Study on Corrosion Characteristics of Grounding Materials in High Corrosion Area

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Abstract. Due to the differences in the causes of corrosion, the soil corrosion characteristics in coastal mountains and coastal areas may be quite different. As a result, there are differences in the corrosion causes, corrosion status and service life of the grounding grids of the transmission line towers built in coastal areas. Based on the difference in apparent resistivity of the soil under the transmission line towers in a coastal area with high corrosion, this paper selects 12 soil samples for physical and chemical analysis. The analysis results show that there are two typical soils of acid and weak alkaline in the transmission line erection area, which are highly corrosive but with different corrosion mechanisms. Then the soil liquids of two typical soils were extracted, and the polarization curve test of carbon steel and galvanized steel, which are commonly used in the grounding grid of poles and towers, was carried out for 7 consecutive days, and the corrosion laws of carbon steel and galvanized steel were obtained. The results show that the corrosiveness of acidic soil is much greater than that of weakly alkaline soil. The corrosion rates of carbon steel and galvanized steel in acidic soil are 3.7 times and 5.2 times that of weakly alkaline soil, respectively. In addition, using the extracted soil liquid, a 30-day accelerated corrosion experiment was performed on carbon steel and galvanized steel, and an empirical formula for the change of corrosion weight with time was obtained. Combined with the surface morphology characteristics and corrosion rate after corrosion, this paper analyzed corrosion mechanism of two grounding materials. The research results of this paper provide a reference for the selection and application of grounding materials.

1. Introduction
The grounding grid is an important part of lightning protection. The grounding grids of substations and transmission line towers are responsible for the lightning protection of the equipment and lines in the station, and are valued by the design and production and operation departments [1]. The grounding grid buried in the soil is affected by different types of soil corrosion, including chemical corrosion, electrochemical corrosion, microbial corrosion, and stray current corrosion caused by power equipment leakage [2,3]. Corrosion products often degrade the flow performance of the grounding grid, and even cause the grounding grid to break [4-6]. The survey results show that the annual corrosion rate of the grounding grid metal can reach 1.0 ~ 2.0mm/a in the corrosive soil, and the highest is 3.0 ~ 4.0mm/a in the corrosive soil [7,8]. The corrosive soil medium can be as high as 8.0mm/a. In these areas, the corrosion of the grounding grid is an important factor affecting the safe operation of the power system [9,10].

At present, there are a large number of researches on the corrosion performance of grounding
materials, and the research object is mainly carbon steel. There is not much research on the corrosion mechanism and behavior of galvanized steel. Literature [11-13] studied the effects of temperature and humidity on the self-corrosion potential, corrosion products and charge transfer resistance of carbon steel, and established the law of the influence of various physical and chemical properties of soil on the corrosion of carbon steel. Literature [14-17] compared the corrosion rate of galvanized steel with other materials, and studied the electrochemical corrosion process of galvanized steel, but the corrosion mechanism of galvanized steel in the soil environment has not been fully studied. Due to the large differences in soil composition in different regions, the differences in corrosion performance are also obvious.

In most coastal areas, thunderstorms are frequent, and the grounding grid is more important. However, for areas with more coastal and mountainous areas, the same transmission line tower will pass through beaches and mountains. Due to different soil causes, the corrosion mechanism is different, and the corrosion rate and service life of the grounding grid of the tower in different areas are also different.

According to the distribution of apparent resistivity of the soil under each base pole and tower, this paper selects 12 samples for soil sampling and analyzes the physical and chemical properties of the soil samples in the area passing through a transmission line along the coast; Two typical soils were selected based on the analysis results of the physical and chemical properties of 12 samples. The soil corrosion liquid was extracted from the soil, and the polarization curve experiment was carried out on carbon steel and galvanized steel to study the corrosion characteristics of the two grounding materials in the soil liquid; A 30-day indoor accelerated corrosion experiment was carried out on carbon steel and galvanized steel in two soils, and the weight loss analysis was carried out to obtain the corrosion rate, and the surface morphology of the corroded sample was analyzed. Finally, the corrosive behavior of two soils on grounding materials is summarized, which provides data support for the design and protection of grounding grids in coastal areas with high corrosion.

