Computer Fraud and Security
ISSN (online): 1873-7056

Research on the Corrosion Impact of DC Grounding Electrode Current on Surrounding Tower Grounding Systems

Nansheng Ding[1,a*], Changzheng Deng[1,b] Yue Zhang[1,c] and Yunlong Yan[2,d]）

[1] College of Electrical and New Energy, China Three Gorges University, Yichang 443002, Hubei, China

[2] State Grid Yichang Power Supply Company, Yichang 443002, Hubei, China

[a]Email: 202208580121035@ctgu.edu.cn

[b]Email: dcz_1980@ctgu.edu.cn

[c]Email: 202208540021051@ctgu.edu.cn

[d]Email: 1010743776@qq.com

[*]Corresponding Author

Abstract: With the widespread application of high-voltage direct current (HVDC) transmission technology, the corrosion of grounding systems in transmission towers caused by the ground current of DC grounding electrodes has become increasingly significant. Currently, existing research, both domestically and internationally, has not fully considered the impact of non-uniform soil conditions on the distribution of DC currents in towers. To address this gap, this study employs the CDEGS simulation software to construct uniform and non-uniform soil models, systematically analyzing the influence of soil resistivity, soil layer thickness, and different grounding electrode configurations on the distribution of DC currents and corrosion characteristics in tower grounding systems. The results reveal that under uniform soil conditions, the ground current of the tower closest to the grounding electrode increases with soil resistivity and exhibits significant spatial attenuation characteristics. In horizontally layered soil models, when the upper soil layer has lower resistivity, the ground current decreases with increasing upper layer thickness, whereas the opposite trend is observed when the upper layer has higher resistivity. As the upper soil resistivity gradually exceeds that of the lower layer, the ground current tends to saturate, while changes in lower layer resistivity have a more pronounced impact on current distribution. Furthermore, the current density distribution varies significantly among different grounding electrode configurations. Type C grounding electrodes exhibit the lowest localized corrosion, while Type B electrodes suffer the most severe corrosion at the ends of their rays. These findings provide technical support for the optimized design and corrosion protection strategies of transmission tower grounding systems, enhancing their operational safety and reliability.

Key words: grounding electrode； tower grounding system,； electrolytic corrosion

1. Introduction

The DC grounding electrode is a key component in DC transmission projects, mainly consisting of grounding conductors, active backfill materials, and the shunt system [1]. The grounding electrode plays a role in clamping the neutral point to zero potential in HVDC systems and provides a path for the DC operating current during monopole grounding loop operation, thereby effectively improving the reliability and availability of the power supply system [2]. However, its grounding current generates a strong, steady-state current field in the soil, which may adversely affect surrounding facilities. For example, it may cause a magnetization effect on transformers with effective neutral point grounding in substations, lead to corrosion and safety issues in nearby buried metal oil and gas pipelines, and cause corrosion in the grounding devices of nearby transmission tower structures [3-4]. Extensive research has been conducted domestically on the first two issues, while research on the third issue is relatively limited. For instance, Dong Xiaohui et al. calculated the influence of parameters such as soil structure, tower grounding resistance, and the cathodic operation probability of the grounding electrode on the DC distribution of the tower, based on a particular ultra-high voltage DC transmission project [5-8]. Liu Weilong used CST simulation software to study the relationship between the corrosion of transmission tower grounding systems and soil models, tower grounding resistance, as well as the vertical distance between the line and the grounding electrode [9]. Zhang Hui et al. assessed the corrosion depth at the end of the ray in the tower grounding system under different monopole operating modes, by analyzing the current density flowing through the rays of the tower grounding system, when the grounding current is 3000 A [10].

Currently, most domestic research still focuses on the corrosion effects in uniform soil environments, without adequately considering the impact of non-uniform soils on DC current distribution, nor the influence of different tower grounding system structures on current distribution and stray current density. To address this, this paper uses the CDEGS electromagnetic transient simulation software to establish a horizontal two-layer soil model and systematically analyzes the impact of soil resistivity and soil thickness on the DC distribution in tower grounding systems. Furthermore, this paper conducts an in-depth comparison of the current distribution, stray current density, and corrosion characteristics of four common grounding system types under different soil conditions. The research findings can provide important reference points for the design of tower grounding systems in practical engineering, further improving the safety and stability of the power system.

2. Corrosion mechanism and safety standards

2.1. Corrosion mechanism

The corrosion effect of high-voltage direct current (HVDC) transmission on underground metal installations can be illustrated in Figure 1. Similar to the corrosion mechanism of underground metal installations in other stray current fields, the figure shows that the current flowing out from the anode of the HVDC transmission line converges underground into part of the metal pipeline, then flows out through another part, ultimately returning to the cathode of the transmission line. The region where current flows into the pipeline is called the cathode zone, where the metal does not dissolve and is typically unaffected; the region where current flows out of the pipeline is called the anode zone, where the metal dissolves into positive ions, thus causing corrosion. This corrosion is essentially anodic corrosion in the electrolysis process. Therefore, when a transmission line with lightning protection is near a grounding electrode, if the electrode is in cathodic operation mode, the DC current will flow from the far-end tower grounding system into the lightning protection wire, along the wire to the near-end tower grounding system, and finally into the soil, leading to electro-corrosion of the grounding system. In contrast, when the grounding electrode is in anodic operation mode, the grounding system of the far-end tower will undergo electro-corrosion.

