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Observation Research on the Effect of UHVDC Grounding Current on Buried Pipelines

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Abstract: In order to research the electromagnetic interference in buried oil and gas pipelines generated by the grounding current of a grounding electrode of Ultra High Voltage Direct Current (UHVDC) system, observation experiments of stray current and pipe-to-soil potential (PSP) in the pipeline were carried out. Monitoring devices were installed at two sites of the Dong-Huang oil pipeline before the commissioning of the Zalute–Qingzhou and Shanghaimiao–Shandong ±800 kV UHVDC projects. Monitoring data on the stray current and PSP of the two monitoring sites were obtained when the two UHVDC projects were operated in monopolar mode on 24 December 2017 and 2 January 2019 and the grounding current reached 6250 A. The amplitude characteristics of the stray current and PSP at different distances from the grounding electrode and the effects of the magnitude of the stray current and PSP on the cathodic protection system are analyzed herein. The results show that the effects of the grounding current on pipeline corrosion are not only closely related to the distance between the grounding electrode and the pipeline but are also related to the running state of the potentiostats of pipelines and the distance between insulation flanges. Optimizing the performance of potentiostats and the distribution of insulation flanges can reduce the effects of UHVDC grounding current on pipeline corrosion.

Keywords: corrosion; electromagnetic interference; HVDC transmission; pipeline; stray current

1. Introduction

Because Ultra High Voltage Direct Current (UHVDC) systems and long-distance oil and gas pipelines are important facilities [1,2], more and more attention has been drawn to the safety of UHVDC and oil and gas pipelines. With the scale of power grids and buried pipelines increasing, the electromagnetic interference caused by high-voltage power transmission systems in pipelines is difficult to avoid [3–5]. In particular, the effects of an UHVDC grounding current on pipelines bring about stray current and pipe-to-soil potential (PSP) offset. When the PSP offset exceeds the standard or when the cathodic protection systems fail to operate effectively, the stray current generated by the grounding current will accelerate corrosion, reduce the service life of pipelines, and even cause explosions which may lead to heavy casualties and economic losses [6,7].

So far, much research has been conducted on the effect of UHVDC grounding current on buried pipelines, including theoretical calculations and PSP monitoring experiments. Based on the transmission line theory, the equivalent circuit model of pipelines was established and the distribution of the stray current and PSP was calculated [8,9]. The results show that the resistivity of the insulating coating is an important factor determining the corrosion of a pipeline; the buried depth of the grounding electrode has no influence on the corrosion of a pipeline [9]; and the magnitude of the grounding current, soil resistivity, and the distribution of insulation coating defects have a great influence on the corrosion of pipelines [6]. The corrosion of a pipeline varies with the magnitude of the grounding current: hydrogen evolution corrosion occurs when the grounding anode is discharged [10], while oxygen absorption corrosion occurs when the cathode is discharged [11].

A large number of experiments aiming to investigate the effect of HVDC and UHVDC grounding current on buried pipelines have been carried out. The experimental results show that an HVDC monopolar operation can lead to a positive PSP offset exceeding the standard [12–14], a rising corrosion rate [15], and even to the cathodic protection device being damaged [16]. Zhenjun Li tested the PSP of a pipeline 44 km from the Hami grounding electrode of the Hami–Zhengzhou UHVDC project [17]. The negative offset of the PSP reached 7.1 V, resulting in hydrogen evolution corrosion. However, only the PSP data were obtained; monitoring data of the stray current and potentiostat output current were not acquired at the same time. During the monopolar commissioning of the Zhalute–Qingzhou (Zhaqing) and Shanghaimiao–Shandong (Shangshan) ±800 kV UHVDC projects, the grounding current reached 6250 A. Monitors were installed at different sites of the Dong-Huang oil pipeline, by which the monitoring data of the stray current, potentiostat output current, and PSP could be received at the same time, to provide more data for further study of the effect of the UHVDC grounding current on buried pipelines.