2. Soil sample analysis and selection

According to the actual measurement results of soil resistivity in a coastal area, the transmission line passes through areas such as coastal beaches and coastal mountains, and the soil resistivity is between 4 Ω·m and 4345 Ω·m. According to the distribution of soil apparent resistivity and topographical characteristics, this paper selected 12 sampling points for soil sampling. When sampling the soil, the ring knife method [17] was used to sample the soil 80 cm away from the surface of the sampling point. Analyze the physical and chemical characteristics of the collected 12 groups of soils in accordance with the standards of soil testing [18], and analyze the content of nitrate nitrogen, carbonate, bicarbonate, chloride, sulfate, water content and pH as shown in Table 1.

| Sample number | Soil resistivity Ω·m | Nitrate mg/kg | Carbonate mg/kg | Bicarbonate mg/kg | Chloride mg/kg | Sulfate mg/kg | Water content % | pH  |
|---------------|----------------------|---------------|-----------------|-------------------|----------------|---------------|----------------|-----|
| 1             | 1181                 | 4.38          | <3              | 68.8              | 0.02           | 344.4         | 21.5           | 4.5 |
| 2             | 1634                 | 2.73          | <3              | 62.5              | 0.02           | 35.6          | 23.7           | 4.8 |
| 3             | 450                  | 6.87          | <3              | 48.8              | 0.03           | 51.5          | 20.7           | 4.7 |
| 4             | 751                  | 0.58          | <3              | 46.3              | 0.02           | 31.7          | 21.4           | 4.9 |
| 5             | 452                  | <0.25         | <3              | 60                | 0.03           | 91            | 19.9           | 4.8 |
| 6             | 452                  | 1.47          | <3              | 51.3              | 0.03           | 112.9         | 19.5           | 4.8 |
| 7             | 314                  | 7.58          | <3              | 61.3              | 0.03           | 126.6         | 19.2           | 5.1 |
| 8             | 7                    | <0.25         | <3              | 169               | 4.09           | 722.5         | 29.4           | 8.5 |
According to the analysis results of soil physical and chemical properties, the 12 samples can be divided into two types: acidic soil (No. 1-7) and weakly alkaline soil (No. 8-12) according to the pH value. Acidic soils are mainly distributed in mountainous areas, hills and areas far away from the sea, and weakly alkaline soils are mainly distributed in offshore areas. Except for No. 5 soil and No. 12 soil, the nitrate nitrogen content of acid soil is basically higher than that of weak alkaline soil. The content of carbonate ions in the 12 soil samples was roughly the same. The bicarbonate ion content of acidic soil is significantly lower than that of weakly alkaline soil. The chloride ion content of acidic soil is also significantly lower than that of weakly alkaline soil. Soil No. 8 is closest to the sea. The seawater can inundate this area at high tide, so its chloride ion content is much higher than other soils. Except for the No. 9 soil sample, the soil moisture content is about 20%.

Among the 12 soil samples, No. 8 soil has the highest pH value, the strongest alkalinity, and contains the most carbonate ions, chloride ions, and sulfate ions, while No. 1 soil has the lowest pH value. This paper selects No. 1 soil and No. 8 soil as the test soil for grounding materials.

3. Analysis of polarization characteristics of grounding materials

The polarization characteristics of metal materials can effectively reflect the electrochemical reaction rate of metals in the electrolytic cell. This paper extracts the soil solution and uses an electrochemical workstation to test the polarization characteristics of the materials.

3.1. Principle of the experiment

For electrochemical corrosion, according to the principle of corrosion potential, when the potentials of the two local reactions are balanced, the relationship between the polarization current $I$ and the electrode potential $E$ is shown in equation (1) [7].

$$I = I_k \left\{ \exp \left[ \frac{2.3(E - E_k)}{b_a} \right] - \exp \left[ \frac{2.3(E_k - E)}{b_c} \right] \right\}$$

(1)

Among them, $I$ is the measured polarization current; $E$ is the polarization potential; $I_k$ is the natural corrosion current; $E_k$ is the natural corrosion potential; $b_a$ is the anode Tafel constant; $b_c$ is the cathode Tafel constant. Taking the logarithm of $I$, in the linear section of the polarization curve, the polarization potential has a linear relationship with the applied current, and two straight lines, namely the Tafel straight line, can be obtained. The self-corrosion potential and self-corrosion current at the intersection point are obtained by extrapolating the intersection of Tafel straight lines in the strong polarization section of the polarization curve [19].

