STUDY ON SOIL CORROSION OF THE Q235 STEEL GROUND GRID IN WEINAN SHAANXI

YAN AIJUN, HOU JUANLING, CHEN YI, FENG LAJUND

Xi'an University of Technology, P. R. China

In order to on-line detect the ground grid corrosion, the relationship between the corrosion rate of Q235 steel and electrical resistance was studied by an accelerated corrosion in the soil where a 750 kV high-voltage transformer substation was established. The corrosion products and morphology were characterized by SEM (scanning electron microscopy) and XRD (X-ray diffraction). The results show that the rusty layer by the accelerated corrosion has the same structure as that by natural corrosion, and the corrosion products consisted mainly of γ-Fe_2O_3 and Fe_3O_4. One-year monitoring was conducted and the relationship of the corrosion rate (V) and the resistivity (R) was established. The error between the nature corrosion rate and the calculated corrosion rate is less than 3%.

Keywords: *ground grid, accelerated corrosion, soil, electric resistance.*

The ground grid is used for the system of earthing, lightening protection and protective earthing of transformer. At present, the corrosive degree of the ground grid is evaluated by the change of the electrical resistance of actual ground grid which is usually regarded as a pure electrical resistance network during detection [1, 2]. Hence, it is necessary for the ground grid corrosion monitoring to establish a relation between corrosion rate and electrical resistance.

Due to the low corrosion rate in soil, it takes a quite long time to establish a formula between corrosion rate and electrical resistance [3]. Consequently, no literature on the new-built high-voltage transformer substation is available. In the present investigation the relation of the corrosion rate and resistance of the ground grid was studied utilizing the electrolytic accelerated corrosion method [4]. The research can afford theory basis for on-line ground grid monitoring of the new built high-voltage transformer substation.

Experimental methods. The Q235 steel with the dimension of $1100 \times 58.9 \times 7.7$ mm was selected as the ground grid material in the study, and soil collected from the depth of 0.8 m in the construction site of 750 kV transformer station at Weinan City of Shaanxi Province was adopted as the corrosion medium. The physical and chemical properties are given in Table 1.

The experiment devices include an adjustable 110 V–15 A voltage-stabilized DC source, an ammeter with a range of 0–3 A, an electrical resistance of 1 Ω, and a cathode box with the sizes of $1000 \times 120 \times 80$ mm.

The cathode box was firstly filled with soil [5], followed by burring a polished Q235 steel sample in the box. Considering a partial exposure of actual ground grid to the air, and the error caused by the galvanic corrosion at the joints, the covered length of soil is 850 mm and other potion was exposed to the air. The experimental principle is shown in Fig. 1.

Corresponding author: HOU JUANLING, e-mail: houjuanling@yahoo.cn

Table 1. Physical and chemical properties of soil in Weinan, Shaanxi Province

Resistivity, $\Omega\cdot m$	Oxidation & reduction potential, mV	Water content, %	Porosity, %	pH values	Na^+, mg/kg	K^+, mg/kg
48.98	322	19.46	33.7	7.89	65.45	48.62
Ca^{2+}, mg/kg	Mg^{2+}, mg/kg	Cl^-, mg/kg	SO_4^{2-}, mg/kg	NO_3^-, mg/kg	HCO_3^-, mg/kg	Total salt, mg/kg
140.42	38.59	12.75	136.36	95.39	621.2	1160

At the initial stage of the experiment, the circuit system was corrected, i.e. the voltage of the standard electrical resistance was read by a multimeter, then the current was calculated and corrected until it was equal to the reading of the ammeter. Then, one hour after the soil was moistened, the corrosion test was conducted. The charge exerted on samples can be solved by integration on the collected current of the circuit. The theoretical corrosion rate was calculated by Faraday's law (see Eq. (1)) [6], and the practical corrosion rate by Weight-loss method (see Eq. (2)) [7].

$$V_t = \frac{Q \cdot M}{2 \cdot F \cdot S \cdot t} \cdot \frac{k}{\rho}, \qquad (1)$$

$$V_m = \frac{m_1 - m_2}{S \cdot t} \cdot \frac{k}{\rho}. \qquad (2)$$

Fig. 1. Schematic diagram of the test:
1 – direct electric current;
2 – cathode box; *3* – steel samples;
4 – soil medium.

