Research on evaluation method of soil corrosive property to grounding grid in transformer substation

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Research on evaluation method of soil corrosive property to grounding grid in transformer substation

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Abstract. In the paper, a nine-index evaluation method of soil corrosive property to grounding grid is established based on analysis of soil physical and chemical properties in 120 transformer substation test stations, inspection of index corrosion condition about soil corrosion to buried metals as well as the test results of influence of soil temperature, water content, pH value, chlorine ion content, sulfate ion content and other factors on metal corrosion. The method is simple and practical, comprehensive influence factors are considered, the accuracy is high, thereby providing scientific basis for surveying and designing newly-established transformer substations, and monitoring corrosion of transformer substation grounding grid in operation. Two factors of air capacity and regional annual average temperature are included into the evaluation method for the first time in China, and the evaluation method of galvanized steel and copper grounding grid is proposed for the first time according to the nine-index evaluation method determined in the paper.

1. Introduction

Power grounding acts as an important guarantee for safe operation of power generation, substation and power transmission systems. Points of the power system are connected with the earth by the grounding grid, and the grounding grid is also used for stabilizing potentials, and supplying zero potential reference points [1]. The grounding short circuit current is constantly increased, higher and higher requirements are also proposed to the safety and reliability of grounding grids with the development of the power system. Since the grounding grid is operated in the underground severe environment for a long time, soil chemical corrosion and electrochemical corrosion are inevitable, the grounding grid also should bear corrosion of counterpoise air diffusion and stray current at the same time, there are many factors affecting corrosion of grounding grids, wherein soil corrosion is one of the most important factors [2, 3]. Since the grounding grid suffers from bad grounding, ground resistance increase and thermal stability worsening due to substandard welding or soil corrosion and other reasons during construction, and fault points of poor electrical connection even appear among voltage-sharing conductors or between ground lead and voltage-sharing conductors, thereby worsening the grounding performance of the grounding grid [4]. Abnormal increase or uneven distribution of ground potential may be caused during system grounding short circuit, operators’ safety is severely threatened, on the one hand, the insulation of secondary equipment also can be ruined due to counterstrike or cable sheath circular current. High voltage plunges into the control room to cause maloperation or operation failure of test or control equipment, thereby expanding accidents and resulting in huge...
economic losses and social influence. Therefore, the grounding grid must be integral during power grid operation.

Soil erosion has been studied in the former Soviet Union, the United States, Germany, and other countries since the beginning of the last century, and many results were obtained. However, the research on its corrosive property to metals is belonged to a long-term and hard work because of soil complexity. Soil, as a corrosive medium, is characterized by diversity, inhomogeneity, illiquidity, seasonality, regionality, etc. compared with other corrosive media [5]. Meanwhile, the soil corrosive property is also related to properties of materials, data obtained from research of other scholars can not be adopted completely without considering the actual situation, the mutual relationship and regularity thereof can be discovered through long-term soil corrosive property test and data accumulation [6].

In the paper, 120 transformer substations distributed in different areas of one region are regarded as test stations. The composition characteristics of transformer substation soil and the corrosive property to carbon steel, galvanized steel, and copper test coupon are analyzed and tested. The influence of soil temperature, water content, pH value, chlorine ion content and sulfate ion content and other factors on metal corrosion are studied in the laboratory. The method of scientifically evaluating soil corrosive property to metals is discovered according to the test results. The soil corrosive property to grounding grid in the test stations is evaluated according to the method. The grounding grid corrosion is evaluated, and excavation is inspected, thereby determining the accuracy of the evaluation method.

2. Research status of soil corrosive property evaluation method

The corrosive property is evaluated, and the soil corrosive property is judged scientifically and accurately according to the final results of analysis on transformer substation soil corrosive property [7]. More and more strict requirements are proposed to the safety and reliability of the grounding grid with the development of the power grid and expansion of transformer substation capacity, thereby establishment, perfection, and development of research method on grounding grid corrosion have important scientific significance and economic value, and it is a necessary measure to prevent the safe operation of the power grid from potential threat due to soil corrosion on the grounding grid [8].

