Study on Corrosion Behavior of X80 Steel in Guangdong Soil with Different Water Contents under HVDC Interference

Hui ZHANG,a Yanxia DU,a,* Runzhi QIN,a Zhenchang XU,a and Qinglin GUB

a Institute for Advanced Material and Technology, University of Science and Technology Beijing, Beijing 100083, China
b PetroChina Shanghai Mansion, PetroChina West East Gas Pipeline Company, Shanghai 200122, China

* Corresponding author: duyanxia@ustb.edu.cn

ABSTRACT

This paper focused on the variation of DC interference parameters and corrosion behavior of X80 steel interfered by 100 V DC potential in Guangdong real soil with 5 different water contents through indoor simulation experiments. The results showed that there existed obvious differences for the current density changes of X80 specimens in various soil conditions with different water contents under interference of 100 V DC potential. At a lower water content (14%, 18%, 21%), the DC current density reached a peak value in a second and then dropped to a stable value rapidly, and the drop rate exceeded 60%. When the water content reached 35% or 43%, the current density reached a peak in about 75 s, and after that there was no obvious downward trend. The stable value accounted for about 80% of the peak value. The corrosion rates in the soil conditions with different water contents of 14%, 18%, 21%, 35%, and 43% were 2.66, 4.12, 5.70, 8.62, and 10.01 µm/h, respectively. The local soil spread resistance contributed to the differences in current density and corrosion rates in different environments. The main corrosion products under HVDC interference were iron oxides such as α-FeOOH, γ-FeOOH, and Fe₂O₄.

Keywords: HVDC Interference, Soil Water Content, Current Density Change, Corrosion Rate and Product

1. Introduction

Since the 1980s, high voltage direct current (HVDC) transmission technology has been developed rapidly and because of the characteristics of long-distance and large-capacity, a lot of HVDC transmission systems have been constructed in the world, especially in China in recent years. There are two grounding electrodes in a HVDC transmission system and a bipolar operation mode is generally adopted in order to improve the efficiency of the system. But unavoidably, monopolar mode has to be used at the initial stage of operation or under emergency fault conditions for HVDC transmission system. When running under monopolar operation mode, the earth will be worked as one part of the HVDC transmission circuit, and at this time, a large amount of current (up to several thousand amps) can be discharged from the electrode to the earth. A portion of the current can be picked up by the pipeline nearby, and then discharges elsewhere faraway, which may result in serious DC interference to the pipelines near the HVDC grounding electrode.

Many cases on underground metal facilities subjected to HVDC interference have been reported in the world. For example, the Quebec-New England Intertie HVDC system brought DC interference to the surroundings, and the pipe-to-soil potential of nearby crude oil and natural gas pipelines can reach 900 mV.1 Caroli investigated the interference suffered by an irrigation pipeline at a distance of 3 km to the southeast of the ±600 kV Itaipu transmission project in Brazil. When the middle of the pipeline was isolated by an insulating flange, the pipe-to-soil potential of the pipeline at this place decreased from 21 V to −46 V, which was enough to cause electric shock.2 The West-to-East gas transmission pipeline in China has been interfered by the nearby HVDC transmission system3,4 and the pipe-to-soil potential could increase up to 304 V (vs. SCE) when the DC grounding electrode was working at monopolar mode. Besides, some pipelines5,6 in Guangdong Province of China were interfered by HVDC projects and the pipe-to-soil potential could reach 150 V. In addition, Fu7 et al. performed indoor DC interference corrosion simulation experiments in Hainan soil with water content of 12.80%. The experimental results showed that when the average current density reached 14.2 A/m², the corrosion rate of Q345 steel was about 1.91 µm/h. Qin8 carried out an indoor HVDC interference simulation experiments in Guangdong soil with water content of 21%, and investigated the current density, the local environmental parameters and the corrosion rates of the specimens at 50 to 300 V DC interference potentials, and the results showed that the highest corrosion rate appeared at 200 V, which was about 10.63 µm/h.