2. Scheme of the Observation Experiment

2.1. Selection of Monitoring Sites

The transmission power of the Zhaqing project and Shangshan project is 10,000 MW and their rated current is 6250 A, making them the largest DC transmission projects at present. There are many buried pipelines near the receiver grounding electrodes of the two projects in Gaoqing and Zhushuangcun. In order to obtain the monitoring data of pipelines with different distances from the grounding electrodes and to study the effect of the distance on the stray current and PSP magnitude, the Xiligu cathodic protection station and Changyi oil transportation station, which are 154 and 187 km from the Gaoqing grounding electrode, respectively, and 68 and 63 km from the Zhushuangcun grounding electrode, respectively, were selected as monitoring sites. The positions of the monitoring sites and the grounding electrodes are shown in Figure 1.

Figure 1. Positions of grounding electrodes and monitoring sites.

2.2. Monitoring Scheme of the Changyi Site

The Changyi site is not only an oil transportation station but also a cathodic protection station. In order to achieve segment protection, two insulating flanges, whose resistance generally exceeds 10 MΩ [18], were installed at both sides of the Changyi site, dividing the whole pipeline into two segments. Two potentiostats were used to compensate the stray current in the pipeline outside the two insulating flanges separately. In recent years, because the pipeline is out of service, there has been no need for segment protection, so only one potentiostat was used to protect the two segments of the pipeline at the same time by using a jumper wire connecting the outsides of the two insulating flanges. The structure of the cathodic protection station is shown in Figure 2.

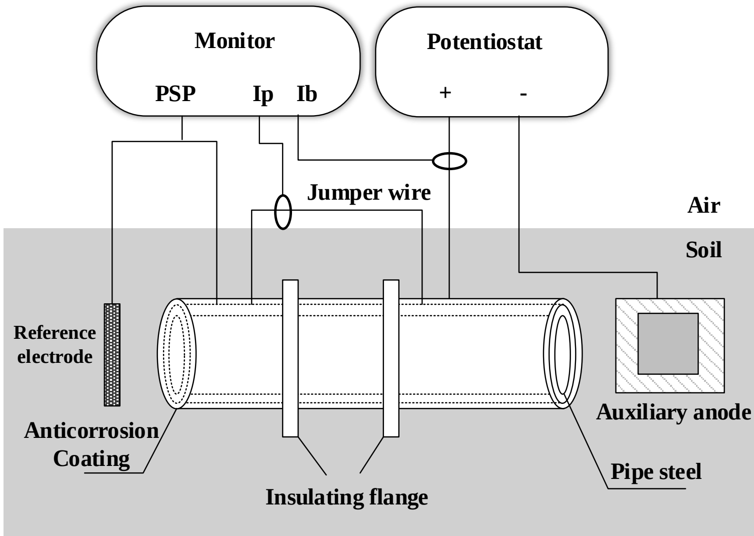

Figure 2. Structure of the cathodic protection station and installation of the monitor, the PSP of the pipeline is the potential difference between pipeline and reference electrode, *I*p is the current in jumper wire, *I*b is the current output by potentiostat.

The pipeline current (*I*p) is composed of the DC stray current (*I*s) and the potentiostat compensation current (*I*b), *I*p = *I*s + *I*b. Because the diameter of the pipeline is large, customized hall sensors are necessary. In addition, excavation is needed to measure the current in the buried pipeline. However, the jumper wire connects the outsides of the two insulating flanges, so all of the current in the pipeline is flowing through the jumper wire in this station. Therefore, the customized hall sensors could be replaced with common high-precision hall sensors to measure the current in the pipeline by installing the sensor on the jumper wire; at the same time, another common sensor was installed on the output line of the potentiostat to measure the compensation current. The PSP data were acquiring by using a hall voltage sensor, and a General Packet Radio Service (GPRS) module was used to transfer the collected data to a terminal database. The installation of the monitor is shown in Figure 2.