Scientific research personnel propose many methods for evaluating soil corrosive property through long-term experimental study, mainly including buried slide weight loss method, single evaluation index method, multiple index comprehensive evaluation method and electrochemical research method [9].

Buried metal test coupon weight loss method is the most traditional and most classic evaluation method. However, it is characterized by long test cycle, time and labor waste as well as poor reproducibility, which can not be used for comprehending the corrosion changes at all stages of test coupon burial period. Its application in practical work is not very convenient.

In single index evaluation method, individual or several indexes are used for evaluating soil corrosive property to buried metal materials according to soil physical and chemical properties (soil electrical resistivity, pH value, salt content, water content and Redox potential, etc.). Evaluation of soil corrosive property on metals by single index has a high restriction, misjudgment phenomena are frequent, and it can only be used as a reference.

In fact, there is no a soil factor to determine soil corrosive property because of the soil complexity. Currently, many domestic and foreign personnel responsible for corrosion research comprehensively evaluate soil corrosive property with many indexes. Many physical and chemical properties related to soil corrosion are integrated into Germany DIN50929 evaluation standard, including soil type, soil water content, pH value, soil electrical resistivity, acidity and alkalinity, neutral salt content, sulfide, sulfate content and soil corrosion potential. Evaluation indexes are given according to test results of all indexes. Then, the sum of all evaluation indexes is calculated, thereby the level of assessment of soil corrosive properties is determined. The method is affirmed by many corrosion workers, but some indexes are measured inconveniently, and its contents are widely targeted. The design of the measuring parameters is more suitable for evaluating to corrosive property of buried pipelines. Therefore, the results of corrosion evaluation for grounding grid are also not ideal. In addition,
different countries have different actual conditions. The transformer substation soil condition and operation condition are also different from that of the underground pipelines, therefore the above method should not be used blindly.

The basic process of U.S. ANSI A21.5 soil erosion evaluation method is similar to the evaluation standard of DIN50929. Firstly, soil physical and chemical property indexes are also scored. Then, corrosion level is evaluated. The method is different in that the evaluation indexes are different, mainly including soil electrical resistivity, pH value, redox potential, water content, and sulfide.

Shaanxi Electrical Power Research Institute adopts numerical analysis method according to experimental research results of soil corrosive property of 30 transformer substations in Shaanxi Province. German DIN50929 standard is appropriately modified and improved. An evaluation method aiming at grounding grid soil corrosive property in transformer substations is obtained, thereby corresponding relationship between the measurement result and scores is more rational [10]. However, because the data sources of this method are relatively few, the conditions such as meteorological factors, soil properties and leakage current are not taken into consideration, so there are still many deficiencies.

3. Research on evaluation method of transformer substation soil corrosive property

Inspection and analysis of soil physical and chemical property in test stations

120 transformer substations were selected as test stations in different regions. Soil samples with a depth of 0.8 ~ 1.0m were exemplified on the site for analyzing and testing soil physical and chemical property as well as electrochemical properties. The metal corrosion index test coupon was buried in soil on the site at the depth of 0.8 ~ 1.0m according to the cycle 2 years. The corrosive property of soil to carbon steel, galvanized steel and copper test coupon was tested. The influence of soil temperature, water content, pH value, chloride ion content, sulfate ion content and other factors on metal corrosion were studied. The data of the test results were processed, and the function laws between soil properties and metal corrosion were analyzed. Some experimental results are shown in Table 1 and Table 2.

The test result showed that soil physical and chemical properties in transformer substations and regional meteorological environment affected soil corrosive property to metals in the grounding grid. In the same transformer substation, the corrosive effect of soil to carbon steel, galvanized steel, and copper was differently, and the corrosion rate of tested materials was respectively carbon steel > galvanized steel > copper. As of grounding grid material, carbon steel was not suitable for transformer substations.

Analysis on soil property showed that sandy soil had the minimum corrosive property, clay had the maximum corrosive property, sandy clay and sandy loam had similar corrosive property. Soil corrosive property was similar generally in transformer substations of the same region, but the property also can be greatly different sometimes because of influence of local soil property and natural conditions possibly.