The above cases show that HVDC interference could result in pipe-to-soil potential as high as hundreds of volts, which is much higher than that in general DC interference. How to understand the corrosion process and evaluate the corrosion risk under such high DC interference need to be studied to provide guidance for the industry. The current researches on HVDC interference are mostly based on field measurements and only a few of researches work focusing on the corrosion process during HVDC interference by indoor simulation experiments have been conducted. In most indoor simulation experiments, generally soil simulation solution was used to simulate the actual soil environment,9–12 although the simulated solution could help amplify the effects of chemical factors such as soil pH, salt content and ion content on the corrosion characteristics of the soil, the porosity, diffusivity and unevenness of real soil could not be well simulated by solution. For the buried pipeline suffered from HVDC interference, high pipe-to-soil potential and current density on the coating defects would change the soil environment and impact the corrosion process of pipeline steel13,14 however, less work has been conducted on this aspect. Many factors contribute to the characteristics of real soil, such as water content, ion content, pH value, oxygen content, soil resistivity etc., and of which water content is one of the most important factors affecting soil characteristics.15,16

In this work, HVDC interference simulated experiments were carried out to study the corrosion behavior of X80 steel in real soil environment with different water contents under HVDC interference.
Figure 1. Schematic diagram of the experimental circuit.

Figure 2. Electrochemical test circuit for $R_{soil}$.

by electrochemical and local environmental parameters monitoring, weight loss tests and corrosion products analyses.

2. Experimental Methods

2.1 Experimental materials and media

The specimen was X80 pipeline steel and the chemical composition in wt% was as follows: C 0.070, Mn 1.61, Si 0.21, Ni 0.12, Cu 0.14, Nb 0.041, Ti 0.012, S 0.0025, P 0.0081, Mo 0.13, and Fe balance. The ion concentration was converted into inorganic salt content of the soil was 18% and the resistivity was about 210.4 $\Omega$·m. The soil used in the experiment was Guangdong reddish-brown clay and it was dug from the depth of about 1 m. The initial water content of the soil was 18% and the resistivity was about 210.4 $\Omega$·m. The soil was composed of a DC power supply of HSPY 400-01 used to produce HVDC interference, the 10 $\Omega$ resistance, an auxiliary electrode (CE), a reference electrode (RE) and a working electrode (WE). The 10 $\Omega$ resistor was connected in series in the interference circuit and the voltage across it was monitored by voltmeter to evaluate the DC current through the circuit. Saturated calomel electrode (SCE) was used as the reference electrode, and placed at a certain distance from the specimen, cm$^2$.

The experimental circuit was shown in Fig. 1 and it was composed of a DC power supply of HSPY 400-01 used to produce HVDC interference, a 10 $\Omega$ resistance, an auxiliary electrode (CE), a reference electrode (RE) and a working electrode (WE). The 10 $\Omega$ resistor was connected in series in the interference circuit and the voltage across it was monitored by voltmeter to evaluate the DC current through the circuit. Saturated calomel electrode (SCE) was used as the reference electrode, and placed at a certain distance from the specimen. In the experiment, the X80 steel specimen was firstly put in the studied soil environment for a certain time until its open circuit potential become stabilized. And then a 100 V DC potential was applied to it for 1 hour through the DC power supply. The current in the circuit was obtained by testing the voltage across the resistor, and the DC current density of the specimen was determined by considering the working area of the specimen, the accuracy of current acquisition was 1 s.

2.2 Process parameter test and soil environmental parameter test

In order to investigate the changes of local environment near the specimen during HVDC interference, the change of soil spread resistance of specimen and water content of the soil close to the specimen were tested. The soil spread resistance $R_{soil}$ represented the resistance between the test specimen and the reference electrode, which was mainly related to the shape and size of the specimen, the physical and chemical properties of the soil near the specimen.

