Study on Overvoltage and Protection of Buried Pipeline Near Lightning Strike Line Considering Soil Grounding Scatter

Jie Zhang, Ning Xiu, Bo Gao, Yinlong Wang, Ting Li, and Yongnai Zhang

Abstract At present, the cross-adjacent conditions of oil and gas pipelines and power lines are more and more frequent. The lightning overvoltage problem under the condition of "two lines—one ground" cross-adjacent to each other has attracted the attention of different industries. Aiming at the lightning overvoltage protection problem of oil and gas pipelines near power lines, firstly, COMSOL Multiphysics software was used to establish the calculation model of lightning overvoltage under the condition of "two lines—one ground" cross adjacent to each other, to clarify the production mechanism of pipeline potential and potential difference of anticorrosive layer. Secondly, the influence law of soil resistivity and soil stratification on the amplitude of pipeline overvoltage is analyzed by simulation calculation, and the method of pipe-line overvoltage protection considering the scatter flow of tower grounding grid is proposed. Finally, the pipeline pressure limiting effect of the optimized transformation scheme is verified by a simulation example and its engineering application value is demonstrated. The conclusions of this paper can provide a reference for the design, construction and safety operation and maintenance of oil and gas pipelines.

Keywords Oil and gas pipelines · Cross and proximity · Lightning overvoltage · Soil current dispersion

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1 Introduction

Due to the great difference between power and oil–gas energy transmission, the former mainly adopts the structure of overhead lines in non-urban areas, while oil–gas pipelines are usually buried in underground soil. Whether it is the power industry or the oil–gas industry, more and more attention has been paid to the safe and stable operation of the two energy transmission pipelines under the condition of "two lines and one ground" crossing each other [1]. For a long time, there have been many studies on electromagnetic compatibility between power lines and oil–gas pipelines in academia. The main research results focus on the induced voltage generated on buried oil–gas pipelines during the normal operation of AC/DC transmission lines, especially the influence of induced potential on pipelines, valve chambers, cathodic protection devices, etc. Some electromagnetic compatibility protection measures have been piloted in the "two lines and one ground" cross-neighboring project [2–5]. In addition to the impact of power lines on oil–gas pipelines under normal operating conditions, some studies have found that the current entering the ground along the tower after the lightning strike of the power line may cause a certain overvoltage risk to the adjacent pipeline. This is an earlier research report in this field in China. Reference [6] proposed that the lightning overvoltage of pipeline anticorrosive coating can be reduced by installing drainage belt and changing the structure of tower grounding device. In reference [7], the potential risk of pipeline lightning strike under the condition of "two lines and one ground" cross and adjacent is analyzed by the simulation calculation software CDEGS theory. The above research shows that in order to avoid the problem of lightning overvoltage in the case of "two lines and one ground" crossing and adjacent between power lines and oil–gas pipelines, clarify the mechanism of overvoltage generation on adjacent pipelines, and propose overvoltage protection measures with small engineering operation surface and low construction cost. It has high engineering application value in the design, operation and maintenance of oil–gas industry and power sector.

In this paper, aiming at the problem of lightning overvoltage in the case of "two lines and one ground" crossing and adjacent between power lines and oil–gas pipelines, a method of pipeline pressure limiting and drainage considering the dispersion effect of tower grounding grid is proposed to reduce the overvoltage amplitude on adjacent oil–gas pipelines. The overvoltage protection effect of this method is verified by simulation examples. This method does not change the structure of oil–gas pipelines. The overall engineering quantity and construction cost are low, and it has high feasibility.