Generally speaking, soil electrical resistivity had the closer relationship to soil corrosive property, the electrical resistivity of soil with the relatively strong corrosive property was smaller than 35Ω.m, the electrical resistivity of soil with the relatively weak corrosive property was mostly higher than 60Ω.m.

The corrosive property of transformer substation soil was prominently regional in different regions.

It was discovered during site soil excavation that soil was not uniform in transformer substations, and some places were even backfilled with a large amount of building residues, and there were a lot of debris such as broken bricks, tiles, plastic, etc. Because the construction quality of backfill soil directly affected the corrosion rate of metals in the grounding grid after grounding grid laying, namely safe service life, the construction quality of the grounding grid should be controlled strictly, and special backfill construction process should be followed if it was available. Original soil was usually used, relatively coarse sand and foreign bodies were removed when the grounding grid ditches were backfilled. The screened soil was filled at the bottom layer firstly according to the thickness of 200
mm - 300 mm, the soil was leveled and compacted, and then the grounding grid was laid during backfilling.

Table 1. Test result of physical and chemical properties of soil.

| Test site number | Regional annual average temperature /°C | Soil texture | Water content /% (m/m) | Air capacity /% (V/V) | pH value | Soluble Cl⁻ content /mg/kg | Soluble SO₄²⁻ content /mg/kg | Redox potential Eh7 /mV | Electrical resistivity /Ω·m |
|------------------|----------------------------------------|--------------|------------------------|-----------------------|----------|---------------------------|----------------------------|----------------------|--------------------------|
| 1                | -2.0                                   | Sandy loam   | 21.5                   | 4.0                   | 7.17     | 3.3                       | 16.9                      | 195                  | 47.2                     |
| 2                | -1.2                                   | Sandy loam   | 22.9                   | 11.7                  | 7.35     | 2.3                       | 23.5                      | 168                  | 48.6                     |
| 3                | -0.6                                   | Sandy loam   | 36.9                   | 0                     | 7.26     | 11.9                      | 42.5                      | 217                  | 43.5                     |
| 4                | 0.1                                    | Loamy clay   | 23.8                   | 4.2                   | 7.78     | 1.8                       | 14.2                      | 59                   | 41.6                     |
| 5                | 0.5                                    | Loamy clay   | 20.7                   | 8.3                   | 7.05     | 13.5                      | 64.3                      | 264                  | 31.4                     |
| 6                | 0.4                                    | Loam         | 28.1                   | 14.5                  | 7.40     | 5.8                       | 26.1                      | 186                  | 42.5                     |
| 7                | 1.9                                    | Loam         | 29.8                   | 1.6                   | 7.74     | 1.7                       | 12.0                      | 177                  | 38.2                     |
| 8                | 0.5                                    | Loam         | 23.0                   | 18.5                  | 8.28     | 1.3                       | 17.5                      | 28                   | 31.9                     |
| 9                | 1.2                                    | Loamy clay   | 13.9                   | 8.1                   | 7.86     | 2.6                       | 9.8                       | 81                   | 56.9                     |
| 10               | 3.5                                    | Loam         | 15.6                   | 19.6                  | 7.35     | 3.8                       | 44.6                      | 79                   | 76.8                     |
| 11               | 2.4                                    | Loam         | 19.5                   | 10.0                  | 7.10     | 13.4                      | 15.6                      | 230                  | 44.1                     |
| 12               | 3.4                                    | Sandy clay   | 22.5                   | 13.3                  | 7.50     | 2.2                       | 66.5                      | 169                  | 44.0                     |
| 13               | 3.4                                    | Sandy clay   | 28.6                   | 0                     | 7.19     | 3.1                       | 27.2                      | 164                  | 31.4                     |
| 14               | 3.4                                    | Loamy clay   | 21.6                   | 14.2                  | 6.61     | 13.8                      | 37.8                      | 152                  | 30.9                     |
| 15               | 3.4                                    | Clay         | 20.1                   | 3.2                   | 7.10     | 8.8                       | 34.3                      | 156                  | 26.2                     |

Table 2. Test result of corrosion rate of soil to metal.