The spread resistance could be measured by using external alternating current (AC) disturbance method, and the test circuit was shown in Fig. 2. The Reference 3000 electrochemical workstation was connected to a three-electrode system (CE, RE and WE) to form a test circuit to test the change of $R_{soil}$ before and after the HVDC interference was applied. The value of $R_{soil}$ was calculated according to the following formula:

$$R_{soil} = \frac{U_{AC}}{J_{AC} S}$$  \hspace{1cm} (1)

Where, $R_{soil}$ is soil spread resistance between the test specimen and the reference electrode, $U_{AC}$ is the AC voltage of the specimen when AC current is applied to it, $V$; $J_{AC}$ is the AC current density flowing through the specimen, $A/cm^2$; $S$ is the working area of the specimen, cm$^2$.

After HVDC interference, the soil near the surface of the specimen was taken out, and the water content of the soil was tested by the drying method.

2.3 Corrosion weight loss test

Immediately after the end of HVDC interference experiment, the corrosion products on the surfaces of the specimens were removed by pickling solution (hydrochloric acid (500 ml) + deionized water (500 ml) + hexamethylenetetramine (3.5 g)), and ultrasonically cleaned in acetone for 5 min. After the specimens were cleaned, they were rinsed with deionized water and dried up by air. Finally, the weight loss of specimen during HVDC interference was measured with an electronic balance, and the corrosion rate was calculated by formula (2).

$$V_{corr} = \frac{10000 \times W_0 - W}{S \rho t}$$  \hspace{1cm} (2)

Where, $V_{corr}$ is the corrosion rate, $\mu$m·h$^{-1}$; $W_0$ is the mass of the specimen before HVDC interference, g; $W$ is the mass of the specimen after HVDC interference, g; $S$ is the working area of the specimen, cm$^2$; $t$ is the interference time, h; $\rho$ is the density of the specimen, g·cm$^{-3}$.

2.4 Corrosion weight loss test

The morphologies of the film and the elemental components were inspected by SEM and EDS on the Hitachi GSM-6510A scanning electron microscope.

3. Results

3.1 The changes of DC current density of the specimens with the application of high DC potential in the soil environments with different water content conditions

The changes of DC current densities for X80 specimens placed in
the Guangdong real soil environments with water contents of 14%, 18%, 21%, 35%, 43% with the application of 100 V DC potentials were shown in Fig. 3(a). It can be seen from the figure that with 100 V DC interference potential, the DC current density curves underwent three stages in different soil environments, as shown in Fig. 3(b), taking the current density in 21% water content condition as an example, right after the application of 100 V DC potential, the current density increased immediately and peaked at time $t_1$, then began to decrease from time $t_1$, and tended to stabilize at time $t_2$, and fluctuated at the stable value.

As shown in Fig. 3, there existed obvious differences for the current density curves under different water content conditions. Table 1 showed the differences between the current density profiles for different water contents. Combined with Fig. 3, it can be seen from the table that, at 14% water content, the current density instantly increased to a peak value about 46 A/m² about one second, and then dropped rapidly. It tended to stabilize after about 460 s. The stable value was about 18 A/m², which was about 38.5% of the peak value. From 18% to 21% water content, the current density curves also peaked instantaneously after the application of 100 V DC potential, but tended to stabilize after peaking for about 1000 s, the steady values of current density were about 25.5 A/m² and 33.6 A/m², accounting for about 24.0% and 37.0% of the peaks, respectively. When the water content reached 35% and above, after the application of the DC interference, it reached the peak after about 70 s, then slowly decreased. After about 1650 s, the current density began to stabilize, and the current density values were about 64.6 and 74.8 A/m² after stabilization, respectively, accounting for about 80% of the peaks. It can be seen that under high DC interference potential in soils, the time $t_1$, $t_2$, the stable value and the peak value of the current density were closely related to the soil water content. The higher the water content, the larger the time $t_1$ and $t_2$, the greater the ratio of the steady value to the peak value of the current density, the smaller the magnitude of the current density decreased.

