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Research on Lightning Overvoltage of Oil-Gas Pipeline Caused by Lightning Strikes on Adjacent Electrical Transmission Line

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As natural lightning strikes on a transmission tower, lightning current will flow along grounding lines into the adjacent tower grounding grid. As lightning current is dispersed from the tower grounding grid into the soil, a lightning overvoltage may be produced on adjacent pipelines. In this paper, the lightning current shunt characteristics in multi-tower scenarios are calculated by simulation method under different soil resistivity conditions. Then, based on the lightning current shunt characteristics, the current dispersion process among multi-tower grounding grids and the pipeline is analyzed with different soil resistivities, gap distances, and lightning current amplitudes. Finally, the protective effect of "drain wire" and "forced commutation" on pipeline overvoltage are compared. Simulation results showed that with increasing soil resistivity, tower grounding resistance was increased and tower shunt coefficient decreased. Considering lightning current through the multi-tower grounding grids, pipeline overvoltage is much larger than that of a single tower. Pipeline overvoltage is increased with soil resistivity and lightning current amplitude, while it is decreased with "pipeline-line" distance. Both "drain wire" method and "forced commutation" method can effectively reduce pipeline potential.

Keywords: transmission line, oil and gas pipeline, the multi-tower grounding grid, pipeline overvoltage, lightning strike

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INTRODUCTION

In recent years, accidents involving the explosion of oil and gas pipelines have happened occasionally in locations such as Kazakhstan, Shiyan in Hubei, and Huangdao in Qingdao. Restricted by land resources and pipeline transportation routes, transmission lines and pipelines are often crossed and parallel (Xun et al., 2017; Xun et al., 2020a; Rui et al., 2020; Yang et al., 2021a; Shen et al., 2021). When lightning strikes the transmission tower, most of the lightning current will flow into the ground through the grounding grid of the tower; but some lightning current also flows along grounding lines into adjacent towers. Lightning current dispersion through the tower grounding grid can create generation-induced overvoltage on the adjacent pipelines that may affect the safety of the pipeline (Hu et al., 2021; Yan et al., 2021). It is therefore of great significance to research the induced lightning overvoltage of pipelines from adjacent transmission lines (Xun et al., 2020b; Yang et al., 2021b).

Many people have done a lot of research work on the overvoltage and protection of the pipeline near the lines. In one study (WAN et al., 2009), the influence of "pipeline-line" distance, "pipeline-

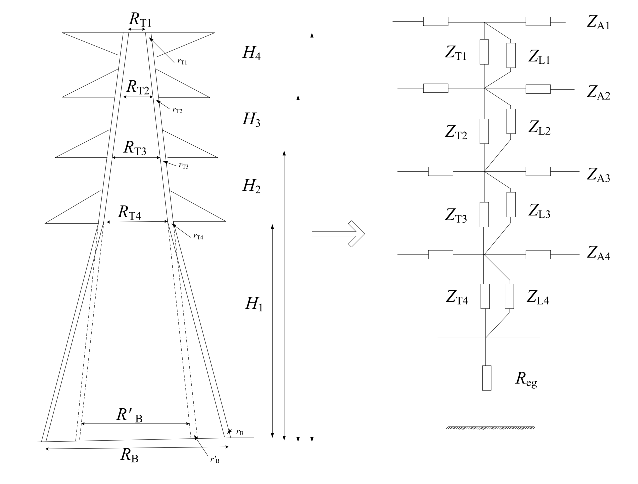

FIGURE 1 | Structure diagram of equivalent model.

line" crossing angle, and soil resistivity on pipeline overvoltage were analyzed in detail. Another (TAN et al., 2019) analyzed the effect of reducing the pipeline overvoltage by arrangement drain wire, and other research (WANG, 2017) has analyzed the pipeline overvoltage under three working conditions of the normal operation of the line, grounding fault, and lightning strike fault. Some studies have (Hongfeng et al., 2012; Ning et al., 2012; CHEN et al., 2017; Zhiqiang et al., 2019; Hongjie et al., 2021) used electromagnetic transient software ATP-EMTP to analyze the interference voltage of pipelines on lightning strike towers or researched the interference of pipelines on the direct current grounding electrode (Longhai, 2019; CHENG et al., 2021). This previous research largely considered the pipeline overvoltage caused by lightning current dispersion from lightning striking transmission towers nearby. However, few studies have considered the influence of multi-tower current shunts. Therefore, we conducted a series of studies on the pipeline lightning overvoltage, considering the current shunt effect of adjacent multi-tower grounding grids. The lightning current distribution feature of multi-tower grounding grids was calculated and analyzed under different soil resistivity conditions. Based on these calculation results, a lightning current dispersion model of a multi-tower grounding grid and oil and gas pipeline was built to analyze the effect of different soil resistivity, "pipeline-line" distance, and lightning current amplitude on pipeline overvoltage. Finally, a comparison study will be carried out between the protective effect of "drain wire" and "forced commutation" on pipeline overvoltage.