3.2. Polarization curve experiment platform

Most of the metal corrosion process is electrochemical corrosion. The electrochemical test of metal corrosion is fast and sensitive, can reflect the instantaneous information of metal corrosion, and can also detect the surface condition of metal electrodes for a long time. Before the experiment, we wipe the corrosion test piece with absolute alcohol, dry it, weigh it, and keep it sealed. The size of the corrosion piece is 50×25×2mm, and the type is Q235 carbon steel and galvanized steel coupons (the thickness of the galvanized layer is 8~10μm). The acid soil and the weakly alkaline soil are crushed, sieved, dried in a constant temperature drying oven at 70°C for 24 hours, and sealed for storage. According to the standard, we take the dried soil, add deionized water according to the ratio of soil and deionized water 1:5, stir evenly, take the supernatant after standing, and put them in two containers A1 and A2 respectively for experiment. The carbon steel sheet and the galvanized steel sheet are placed in
a sealed container, and the sealed container is placed in a constant temperature and humidity box with a temperature of 70°C and a relative humidity of 20%, and the corrosion test is carried out for 7 consecutive days. The corroded sheet was taken out at a fixed time every day, and the polarization curve experiment was performed on the test bench shown in Figure 1.

Figure 1. The schematic figure of experiment platform for polarization curve

The working electrode is the piece to be tested. The diameter of the wire is 2.5mm, and the copper wire is wound around the missing hole of the test piece. The wire and the entire test piece are wrapped by the insulating tape, and cuts the electrode working surface of 10mm×10mm. The auxiliary electrode is a platinum electrode with a size of 20mm×20mm×0.1mm, which provides a current loop for the external excitation signal. The reference electrode is a saturated calomel electrode [20] (the salt bridge solution is saturated potassium chloride), which provides a stable potential reference point for the three-electrode system. The working surface of the working electrode is horizontally opposite to the platinum electrode at a distance of 5mm. The saturated calomel electrode of the reference electrode is placed in the third position at a distance of 5mm in parallel. Put the working electrode, platinum chip electrode and saturated calomel electrode with a working area of 1cm² into a customized 250ml electrolytic cell with an electrode slot reserved on the electrolytic cell.

3.3. Experimental results and analysis

A 7-day polarization curve experiment was performed on carbon steel sheets and galvanized steel sheets of the same size in acidic soil liquid and weakly alkaline soil liquid, respectively. Figure 2 shows the polarization curves of two grounding materials on the first and sixth days of corrosion in acidic soil liquid. Figure 3 shows the polarization curves of two grounding materials on the first and sixth days of corrosion in a weakly alkaline soil solution. The solid line is carbon steel and the dotted line is galvanized steel.

In the acidic solution, in terms of self-corrosion potential, on the first day of corrosion, carbon steel is the highest and galvanized steel is the lowest. On the 6th day of corrosion, galvanized steel was the highest and carbon steel was the lowest. As the corrosion progresses, the self-corrosion potential of carbon steel gradually decreases, and the self-corrosion potential of galvanized steel is basically similar. The lower the self-corrosion potential, the easier the corrosion is. In the self-dissolution process of galvanized steel, the standard electrode potential of the oxidation-reduction reaction of the oxidant Zn is lower than that of Fe. Therefore, the metal oxidation reaction on Zn is dominant during the corrosion process and becomes the anode zone. The dissolution reaction of zinc occurs first. Therefore, the self-corrosion potential of galvanized steel is lower than that of carbon steel on the first day. At this time, the corrosion reaction of galvanized steel is the galvanized layer. As the corrosion progresses, the galvanized layer of the galvanized steel is gradually corroded, and the exposed carbon steel in the galvanized steel begins to corrode in the acid soil solution. Since the self-corrosion potential of carbon steel is higher than that of galvanized steel, this increases the self-corrosion potential of galvanized steel to some extent, and the self-corrosion potential of galvanized steel
gradually approaches carbon steel. When the galvanized layer is completely dissolved, only carbon steel is left in the galvanized steel that participates in the corrosion reaction. And at this time, the iron in the galvanized steel participates in corrosion for a shorter time than that in the carbon steel. Therefore, on the sixth day, the self-corrosion potential of the galvanized steel is already higher than that of the carbon steel.