2 Overvoltage Generation Mechanism and Simulation Model

2.1 Overvoltage Generation Mechanism of Adjacent Pipeline

Subject to the constraints of public land resources, the construction of power lines and the location of oil–gas industries generally adopt a common “energy corridor”. Therefore, power overhead transmission lines and buried oil–gas pipelines often share a common “energy corridor”. As shown in Fig. 1, the vertical distance between the power line and the oil–gas pipeline is even within ten meters. If the grounding grid of the tower is buried, the minimum distance between the underground scattered point of the tower and the pipeline even reaches several meters. Because the transmission line is above the surface, its tower top and lightning conductor are often struck by lightning. Most of the tower ground current components will disperse through the “lightning conductor (or tower top)-hit tower-buried grounding grid”. Due to the grounding current dispersion of the tower, on the one hand, it exists in the buried horizontal grounding grid, on the other hand, it relies on the reinforced structure inside the concrete pile foundation of the tower to carry out the grounding current dispersion [8]. Due to the direct contact between the oil–gas pipeline and the soil, the lightning current near the pile foundation of the tower will inevitably generate a certain amplitude overvoltage on the pipeline body [9]. Because the pipeline is a good conductor, if there is no insulation flange, the potential generated on the pipeline will have a greater impact on the outer insulation coating, and in some cases, there is a potential risk of electric shock to the remote pipeline operation and maintenance personnel.

Because the grounding resistance of the power industry tower is generally maintained within 10 Ω, and the shunt ratio of the lightning conductor is small, it is

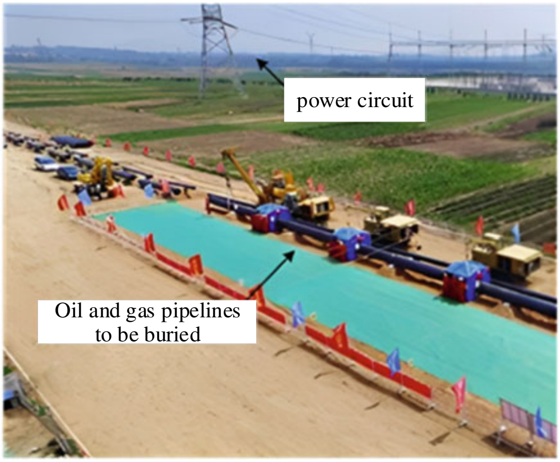


Fig. 1 Schematic diagram of “two lines and one ground”

generally considered that the resistive coupling component is the main factor in the case of lightning strike [10]. In addition, the insulation withstand voltage of the pipeline insulation coating is an important index to measure the lightning overvoltage problem when the power line and the oil–gas pipeline are adjacent to each other, and the damage degree of the insulation layer is related to the integrity of the pipeline surface and the pipeline structure: If there are damage points or metal flanges in the coating around the pipeline, the ground potential on the pipeline is high and the withstand potential of the coating is the potential difference on both sides. If the anticorrosive coating around the pipeline is intact and has no damage point, the metal pipeline body is grounded through the distal end. At this time, the tolerance potential difference of the pipeline anticorrosive coating is high, and there is a risk of insulation breakdown.

2.2 Simulation Model and Parameter Setting

Through COMSOL Multiphysics finite element simulation software, the calculation model of lightning overvoltage under the condition of "two lines and one ground" crossing and adjacent between power lines and oil–gas pipelines is established. The finite element simulation calculation can calculate the potential, current and electric field components of any point in the soil medium, and can solve the withstand voltage on the pipeline body and insulation coating. In the simulation model shown in Fig. 2, the distance between the tower and the natural gas pipeline is $d_{\mathrm{pg1}} = 40$ m, and the vertical distance between the extension end of the Φ12 mm galvanized steel grounding grid and the pipeline is d_{pg2}. According to the standard construction specification, the buried depth of galvanized steel grounding conductor and pipeline is 0.8 m and 1.5 m respectively, and the frame and extension of grounding grid are $l_{\mathrm{g1}} = 16$ m and $l_{\mathrm{g2}} = 20$ m respectively. The length l_{p} of the oil–gas pipeline is 500 m, the outer diameter is Φ530 mm, and the wall thickness of the steel pipe is 13 mm. Three layers of polyethylene material (3LPE) are used as the anticorrosion layer of the pipeline. The thickness of the insulation anticorrosion layer is 3 mm, and the surface resistivity ρ_F is 10^5 Ω·m.