2.3. Monitoring Scheme of the Xiligu Site

The Xiligu cathodic protection station does not adopt the segment protection strategy. There is no insulation flange in this station. Therefore, we only monitored the PSP at this site. The PSP monitoring scheme was the same as that for the Changyi site which is shown in Figure 2. It should be noted that the output current and voltage of the potentiostat at the Xiligu site were normal during the commissioning of the Zhaqing project. However, at the time of the commissioning of the Shangshan project, the potentiostat was shut down and was unable to output the protection current and voltage.

3. Analysis of the Monitoring Data

The installation and debugging of the monitors were completed before 30 July 2017. The full-load commissionings of the Zhaqing project and the Shangshan project were carried out on 24 December 2017 and 2 January 2019, respectively. The monitoring data of the pipeline during these periods were obtained. The horizontal coordinates of the monitoring data were unified in Beijing time.

3.1. Analysis of the Effect of the Grounding Current from the Gaoqing Electrode on Pipelines

The grounding current from the Gaoqing electrode, the monitoring data of the pipeline including the PSP of the Xiligu site, and the stray current and the PSP of the Changyi site on 24 December 2017 are shown in Figure 3a–d, respectively. The potentiostats at Changyi and Xiligu stations operated normally during the commissioning.

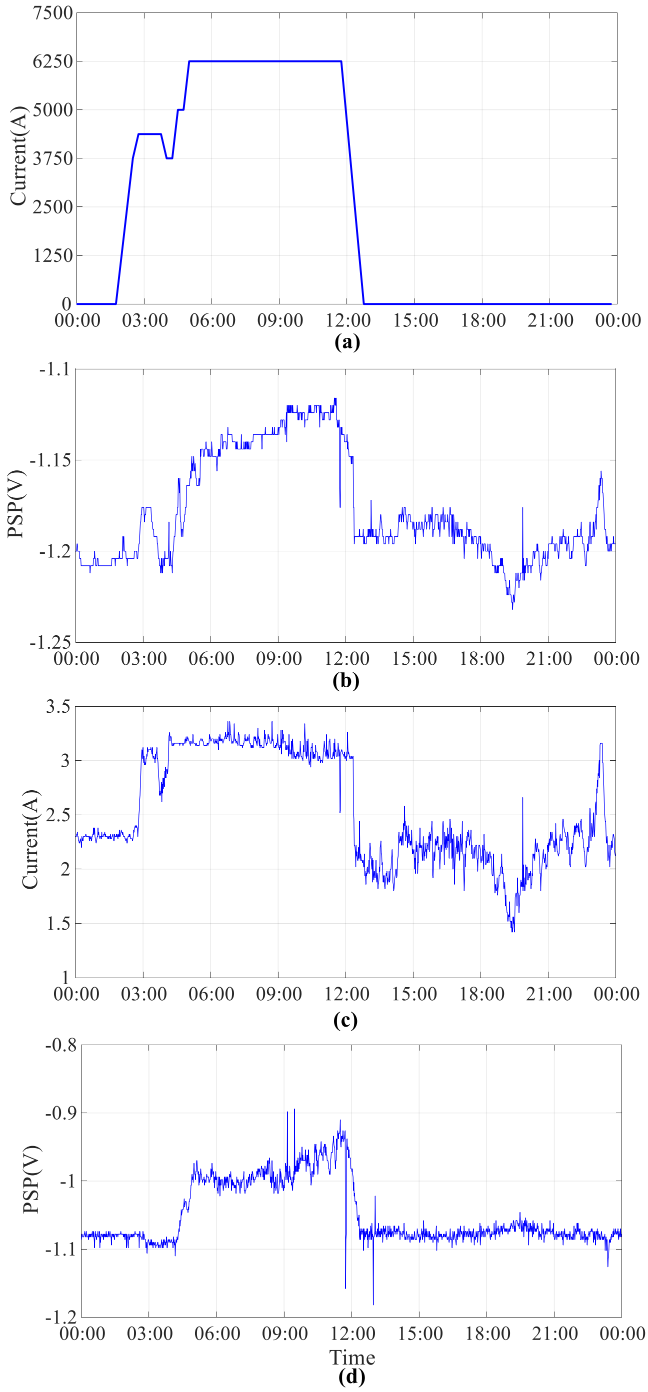

Figure 3. Monitoring data during the commissioning of the Zhaqing project on 24 December 2017: (**a**) Grounding current of the Gaoqing electrode; (**b**) PSP of the Xiligu site; (**c**) stray current of the Changyi site; (**d**) PSP of the Changyi site.