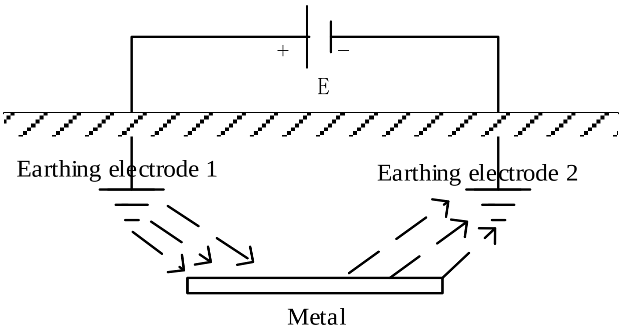

Figure1. Schematic diagram of corrosion impact

2.2. Safety standards

According to the relevant provisions in DL/T 5224-2014 "Technical Specifications for the Design of HVDC Ground Return Systems," the minimum distance between the electrode site and the grounded overhead earth wire of the power line should not be less than 5 km. If this requirement is not met, calculations must be carried out to determine whether insulation measures are needed for the overhead earth wire to mitigate such effects [11].

3. Establishment of the calculation model

In this study, the grounding electrode is designed with a concentric double-ring structure, where the outer ring has a radius of 400 meters and the inner ring a radius of 300 meters, both buried at a depth of 3.5 meters. The electrode material is low-carbon round steel with a diameter of 80 mm and a resistivity of 2.1×10^{-7} Ω·m. In the CDEGS software, the default conductor material is pure copper with a resistivity of 1.68×10^{-8} Ω·m. Therefore, the low-carbon round steel can be simulated using a conductor with a relative resistivity of 12.5 [12-13]. Near the grounding electrode, there is a single-circuit transmission line with an overhead ground wire made of JLB20A-150 aluminum-clad steel strand (DC resistance of 0.5807 Ω/km), which is directly grounded. The tower grounding system is modeled using a galvanized round steel grid buried at a depth of 0.8 meters (relative resistivity of 10). The side length of the tower grounding grid is adjusted to ensure consistent grounding resistance across different soil models, thereby eliminating the influence of tower grounding resistance.

Taking the grounding electrode operating in cathode mode as an example, the current direction is defined as positive when it flows from the tower into the ground. According to the principles of current field distribution, when the grounding electrode operates in anode mode, the magnitude of the current flowing out of each tower remains the same as in cathode mode, but the direction is reversed. Therefore, repeated calculations are unnecessary. The tower closest to the grounding electrode is labeled #0, with the numbering increasing sequentially along the line ahead and decreasing sequentially behind, totaling 71 towers with a spacing of 500 meters. Tower #0 is located 3 kilometers from the grounding electrode. The computational model is illustrated in Figure 2 [14].

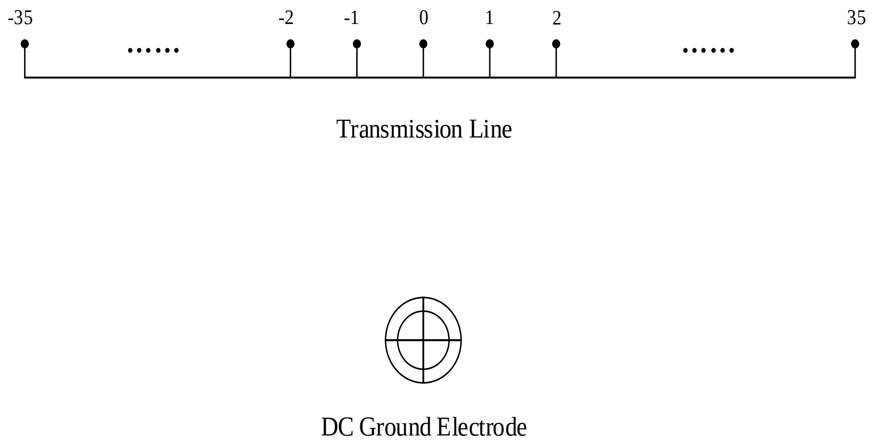

Figure2. Calculation model of DC current distribution in transmission tower

4. The impact of soil parameters on tower dc distribution

4.1 Impact of uniform soil conditions

Soil resistivity, a critical parameter characterizing the electrical conductivity of soil, is one of the key factors influencing the corrosion behavior of grounding systems. It not only reflects the physicochemical properties of the soil, such as soluble salt content, moisture level, and temperature, but also directly determines the current dissipation capability of the grounding system. To thoroughly analyze the impact of soil resistivity on the distribution of DC currents in transmission line towers, this study selected three representative soil resistivity values: 200 Ω·m, 500 Ω·m, and 1000 Ω·m. These values correspond to typical low-resistivity, medium-resistivity, and high-resistivity soil environments, respectively [15-16].