### 3.2 Corrosion rates of the specimens with the application of high DC potential in the soil environments with different water content conditions

The relationship between the corrosion rates of specimens under 100 V DC interference in different soil environments and the water contents was shown in Fig. 4. It can be seen from the figure that as the water content increased, the corrosion rate increased gradually. When the water content increased from 14% to 18%, the corrosion rate increased by 2.56 times from 2.66 µm/h to 4.12 µm/h. At 21% water content, the corrosion rate increased to 5.70 µm/h, and when the water content was 35%, the corrosion rate was 8.62 µm/h, as the water content increased to 43%, the corrosion rate increased by 1.16

---

**Figure 3.** The profile of the variations in current density curves during HVDC interference (a) Current density curves in different water content conditions (b) Current density curves in 21% water content condition.

**Table 1.** Variations of current density parameters under different water content conditions.

| Water content | $0-t_1$/s | $t_1-t_2$/s | $i_{\text{max}}$/A/m² | $i_{\text{stable}}$/A/m² |
|---------------|-----------|-------------|-------------------|-------------------|
| 14%           | 1         | 460         | 46.0              | 17.7              |
| 18%           | 1         | 851         | 106.3             | 25.5              |
| 21%           | 1         | 1294        | 90.8              | 33.6              |
| 35%           | 84        | 1623        | 80.4              | 64.6              |
| 43%           | 56        | 1689        | 94.4              | 74.8              |
times to 10.01 µm/h. The corrosion rates showed that, as the water content increased, the corrosion rate gradually increased, but the relationship between corrosion rate and water content was not linear, and the corrosion rates differed little between 35% and 43% water contents.

3.3 The changes of soil characteristics near specimens with the application of high DC potential in the soil environments with different water content conditions

After HVDC interference experiment, the water content of soil near the specimen ($w_{t1}$) was measured, and compared with that before the interference ($w_{t0}$), which was shown in Fig. 5. It can be seen from the figure that after the interference, $w_{t1}$ was significantly lower than $w_{t0}$. When $w_{t0}$ were 14%, 18%, 21%, 35% and 43% before interference, $w_{t1}$ decreased to 10.43%, 11.84%, 12.63%, 15.92%, and 18.40% after interference, respectively. Under the conditions of 21% or lower water content, the decline of near surface water content was below 38%, and under the conditions of high moisture content above 21%, the decline were above 54%. The higher of the initial soil water content, the greater the decrease amplitude of near surface soil water content after interference.

The spread resistances of specimens before and after HVDC interference were represented by $R_{beforesoil}$ and $R_{aftersoil}$ and the changes of them were shown in Fig. 6. As shown in Fig. 6, the spread resistance of specimen before the HVDC interference decreased slightly with the increase of water content and it remains at about 12 kΩ. However, after the interference, the spread resistance of specimen increased significantly to 47.1, 36.97, 25.01, 12.73 and 10.7 kΩ, corresponding to the water content of 14%, 18%, 21%, 35% and 43%, respectively. The spread resistance after interference was significantly increased compared with that before the interference. At the same water content, $R_{beforesoil}$ and $R_{aftersoil}$ respectively indicated the spread resistance before and after the interference. It can be seen from the figure that in the soil environment with low water content of 21% or less, the $R_{aftersoil}$ after the interference changed greatly, which was about 3 times that of $R_{beforesoil}$. When the water content was 35% or 43%, the $R_{aftersoil}/R_{beforesoil}$ was about 1.1. It can be seen that as the water content increased, at low water content, $R_{aftersoil}$ increased compared with $R_{beforesoil}$, and the lower the water content, the more obvious the increase.