Figure 2. Polarization curves of two types of grounding materials in acidic soil fluids, (a) the first day, (b) the sixth day
Figure 3. Polarization curves of two types of grounding materials in weak alkaline soil fluids, (a) the first day, (b) the sixth day.
In the weak alkaline solution, the self-corrosion potential of carbon steel is higher than that of galvanized steel from day 1 to day 6 of corrosion. As the corrosion progresses, the self-corrosion potential of both carbon steel and galvanized steel increases. This is because the galvanized layer is not completely corroded during the corrosion process, that is, the corrosion rate in weakly alkaline soil is lower than that in acid soil. The increased self-corrosion potential of carbon steel may be due to the corrosion products of carbon steel in the weakly alkaline soil solution inhibiting corrosion.

According to the self-corrosion potential, whether in acidic soil liquid or alkaline soil liquid, the order of corrosion is zinc before iron. The anti-corrosion principle of galvanized steel is to sacrifice the anode to protect the cathode, that is, to let the galvanized layer undergo corrosion reaction first to protect the inner steel.

4. Weightlessness analysis of accelerated corrosion of grounding materials

4.1. Principles of Weightlessness Analysis

The weight loss method calculates the metal corrosion rate according to the change in the mass of the metal sample measured before and after corrosion, and the average corrosion rate can be obtained by the weight loss method [21]:

\[ v = \frac{m_0 - m_1}{S \cdot t} \]  

In the formula, \( v \) represents the corrosion rate of the metal, \( \text{g/(m}^2\text{h}) \); \( m_0 \) is the mass of the specimen before corrosion, \( \text{g} \); \( m_1 \) is the mass of the specimen to remove the corrosion products after corrosion, \( \text{g} \); \( S \) is the surface area of the test piece in a corrosive environment, \( \text{m}^2 \); \( t \) is the corrosion time of the specimen, \( \text{h} \).

4.2. Indoor accelerated corrosion experiment design

The weightlessness method is a classic method suitable for laboratory and field corrosion tests. It is the most reliable and closest method to the actual conditions for determining the corrosion rate of metals. The weightlessness method calculates the average corrosion rate of metals based on the changes in the mass of the sample before and after corrosion. Before the experiment, we wipe the corrosion test piece with absolute alcohol, dry it, weigh it, and keep it sealed. The size of the corrosion piece is 50×25×2mm, and the type is Q235 carbon steel and galvanized steel coupons (the thickness of the galvanized layer is 8~10μm). The acid soil and the weakly alkaline soil are crushed, sieved, dried in a constant temperature drying oven at 70°C for 24 hours, and sealed for storage. According to the standard, we take the dried soil, add deionized water according to the ratio of soil and deionized water 1:5, stir evenly, take the supernatant after standing, and put them in two containers A1 and A2 respectively for experiment. The carbon steel sheet and the galvanized steel sheet are placed in a sealed container, and the sealed container is placed in a constant temperature and humidity box with a temperature of 70°C and a relative humidity of 20%. The accelerated corrosion test is carried out, and the test period is 30 days. Add water to the soil at a fixed time every day to ensure that the soil moisture content is 20% every day. The corroded pieces are taken out and photographed and kept on the 1st, 2nd, 3rd, 4th, 5th, 6th, 7th, 10th, 15th, 20th, 25th, and 30th days. All corroded pieces are derusted in a mixture of urotropine and 50% hydrochloric acid [5]. The corroded pieces after rust removal are washed with deionized water, dehydrated in absolute ethanol, and then dried in a constant temperature oven at 70°C and weighed. According to the weight before and after corrosion, the corrosion rate of each corroded piece is calculated. The schematic diagram of the experimental platform of the indoor accelerated corrosion experiment is shown in Figure 4.
4.3. Experimental results and analysis