As shown in Figure 3, the monitoring data of the stray current and the PSP have a strong correlation with the grounding current. It is illustrated that the grounding electrodes 154 km and 187 km away from the pipeline can cause a stray DC current and PSP offset in the pipeline. The variation of the stray current and PSP during the period when there was no grounding current was caused by geomagnetic disturbance.

The variation characteristics of the stray current indicate that before the grounding current reached 4375 A, the correlation between the stray current and the grounding current was low. After the grounding current reached 4375 A, the correlation between the stray current and the grounding current was quite high. The variation characteristics of the PSP are similar to those of the stray current. Therefore, the grounding current reaching 4375 A can be regarded as a sufficient condition for pipeline interference by a grounding electrode 154 km away.

The analysis results show that the monitoring scheme in this paper is effective, and the monitor can also acquire the interference of geomagnetic disturbance on pipelines [18]. When the grounding current reached 6250 A, the maximum stray current of the Changyi site pipeline was 3.36 A. The maximum PSP offset at the Changyi site was 190 mV, and the maximum PSP offset at the Xiligu site was 94 mV. The standard [19] stipulates that DC current interference can be confirmed when the PSP is positively offset by 20 mV. Drainage or other protective measures must be taken when the PSP is positively offset by 100 mV. Therefore, for pipelines 154 km and 187 km away from the Gaoqing electrode, drainage measures are needed to prevent the large grounding current. If the cathodic protection device of the pipeline fails, the corrosion of pipelines will be accelerated and the service life of pipelines will be reduced.

3.2. Analysis of the Effect of the Grounding Current from the Zhushuangcun Electrode on Pipelines

Shown in Figure 4a–d are, respectively, the grounding current of the Zhushuangcun electrode, the PSP at the Xiligu site, stray current at the Changyi site, and the PSP at the Changyi site during the commissioning of the Shangshan project on 2 January 2019. Because the potentiostat of Xiligu Station was overhauled, the PSP we obtained is the natural potential.

The maximum stray current of the pipeline at the Changyi site was 13.6 A, the maximum PSP offset at the Changyi site was 900 mV, and the maximum PSP offset at the Xiligu site was 984 mV when the UHVDC grounding current was 6250 A. It can be seen that, compared to the commissioning of the Zhaqing project, the correlation between the stray current and the grounding current is stronger because the respective distances between the monitoring sites of the pipeline and the Zhushuangcun electrode are 68 and 63 km, which is nearer than the Gaoqing electrode. It is indicated that the pipeline would be more seriously interfered with by the grounding current from the Zhushuangcun electrode.