3.4 Corrosion morphologies of the specimens with the application of high DC potential in the soil environments with different water content conditions

Figure 7 were macroscopic morphologies of X80 steel specimens interfered with high DC potential for 1 h under different water contents. Combined with the morphologies before and after pickling, it can be seen that in the soil with water contents of 14% to 18%, there were only a few of corrosion products distributed unevenly on the working surface of the specimens, which were mainly reddish brown with interphase distribution of dark green products and tightly bound to the substrates. After pickling, there was still a small area of bright substrate on the working area, and a small-sized corrosion pits appeared on the surface that corresponded to the position of the dark green corrosion products. When the water content increased to 21%, the morphology of the corrosion product was similar to that of the low water contents, but after pickling, it can be seen that the bright substrate basically disappeared, besides, the area of the corrosion pits decreased. When the water content continued to increase, the quantity of the products increased, but their contact with the substrate was loose and easy to be peeled off. The positions shown by the arrows in the Fig. (1-d) and (1-e) were the bare substrates after the products were peeled off from the substrates, the integrity of the films were destroyed. For these situations, the surfaces of films were mainly dark green. After standing for a while, the dark green products gradually turned reddish brown. In addition, the corrosion pits dispersed at the edges, the number and area of which decreased, the depth increased.
3.5 Surfaces characterization of the specimens with the application of high DC potential in the soil environments with different water content conditions

The SEM micrographs of X80 steel specimen suffered from 1 h of HVDC interference in soil with different water contents were shown in Fig. 8. It can be seen that the morphological structures of the corrosion products were different in the soil with different water contents. Under the condition of 14% water content, the corrosion products were mainly continuous honeycomb-structure, with flaky and fine granular products attached, and the products were arranged neatly and compact, which had a certain protective effect.21 When the water content increased to 18%, the products were cotton-like structure, more dispersed, connected by neatly arranged and dense needle-like products, besides, cracks appeared among needle-like products. For water content of 21%, the corrosion products had flower-like structure, there were needle-like or needle-like crystal structures at the edges of those structures. When the needle-like structure was enlarged, it can be seen that each needle was actually a small piece structure. There were still a small amount of cotton-like corrosion products around flower-like products, simultaneously, the width of the cracks increased. When the water content was 35%, the film of the products showed flaky structure with small-size needle-

![Figure 7](image1.png) **Figure 7.** Macroscopic corrosion morphologies with HVDC interference under different water content conditions (1) before pickling (2) after pickling (a) wt = 14% (b) wt = 18% (c) wt = 21% (d) wt = 35% (e) wt = 43%.

![Figure 8](image2.png) **Figure 8.** SEM morphologies and EDS analyses with HVDC interference under different water content conditions (1) SEM (2) EDS (a) wt = 14% (b) wt = 18% (c) wt = 21% (d) wt = 35% (e) wt = 43%.
like products at the edges, and granular corrosion products were deposited around the flaky corrosion products, at this time, the overall morphology was significantly looser than that in the soil with lower water content. When the water content increased to 43\%\%, the plate-like corrosion products appeared in the film, besides the presence of sand-like products, the width of cracks between the deposited products reached the maximum.

The elemental composition of corrosion products were analyzed by EDS. The results mainly were Fe, O, Si, Al, Mn, Au and other elements. Among them, Au was caused by gold injection before electron microscopy test, and the contents of Si, Al, Mn and other elements were very low, which were residual soil composition. Therefore, the corrosion products on the films are mainly Fe oxide or hydroxide,\textsuperscript{23–24} then the corrosion compositions were determined by combining with the microscopic structures and EDS results of the corrosion products.\textsuperscript{25} The value of O:Fe in the honeycomb corrosion products at 14\% water content, the cotton-like products at 18\% water content and the flower-like products at 21\% water content were about 2, which was the main component of FeOOH.\textsuperscript{26–28} The value of O:Fe of the product in the flake product at 35\% water content was nearly 1.7, which might be a mixture of iron oxides and hydroxides.\textsuperscript{29,30} At 43\%, the plate-like corrosion products, of which the O:Fe was nearly 1.3, were mainly FeO\textsubscript{2}.\textsuperscript{31–33}