In the equations, V_t and V_m represent the theoretical and practical corrosion rate, mm/a; Q is the exerted charge, C; M is the mole quantity of iron, g/mol; 2 is the number of losing electron number when Fe is corroded into Fe^{2+}; F is the Faraday's constant, 1 F = 96485 C; S is the surface area of samples covered with soil, m^2; t is the corrosion time, h; k is the conversion factor of the corrosion rate unit from $g \cdot m^{-2} \cdot h^{-1}$ to mm/a, 8.76; ρ is the density of iron, $g \cdot cm^{-3}$; m_1 and m_2 are the practical mass of samples before and after corrosion, g.

The Transformer Station Comprehensive Diagnosis System of ground grid Faults' was employed to measure the electrical resistance. Its principle is to apply a constant direct current at both ends of samples, detect the voltage of the sample at a certain length, and calculate the electrical resistance. The variation of electrical resistance after corrosion can be obtained by dividing the electrical resistances before and after corrosion.

Experimental results and discussion. *Relation between electrolytic current and time.* The change of electrolytic corrosion current with time is shown in Fig. 2. In this figure the electrolytic current drops rapidly during the initial 5 h, while current has no obvious change if the time is above 5 h. In order to accelerate corrosion, water was added into the cathode box every 24 h to restore the maximum current.

The reason why the corrosion electric current decreases with time can be explained as follows. Three sorts of water, i.e. free water, bound water and equilibrium water, exist in soil [8]. When the water in soil exists as free water, the salinity in the soil can move freely, resulting in a higher electric conductivity, as shown in the early stage of
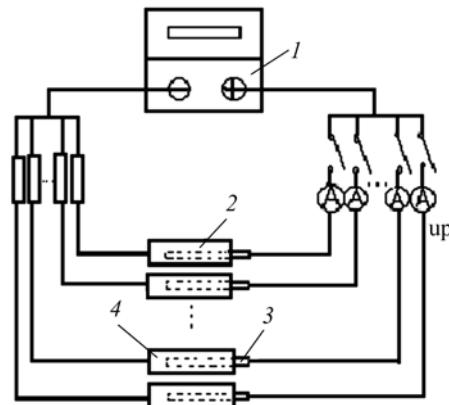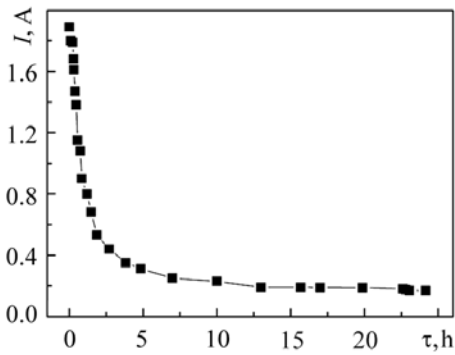
Fig. 2. Electrolytic current – time curve.

less than 5 h (Fig. 2). When it is as the bound water, both the water and salt in the soil will be absorbed in the internal soil, and, thus, the moving distance will be constrained, and the resistivity of the soil increases, as illustrated in the range of 5 to 24 h. When water of soil is in equilibrium state, the soil will be almost dry, thus causing much higher resistivity.

