Corrosion Failure Analysis of Fittings Used for Electrical Equipment in 220 kV Substation

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Abstract—Electric power fitting is a metal accessory that connects and combines different devices in the electric power system, and transfers mechanical load and electrical load. Once the fitting fails, it would lead to large-scale blackout, so its reliability is of great importance for the security and stability of power system. In this paper, the seriously corroded electric power fitting in 220kV substation was investigated by means of macro-morphism inspection, chemical composition analysis, microstructure analysis, scanning electron microscope, zinc coating thickness measurement and energy spectrum analysis. The result showed that sulfur dioxide emitted from industrial production was the main cause of corrosion failure of the fitting. Meanwhile, the insufficient corrosion resistance of the fittings led to acceleration of corrosion process and premature failure of zinc coating. Additionally, effective suggestions were put forward in order to improve the anti-corrosion performance of the fittings in typical industrial pollution area.

1. INTRODUCTION

Electric power fitting plays an important role in connecting and fixing conductor and insulator, transferring mechanical and electrical load [1]. Due to the high altitude, the inspection and maintenance of fittings is inconvenient. Meanwhile, most of the power fittings are installed outdoors, therefore atmospheric corrosion is inevitable. In case of corrosion failure of fittings, the connecting line would break or fall off, resulting in large-scale blackout. Therefore, in order to ensure the reliability of power system, more and more attention has been paid to corrosion and protection of fittings.

In recent years, domestic and foreign scholars have conducted a lot of research on atmospheric corrosion of metal material, and have obtained great achievements in this field. Li [2] studied the initial corrosion properties of Q235 in simulated atmospheric environments containing different contents of SO₂ and NaCl by means of electrochemical impedance spectroscopy and found that both SO₂ and NaCl could promote the corrosion rate of Q235 steel. Liu [3] investigated the effect of simulated acidified marine aerosols on the corrosion morphology of carbon steel using an in situ optical stereomicroscope and scanning electron microscope equipped with an energy-dispersive spectrometer and a white-light interferometer. Karpov [4] proposed a mathematical model to characterize the relationship between the time of wetness of metal surface, atmospheric pollution, and corrosion rate. Xia [5] established a portable EN monitoring system was and designed two electrochemical probes to in-situ monitor the atmospheric corrosion of steels exposed to Zhoushan offshore environment. Wu [6] studied the
corrosion behavior of Ni-advanced weathering steel, as well as carbon steel and conventional weathering steel, in a simulated tropical marine atmosphere and found that the additive Ni in weathering steel played an important role during the corrosion process.

With the rapid improvement of power capacity and voltage level, more and more accidents caused by corrosion of fittings occurred, thus the safety and stability of power grids would be severely affected. However, the research on atmospheric corrosion mechanism of electric power fittings has not much been presented in literature so far. In this paper, different physical and chemical test methods were adopted to study the corrosion mechanism and analyze the corrosion reason of the seriously corroded fittings in a 220kV substation. Meanwhile, the corrosion laws of the fittings in typical industrial areas were summarized and the targeted corrosion prevention suggestions were presented, which could provide the basis for the operation and maintenance of electric power fittings.

2. EXPERIMENT RESULTS AND ANALYSIS

2.1. Macroscopic observation

The corroded fitting is composed of U-shaped hanging ring, right-angle hanging plate, ball head hanging ring and connecting bolts. The fitting made of Q235B is used for connecting conductor and insulator, and hot dip galvanizing process is adopted for the fittings as anticorrosive coating.

Figure 1 shows the macro-morphology of the corroded fittings. And it is clearly observed that the ball head hanging ring, the right-angle hanging plate and its connecting bolts have been rusted seriously and their surfaces have been completely covered with brown corrosion products, which illustrates that the zinc coating has been exhausted. Meanwhile, the surfaces of the corroded fittings are rough with a lot of corrosion pits. However, the zinc coating of U-shaped hanging ring and its connecting bolts is relatively intact without obvious corrosion. In addition, there is no obvious mechanical damage and plastic deformation in the whole connecting fitting.