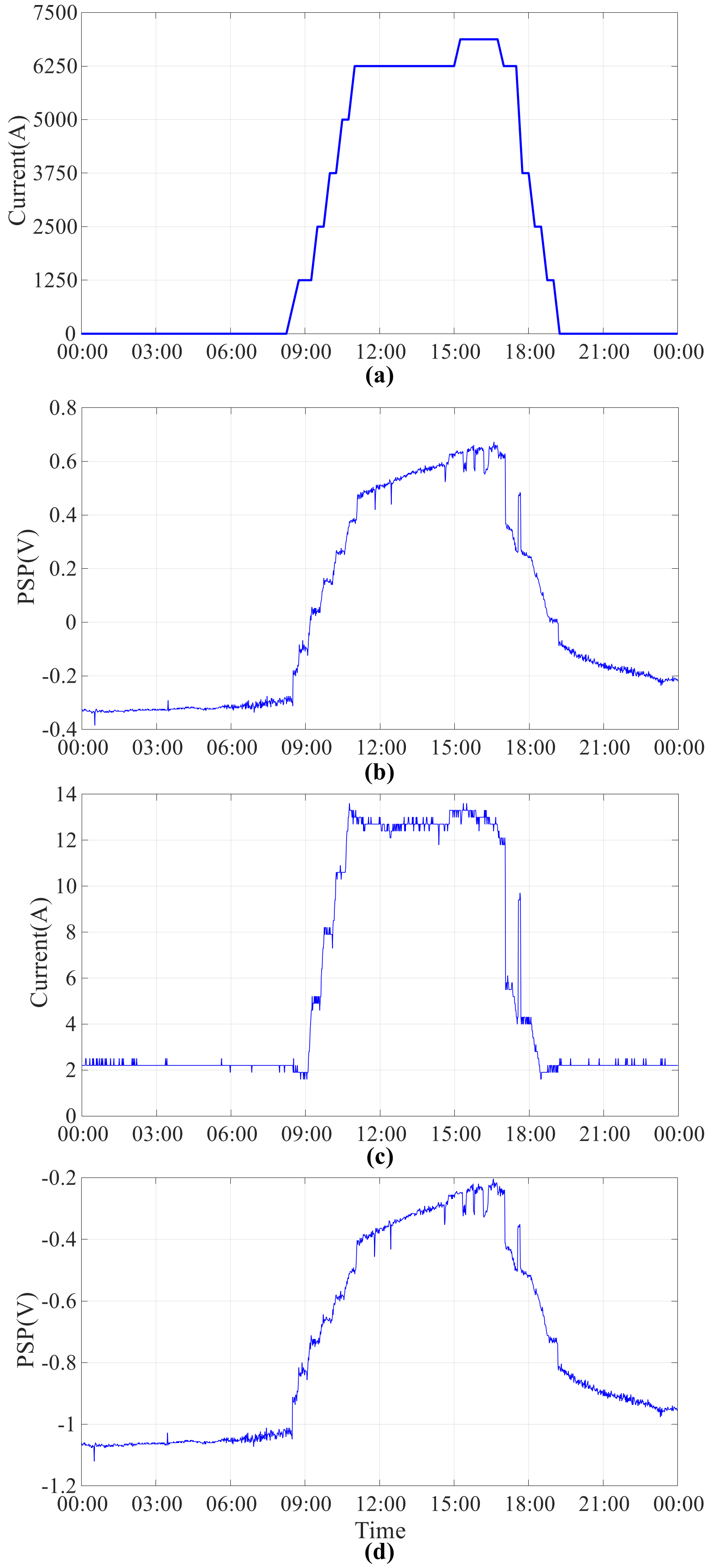

Figure 4. Monitoring data during the commissioning of the Shangshan project on 2 January 2019: (**a**) Grounding current of the Gaoqing electrode; (**b**) PSP of the Xiligu site; (**c**) stray current of the Changyi site; (**d**) PSP of the Changyi site.

4. The Law of Grounding Current Affecting Pipelines

In order to get the law of the effect of the grounding current from grounding electrodes on buried pipelines and to explain the problems reflected by the observation experiments, an equivalent circuit model of the buried pipeline was established according to the transmission line theory [9]; the distribution of the stray current and PSP in the pipeline was then calculated. The pipeline can be subdivided indefinitely into countless segments; the T-type equivalent circuit model of each pipeline segment can then be established as shown in Figure 5. $V(x)$ is the equivalent voltage source generated by grounding current, while Δx is the unit length of the pipeline. The calculation formulas of the stray current (I_1) and PSP (φ_0) are as follows:

$$I_1(x) = \frac{1}{2K}\int_0^{\infty} E_x(u)\left[\mathrm{e}^{-\gamma|x-u|} - \mathrm{e}^{-\gamma(x+u)}\right]\mathrm{d}u \tag{1}$$

$$\varphi_0(x) = \frac{1}{G}\frac{\mathrm{d}I_1(x)}{\mathrm{d}x} + \frac{\gamma}{2}\int_0^{\infty} V(u)\left[\mathrm{e}^{-\gamma|x-u|} - \mathrm{e}^{-\gamma(x+u)}\right]\mathrm{d}u \tag{2}$$

where $K = \sqrt{Z/G}$, $\gamma = \sqrt{ZG}$, Z is the equivalent impedance of a steel pipeline, G is the equivalent admittance of the insulating coating, and E_x is the electric field along the path of the pipeline.