To ensure comparability across different soil models, the grounding resistance of the towers was maintained at a typical value of 10 Ω in all scenarios [15-16]. The study focused on examining the distribution characteristics of DC currents in the towers when the grounding electrode operated in cathode mode with a rated current of 4500 A. The variation in DC current distribution with respect to soil resistivity is illustrated in Figure 3.

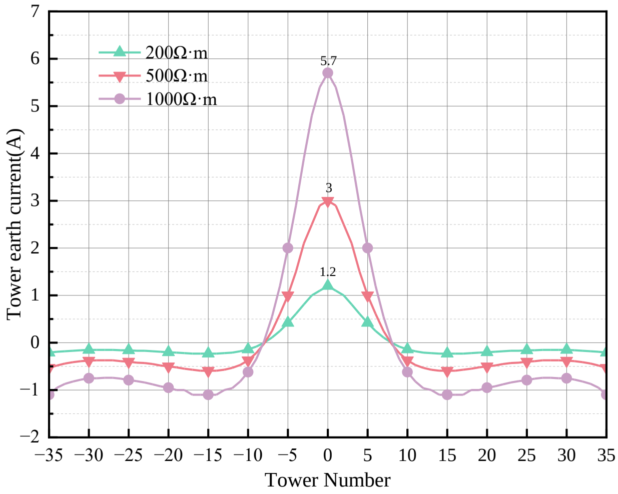

Figure3. Impact of uniform soil models on DC current distribution in transmission towers

Through numerical calculations, this study reveals the influence of soil resistivity on the distribution characteristics of ground currents in transmission towers under uniform soil conditions. The results demonstrate a significant positive correlation between soil resistivity and the magnitude of ground currents in the towers. Specifically, as soil resistivity increases, the ground currents in the towers exhibit a pronounced upward trend, accompanied by a well-defined spatial symmetry in current distribution. The spatial distribution characteristics indicate that the amplitude of the ground currents decreases with increasing distance from the grounding electrode, with the tower closest to the electrode exhibiting the highest ground current value.

Notably, the study observes a significant reversal in the direction of tower currents beyond a distance of 5 km (corresponding to 8 spans) from the grounding electrode. In this region, the current direction shifts from flowing from the tower into the ground (defined as the positive direction) to flowing from the ground into the tower. This phenomenon indicates that the grounding systems of towers in this region are under cathodic protection, thereby avoiding electrochemical corrosion. This finding holds significant engineering implications for the corrosion protection design of grounding systems.

Quantitative analysis reveals that when the soil resistivity increases to 2.5 times and 5 times the baseline value, the ground current of Tower #0 increases to 2.5 times and 4.75 times the baseline value, respectively. This nonlinear growth relationship suggests that the influence of soil resistivity on ground currents becomes more pronounced as resistivity increases. Based on electromagnetic field theory, this study employs a potential distribution model of a point current source in a uniform, isotropic, and infinite medium for analysis. The tower potential can be calculated using Equation (1):

$$\phi(r) = \frac{\rho \cdot I}{2\pi r} \quad (1)$$

In the equation, ρ represents the resistivity of the uniform soil (unit: Ω·m), and *I* denotes the strength of the current source (unit: A). This formula quantitatively describes the functional relationship between the potential, soil resistivity, and the strength of the current source.

Furthermore, the potential difference between any two towers in the medium can be expressed by Equation (2):

$$\triangle\phi = \phi(A) - \phi(B) \quad (2)$$

Equations (1) and (2) demonstrate that the potential difference is positively correlated with soil resistivity, the strength of the point current source, and the difference in distance between the observation points and the current source. This theoretical derivation aligns well with the numerical calculation results, robustly confirming a significant proportional relationship between the ground current values of the towers and soil resistivity. The findings provide a theoretical foundation for the optimized design of grounding systems in transmission lines, offering significant practical value, particularly for engineering applications in regions with high soil resistivity.

4.2 Impact of non-uniform soil conditions

In practical engineering applications, soil resistivity often exhibits significant spatial heterogeneity, which can typically be simplified into horizontal or vertical layered structure models for analysis. Research has shown that layered soil structures lead to fundamental differences in the distribution of ground current fields and potential compared to uniform soil conditions. These differences are primarily reflected in variations in current density distribution and potential gradients [17]. Given that the thickness of the top humus layer of soil is usually limited to a range of several meters to tens of meters, the electrical properties of the uppermost soil layer can be neglected when studying current distribution over large areas. Therefore, a horizontally layered two-layer soil model is commonly used in grounding electrode calculations and is adopted in this study.