| Test site number | Instantaneous corrosion rate of metals /mm (a/60 min) | Average annual corrosion rate of metals /mm (a/1 a) |
|------------------|------------------------------------------------------|--------------------------------------------------|
|                  | Carbon steel Galvanized steel Copper Carbon steel Galvanized steel Copper |
| 1                | 0.0515 0.0165 0.00097 0.0492 0.0157 0.00087 |
| 2                | 0.0976 0.0236 0.00156 0.0913 0.0298 0.00179 |
| 3                | 0.0915 0.0187 0.00645 0.0817 0.0218 0.00529 |
| 4                | 0.1394 0.0298 0.00154 0.1361 0.0395 0.00175 |
| 5                | 0.1266 0.0268 0.00082 0.1436 0.0257 0.00090 |
| 6                | 0.1689 0.0287 0.00122 0.1635 0.0310 0.00181 |
| 7                | 0.1708 0.0265 0.00281 0.1778 0.0246 0.00269 |
| 8                | 0.1502 0.0326 0.00167 0.1452 0.0305 0.00182 |
| 9                | 0.1310 0.0165 0.00192 0.1418 0.0176 0.00202 |
| 10               | 0.1526 0.0212 0.00225 0.1558 0.0206 0.00215 |
| 11               | 0.1713 0.0198 0.00237 0.1685 0.0214 0.00219 |
| 12               | 0.2485 0.0513 0.00921 0.2422 0.0626 0.00989 |
| 13               | 0.1231 0.0215 0.00176 0.1209 0.0302 0.00192 |
| 14               | 0.1936 0.0564 0.00179 0.2049 0.0620 0.00185 |
| 15               | 0.2215 0.0339 0.00517 0.2182 0.0442 0.00492 |
Establishment of soil corrosive property evaluation method

Table 3. Evaluation method of transformer substation soil corrosive property to grounding grid metals.