The finite element simulation software can take any waveform as the excitation source. In order to accurately simulate the actual lightning current, this paper uses the wave front and half-wave length of 2.6/50 μs standard lightning current waveform recommended by the power industry test regulations when setting the input conditions. The standard lightning current double exponential function waveform is established in COMSOL Multiphysics finite element simulation software:

$$i(t) = 1.0474 I_m (e^{-14790.18t} - e^{-1877833t}) \tag{1}$$

According to the simulation calculation model shown in Fig. 2, the soil resistivity ρ under typical soil conditions is taken as 300 Ω·m, and the pipeline potential and the

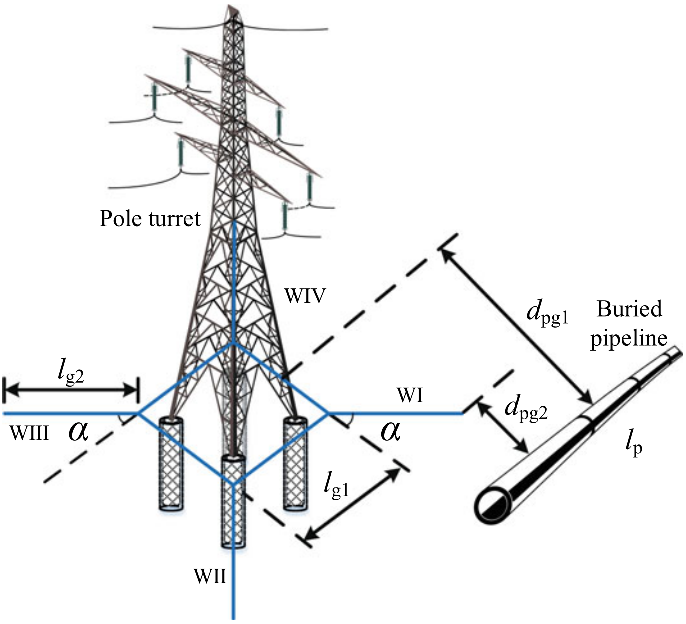
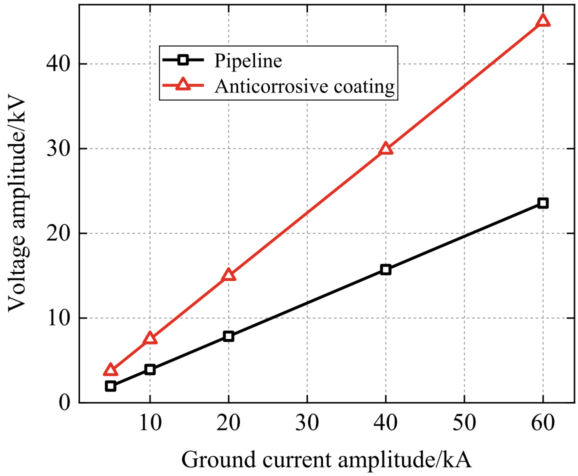


Fig. 2 Finite element model of "two lines and one ground"

corrosion resistance voltage difference under different lightning current amplitudes are shown in Fig. 3.

According to the simulation results of Fig. 3, it can be seen that the transient potential of the pipeline metal body and the insulation layer increases during the lightning flow to the soil medium around the tower, and the peak value reaches

Fig. 3 The potential of the pipeline body and the outer side of the anticorrosive coating