The horizontally layered two-layer soil model used in this study includes the following key parameters: the resistivity of the upper soil layer ($\rho 1$), its depth (h), and the resistivity of the lower soil layer ($\rho 2$), which is assumed to extend infinitely. To ensure comparability across all simulation experiments, the grounding resistance of the tower grounding systems is maintained at a constant value of 10 Ω [18].

By establishing this horizontally layered soil model, the study focuses on investigating the following two aspects:

1.The influence of variations in the depth of the upper soil layer (h) on potential distribution characteristics.

2.The impact of different resistivity ratios between the soil layers ($\rho 2/\rho 1$) on the distribution of ground currents.

This research approach not only reflects the complexity of soil structures in practical engineering but also provides more accurate theoretical foundations for the optimized design of grounding systems. The results are expected to reveal unique patterns of current distribution under layered soil conditions, offering critical insights for the design of grounding systems in high-voltage direct current (HVDC) transmission lines.

4.2.1 Impact of upper soil layer depth on potential distribution characteristics

To investigate the impact of upper soil layer depth on the distribution characteristics of DC currents in transmission towers, this study selected two representative soil resistivity combination models for comparative analysis:

1.Model 1: 200/500 Ω·m ($\rho 1<\rho 2$), representing a scenario where the upper soil layer has lower resistivity than the lower layer.

2.Model 2: 500/200 Ω·m (ρ1>ρ2), representing a scenario where the upper soil layer has higher resistivity than the lower layer.

This comparative design comprehensively reflects the influence of upper soil thickness under different resistivity combinations.

In the experimental design, the depth of the upper soil layer (h) was systematically increased to observe the variation in ground current at Tower #0. Specifically, the thickness h was varied across a typical range from shallow to deep layers to ensure the universality of the results. Numerical simulations were conducted to obtain the characteristic curve of the ground current at Tower #0 as a function of upper soil thickness, as shown in Figure 4.

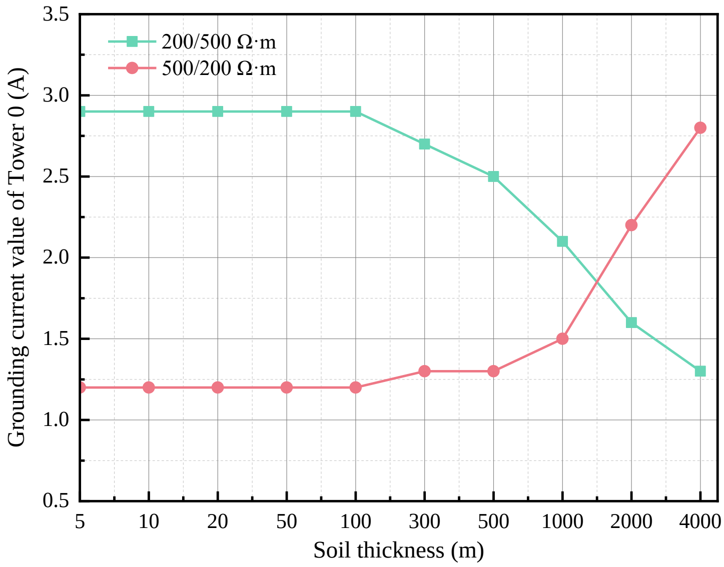

Figure4. Impact of soil thickness on DC distribution

The results reveal that the ground current distribution at Tower #0 exhibits distinctly different trends in the two soil models, primarily due to differences in current distribution and conduction mechanisms in layered soils. When the upper layer has lower resistivity, current tends to flow predominantly through the upper soil layer. As the upper soil thickness increases, the current diffusion range expands, leading to a gradual reduction in the potential gradient and the potential difference between towers. Conversely, when the upper layer has higher resistivity, current preferentially flows through the lower soil layer, resulting in a smaller initial potential difference between towers. However, as the upper soil thickness increases, the proportion of current distributed in the upper layer gradually rises, enhancing the potential gradient and increasing the potential difference between distant towers.

When the upper soil thickness reaches a critical value, the distribution characteristics of the grounding electrode current approach those of a uniform soil model with an equivalent resistivity of ρ1. Determining this critical thickness is of significant practical importance, as it indicates the point at which the influence of soil layering on current distribution diminishes substantially.

These findings not only elucidate the complex mechanisms of current distribution in layered soils but also provide critical guidance for the design of grounding systems in HVDC transmission lines. In practical engineering, the layered characteristics and thickness distribution of local soils should be carefully considered to develop optimal grounding system designs that ensure both safety and cost-effectiveness.

4.2.2 Impact of resistivity ratio between soil layers on ground current distribution

To study the impact of upper soil resistivity on DC current distribution in towers, the simulation model was configured as follows: the upper soil layer thickness h=500m, and the lower soil layer was assumed to be infinitely deep. When analyzing the influence of upper resistivity (ρ1), ρ2 was fixed at 500 Ω·m, while ρ1 was varied between 100 and 1000 Ω·m. Conversely, when analyzing the influence of lower resistivity (ρ2), ρ1 was fixed at 500 Ω·m, while ρ2 was varied between 100 and 1000 Ω·m. Using CDEGS software, the characteristic curve of the ground current at Tower #0 as a function of soil resistivity was obtained, as shown in Figure 5.