| No. | Soil physical and chemical index | Measurement result | Evaluation index Z<sub>i</sub> | Carbon steel | Galvanized steel | Copper |
|-----|---------------------------------|--------------------|-------------------------------|--------------|-----------------|--------|
| 1   | Soil texture (X<sub>i</sub>)     | Sandy soil         | 0                             | 1            | 2               |        |
|     | Sandy loam soil                 | -1                 | 0                             | 1            |                 |        |
|     | Loam                           | -2                 | 0                             | 0            |                 |        |
|     | Loam clay                       | -3                 | -1                            | 0            |                 |        |
|     | Clay                            | -4                 | -2                            | -1           |                 |        |
|     | >500                            | 4                  | 6                             | 1            |                 |        |
|     | 200 - 500                       | 2                  | 4                             | 1            |                 |        |
|     | 100 - 200                       | 1                  | 2                             | 1            |                 |        |
| 2   | Soil electrical resistivity (X<sub>j</sub>), Ω·m | 50 - 100          | 0                              | 0            | 0               |        |
|     | 20 - 50                         | 0                  | -2                            | 0            | 0               |        |
|     | 10 - 20                         | -2                 | -2                            | 0            | 0               |        |
|     | <10                             | -4                 | -4                            | 0            |                 |        |
|     | <=5                             | 0                  | 0                             | 0            |                 |        |
|     | 5 - 10                          | -1                 | -1                            | -1           |                 |        |
|     | 10 - 20                         | -2                 | -2                            | -2           |                 |        |
|     | 20 - 30                         | -1                 | -1                            | -1           |                 |        |
|     | >30                             | 0                  | 0                             | 0            |                 |        |
|     | Water logging                   | -1                 | -1                            | -1           |                 |        |
|     | 0~10                            | 0                  | 1                             | 1            |                 |        |
|     | 10~20                           | -1                 | 0                             | 0            |                 |        |
|     | 20~30                           | -2                 | -1                            | -1           |                 |        |
|     | >30                             | -3                 | -2                            | -2           |                 |        |
|     | >9                              | 2                  | 3                             | 2            |                 |        |
|     | 6.5 ~ 9                         | 1                  | 2                             | 3            |                 |        |
| 3   | Water content (X<sub>j</sub>) , % (mass fraction) | 5.5 ~ 6.5         | -1                            | 0            | 1               |        |
|     | 4.5 ~ 5.5                       | -2                 | -2                            | -2           |                 |        |
|     | <4                              | -3                 | -3                            | -4           |                 |        |
|     | <100                            | 0                  | 0                             | 1            |                 |        |
|     | 100 ~ 500                       | -1                 | -1                            | 0            |                 |        |
|     | 500 ~ 1000                      | -2                 | -1                            | 0            |                 |        |
|     | 1000 ~ 2000                     | -4                 | -2                            | -1           |                 |        |
|     | 2000 ~ 5000                     | -3                 | -2                            | -1           |                 |        |
|     | >5000                           | -2                 | -2                            | -2           |                 |        |
|     | <100                            | 0                  | 0                             | 0            |                 |        |
|     | 100 ~ 300                       | -1                 | 0                             | 0            |                 |        |
|     | 300 ~ 500                       | -2                 | 0                             | 0            |                 |        |
|     | 500 ~ 800                       | -3                 | -1                            | 0            |                 |        |
|     | >800                            | -4                 | -2                            | -1           |                 |        |
|     | >400                            | 1                  | 0                             |              |                 |        |
| 4   | Air capacity (X<sub>k</sub>) , % (volume fraction) | 6.5 ~ 9            | 1                              | 2            | 3               |        |
| 5   | pH value (X<sub>k</sub>)        | 5.5 ~ 6.5          | 1                              | 0            | 1               |        |
|     | 4.5 ~ 5.5                       | -2                 | -2                            | -2           |                 |        |
|     | <4                              | -3                 | -3                            | -4           |                 |        |
|     | <100                            | 0                  | 0                             | 1            |                 |        |
| 6   | Soluble Cl<sup>-</sup> content (X<sub>k</sub>), mg/kg | 500 ~ 1000        | -2                             | -1           | 0               |        |
|     | 1000 ~ 2000                     | -4                 | -2                            | -1           |                 |        |
|     | 2000 ~ 5000                     | -3                 | -2                            | -1           |                 |        |
|     | >5000                           | -2                 | -2                            | -2           |                 |        |
|     | <100                            | 0                  | 0                             | 0            |                 |        |
|     | 100 ~ 300                       | -1                 | 0                             | 0            |                 |        |
|     | 300 ~ 500                       | -2                 | 0                             | 0            |                 |        |
|     | 500 ~ 800                       | -3                 | -1                            | 0            |                 |        |
|     | >800                            | -4                 | -2                            | -1           |                 |        |
|     | >400                            | 1                  | 0                             |              |                 |        |
| 7   | Soluble SO<sub>4</sub><sup>2-</sup> content (X<sub>k</sub>), mg/kg | 200 ~ 400         | 0                              | 0            | 0               |        |
|     | 100 ~ 200                       | -1                 | 0                             | 0            |                 |        |
|     | <100                            | -2                 | -1                            | -1           |                 |        |
|     | <=5                             | 1                  | 1                             | 1            |                 |        |
|     | -5 ~ 10                         | 0                  | 0                             | 0            |                 |        |
| 8   | Redox potential Eh7 (X<sub>k</sub>), mV | 0 ~ 5              | -1                             | -1           | -1              |        |
|     | 5 ~ 10                          | -2                 | -2                            | -2           |                 |        |
|     | 10 ~ 20                         | -3                 | -3                            | -2           |                 |        |
|     | >20                             | -4                 | -4                            | -2           |                 |        |
| 9   | Regional annual average temperature (X<sub>k</sub>, °C) | 0 ~ 5              | -1                             | -1           | -1              |        |
|     | 5 ~ 10                          | -2                 | -2                            | -2           |                 |        |
|     | 10 ~ 20                         | -3                 | -3                            | -2           |                 |        |
|     | >20                             | -4                 | -4                            | -2           |                 |        |
Table 4. Evaluation classification of carbon steel soil corrosive property