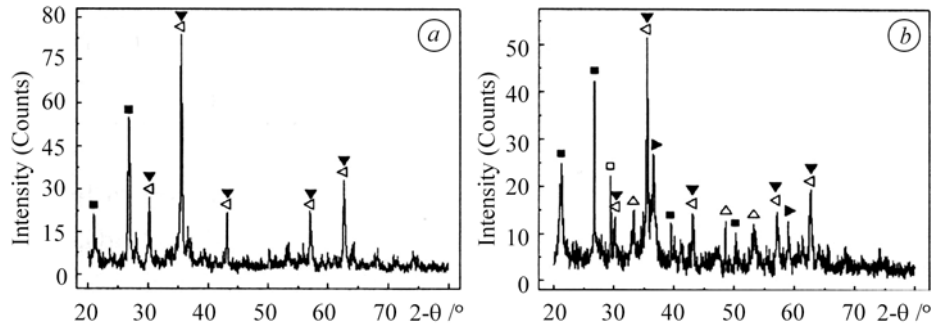***Current efficiency of electrolytic corrosion.*** The theoretical and practical corrosion rate of the samples could be calculated by equations (1) and (2). The current efficiency could be obtained from the equation η = (practical corrosion rate/ theoretical corrosion rate) ×100%.

As seen in Table 2, the current efficiency decreases from about 90% at initial corrosion to less than 85% for the later period. That derives from the fact that all theoretically calculated current is exclusively treated as electrolytic current. In fact, there is some electrical resistance in the practical medium. In addition, the sample surface is adhered with a large amount of corrosion products during the corrosion process, which increases the electrical resistance, and thus decreases the corrosion rate. On the other hand, partial Fe will be corroded into Fe^{3+} at strong current, which will consume one more charge when compared with Fe^{2+}. This is not coincided with the assumption in the theoretical calculation. Therefore, the practical ground grid materials have a larger corrosion rate at the initial stage, and lowered corrosion rate once the corrosion products film was formed.

Table 2. The current efficiency of corrosion process

Theoretical corrosion rate, mm	0.30	1.06	1.95	3.05	4.75	6.27	6.80	8.66
Practical corrosion rate, mm	0.28	0.96	1.67	2.60	4.03	5.29	5.73	7.26
Current efficiency, %	93.33	90.57	85.64	85.25	84.84	84.37	84.26	83.83

Analysis of corrosion products. In order to verify whether the relationship between the corrosion data and the resistance can be used in the practical diagnosis, the morphology of the carbon steel samples for electrolytic accelerated corrosion and natural corrosion was checked by SEM, and the corrosion products were analyzed by XRD. It is found that surface rusty layer in the electrolytic corrosion is almost the same as in natural corrosion. Two layers present in the samples. The Fe_2O_3 product is formed in the internal layer due to the corrosion of Q235 steel, while the external layer consists of the mixture of corrosion products and substance in soil as SiO_2, Al_2SiO_5 and $CaCO_3$ [9]. Due to no tight bond with the matrix surface, the external layer is easily peeled off in the later treatment. The corrosion products were characterized by XRD. The XRD patterns of accelerated-corroded Q235 steel and nature-corroded Q235 steel are shown in Fig. 3*a* and Fig. 3*b*, respectively.

From Fig. 3, it could be known that Si in Q235 material was transformed into SiO_2 under the two corrosion conditions. In the accelerated corrosion, the corrosion products of carbon steel are α-Fe_2O_3, γ-Fe_2O_3, Fe_3O_4, FeOOH and $FeSiO_3$ in natural corrosion. Although there are some differences in the corrosion products under both corrosion conditions, the main corrosion products are almost the same, which are mainly γ-Fe_2O_3 and Fe_3O_4.

Fig. 3. XRD energy spectrum of Q235 rusty scale in: *a* – accelerated corrosion

($\blacksquare$ – SiO_2, $\blacktriangledown$ – γ-Fe_2O_3, $\triangleleft$ – Fe_3O_4); *b* – nature corrosion

($\blacksquare$ – SiO_2, $\triangle$ – α-Fe_2O_3, $\blacktriangledown$ – γ-Fe_2O_3, $\triangleleft$ – Fe_3O_4, $\blacktriangleright$ – FeOOH, $\square$ – $FeSiO_3$).