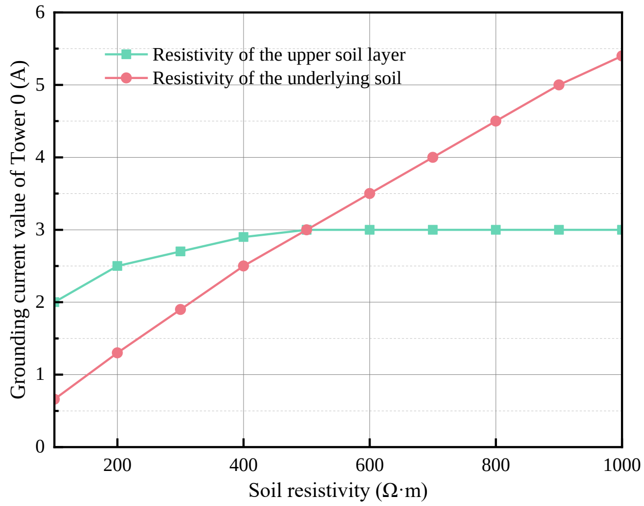

Figure5. Impact of Layered Soil Resistivity on DC Current Distribution

The simulation results indicate that the influence of upper resistivity (ρ1) on current distribution exhibits significant nonlinear characteristics. When ρ1 is low, the ground current at Tower #0 increases gradually as ρ1 rises. This is because low ρ1 reduces the impedance of the upper soil layer, allowing more current to diffuse through it. However, when ρ1 exceeds ρ2, the rate of increase in ground current slows and eventually saturates. This occurs because higher ρ1 significantly increases the impedance of the upper layer, causing most of the current to flow through the lower layer with lower resistivity. As a result, the influence of the upper layer on current distribution diminishes until it becomes negligible.

In contrast, as the lower soil resistivity (ρ2) increases, the ground current at Tower #0 rises progressively without saturation. This is because, at low ρ2, current primarily flows through the lower layer, resulting in a smaller potential difference between towers. As ρ2 increases, more current is diverted to the upper layer, enhancing the potential gradient and increasing the potential difference between towers, thereby driving the ground current upward.

5. Impact of different tower grounding electrode configurations on tower corrosion

In engineering, the assessment of tower corrosion is typically based on the total current flowing into or out of the metal. However, the current density varies at different locations on the conductor, with the highest density occurring at the ends of the rays, leading to the most severe corrosion. Therefore, studying the maximum current density in tower grounding conductors is crucial for evaluating corrosion severity. This study compares four differentiated grounding electrode topologies (A, B, C, and D) with the same total electrode length (80 m) based on economic considerations, as shown in Figure 6.

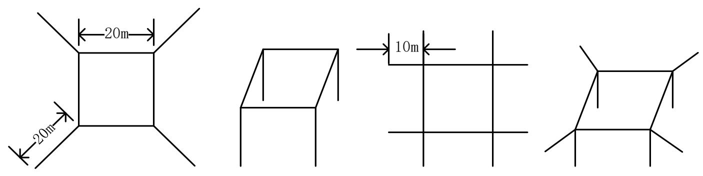

Figure 6. Schematic Diagrams of Four Tower Grounding Electrode Configurations

- **Type A**: A common square-frame ray configuration.
- **Type B**: A vertical layout with four 20 m vertical grounding electrodes.
- **Type C**: A dense horizontal expansion with eight 10 m horizontal rays.
- **Type D**: A composite topology with four 10 m horizontal rays and four 10 m vertical grounding electrodes.

To compare the corrosion impact of these four grounding configurations on tower grounding systems, the study modifies only the grounding electrode type in the model shown in Figure 2. The ground current values at Tower #0 for the four configurations were analyzed as soil resistivity increased from 100 Ω·m to 1000 Ω·m, as summarized in Table 1.

Table 1. Impact of Tower Configurations on Current Distribution

Soil resistivity(Ω·m)	Current value of the pole and tower entering the ground (A)			
	Type A	Type B	Type C	Type D
100	1.3	1.3	1.3	1.3
200	2	2	2	1.9
300	2.5	2.5	2.5	2.4
400	2.9	2.9	2.9	2.7
500	3.2	3.2	3.3	3.1
600	3.5	3.5	3.5	3.3
700	3.7	3.7	3.8	3.5

800	3.9	3.9	4	3.7
900	4.1	4.1	4.2	3.8
1000	4.2	4.2	4.3	4

The metal corrosion of the grounding electrodes can be quantitatively characterized using Faraday's law, as expressed in Equation (3):

$$G = \frac{\mathrm{M}_e \cdot I \cdot t}{\mathrm{n} \cdot F} \quad (3)$$

where:

- G is the metal corrosion mass (g),
- M_e is the molar mass of the metal (g/mol; 55.85 g/mol for iron),
- *I* is the equivalent corrosion current (A), considering the time-weighted effect of the DC grounding electrode operation mode,
- *t* is the cumulative exposure time (h),
- n is the number of electrons transferred in the electrochemical reaction (n=2 for iron oxidation),
- F=96490 C/mol is Faraday's constant.