4. Discussion

4.1 The relationships between current density changes of specimens and the local soil characteristics near the specimens during HVDC interference in the soil environments with different water content conditions

As shown in Fig. 3 and Table 1, there were obvious differences among the peak values, stable values, the time to reach the peak value and the stable value on the current density curves of specimens suffered from HVDC interference in Guangdong real soil with five kinds of water contents. At the same time, it also could be seen from Fig. 4 to 8 that the water contents of the soil near specimens and spread resistances of the specimens experienced different changes during HVDC interference for different water conditions. The parameters of peak value of current density, stable value of current density, stable value/peak value of current density, water content of near-surface soil, local soil spread resistance of specimen for different water contents were put together in Table 2. From Table 2, it can be seen that under the conditions of 14\%, 18\% and 21\% low water contents, there existed great decrease between peak value and stable value on the current density curves, at the same time, the water contents of the near-surface soil decreased to 10.43\%, 11.84\%, 12.63\%, respectively, which all were below 13\%. And the local soil spread resistances which were above 25 k\(\Omega\) increased significantly after the HVDC interference. Under the conditions of 35\% and 43\% high water contents, the water contents of the soil near surface of the specimens were kept above 15\%, the local soil spread resistance changed little compared with it under low water conditions, the differences between the peak and the stable value of current density were small. Therefore, the current density changes of specimens were mainly related to the changes of water contents in the local soil near the specimens and spread resistances of specimens.

The appearance of the peak value on current density curve was due to the relatively active surface state at the moment of the application of DC potential,\textsuperscript{22} meanwhile, the process was accompanied by ionization and discharge, the soil had high conductivity, the current density rapidly reached a maximum. At the same time, ionization or discharge released a large amount of heat, as the interference time extended, near-surface soil was caused dry, leading to the soil resistivity increasing and the current density decreasing. The electric field accelerated the ion directional movements and also affected the process of electrode reactions,\textsuperscript{24} when the speeds of ion accumulations, migrations and diffusions in soil near the electrode region reached a certain balance, the current density was basically stable.\textsuperscript{34}

4.2 The corrosion behaviors of X80 steel under HVDC interference in the soil environments with different water contents

According to the EDS analyses in Fig. 8, the corrosion products of HVDC interference in different water content conditions were mainly iron oxides and oxyhydroxides. Under the conditions of 14\%, 18\% and 21\% low water contents, the corrosion products were mainly in the form of FeOOH, and the content of FeOOH decreased with the increasing of water content, at the same time, the quantity of Fe\textsubscript{2}O\textsubscript{3} increased.

The corrosion mechanism in the process of HVDC interference under different water content conditions was shown in Fig. 9. From the figure, it could be seen that at 14\% and 18\% water content, the continuous honeycomb and cotton-like products were typical morphology of \(\alpha\)-FeOOH. The continuous honeycomb and cotton-like \(\alpha\)-FeOOH appeared under conditions of mild corrosion. At 21\% water content, the products were mainly flower-like \(\gamma\)-FeOOH, and at the center of the products there were still cotton-like \(\alpha\)-FeOOH products, cotton-like \(\alpha\)-FeOOH products grew aggregately on the dense needle-like corrosion products, and small cracks were produced among needle-like products. Meanwhile, the flower-like \(\gamma\)-FeOOH was structurally dispersed.\textsuperscript{27} At 35\% and 43\% water content, the corrosion products under HVDC interference were loose and easy to fall off, besides, the micrographs showed flaky and massive corrosion products whose main component were Fe\textsubscript{2}O\textsubscript{3}. In addition, there were granular corrosion products, which may be an amorphous products during the formation of FeOOH. Under the condition of higher water content, the Fe\textsuperscript{2+} formed by continuous dissolution of X80 steel can continue to react with FeOOH to form

