, the soil in the vicinity of the entire DC grounding pole may have a different resistivity, and the stride voltage caused by the DC ground potential distribution may affect the safety of humans and animals. By analyzing and calculating the soil parameters of the unequal buried double-ring type grounding pole, it is possible to determine the surface potential and stride voltage of the entire DC grounding device, which is of great significance for better achieving a safe, reliable and economical power grid.

In the past years, many experts all over the world are also engaged in the study of the distribution characteristics of HVDC grounding poles. The United States took the lead in studying the constant current field generated by the DC grounding electrode in a homogeneous medium, and proposed a series of calculation formulas [1]. Study on the Distribution of Surface Potential and the Calculation Method of Cylindrical Soil Model [2]. Depicting the equivalent mirror image of the point source in the horizontal two-layer soil, eliminating the interface effect of the medium [3]. A Green's function recursive method suitable for horizontally layered soil is proposed; as a result, expression of each layer can be obtained by using computer program [4]. A point current source current field recursive algorithm suitable for soil horizontal or vertical arbitrary layered structure is proposed [5]. Using the equivalent complex image method to derive the Green's function of calculating the DC ground potential distribution when the earth is horizontal and vertical composite layering [6]. Combining the conformal transformation with the image method, the ground potential distribution function suitable for peninsula geology is derived [7]. The AC/DC interconnection system is divided into different regions, and the surface potential of each regional site is calculated by Gauss's theorem distribution [8].
The surface potential calculations around the three grounding poles of the point, line and ring in the uniform soil layer are derived and verified by actual engineering [9]. Calculate the ground potential distribution under the two soil structure models, shallow and deep, and consider the influence of substation outlet, grounding resistance, rivers and lakes on ground potential distribution [10]. This paper introduces the design method of DC grounding system, and studies the grounding resistance and ground potential of three kinds of grounding poles: ring, star and horizontal [11]. Describe the equipotential lines near the poles in the case where water and soil coexist [14]. The ground potential distribution curves when the direct current is 100 A, 600 A, 1500 A, 2300 A are measured in eight directions [15]. The calculation of DC step voltage and ground potential rise is discussed. The Geshang HVDC project is taken as an example for further explanation [16].

In this paper, the double-ring type grounding pole unequal depth embedding model of HVDC transmission system is proposed, and the new Green's function algorithm is applied to solve the problem of grounding pole surface potential. The structure of this paper is as follows: Section 2 discusses the potential distribution in infinitely uniform media, Section 3 presents the potential distribution formula of the double-ring grounding electrode in horizontally layered media, Section 4 presents the simulation results of the power system analysis software CDEGS, and Section 5 explains the conclusions of this paper. The main contribution of this paper is to propose a double-ring type grounding pole unequal depth embedding model and the distribution formula of the ground potential of this model in horizontal layered medium. The main advantages of this model are: saving land resources; current overflow density and potential the overall distribution is relatively uniform; and there is no serious concentration of local current. Using this model can effectively reduce the stride voltage.

2. Potential distribution in infinitely uniform media

2.1. Point source potential distribution

According to the electromagnetic field theory, the current flowing through any closed curved surface is:

\[ I = \int_S J \cdot dS \]  

(1)

Where \( I \) is the total current flowing through any closed surface \( S \) (A), \( S \) is the arbitrarily closed surface, \( J \) is the current density at any point on the surface \( s \) that is the density of the dispersion throughout the medium \((A / m^2)\).

The current density at any point from the point source in an infinitely uniform medium is:

\[ J = \frac{I}{4\pi r^2} \]  

(2)

Where \( r \) is the distance from point source to observation point.

Due to \( E = J \cdot \rho = \frac{I \rho}{4\pi r^2} \), if the potential at infinity is 0, the potential at the point from the point source \( r \) is:

\[ V_a = \int_{-\infty}^{\infty} Edr = \int_{-\infty}^{\infty} \frac{I \rho}{4\pi r^2} dr = \frac{I \rho}{4\pi r} \]  

(3)

Where \( V_a \) is the potential from the point source \( r(V), \rho \) is the earth resistivity \((\Omega \cdot m)\).

2.2. DC single-ring grounding ground potential distribution
DC ring grounding electrode is bent by a round conductor. The diameter of the circular conductor is 2a, and the diameter of the ring is 2b. The current flowing through the ring into the medium is uniformly distributed along the circumference of the ring. In general case, \( ba \gg \), so when the DC current overflows from the round conductor, it can be considered concentrated on the conductor axis. If \( \delta \) represents the surface relief density of the pole ring, \( \delta \) expressed as follow:

\[
\delta = \frac{I}{2\pi \rho b}
\]

(4)

![Figure 1. Potential distribution around the DC ring electrode.](image)

As shown in figure 1, Due to the symmetry of the circular ring, the cylindrical coordinate system is selected, and the potential of any point \( N(r, 0, z) \) in the space around the DC ring electrode can be obtained from the figure:

\[
V_n = \frac{\rho I}{4\pi \rho} \int_0^{2\pi} b \delta d\alpha \left( z^2 + r^2 + b^2 - 2br \cos \alpha \right)^{1/2}
\]

(5)

Where \( \rho \) is the earth resistivity \(( \Omega \cdot \text{m} )\), \( \delta \) represents the surface relief density of the pole ring, \( b \) is the radius of the circle, \( z \) is the coordinate axis (the surface is extended downwards from the surface), and \( r \) is the distance from the point source to the observation point.