Assuming a grounding electrode lifespan of 40 years and a 50% probability of cathode operation, the operating ampere-hours include both bipolar unbalanced operation and single-pole ground operation. The unbalanced current is approximately 1% of the rated current, so the unbalanced operating ampere-hours IT1 over the electrode's lifespan are given by Equation (4):

$$\mathrm{IT}_1 = 4500 \times 1\% \times 40 \times 365 \times 24 \times 50\% = 4500 \times 1752\mathrm{A} \cdot \mathrm{h} \quad (4)$$

The annual single-pole ground operation time is conservatively estimated at no more than 20 hours [19], so the single-pole ground operating ampere-hours IT2 over 40 years are given by Equation (5):

$$\mathrm{IT}_2 = 4500 \times 40 \times 20 \times 50\% = 4500 \times 400\mathrm{A} \cdot \mathrm{h} \quad (5)$$

Thus, the total operating ampere-hours IT over the electrode's lifespan are given by Equation (6):

$$\mathrm{IT} = \mathrm{IT}_1 + \mathrm{IT}_2 = 4500 \times 2152\mathrm{A} \cdot \mathrm{h} \quad (6)$$

Based on the above total ampere-hours, the cumulative corrosion mass of the four grounding configurations over the 40-year lifespan of the converter station grounding electrode is shown in Figure 7.

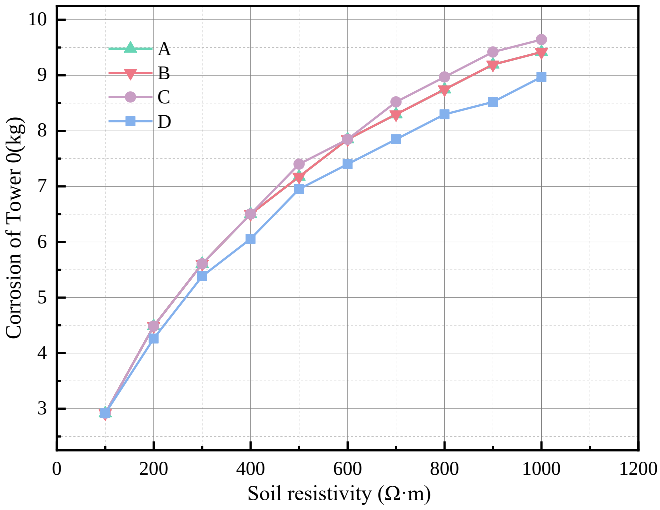

Figure 7. Corrosion Mass of Different Tower Grounding Electrode Configurations

All four grounding electrode types are constructed from 160 m of 12 mm diameter galvanized round steel, so the total weight M of a single tower grounding system is given by Equation (7):

$$M = 160 \times 3.14 \times (0.006)^2 \times 7.86 \times 10^3 \mathrm{kg/m^3} = 142.16\mathrm{kg} \quad (7)$$

From the simulation results in Figure 7, as soil resistivity increases, the ground current of the towers gradually increases, and the differences between the configurations become more pronounced. Specifically, Type C exhibits the highest ground current, while Types A and B show similar values slightly lower than Type C. In contrast, Type D has the lowest ground current, likely due to its higher grounding efficiency.

Despite the significant difference in ground current between Types C and D, their cumulative corrosion masses over 40 years are not markedly different. The corrosion mass of Type C is slightly higher, increasing from 2.05% to 6.78% with rising soil resistivity, while Type D increases from 2.05% to 6.31%. Thus, the overall differences in cumulative corrosion mass among the four configurations are relatively small.

Additionally, the current density distributions for the frames and rays of the four grounding configurations were obtained using CDEGS software, as summarized in Table 2.