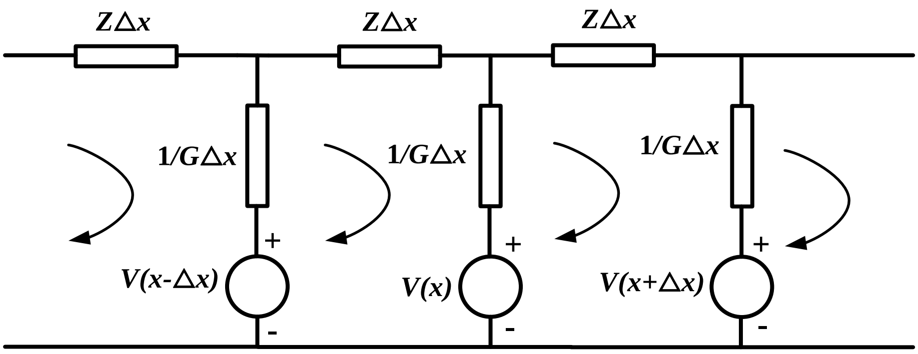

Figure 5. Equivalent circuit model of the pipeline.

The output current of the potentiostat in a cathodic protection station varies with the magnitude of the PSP. Its function is to output a current to compensate the lost electrons at the insulation coating defects of the pipeline. It can be regarded as a dynamic DC current source. Without considering the effect of the electromagnetic interference source, the circuit model of a pipeline under the protection of a potentiostat is shown in Figure 6.

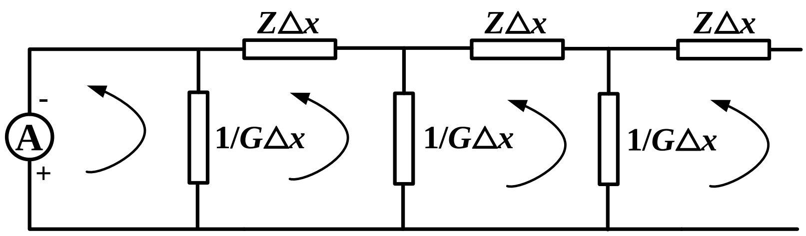

Figure 6. Equivalent circuit model of a pipeline with a potentiostat.

According to Figure 6 and Kirchhoff's law, the protection current (I_2) in the pipeline can be obtained as follows [6].

$$I_2(x) = -\left(C_1 e^{\sqrt{ZG}x} + C_2 e^{-\sqrt{ZG}x}\right) \tag{3}$$

$$C_1 = I_O - \frac{I_O - ZGI_O\Delta x^2 - I_O e^{\sqrt{ZG}}}{e^{-\sqrt{ZG}} - e^{\sqrt{ZG}}} \tag{4}$$

$$C_2 = \frac{I_O - ZGI_O\Delta x^2 - I_O e^{\sqrt{ZG}}}{e^{-\sqrt{ZG}} - e^{\sqrt{ZG}}} \tag{5}$$

I_O is the output current of the potentiostat, and the PSP (φ_i) produced by I_O is

$$\varphi_i(x) = I_2(x) \cdot \frac{1}{G\Delta x} \tag{6}$$

Therefore, the current and the PSP in a pipeline with a potentiostat under the interference of a UHVDC grounding current can be written as follows:

$$I(x) = I_1(x) + I_2(x) \tag{7}$$

$$\varphi(x) = \varphi_O(x) + \varphi_i(x) \tag{8}$$

The distance between the two grounding electrodes and the two monitoring sites as well as the length of each segment of the pipeline are shown in Figure 1. Considering the pipeline as an ideal pipeline, the parameters of the pipeline are $Z = 5 \times 10^{-3}\ \Omega\cdot\text{km}^{-1}$, $G = 5 \times 10^{-2}\ \Omega^{-1}\cdot\text{km}^{-1}$ [20]. During the commissioning of the Zhaqing project, the output current of the potentiostats in the two monitoring sites was 2 A when the grounding current was 6250 A. During the commissioning of the Shangshan project, the output current of the potentiostat at the Changyi site was 10 A when the grounding current was 6250 A, while the potentiostat at the Xiligu site had no output current. From Equations (7) and (8), the distribution during the commissioning periods of the stray current and PSP of the two pipeline segments containing the monitoring sites was obtained, as shown in Figure 7.

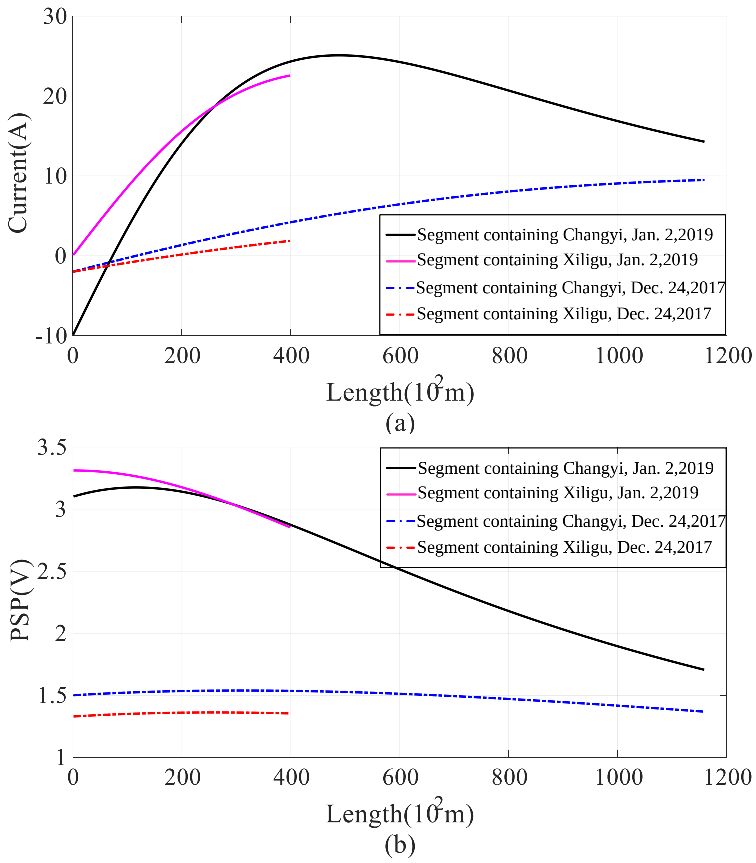

Figure 7. Calculation results of the stray current (**a**) and PSP (**b**) in the two pipeline segments during the commissioning of the two UHVDC projects.

According to the transmission line theory, when the pipeline is equivalent to a circuit connected by several T-type circuits, the grounding current is equivalent to a voltage source in each circuit. The output voltage of these voltage sources decreases with increasing distance between the pipeline and the grounding electrode, but the stray current generated by these sources accumulates with the increasing length of the pipeline. When the distance between the pipeline and the grounding electrode reaches a certain value, the voltage formed by the grounding current reaches zero. At this time, the stray current reaches its maximum value and gradually decreases with increasing distance. Therefore, the distribution of the stray current in the pipeline caused by the grounding current presents an approximate parabolic waveform as shown in Figure 7.