Keeping the temperature in the constant temperature and humidity box at 70°C and the soil moisture content of 20%, after 30 days of accelerated corrosion experiments in the room, the carbon steel sheets and galvanized steel sheets were subjected to rust removal and weight loss analysis. The results are shown in Figure 5. Among them, the red is carbon steel; the green is galvanized steel; the scattered points are the actual measurement results of weight loss; the solid line is the curve fitting according to the power exponential function. The figure (a) is the result in acidic soil, and the figure (b) is the results in alkaline soil. The corrosion weight of metals in the soil can be fitted with a power exponential function [22], and the fitting formula is:

\[ M = D t^n \]  

(3)

Among them, \( M \) is the reduced mass, the unit is g; \( t \) is the corrosion time, the unit is d; \( D \) and \( n \) are both fitting constants, and the fitting parameters are shown in Table 2.

| Soil          | Material      | \( D \)   | \( n \)   | Goodness of fit \( R \) |
|---------------|---------------|-----------|-----------|--------------------------|
| Acid soil     | Carbon steel  | 0.05379   | 1.009     | 0.9875                   |
|               | Galvanized    | 0.015254  | 1.473     | 0.9981                   |
| Weakly alkaline soil | Carbon steel   | 0.04788   | 0.855     | 0.9975                   |
|               | Galvanized    | 0.03424   | 0.7587    | 0.9939                   |

According to the fitting results, the weight loss of carbon steel and galvanized steel after accelerated corrosion in acid soil and alkaline soil satisfies the power exponential function, and the goodness of fit is good. For carbon steel, the coefficient \( D \) and power exponent \( n \) of the fitting function in acid soil are both larger than those in weak alkaline soil, which indicates that the corrosion rate is faster in acid soil; similar results are also obtained for galvanized steel. The weight loss of carbon steel is greater than that of galvanized steel from the beginning, whether it is in acid soil or weakly alkaline soil. That is to say, carbon steel is more prone to corrosion than galvanized steel in acid soil or weak alkaline soil.

After 30 days of indoor accelerated corrosion experiment, total weight loss (g), average corrosion rate (g/m²·h), and annual corrosion depth (mm/a) of the two grounding materials of carbon steel and galvanized steel are shown in Table 3 respectively.
Table 3. Comparison of grounding materials corrosion rate after accelerated corrosion experiment

| Soil          | Material    | Total weightlessness (g) | Average corrosion rate (g/m²·h) | Annual average corrosion depth (mm/a) |
|--------------|-------------|--------------------------|---------------------------------|--------------------------------------|
| Acid soil    | Carbon steel| 3.1576                   | 1.5663                          | 1.7933                               |
|              | Galvanized steel | 2.2590               | 1.1205                          | 1.2219                               |
| Weakly alkaline soil | Carbon steel | 0.8623                   | 0.4277                          | 0.4988                               |
|              | Galvanized steel | 0.4326               | 0.2146                          | 0.2333                               |

No matter in acid soil or weak alkaline soil, the average annual corrosion depth and average corrosion rate of carbon steel are higher than the corresponding values of galvanized steel. The corrosion rate of carbon steel in acid soil is about 1.4 times that of galvanized steel. The corrosion rate of carbon steel in weak alkaline soil is about twice that of galvanized steel. The corrosion rate of carbon steel in acid soil is about 3.7 times that of alkaline soil, and the corrosion rate of galvanized steel in acid soil is about 5.2 times that of alkaline soil. Therefore, the corrosion resistance of galvanized steel is better than that of carbon steel no matter in acid soil or weak alkaline soil, and whether it is carbon steel or galvanized steel, the corrosion resistance of acid soil is much stronger than that of weak alkaline soil.