Table 2. Current Density Distribution of Different Tower Grounding Electrode Configurations

Soil resistivity(Ω·m)	Current density(A/m²)							
	Square of A	Ray of A	Square of B	Ray of B	Square of C	Ray of C	Square of D	Ray of D
100	0.8952	1.577	0.8099	1.577	0.0980	0.213	0.8952	1.619
200	1.2362	2.344	1.1936	2.387	0.1449	0.315	1.3215	2.387
300	1.6199	2.898	1.4920	2.941	0.1790	0.387	1.6199	2.941

400	1.8757	3.282	1.7052	3.367	0.2046	0.426	1.8330	3.367
500	2.0888	3.623	1.8757	3.751	0.2302	0.511	2.0462	3.708
600	2.2593	3.921	2.0462	4.049	0.2472	0.511	2.2167	4.007
700	2.3872	4.17	2.17413	4.263	0.26430	0.554	2.34465	4.263
800	2.51517	4.263	2.30202	4.689	0.27709	0.596	2.47254	4.263
900	2.64306	4.689	2.38728	4.689	0.28988	0.639	2.5578	4.689
1000	2.7282	4.68	2.4724	5.115	0.30267	0.639	2.68569	4.689

The corrosion depth of the grounding electrodes can be estimated using the CIGRE guidelines. For a leakage current density of 0.01 A/m², the annual corrosion thickness of iron is approximately 0.174 mm [20]. Over the 40-year lifespan of the DC grounding electrode, the equivalent exposure time is 0.245 years, as given by Equation (8):

$$T = \frac{2152}{365 \times 24} = 0.245 \text{ years} \tag{8}$$

The cumulative corrosion thicknesses of the four grounding configurations over 40 years are shown in Figure 8.

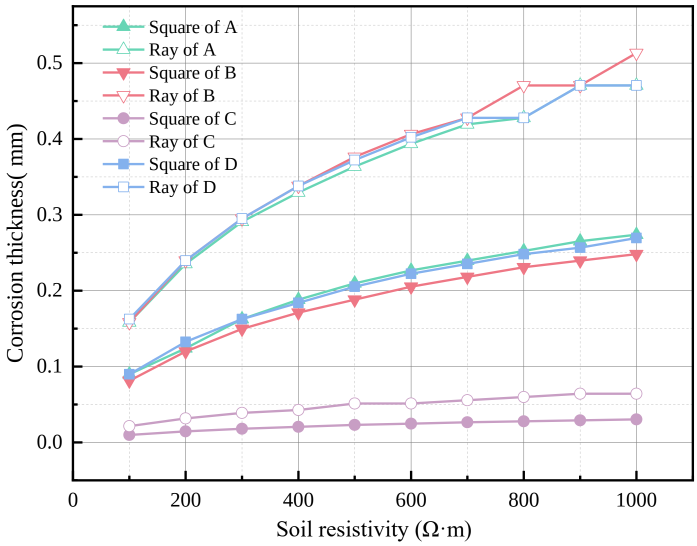

Figure 8. Current Density Distribution of Different Grounding Electrode Configurations

From Table 2 and Figure 8, although the overall corrosion masses of the four configurations are similar, the current density of Type C is significantly lower, approximately 12% of the other models. At a soil resistivity of 1000 Ω·m, the maximum corrosion depth of Type C rays is 10.66% of the diameter, while the frame's maximum corrosion depth is only 5.04%. In contrast, Type B exhibits the most severe corrosion at the ray ends, with diameter loss reaching 85.26%, and frame diameter loss reaching 41.21%. This could lead to shortening of the grounding electrodes or even frame conductor breakage, potentially causing ineffective current dissipation during lightning strikes or short circuits, leading to line tripping and large-scale power outages. Therefore, Type C is recommended as the preferred grounding configuration.

6.Conclusion

1. Under uniform soil conditions, the current flowing out of the tower grounding systems is primarily concentrated on the towers closest to the grounding electrode. As soil resistivity increases, the ground current at the nearest tower rises significantly.
2. In horizontally layered soil models, if the upper soil layer has lower resistivity than the lower layer, the ground current at the nearest tower decreases as the upper layer thickness increases. Conversely, if the upper layer has higher resistivity, the ground current increases with upper layer thickness. When the upper layer thickness reaches a certain value, the current distribution trends approach those of a uniform soil model, with an equivalent resistivity close to that of the upper soil layer. Additionally, under constant upper layer thickness, changes in lower soil resistivity have a more pronounced impact on the distribution of ground currents in the towers.
3. The influence of different grounding electrode configurations on corrosion behavior varies significantly. Type C grounding electrodes exhibit the lowest local current density and the smallest corrosion depth, making them suitable for engineering applications requiring high reliability. In contrast, Type B grounding electrodes suffer the most severe corrosion at the ends of their rays, which may lead to degradation of grounding performance over time, increasing the risk of line tripping and equipment damage. Therefore, Type C configurations should be prioritized in the design of tower grounding systems to enhance durability and operational safety.

References

[1] M. Bahrman and B. Johnson, “The ABCs of HVDC transmission technologies,” *IEEE Power and Energy Magazine*, vol. 5, no. 2, pp. 32–44, Apr. 2007, DOI: 10.1109.mpae.2007.329194.

[2] T. J. Hammons et al., “State of the Art in Ultrahigh-Voltage Transmission,” *Proceedings of the IEEE*, vol. 100, no. 2, pp. 360–390, Feb. 2012, DOI: 10.1109.JPROC.2011.2152310.

[3] J. L. He and R. Zeng, *Power System Grounding Technology*, Science Press, Beijing, China, 2007.