The calculation expression of the surface potential around the DC single ring electrode is:

\[
V_n = V_n(r, z-h) + V_n(r, z+h) = \frac{\rho I}{2\pi} \left[ \frac{K(k)}{h^2 + (r+b)^2} \right]^{1/2} = \frac{\rho I}{2\pi} \left[ 1 + \sum_{m=1}^{n} \left( \frac{2m-1}{m} \right) \frac{(br)^m}{(r+b)^{2m}} \right]^{1/2}
\]

(6)

Where \( \rho \) is the earth resistivity \(( \Omega \cdot \text{m} )\), \( b \) is the radius of the circle, \( z \) is the coordinate axis (the surface is extended downwards from the surface), \( r \) is the distance from the point source to the observation point, and \( I \) is the injection current of a ring-shaped grounding electrode \(( A )\).

3. DC double-ring grounding ground potential distribution

3.1. Surface potential distribution of double-ring grounding electrode in unbounded medium

Suppose the double-ring grounding pole radius are \( b_1 \) and \( b_2 \) respectively. After establishing the cylindrical coordinate system, the potential expression at any point in the unbounded medium is:

\[
V(r, z) = \frac{\rho I b_1}{4\pi^2 r^2} \left[ \frac{K(k_1)}{z^2 + (b_1 + r)^2} \right]^{1/2} + \frac{\rho I b_2}{4\pi^2 r^2} \left[ \frac{K(k_2)}{z^2 + (b_2 + r)^2} \right]^{1/2}
\]

(7)

Where \( \rho \) is the earth resistivity \(( \Omega \cdot \text{m} )\), \( \delta \) represents the surface relief density of the pole ring, \( b_1 \) is
the radius of the inner ring of the double ring, and \( b_2 \) is the radius of the outer ring of the double ring. \( z \) is the coordinate axis (the surface is extended downwards from the surface), and \( r \) is the distance from the point source to the observation point, and \( I \) is the injection current of a ring-shaped grounding electrode.

\[
K(k) = \frac{\pi}{2} \left[ 1 + \sum_{m=1}^{\infty} \left( \prod_{n=1}^{m} \frac{2m-1}{m} \right)^2 \left( \frac{br^m}{(r+b)^{2m}} \right) \right], \quad k_1 = \left[ \frac{4br}{z^2 + (r+b_1)^2} \right]^{1/2},
\]

\[
k_2 = \left[ \frac{4b_2r}{z^2 + (r+b_2)^2} \right]^{1/2}.
\]

3.2. Potential distribution of double-ring grounding electrode in horizontal single-layer medium

In engineering practice, since the earth has a layered interface in the air, the actual earth is not an unbounded medium. This section discusses the DC ring grounding pole in horizontal single-layer media. In order to eliminate the influence of the boundary, the constant electric field problem with the boundary is transformed into the superimposed field problem of the electrode and the mirror electrode. The inner ring radius is \( b_1 \), the buried depth is \( h_1 \), the outer ring radius is \( b_2 \), and the buried depth is \( h_2 \). The ground potential distribution of the double-ring grounding electrode in the horizontal single-layer medium is:

\[
V = V(r, z - h_1) + V(r, z + h_1) + V(r, z - h_2) + V(r, z + h_2)
\]

When seeking the DC double-ring grounding pole in the horizontal surface potential of the horizontal single-layer medium, let \( z = 0 \), then:

\[
V = \frac{\rho l}{8\pi r}\left( p_1' + p_2' + p_3' + p_4' \right)(b_1 + b_2)\left[ 2 + \sum_{m=1}^{\infty} \left( \frac{2m-1}{m} \right)^2 \left( \frac{(br)^m}{(r+b_1)^{2m}} + \frac{(br)^m}{(r+b_2)^{2m}} \right) \right]
\]

Where 
\[
p_1' = \left[ h_1^2 + (r + b_1)^2 \right]^{-1/2}, \quad p_2' = \left[ h_1^2 + (r + b_2)^2 \right]^{-1/2}, \quad p_3' = \left[ h_2^2 + (r + b_1)^2 \right]^{-1/2}, \quad p_4' = \left[ h_2^2 + (r + b_2)^2 \right]^{-1/2}, \quad \rho \text{ is the earth resistivity (}\Omega \cdot \text{m}), \quad b_1 \text{ is the radius of the inner ring of the double ring, and } b_2 \text{ is the radius of the outer ring of the double ring}, \ z \text{ is the coordinate axis (the surface is extended downwards), and } r \text{ is the distance from the point source to the observation point, and } I \text{ is the injection current of a ring-shaped grounding electrode } (A).