Relationship between corrosion rate and resistivity. In Fig. 4, it can be seen that the electrical resistance increases slightly with the corrosion rate. When the corrosion rate is less than 2.02 mm, the change in the electrical resistance is quite low, which is no more than 2. When the corrosion rate reaches 2.94 mm, the variation in electrical resistance is 4.9 times. At a depth of 3.63 mm, the sample is in severe corrosion state and the corrosion is almost finished, while the variation in electrical resistance is 8.4 times.
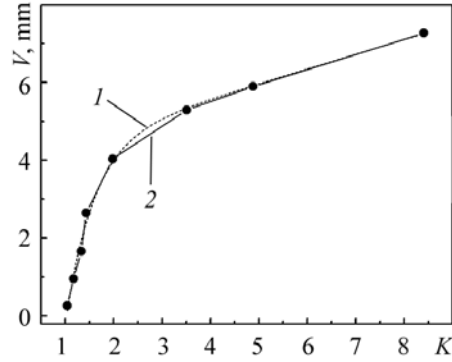

Fig. 4. The variation of electrical resistance with corrosion rate:
1 – experiment curve; *2* – fitting curve.

Based on the electrical resistance equation, the direct current electrical resistance is related with the inherent parameters, such as the resistivity, the length and the cross section areas of the metal conductors. As the corrosion progresses, the decreased cross-section of the samples leads to the increase in electrical resistance. The following equation can be obtained by fitting the non-linear curve in Fig. 4.

$$V = \frac{R - 1.029}{0.21 + 0.311(R - 1.029) - 0.008(R - 1.029)^2} \text{ (mm)}. \tag{3}$$

The fitting is shown as the dotted line in Fig. 4, and the related coefficient of fitting curve R^2 is over 0.99.

In-situ test. After one-year monitoring on the ground grid corrosion of 750 kV transformer substation in Weinan city of Shaanxi Province, the corrosion morphology of the ground grid buried beneath 0.8 m at the substation was observed. It was found that the corrosion occurred on the surface but no great change in the electrical resistance was detected after 3 months. After 12 months, the measured resistance is 1.037, and the corrosion rate calculated by formula (3) is 0.038 mm, while the practical corrosion rate obtained by the Weight-loss experiment is 0.039 mm. The error is only 2.56%, which can meet the requirement of the in-site test on the ground grid corrosion.

CONCLUSION

The electrolytic accelerated corrosion of Q235 ground grid was studied by simulating soil environment of Weinan city of Shaanxi Province. Under the constant voltage, the electrolytic corrosion electric current of Q235 steel in soil changes with corrosion time. At the initial stage of 5 h, the electrolytic current drops significantly, and the current changes slightly above 5 h. The electrolytic efficiency decreased from the 90% to 85% with increase of corrosion rate. The electrical resistance of Q235 steel in corrosion increases with the corrosion rate. The corrosion products in electrolytic accelerated corrosion of Q235 steel are similar to the natural corrosion, which are mainly composed of γ-Fe_2O_3 and Fe_3O_4. The relationship between corrosion rate V and electric resistivity R is established. The error between that in site test and the calculated value is less than 3%.

РЕЗЮМЕ. В операційному режимі виконано пришвидшені корозійні випробування сітки електричного заземлення зі сталі Q235 у ґрунті трансформаторної підстанції. Залежність глибини корозії від електричного опору сітки вивчали на спеціальній установці. Особливості корозії металу та склад її продуктів досліджували за допомогою сканівної електронної мікроскопії та методу рентгенодифракції. Встановлено, що продукти корозії сталі Q235 відповідають природі іржі, утвореної під час тривалої експлуатації сіткової конструкції. На основі річних спостережень запропоновано формулу для визначення швидкості корозії сталі за цих умов.

РЕЗЮМЕ. В операционном режиме проведены ускоренные коррозионные испытания сетки электрического заземления из стали Q235 в почве трансформаторной подстанции. Зависимость глубины коррозии от электрического сопротивления сетки изучали на специальной установке. Особенности коррозии металла и состав ее продуктов исследовали с помощью сканирующей электронной микроскопии и метода рентгенодифракции. Установлено, что продукты коррозии стали Q235 отвечают природе ржавчины, образованной во время длительной эксплуатации сеточной конструкции. На основе годовых наблюдений предложено формула для определения скорости коррозии стали при данных условиях.

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