| Water content | 14\% | 18\% | 21\% | 35\% | 43\% |
|---------------|------|------|------|------|------|
| Water content of near-surface soil after interference/\% | 10.43 | 11.84 | 12.63 | 15.92 | 18.40 |
| Local soil spread resistance of specimen after interference/\k\(\Omega\) | 47.1 | 36.9 | 25.0 | 12.7 | 10.7 |
| Peak value of current density/A/\text{m}^2 | 46.0 | 106.3 | 90.8 | 80.4 | 94.4 |
| Stable value of current density/A/\text{m}^2 | 17.7 | 25.5 | 33.6 | 64.6 | 74.8 |
| Stable value/peak value of current density/\% | 38.5 | 24.0 | 37.0 | 80.3 | 79.2 |
and the increase of water content led to the increase of oxygen transmission resistance, thus, in the low oxygen environment, Fe(OH)$_2$ and Fe(OH)$_3$ can directly generate Fe$_3$O$_4$. The dark green corrosion product was an intermediate product in the formation of Fe$_3$O$_4$, and the products were deposited on the surface of specimen forming a sheet or plate of corrosion products. Due to the high DC potential, the corrosion rate was further accelerated. In summary, with the increase of water content, the corrosion product of α-FeOOH was gradually reduced, while γ-FeOOH gradually increased, and when the water content was 35% or more, under the action of the electric field, the conversion of FeOOH to Fe$_3$O$_4$ was promoted.

5. Conclusions

(1) During HVDC interference, there existed obvious differences for the current density changes of X80 specimens in various soil conditions with different water contents under interference of 100 V DC potential. At a lower water content (14%, 18%, 21%), with the application of 100 V DC potential, the DC current density reached a peak value in a second and then dropped to a stable value rapidly, and the drop rate exceeded 60%. When the water content reached 35% or higher, the current density reached a peak in about 75 s, and after that there was no obvious downward trend. The stable value accounted for about 80% of the peak value.

(2) The corrosion rates of X80 steel under 100 V DC interference in the soil with different water contents of 14%, 18%, 21%, 25%, and 43% were 2.66, 4.12, 5.70, 8.62, and 10.01 µA/cm$^2$, respectively. As the water content increased, the corrosion rate increased gradually. (3) The application of HVDC interference caused the significant decrease of water content of the local soil near specimen and sharp increase of spread resistance of the specimen for low water content condition of 14%, 18% and 21%, which contributed to the decrease of current density of specimen from peak to stable value. But at high water contents of 35% and 45%, there were no obvious change for water content of the soil near the specimen and spread resistance of the specimens, which were in correspond with there were no obvious decrease on current density curves.

(4) After HVDC interference, the main components of the corrosion products were were α-FeOOH, γ-FeOOH and Fe$_3$O$_4$. The products under low water content conditions of 14%, 18% and 21% as the water content increased, the honeycomb and cotton-like α-FeOOH gradually decreased, and the flower-like γ-FeOOH gradually increased. When the water content was 35% or more, under the action of the HVDC interference, the conversion of FeOOH to Fe$_3$O$_4$ was promoted.

Acknowledgment

This work was supported by China Scholarship Council (Grant No. 201606465052) and National Key R&D Program of China (Grant No. 2016YFC0802101).