![Figure 1. The macro morphology of the corroded fittings.](image-url)
2.2. Chemical composition analysis
The chemical compositions of the corroded fitting are determined by means of chemical composition analysis and the testing results (mass fraction) are shown in Table 1. The result illustrates that the contents of each element in the ball head hanging ring, the right-angle hanging plate and the U-shaped hanging ring meet the requirement of standard GB/T 700-2006 for Q235B steel.

| Chemical element               | C  | Si | Mn  | P     | S       |
|-------------------------------|----|----|-----|-------|---------|
| Standard requirements         | ≤0.22 | ≤0.35 | ≤1.40 | ≤0.045 | ≤0.050 |
| Ball head hanging ring        | 0.15 | 0.26 | 0.51 | 0.012 | 0.019   |
| Right-angle hanging plate     | 0.17 | 0.22 | 0.49 | 0.018 | 0.025   |
| U-shaped hanging ring         | 0.11 | 0.25 | 0.55 | 0.014 | 0.017   |

2.3. Microstructure and energy spectrum analysis of corrosion products
Figure 2 shows the micro morphology of the corrosion products sampled from the corroded fitting and it is clearly seen that there are a large number of compact corrosion products and corrosion pits on the surface of the ball head hanging ring, the right-angle hanging plate and its connecting bolts, accompanied by a few corrosion holes. Additionally, the corrosion products of the ball head hanging ring and the right-angle hanging plate are irregular cluster particles, and the ones of the connecting bolt are cluster particles or irregular blocks.
The chemical compositions of the corrosion products on the surface of the corroded fitting are analyzed by energy spectrum analyzer, and the testing results are shown in table 2. The result shows that the corrosion products of the ball head hanging ring, the right-angle hanging plate and its connecting bolt are mainly composed of iron oxide, silica, calcium oxide and sulphate, and the silica and calcium oxide should be the sand adsorbed on the surface of the fitting.

**TABLE 2. ENERGY SPECTRUM ANALYSIS RESULT OF CORROSION PRODUCTS (WT%)**

| Chemical element                | Fe   | Si   | O    | S    | K    | Ca   | Al  |
|--------------------------------|------|------|------|------|------|------|-----|
| Ball head hanging ring         | 70.39| 0.77 | 27.67| 1.16 | —    | —    | —   |
| Right-angle hanging plate      | 50.01| 4.54 | 30.47| 2.23 | 3.24 | 8.32 | 1.2 |
| Connecting bolt                | 64.45| 1.94 | 26.65| 1.95 | 1.05 | 3.6  | —   |

2.4. Zinc coating thickness measurement
Using coating thickness gauge, the thickness of zinc coating for the U-shaped hanging plate is determined in the range of 21~75μm, and it is uneven and lower than the minimum thickness of 86μm required in the standard. While the one of the connecting bolt is in the range of 17~43μm, which could not meet the standard requirement that the minimum thicknesses is greater than 45μm.

2.5. Metallographic structure Analysis
Figure 3 and figure 4 shows the metallographic microstructures of the ball head hanging ring and the right-angle hanging plate, respectively. It could be seen that the metallographic structures of the corroded fittings are mainly polygonal ferrite and equiaxed pearlite, without abnormal microstructure. Additionally, there are many corrosion pits in different sizes and depths on the surface of the corroded fittings.
2.6. Hardness testing

Table 3 shows the hardness test result of the connecting fitting. The result shows that the Vickers hardness of the connecting bolt used in the right-angle hanging plate and the U-shaped hanging ring meet the requirements of DL / T 284-2012 standard. Meanwhile, the ones of the ball head hanging ring, the right-angle hanging plate and the U-shaped hanging ring is determined in the range of 120~145HV, which basically meets the usage requirements.

| Test components          | Vickers hardness / (HV30) | Standard requirements |
|--------------------------|---------------------------|-----------------------|
| Ball head hanging ring   | 121                       | —                     |
| Right-angle hanging plate| 143                       | —                     |
3. ANALYSIS AND DISCUSSION

In the atmospheric environment without serious population, the hot-dip galvanized layer could form a protective oxide film with oxygen to inhibit further corrosion of the coating, which effectively prevents the steel substrate from the external corrosive medium. Once the zinc coating is damaged, it could be used as a sacrificial anode to protect the exposed steel substrate from corrosion. Therefore, the hop-dip galvanized layer has good corrosion resistance in the general atmospheric environment.

In substance, corrosion of electric power fittings could be regarded as electrochemical corrosion. The potential of zinc in the hot dip galvanizing layer is relatively low, so it would be corroded prior to the iron matrix. When the rainwater or moisture adsorbs on the zinc coating, it could form a thin liquid film as the electrolyte, resulting in micro corrosion battery reaction [7].