3.3. Potential distribution of double-ring grounding electrode in horizontal double-layer medium

In actual engineering, it is very rare for soil to be completely homogeneous, and most soil models are two-layer models. The image method is used to eliminate the boundary effect, and the constant electric field problem with the boundary is transformed into the superimposed field problem of the electrode and the mirror electrode. The determination of the ring-grounded extremely mirrored electrode embedded in the first layer of the horizontal double-layer medium requires the traveling wave method. The traveling wave method compares the constant current field with the time-varying field, and regards the flow of the direct current in the soil layer as a wave. Propagation, using the reflected waves of traveling waves at different media interfaces to simulate the boundary effects, thereby determining the position of the mirror electrode and the magnitude of the current flowing out.

Since the mirror of the ring ground is similar to the mirror of the point source, the mirror of the point source is first sought here. The positive half-axis direction of the coordinate axis \( z \) is set to be pointed to the ground by the interface between the earth and the air, and the angle between the traveling wave from the point source and the positive half-axis of the \( z \)-axis can be selected within the range, but the corresponding equivalent The mirror point source location does not change as the angle of reflection changes. The coordinates of the equivalent mirror point source on the \( z \)-axis are obtained
from a simple geometric relationship. The coordinates of the inner ring grounding electrode are respectively \( \pm h_1, \pm (2s - h_1), \pm (2s + h_1), \ldots, \pm (2is - h_1), \pm (2is + h_1) \) and the coordinates of the outer ring grounding electrode are respectively \( \pm h_2, \pm (2s - h_2), \pm (2s + h_2), \ldots, \pm (2is - h_2), \pm (2is + h_2) \). The traveling wave is reflected once in the interface and then enters the upper layer of the soil. Its size becomes \( \beta_{12} \) times, and the equivalent mirror source current values corresponding to the double-ring grounding electrode are respectively \( I \beta_{12}, \ldots, I \beta_{12}^n \). At this time, the boundary electrode can be used to eliminate the influence of the boundary, and the entire space can be regarded as a uniform soil having a resistivity of \( \rho_1 \), and the potential of an arbitrary position in the upper layer can be obtained by using the superposition theorem for the original electrode and its mirror electrode.

Then the surface potential of the double-ring grounding electrode in the horizontal layered medium:

\[
V_i (r, z = 0) = V + \sum_{i=1}^{\infty} \beta^r \left[ V \left( r, z = 2is - h_1 \right) + V \left( r, z = 2is + h_1 \right) \right] \left( b_1 - b_2 \right) \left( p_i^r + p_2^r + p_i^a + p_4^r \right) \\
+ V \left( r, z = 2is - h_2 \right) + V \left( r, z = 2is + h_2 \right) \left( \frac{\rho_1}{8 \pi r} \right) \left( b_1 + b_2 \right) \left( p_i^r + p_2^r + p_i^a + p_4^r \right)
\]

\[
\cdot \left( p_{i1} + p_{i2} + p_{i3} + p_{i4} \right) \left( 2 + \sum_{m=1}^{\infty} \left( \prod_{m=1}^{\infty} \frac{2m-1}{m} \right)^2 \left( \frac{\left( b_1 r \right)^m}{\left( r + b_1 \right)^{2m}} + \frac{\left( b_2 r \right)^m}{\left( r + b_2 \right)^{2m}} \right) \right)
\]

Where

\[ p_1^r = \left[ h_1^2 + (r + b_1)^2 \right]^{-\frac{1}{2}}, \quad p_2^r = \left[ h_1^2 + (r + b_2)^2 \right]^{-\frac{1}{2}}, \quad p_3^r = \left[ h_2^2 + (r + b_1)^2 \right]^{-\frac{1}{2}}, \quad p_4^r = \left[ h_2^2 + (r + b_2)^2 \right]^{-\frac{1}{2}}, \]

\[ p_{i1} = \left[ \left( 2is + h_1 \right)^2 + (r + b_1)^2 \right]^{-\frac{1}{2}}, \quad p_{i2} = \left[ \left( 2is + h_2 \right)^2 + (r + b_2)^2 \right]^{-\frac{1}{2}}, \quad p_{i3} = \left[ \left( 2is + h_2 \right)^2 + (r + b_1)^2 \right]^{-\frac{1}{2}}, \quad p_{i4} = \left[ \left( 2is + h_1 \right)^2 + (r + b_2)^2 \right]^{-\frac{1}{2}}, \]

\[ \beta = \frac{\rho_2 - \rho_1}{\rho_2 + \rho_1}. \]

The inner ring radius is \( b_1 \), the buried depth is \( h_1 \), the outer ring radius is \( b_2 \), the buried depth is \( h_2 \), \( \rho_1 \) is the resistivity of the upper layer soil, \( \rho_2 \) is the resistivity of the lower layer soil, and \( \beta \) is the reflection coefficient.