[4] K. Tykeson, A. Nyman, and H. Carlsson, “Environmental and geographical aspects in HVDC electrode design,” *in IEEE Transactions on Power Delivery*, vol. 11, no. 4, pp. 1948–1954, Oct. 1996, DOI: 10.1109.61.544281.

[5] X. D. Dong, W. Yang, C. Tang, et al., “Evaluation of the corrosion effect of ultrahigh-voltage DC grounding current on nearby tower grounding networks,” *High Voltage Engineering*, vol. 35, no. 7, pp. 1546–1552, Jul. 2009, DOI: 10.13336.j.1003-6520.hve.2009.07.021.

[6] K. Zhu, C. Wu, and W. Yang, “Study on the corrosion effect of DC grounding electrodes on nearby transmission line towers and protective measures,” *High Voltage Apparatus*, vol. 47, no. 10, pp. 41–47, Oct. 2011, DOI: 10.13296.j.1001-1609.hva.2011.10.009.

[7] R. Y. Qin, M. Gao, Q. Q. Xia, et al., “Study on electro-corrosion of grounding bodies of towers near grounding electrodes,” *Insulators and Lightning Arresters*, vol. 2019, no. 5, pp. 139–144, May 2019, DOI: 10.16188.j.isa.1003-8337.2019.05.022.

[8] L. Y. Gao, X. S. Guo, and X. D. Dong, "Study on corrosion and protection of tower grounding due to grounding current of DC electrodes," *China Electric Power*, vol. 42, no. 12, pp. 38–41, Dec. 2009, DOI: 10.3969.j.issn.1004-9649.2009.12.008.

[9] W. L. Liu, "Simulation study on the corrosion effect of DC grounding electrodes on transmission lines," Ph.D. dissertation, Changjiang University, Jingzhou, China, 2015.

[10] H. Zhang, Y. Du, R. Z. Qin, et al., "Interference of high voltage direct current grounding current on nearby transmission line tower grounding bodies," *Corrosion and Protection*, vol. 41, no. 5, pp. 40–48, May 2020, DOI: 10.11973.fsyfh-202005009.

[11] DL/T 5224-2014, *Design Technical Code for HVDC Ground Return System*, State Grid Corporation of China, Beijing, China, 2014.

[12] J. X. Ma, F. P. Dawalibi, and W. Ruan, "Design Considerations of HVDC Grounding Electrodes," *2005 IEEE/PES Transmission & Distribution Conference & Exposition: Asia and Pacific*, Dalian, China, 2005, pp. 1–6, DOI: 10.1109.TDC.2005.1546811.

[13] L. S. Zeng, "Land grounding electrodes for HVDC transmission—Determination of electrode shape, size, and burial depth," *Power Construction*, vol. 1994, no. 2, pp. 12–17, 1994.

[14] M. Cui, Y. Chu, and L. Liu, "Research on Scope of Environmental Influence of DC Grounding Electrode Rated ±800kV," *2010 Asia-Pacific Power and Energy Engineering Conference*, Chengdu, China, 2010, pp. 1–4, DOI: 10.1109.APPEEC.2010.5449266.

[15] Z. Pan, W. Li, C. Liu, H. Lu, and X. Wen, "Earth surface potential induced by ground-return current of HVDC links—Part I: Measurement and estimation of the earth resistivity," *2016 IEEE International Conference on High Voltage Engineering and Application (ICHVE)*, Chengdu, China, 2016, pp. 1–4, DOI: 10.1109.ICHVE.2016.7800813.

[16] S. Fan, X. Guanghu, Z. Yuan, W. Biao, and M. QingYong, "The basic law and influencing factor of DC bias distribution in AC power near the grounding electrode of 800kV HVDC," *2014 International Conference on Power System Technology*, Chengdu, China, 2014, pp. 2417–2421, DOI: 10.1109.POWERCON.2014.6993951.

[17] C. Z. Deng, K. W. Zhang, B. Tan, et al., "Effect of soil characteristics on current density along buried metal pipelines," *Corrosion and Protection*, vol. 40, no. 4, pp. 235–239, 265, Apr. 2019.

[18] Q. Liu, L. Li, J. Zheng, and Z. Guan, "Research on potential distributions of soil surface caused by ground electrode of HVDC system in heterogeneous soil structure," *2007 IEEE Power Engineering Society General Meeting*, Tampa, FL, USA, 2007, pp. 1–4, DOI: 10.1109.PES.2007.385516.

[19] T/CSEE 0305-2022, *Technical Specification for the Impact Assessment of HVDC Ground Electrodes on Surrounding Buried Steel Oil and Gas Pipelines*, China Electric Power Research Institute, Beijing, China, 2022.

[20] IEC/PAS 62344-2007, *General Guidelines for the Design of Ground Electrodes for High-Voltage Direct Current (HVDC) Links (NPPAS)*, International Electrotechnical Commission, Geneva, Switzerland, 2007.