5. Analysis of products after accelerated corrosion of grounding materials

After 30 days of accelerated corrosion tests on carbon steel and galvanized steel in acidic and weakly alkaline soils with a temperature of 70°C and a soil humidity of 20%, the types and contents of the corrosion products on the surface of the corroded sheet are analyzed respectively by the 550i X-rays energy spectrum analyzer (EDS), and the corrosion product composition of the corroded piece is analyzed by D8 Advance X-ray diffractometer (XRD). The element content of surface corrosion products is shown in Table 4.

Table 4. Element content (%) of corrosion products on the surface of grounded materials after indoor accelerated corrosion test

| Soil          | Material    | C  | O  | Al  | Si  | S  | Cl  | K  | Ca  | Mn  | Fe  | Zn  |
|--------------|-------------|----|----|-----|-----|----|-----|----|-----|-----|-----|-----|
| Acid soil    | Carbon steel| 2.272 | 20.206 | 3.453 | 7.980 | 0  | 0   | 0.492 | 0.383 | 4.384 | 60.829 | 0   |
|              | Galvanized steel | 14.761 | 45.335 | 4.187 | 7.878 | 0.222 | 0.345 | 0.476 | 0.263 | 0.739 | 19.125 | 7.560 |
| Weakly alkaline soil | Carbon steel | 3.549 | 26.058 | 2.744 | 5.687 | 0  | 0   | 0.569 | 14.091 | 1.052 | 54.106 | 0   |
|              | Galvanized steel | 2.024 | 17.190 | 1.171 | 2.009 | 0  | 0.274 | 0  | 0    | 0.788 | 56.451 | 20.232 |

Among the corrosion products of carbon steel, the most abundant elements are Fe and O, and a small amount of C, Al, Si, K, Ca, Mn and other elements from the soil or matrix. No matter in acid soil or weak alkaline soil, the content of Fe and O together exceeds 80%, so the corrosion products of carbon steel are mainly Fe oxides. Among the corrosion products of galvanized steel, the most content elements are Fe, Zn, O, and a small amount of C, Al, Si, K, Ca, Mn, Cl, S and other elements from the soil or matrix. In acid soils, the content of O is the highest, while the content of Fe in weakly alkaline soils is the highest. This indicates that the corrosion products in acid soils are mainly Fe oxides with higher oxygen content, while Fe oxides and Zn oxides dominate in weakly alkaline soils.

6. Conclusion

In this paper, two types of highly corrosive typical soils in a coastal area are tested on the corrosion characteristics of two grounding materials. The electrochemical characteristics of the soil extract are measured, and the accelerated corrosion experiment of grounding materials is carried out. The weightlessness analysis, surface morphology analysis and corrosion product analysis of the corroded grounding materials are carried out. The main conclusions of this paper are as follows:

(1) These two typical highly corrosive soils have obvious differences in physical and chemical properties, so the corrosiveness of grounding materials is obviously different. The corrosiveness of
acidic soil is much greater than that of weakly alkaline soil. The corrosion rates of carbon steel and galvanized steel in acid soil are 3.7 times and 5.2 times that in weak alkaline soil, respectively.

(2) The results of accelerated corrosion experiments on carbon steel and galvanized steel show that in acid soil, the average corrosion rate of carbon steel is about 1.7 times that of galvanized steel, and in weak alkaline soil, the average corrosion rate of carbon steel is about twice that of galvanized steel. On this basis, the fitting curve of corrosion weight loss of galvanized steel and carbon steel in typical soil is given.

(3) After being corroded by acid soil, the corrosion products of carbon steel appear as large lumps and layers, which are uniform corrosion, while the corrosion products of galvanized steel show larger and deeper pores locally, and the type of corrosion is between uniform corrosion and pitting corrosion. After being corroded in weakly alkaline soil, the corrosion products of carbon steel show partial stratification, which belongs to incomplete uniform corrosion, while the corrosion products of galvanized steel show dense small cavities, which belong to pitting corrosion. The corrosion products of carbon steel are mainly Fe₂O₃ and its water compound FeOOH. In addition to Fe₂O₃ and its water compound FeOOH, the corrosion products of galvanized steel also include ZnO and its hydrate Zn(OH)₂.

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