Anodic reaction: \[2\text{Zn} + 2\text{e} \rightarrow 2\text{Zn}^{2+}\]

Cathodic reaction: \[\text{O}_2 + 2\text{H}_2\text{O} + 4\text{e} \rightarrow 4\text{OH}^-\]

Thus, zinc as anode dissolves continuously at the defect of the zinc coating, leading to a number of corrosion holes. Meanwhile, around these holes, the depolarization reaction of oxygen occurs at the cathode. The reaction equation is described as follows:

\[\text{Zn}^{2+} + \text{OH}^- \rightarrow \text{Zn(OH)}_2 \rightarrow \text{ZnO} \cdot \text{H}_2\text{O}\]

If the atmosphere is not polluted and the concentration of acid medium is lower, the zinc hydroxide(\(\text{Zn(OH)}_2\)), zinc oxide(\(\text{ZnO}\)), zinc carbonate(\(\text{ZnCO}_3\)) and other compounds produced by corrosion reaction, would further form a dense film of basic zinc carbonate (\(\text{Zn}_2\text{(OH)}_2\text{CO}_3\)) with a thickness of more than 8μm. As the insoluble film could prevent the infiltration of water, the subsequent corrosion would be slowed down, which is considered as a self-healing process.

The 220kV substation is located in a typical industrial park, around which there are many heavy industrial enterprises such as coal mines, steel mills and chemical plants. With the continuous emission of smoke and dust from industrial production, the sulfur dioxide (\(\text{SO}_2\)) content around the substation becomes higher and higher.

Hydrogen ions (\(\text{H}^+\)) could be released during the dissolution and oxidation of sulfur dioxide (\(\text{SO}_2\)), which results in the acidification of the thin liquefied membrane on the surface of zinc coating. On the one hand, as the depolarizer, hydrogen ions (\(\text{H}^+\)) could participate in cathode reaction and accelerate the dissolution of zinc at the anode. On the other hand, in acid environment, the dense basic zinc carbonate (\(\text{Zn}_2\text{(OH)}_2\text{CO}_3\)) protective film could react with sulfur to form zinc sulfate (\(\text{ZnSO}_4\)). The reaction equation is as follows:

\[\text{Zn(OH)}_2\text{ZnCO}_3 + 2\text{SO}_2 + \text{O}_2 \rightarrow 2\text{ZnSO}_4 + \text{H}_2\text{O} + \text{CO}_2 \]

Owing to its good water solubility, zinc sulfate (\(\text{ZnSO}_4\)) would be easily washed away by rain water, leading to the rapid depletion of the hot-dip galvanizing layer. Once the zinc coating is exhausted, the steel matrix begins to corrode at a higher corrosion rate until the fitting is scrapped. Therefore, in the atmosphere with high sulfur dioxide content, the hot-dip galvanizing layer could not play an effective role in anti-corrosion, so the surface treatment process with better sulfur corrosion resistance should be considered for corrosion protection [8, 9].

Generally, the quality of the zinc coating is of great importance for the atmospheric corrosion of electric power fittings. The better the quality of the zinc coating, the stronger the corrosion resistance of fitting. Due to the poor quality of the zinc coating, the steel substrate of the ball head hanging ring and
the right-angle hanging plate has been seriously corroded. However, the U-shaped hanging ring with better corrosion resistance only suffers from the corrosion of the zinc coating [10].

In conclusion, sulfur dioxide (SO₂) caused by industrial pollution have constantly react with zinc coating to generate water-soluble zinc sulfate (ZnSO₄), which is easily washed away by rain water. With continuous consumption of zinc coating on the fitting, the steel substrate would be exposed to corrosive atmosphere directly, and be corroded at a corrosion rate several times higher than that of general atmosphere. Additionally, due to thinner thickness of zinc coating or poor adhesion, the corrosion resistance of some fittings is insufficient, which leads to premature failure of zinc coating and serious corrosion of fittings.

4. CONCLUSIONS
In this paper, the reason and mechanism of corrosion of the connecting fitting was systematically investigated and analyzed. Through comparing and analyzing the experimental results, the following conclusions are drawn.

1) The continuous emission of waste gas by industrial production makes the sulfur dioxide content in the atmosphere around the 220kV substation higher. As sulfur dioxide could react with zinc of the fitting to form soluble zinc sulfate, which leads to rapid consumption of zinc coating and serious corrosion of fitting.

2) Considering that corrosion failure of connecting fitting has occurred many times in the power grid, more and more attention should be paid to the inspection of the fittings used for the electrical equipment in the 220kV substation and the seriously corroded fittings should be replaced in time.

3) Before the fitting is put into use, the quality of galvanized layer should be comprehensively tested, and the thickness of zinc coating should be increased as much as possible on the premise of ensuring the dimensional accuracy.

4) In the typical industrial pollution area, due to the rapid depletion of the zinc coating, the aluminum zinc alloy with stronger resistance to sulfide corrosion could be considered as anticorrosive coating, in order to ensure the safety and stability of power grid.

ACKNOWLEDGMENT
The authors would like to acknowledge the financial support from the Science and Technology Project of Inner Mongolia Power Company (Grant No. 2019-102).

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