4. Simulations

Use the power system grounding pole analysis software CDEGS to establish a double-ring type grounding pole unequal depth embedding model, as shown in figure 2 below.

![Figure 2. Double ring grounding pole model.](image)

The double-ring grounding pole data analyzed in this section is from the Yulongling grounding pole. The electrode parameters are shown in table 1, and soil stratification and soil resistivity are shown in table 2. Calculated values and simulated values of surface potentials are shown in table 3.

From table 1, it compares the calculated values of the surface potential (10) and the software CDEGS simulation values when the soil layer is a horizontal double-layer medium, which verifies the feasibility of the formula.
### Table 1. Yulongling grounding pole parameters.

| Parameter                                    | Value                                |
|----------------------------------------------|--------------------------------------|
| Rated current /A                             | 3000                                 |
| Pole radius /m                               | Inner ring 350/ Outer ring 470       |
| Polar ring depth /m                          | Inner ring 3.5/ Outer ring 4         |
| Coke side length /m                          | Inner ring 0.7×0.7/ Outer ring 1.1×1.1 |
| Round steel cross section diameter /mm       | Inner ring 60/ Outer ring 70         |
| Maximum step voltage limit /V                | 7.1                                  |
| Surface overflow density limit / (A / m²)    | 1                                    |

### Table 2. Soil stratification and soil resistivity in Yulongling.

| Sequence | Layer thickness /m | Resistivity / (Ω · m) |
|----------|--------------------|-----------------------|
| 1        | 6                  | 70                    |
| 2        | 25                 | 120                   |
| 3        | 60                 | 90                    |
| 4        | 300                | 220                   |
| 5        | ∞                  | 2000                  |

### Table 3. Calculated values and simulated values of surface potentials when the soil layer is horizontal double-layer medium.

| r/m    | Calculated /V | Simulation value /V |
|--------|---------------|--------------------|
| 100    | 86.356        | 87.248             |
| 400    | 52.167        | 54.237             |
| 900    | 85.626        | 86.098             |

Power system grounding pole analysis software CDEGS simulation results, the surface potential is shown in figure 3, and the step voltage is shown in figure 4.

![Figure 3. Surface potential.](image1)

![Figure 4. Step voltage.](image2)

It can be seen from the curve distribution in the above figure:

- The surface potential of the double-ring grounding outer ring with a buried depth greater than the inner ring buried depth has four extreme values, which respectively appear at the radius of the inner and outer rings (350 m and 470 m), and the potential above the inner ring is slightly higher than that above the outer ring. When the polar distance is smaller than the radius of the inner ring or larger than the radius of the outer ring, the surface potential decreases rapidly.
with the decrease or increase of the polar distance.

- The step voltage distribution curve also has four extremum, which appear at the radius of inner and outer ring respectively. The maximum step voltage is at the radius of the inner ring, but its value is far less than the maximum allowable step voltage in China (2.5 v). The step voltage of inner ring, inner ring and outer ring decreased rapidly.

5. Conclusions

In this paper, a double-ring type grounding pole unequal-buried model for high-voltage direct current (HVDC) transmission system is proposed. According to the unequal depth of the pole ring, the surface potential and stride voltage are greatly reduced under the same grounding conditions. The goal is that the grounding current overflow density and the potential distribution are relatively uniform, and there is no serious local current concentration.

The calculation formula of the space potential around the grounding pole of the DC ring can be obtained by solving the elliptic integral on the basis of the point source. The entire integration process utilizes the McLaughlin expansion, and the more the number of items, the more accurate. When the soil layer is a semi-infinite and uniform medium, the ring grounding pole has only one image of equal size and positional symmetry, and the ground potential distribution is calculated according to formula (9). When the soil layer is a horizontal double-layer medium, the ring grounding pole has an infinite number of images, which can be obtained by multiple reflections of traveling waves on the medium interface, and the ground potential distribution is calculated according to formula (10). Therefore, the formula proposed in this paper can be applied to engineering practice, which can greatly simplify the calculation amount and improve the calculation accuracy.

In future, it is conceivable to use the double-ring type grounding pole unequal depth burying to solve the problem of grounding surface potential and over-stepping voltage. In addition, a three-ring type grounding pole unequal depth embedding model will be proposed in the future. To solve this problem, and to better save land resources and reduce costs.

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