| Carbon steel | B_E value | Galvanized steel | Copper | Depth of pitting corrosion or sheet corrosion pit | Uniform corrosion rate | Corrosive Property |
|--------------|-----------|------------------|--------|-----------------------------------------------|------------------------|-------------------|
| >= -1        | >= -1     | >= -1            | <= 0.1 mm/a | <0.1 mm/a | 0.02 - 0.05 mm/a | Slight             |
| -2, -3       | -2, -3, -4| -2, -3, -4       | 0.1 - 0.5 mm/a | 0.05 - 1.0 mm/a | 0.10 - 0.20 mm/a | Weak               |
| -4, -5       | -5, -6    | -5, -6           | 0.5 - 1.0 mm/a | 0.10 - 0.20 mm/a | >1.5 mm/a       | Medium             |
| -6, -7       | -7, -8    | -7, -8           | 1.0 - 1.5 mm/a | >1.5 mm/a       | >2.0 mm/a       | Strong             |
| <= -8        | <= -9     | <= -9            | >1.5 mm/a   | >2.0 mm/a       | Very strong      |

Where, $B_E = Z_1 + Z_2 + Z_3 + Z_4 + Z_5 + Z_6 + Z_7 + Z_8 + Z_9$.

The data of soil corrosion test was entrusted to the data processing center of Harbin engineering university for analysis and processing. Many physical and chemical properties related to soil corrosion are found out and adopted for establishing a soil corrosive property evaluation method with reference to the German DIN50929 evaluation standard.

Nine indexes of soil texture, electrical resistivity, pH value, water content, soluble Cl⁻ content, soluble SO₄²⁻ content, air capacity, Redox potential and regional annual average temperature were adopted for evaluating soil corrosive property to buried metals according to test results of soil corrosive property in 120 transformer substations.

The influence of the above nine indexes was relatively more significant aiming at carbon steel and galvanized steel; soil corrosive property had lower correlation to its electrical resistivity aiming at copper. Therefore, eight indexes of soil type, pH value, water content, soluble Cl⁻ content, soluble SO₄²⁻ content, air capacity, Redox potential and regional annual average temperature were selected as evaluation factors for soil corrosive property to copper.

Based on the results of calculation and data processing of the test results of soil corrosive property in 120 transformer substations, determine the evaluation method of the corrosive property of transformer substation soil to metals in the grounding grid as shown in Table 3 and Table 4.

4. Evaluation of soil corrosive property in test station

In the 120 selected stations, copper was regarded as main grounding grid material in 6 transformer substations, and galvanized steel was selected as main grounding grid material in other transformer substations. The corrosive property of soil in the test stations was evaluated according to the above evaluation method. The evaluation result was consistent with that of the buried slide test, which was similar to the inspection result of grounding grid excavation on the site.

Figure 1 showed the appearance of two test station galvanized steel corrosion coupons with strong and weak galvanized steel corrosive property. Figure 2 showed the appearance of two test station copper corrosion coupons with strong and weak copper corrosive property. Figure 3 showed the inspection results of main grounding grid excavation in two test stations.

(a) Strong corrosive property

(b) Weak corrosive property

Figure 1. Appearance of galvanized steel test coupon after buried slide test.
Figure 2. Copper test coupon appearance after buried slide test.

Figure 3. Excavation inspection result of transformer substation grounding grid.

5. Conclusions
(1) Nine indexes of soil type, electrical resistivity, pH value, water content, soluble Cl\textsuperscript{-} content, soluble SO\textsubscript{4}\textsuperscript{2-} content, air capacity, Redox potential and regional annual average temperature are adopted for evaluating soil corrosive property to buried metals. The method is simple and practical. Comprehensive influence factors are considered, and the method has high accuracy, which is similar to actual excavation inspection result in the grounding grid.

(2) According to the nine-index evaluated method determined in the paper, two factors of air capacity and regional annual average temperature are included into the evaluation method for the first time in China, and the method of evaluating galvanized steel and copper grounding grid is proposed for the first time.

(3) Many literatures and research results show that the leakage current, stray current and microbial effect have high influence on grounding grid corrosion. However, there is no ability in the project to test and study the aspect due to deficient test means at present. Therefore, the corrosion evaluation method on the grounding grid still should be perfected constantly.

(4) The corrosive property of soil in newly-established transformer substations should be evaluated. The technical files should be established. Metal materials of the grounding grid should be selected rationally according to physical and chemical properties of soil, and corresponding corrosion resistance measures should be adopted.
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