References

1. D. T. Fowles, J. Am. Water Works Assoc., 63, 233 (1971).
2. C. E. Caroli, N. Santos, D. Kovarovsky, and L. J. Pinto, IEEE Trans. PWRS, 5, 1583 (1990).
3. R. Qin, Y. Du, G. Peng, M. Lu, and Z. Jiang, NACE International, Houston, Texas, USA (2017, April).
4. W. Bi, H. Chen, and Z. Li, NACE International, Houston, Texas, USA (2016, March).
5. B. Ying, Oil and Gas Field Ground Works, 33, 23 (2014).
6. Y. Gong, C. Xue, Z. Yuan, Y. Li, and F. P. Dawalibi, J. Power Energy Eng., 3, 332 (2015).
7. C. Fu, B. Yang, D. Yang, J. Hu, J. Zhao, E. Han, and W. Ke, Corros. Prot., 38, 756 (2017).
8. R. Qin, Y. Du, M. Lu, O. U. Li, and H. Sun, J. Met., 54, 886 (2018).
9. Y. Wu, T. Liu, S. Luo, and C. Sun, Mater. Sci. Eng. Technol., 41, 142 (2010).
10. I. S. Cole and D. Marney, Corros. Sci., 56, 5 (2012).
11. T. Huang, X. Chen, X. Wang, H. Su, J. Li, and Y. Yu, J. Mater. Prot., 47, 58 (2014).
12. J. Li, M. D. Thesis, University of Science and Technology Beijing, Beijing (2015).
13. C. A. M. Ferreira, J. A. C. Ponciano, D. S. Vaitman, and D. V. Pérez, Sci. Total Environ., 388, 250 (2007).
14. C. Du, X. Li, J. Wu, Y. Song, and J. Xu, J. Eng. Sci., 26, 529 (2004).
15. M. N. Norhazlilin, Y. Noordin, K. S. Lim, R. O. Siti, A. R. A. Safian, and M. H. Norhazlilin, J. Appl. Sci. Res., 8, 1739 (2012).
16. A. I. M. Ismail and A. M. Elshamy, Appl. Clay Sci., 42, 356 (2009).
17. Y. Wu, C. Sun, S. Zhang, D. Cai, G. Li, and X. Liu, Corros. Sci. Prot. Technol., 9, 135 (1993).
18. L. V. Nielsen and K. V. Nielsen, NACE International, San Diego, California, USA (2003, March).
19. L. V. Nielsen, H. Rosenberg, and B. Baumgarten, NACE International, New Orleans, Louisiana, USA (2004, March).
20. L. V. Nielsen and F. Galugard, NACE International, Houston, Texas, USA (2005, May).
21. C. Shao, Study of Science and Engineering at RTVU, 4 (2011).
22. M. Li, H. Lin, and C. Cao, Corros. Sci. Prot. Technol., 12, 218 (2000).
23. H. Keles, M. Keles, I. Dehri, and O. Serindag, Colloids Surf., A, 320, 138 (2008).
24. H. Huang, X. Guo, G. Zhang, and Z. Dong, Corros. Sci., 53, 3446 (2011).
25. G. Yan, Y. Huang, X. Meng, Y. Liao, and R. Li, J. South China Univ. Technol., 45, 135 (2017).
26. T. Misawa, T. Kyuno, W. Saitaka, and S. Shimodaira, Corros. Sci., 11, 35 (1971).
27. R. A. Antunes, I. Costa, and D. L. A. D. Faria, Mater. Res., 6, 403 (2003).
28. N. Dai, J. Zhang, Q. Chen, B. Yi, F. Cao, and J. Zhang, Corros. Sci., 99, 295 (2015).
29. D. de la Fuente, J. Alcántara, B. Chico, I. Díaz, J. A. Jiménez, and M. Morcillo, Corros. Sci., 110, 253 (2016).
30. J. I. S. Rodriguez, F. J. S. Hernández, and J. E. G. González, Corros. Sci., 45, 799 (2003).
31. A. Raman, N. Nasrafadani, and L. Sharma, Metallurgical, 22, 79 (1989).
32. A. Ravzan and A. Raman, Pract. Met., 23, 223 (1986).
33. A. Raman, N. Nasrafadani, L. Sharma, and A. Rafvan, Prakt. Metallurgie, 24, 577 (1987).
34. X. Cao, G. Wu, L. Fu, W. Jiang, and X. Zhang, Corros. Sci. Prot. Technol., 28, 37 (2008).
35. Y. Tamaura, K. Ito, and T. Katsura, J. Chem. Soc., Dalton Trans., 2, 189 (1983).