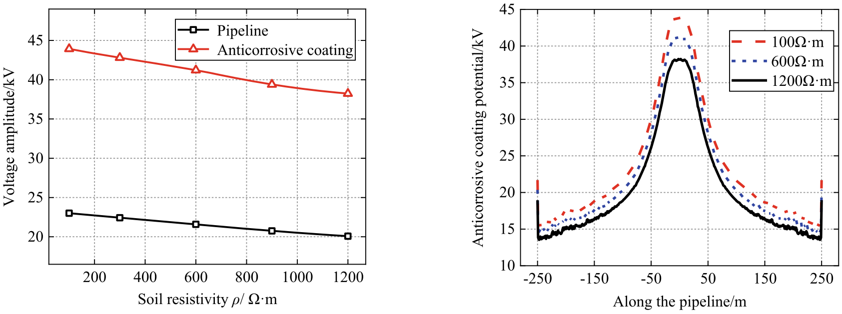


tens of kV. When the lightning current amplitude increases from 10 to 60 kA, the potential on the outer side of the coating and the potential on the metal conductor of the pipeline basically show a linear increase trend. Because the potential on the outer side of the coating increases more, the difference between the inner and outer sides of the pipeline increases accordingly. When the lightning current amplitude is 60 kA, the withstand voltage difference of the coating is 21.99 kV, and the transient voltage value is generally less than 109 kV of the 3LPE material [7, 11]. If there is a damage point in the pipeline, the leakage current of this amplitude is likely to further increase the damage gap. Because the metal body of the pipeline is a good conductor, there is a potential risk of electric shock to pedestrians or operation and maintenance personnel at the far end of the pipeline in a few cases.

3 Effects of Soil Conditions

In order to further analyze the influence of grounding current on the pipeline potential and the withstand voltage difference of the anticorrosive coating, considering that the actual pipeline laying soil and terrain conditions are different, the simulation parameters under different terrain conditions are different. Therefore, the finite element simulation software COMSOL Multiphysics is used to establish the lightning overvoltage calculation model of "two lines and one ground" of power lines and oil–gas pipelines under different soil conditions. The calculation results of the double exponential lightning current peak of 60 kA and the soil resistivity ρ in the range of 100–1200 Ω·m are shown in Fig. 4.

From the simulation results shown in Fig. 4a, b, it can be seen that the change of soil resistivity basically shows a linear change law on the potential of the pipeline body and the surface anticorrosive layer: when the soil resistivity is low, the lightning is released into the soil medium near the tower, and the dispersion flow can be completed



(a) External potential of pipeline body and coating.

(b) The potential distribution along the pipeline outside the coating.

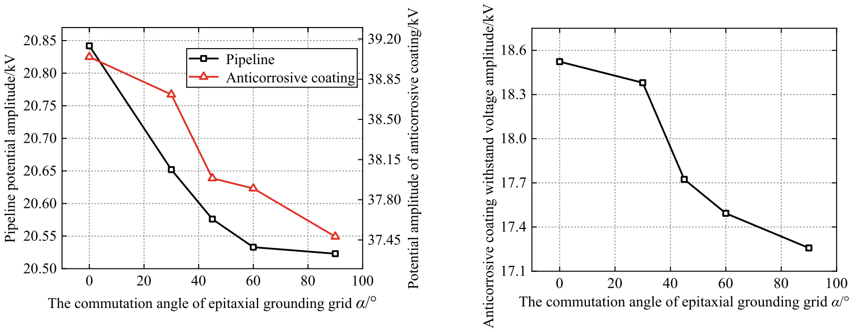
Fig. 4 Influence of soil conditions on pipeline overvoltage within a limited construction area, and the pulse current component to the far end, that is, the pipeline side, is less. When the soil resistivity increases from 100 to 1200 Ω·m, the pulse lightning current needs to be dispersed through the far end, which makes the current component on the side of the adjacent pipeline increase significantly, which will have an adverse effect on the potential on the side of the pipeline. From the simulation results, the withstand voltage difference of the pipeline coating under different soil conditions is still below 18.6 kV, and the withstand voltage difference does not exceed the limit withstand voltage (generally, the limit withstand voltage of the 3PE coating in uniform medium is about 109 kV). If the pipeline itself includes multiple layers, it can be considered not enough to break through the 3PE coating on the outside of the pipeline.