Compared with the Xiligu site, the Changyi site is farther away from the Gaoqing electrode, but the monitoring results show that the PSP offset at the Changyi site was larger than that at the Xiligu site during the commissioning on 24 December 2017. The calculation results of the stray current and PSP show that the reason for this phenomenon is that the distance between insulating flanges at both ends of the Changyi site is larger than that of the Xiligu site, and the stray current accumulates with increasing length of the pipeline. Therefore, the larger the distance between the insulating flanges is, the larger the stray current and PSP offset will be. In addition, Reference [21] calculated the effect of insulating joints on the distribution of the PSP. The results showed that insulating joints make the metal of the pipeline no longer an electrically connected conductor but a conductor divided into several insulation segments. At the same time, insulating joints do not change the ground potential around the pipeline. Thus, a pipeline with insulating joints cannot be regarded as an equipotential body. The potential difference between two adjacent pipeline segments may be very large, and the potential of each section of the pipeline is close to its own ground potential, so the magnitude of the PSP in the overall pipeline segment decreases significantly. Near their respective ground potentials, the overall PSP decreased significantly. The distance between the insulating flanges at both ends of the Changyi site is large; in order to reduce the effect of grounding current on the corrosion of pipelines, a more reasonable distribution scheme of insulation flanges should be adopted in this segment of the pipeline.

In addition, the operation state of the potentiostat has a great influence on the magnitude of the stray current and PSP offset. Compared with the Changyi site, the Xiligu site is farther from the Zhushuangcun electrode and the distance between its insulating flanges is smaller. However, the monitoring results in Figure 4 show that the PSP offset at the Xiligu site is larger than that at the Changyi site. The calculation results show that this phenomenon is caused by the potentiostat at the Xiligu site having no output during the commissioning, so the current in the pipeline did not contain the compensation current component.

Compared with the Gaoqing electrode, the Zhushuangcun electrode is closer to the pipeline. The monitoring and calculation results show that the magnitudes of the stray current and PSP offset generated by the commissioning of the Shangshan project on 2 January 2019 are much higher than those generated by the commissioning of the Zhaqing project on 24 December 2017. Due to the limitations of cathodic protection technology and the unreasonable distribution of the insulation flanges, the cathodic protection devices of the two monitoring sites cannot provide effective protection against the DC interference caused by the grounding current from the Gaoqing electrode, and the grounding current of the Zhushuangcun electrode will bring more serious corrosion. More effective drainage and protection measures are needed for the Dong-Huang oil pipeline.

5. Conclusions

In this paper, the monitoring data of the stray current and PSP in a pipeline generated by a 6250 A grounding current were obtained for the first time. According to the mechanism of pipeline corrosion caused by a stray DC current and the principle of cathodic protection, the main conclusions of this paper are as follows:

(1) The monitoring results show that the PSP offset of the pipeline 150 km away from the grounding electrode will exceed the limit of the drainage standard, due to the large grounding current of the high-power UHVDC project. The effect of the UHVDC project on the buried pipeline will be more serious in the range of 100 km from the grounding electrode. It is suggested that the effect of the grounding current on pipelines should be paid attention to in the design of the grounding electrode location during the initial stage of UHVDC project construction.
(2) The corrosion of pipelines near the grounding electrode can be reduced by the protection of the potentiostat. However, due to the limitations of the technology, for different pipelines, the protection effects and effective protection distances of potentiostats are very different. When the potentiostat fails to provide control or the pipeline exceeds the effective protection range, the corrosion is still very serious. As the scale of pipelines is getting larger and larger, the optimization design of cathode protection devices and the rational distribution of cathodic protection stations are problems that need to be solved in pipeline corrosion control work in the future.
(3) The effect of a UHVDC grounding current on buried pipelines is related to the distance between the grounding electrode and the pipeline, the operation state of the cathodic protection devices, and the distance between the insulation flanges. The smaller the distance between the insulating flanges is, the lower the values of stray current and PSP offset will be. Compared with the construction of cathodic protection stations and drainage devices, the proper distribution of insulation flanges is a more economical measure. It is suggested that the distribution of the insulating flanges needs to be improved and further research on protection against stray DC current in pipelines needs to be carried out.

Author Contributions: L.L. is responsible for the overall structure of the paper; Z.Y. conducts theoretical research and data acquisition; Z.J. is responsible for the simulation; J.H. is responsible for theoretical analysis; W.L. is responsible for the development of experimental equipment.

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