4 Effect of Grounding Structure on Pipeline Potential

The tower grounding grid is the main channel for lightning current discharge. The absolute distance between the grounding grid terminal and the pipeline is an effective way to achieve pipeline voltage suppression. Considering the actual power system lightning protection project, the structure of the general grounding grid has requirements for grounding resistance, and the grounding resistance of the tower needs to be limited within a certain range. Too many tower grounding bodies make the grounding resistance increase greatly, and the risk of power frequency freewheeling after lightning strikes the tower increases. The power frequency freewheeling problem caused by the lightning counterattack of the tower will cause the pipeline insulation layer to withstand milliseconds or even seconds of short-circuit impulse current.

Considering the actual lightning protection requirements of power towers, this paper proposes a corresponding structural optimization method for the tower grounding grid adjacent to oil–gas pipelines. By changing the angle and relative position between the epitaxial grounding grid and the pipeline, the structure of the grounding grid is optimized under the premise of maintaining the grounding resistance limit of the grounding grid, and the overvoltage protection of adjacent pipelines is realized. In the calculation model shown in Fig. 2, the angle between the epitaxial grounding grid and the vertical line of the pipeline is α, and the horizontal interval between the buried oil–gas pipeline and the tower grounding grid is consistent with Fig. 2. The distance between the center of the square galvanized steel grounding grid of the tower and the pipeline is $d_{\mathrm{pg1}} = 40$ m. The buried depth of the galvanized steel grounding conductor and the pipeline is 0.8 m and 1.5 m respectively. The peak current of the mine is set to 60 kA. The uniform soil resistivity ρ is 300 Ω·m, and the simulation results of α between 0° and 90° are shown in Fig. 5.

From the simulation results of Fig. 5a, b, it can be seen that as the angle α increases, the potential of the pipeline metal body and the outer side of the anticorrosive coating shows a certain trend: before the optimization and transformation of the tower grounding grid, the overvoltage amplitude of the pipeline metal body reaches 20.84 kV, the potential in the soil outside the anticorrosive coating is about



(a) Radial potential distribution of different α angle pipeline and coating outside.

(b) The withstand voltage distribution of anticorrosion coatings with different α angles.

Fig. 5 Influence of grounding grid structure optimization on potential distribution

39.36 kV, and the withstand potential difference $\Delta U_{\alpha 0}$ of the anticorrosive coating is about 18.52 kV. When α increases from 0° to 90°, the overvoltage amplitude of the pipeline metal body is about 20.52 kV and decreases to a certain extent. Due to the change of the dispersion direction of the grounding grid, the calculated value of the potential outside the anticorrosion layer is 37.78 kV. At this time, the withstand potential difference $\Delta U_{\alpha 90}$ of the anticorrosion layer is about 17.26 kV. The change of α limits the component flowing to the pipeline side, which limits the overvoltage peak value of the pipeline and the outer side of the anticorrosion layer to a certain extent.

5 Conclusion

Aiming at the problem of lightning overvoltage protection of oil–gas pipelines near power lines, a method of pipeline overvoltage protection considering the current dissipation of tower grounding grid is proposed. The mechanism of pipeline overvoltage is analyzed by simulation model and the application value of the optimization scheme is verified. The main research conclusions include:

(1) The potential of the pipeline body and the withstand voltage difference of the coating are greatly affected by the direction of the grounding body, and the two show a symmetrical distribution on both sides. The tolerance potential difference of the pipeline anticorrosive coating at the center point has zero crossing or even “reverse”. The axial potential of the pipeline is related to the distal grounding drainage point and the anticorrosive coating damage point.

(2) The withstand voltage difference of the pipeline coating under typical soil resistivity conditions does not exceed the limit value, and a single lightning discharge is not enough to break through the 3PE coating on the outside of the pipeline.

(3) By changing the angle and relative distance between the oil–gas pipelines and the tower discharge grounding grid, the tolerance potential difference between the pipeline body point and the anticorrosive coating can be effectively reduced.

The conclusions of this paper can provide reference for the design and safe operation of power transmission and oil–gas pipelines.

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