SIMULATION MODEL AND PARAMETERS OF TRANSMISSION LINE AND PIPELINE

To reduce the influence of the high-frequency component of lightning current on transmission line parameters, a frequency dependent Jmarti line model is applied (Salarieh et al., 2020). Considering the lightning current propagation process in a tower, the equivalent distribution multi-wave impedance tower model is used. The model equates the tower to the model shown in **Figure 1**; the calculation formula of the wave impedance of each part is as follows (Ishii et al., 1991).

$$Z_{Tk} = 60\left(ln\,\frac{2\sqrt{2}H_k}{r_{ek}} - 2\right)(k = 1, 2, 3, 4 \ldots\ldots) \tag{1}$$

$$Z_{Lk} = 9Z_{Tk}\,(k = 1, 2, 3, 4 \ldots\ldots) \tag{2}$$

$$Z_{Ak} = 60\ln\frac{2H_k}{r_{Ak}}\,(k = 1, 2, 3, 4 \ldots\ldots) \tag{3}$$

$$r_{ek} = 2^{1/8}\left(r_{TK}^{1/3} r_B^{2/3}\right)^{1/4}\left(R_{TK}^{1/3} R_B^{2/3}\right)^{4/3} \tag{4}$$

The lightning current will be damped to 0 after a traveling distance of five transmission spans (Visacro et al., 2004). Therefore, six spans are considered on both sides of a lightning struck tower. As shown in **Figure 2A**, T_0 represent the lightning strike tower, T_{Rx} and T_{Lx} represent the right and left towers of the lightning strike towers respectively.

The tower grounding grid and adjacent pipeline model is calculated by the finite element method. The grounding resistance of the grounding grid is calculated under different soil resistivities.

The grounding grid material is galvanized round steel with a diameter Φ = 16 mm. The buried depth is 0.8 m. The grounding grid is a square with a side length of 15 m and the extended grounding electrode length of 20 m. The angle between them is 135°. The down-lead length of the grounding grid is 0.8 m. The length of the oil and gas pipeline is 400 m with two ends grounded.

Transmission lines, tower grounding grids, and pipeline models are shown in **Figure 2B**. The "pipeline-line" distance D_1 and D_2 represent the distance between the T_0 and T_{R1} towers grounding grid and pipeline respectively. Here, the value of D_1+ D_2 is constant as 300 m.

CALCULATION OF LIGHTNING CURRENT SHUNT AMONG MULTI-TOWER GROUNDING GRIDS

Lightning Current Distribution

The applied waveform of the lightning current is 2.6/50 μs with an amplitude of 100 kA. The soil resistivity is 500 Ω m for lightning current is symmetrically distributed on the right and left sides of the lightning striking tower, lightning current distribution in towers is shown in **Figure 3A**. The lightning current through the T_0 tower is the largest of about 96 kA; the lightning current through T_{R1} and T_{L1} tower is about 24 kA. Because of the lightning current of the tower grounding grid and "pipeline-line" distance, the lightning current through the T_{L1} T_{R2}, T_{L2}, T_{R3}, T_{L3}, T_{R4}, T_{L4}, T_{R5}, T_{L5}, $T_{R6,}$ and T_{L6} towers are too small to affect the adjacent pipelines.

Lightning Current Shunt Coefficient

The lightning current shunt coefficient $\boldsymbol{\beta}$ of the tower reflects the lightning current entering the ground through the tower (WU and Xianglin, 2012; WU and WANG, 2014; Tang et al., 2015; Bai et al., 2016). The tower shunt coefficient β is defined as the ratio of the tower grounding current $\boldsymbol{I_t}$ to the total lightning current $\boldsymbol{I_z}$.

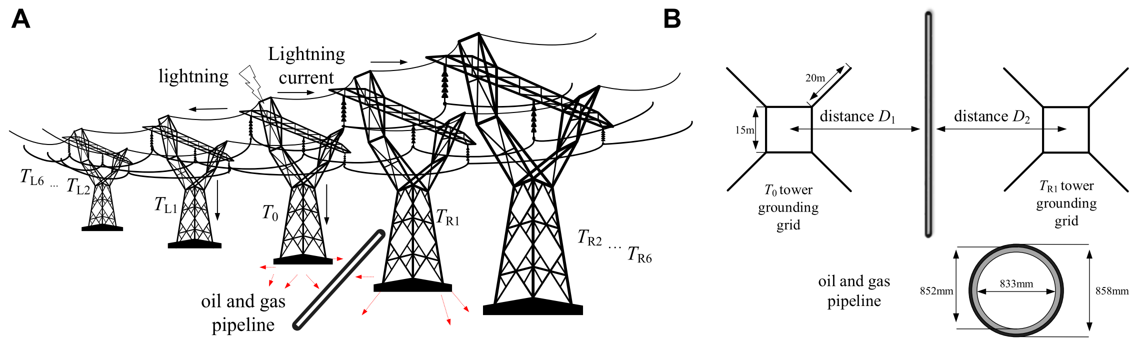

FIGURE 2 | Simulation diagram of tower grounding grid and pipeline. **(A)** shows the diagram of lightning striking case between transmission lines and oil and gas pipeline. **(B)** shows the relative position of the tower grounding grid and the oil and gas pipeline.

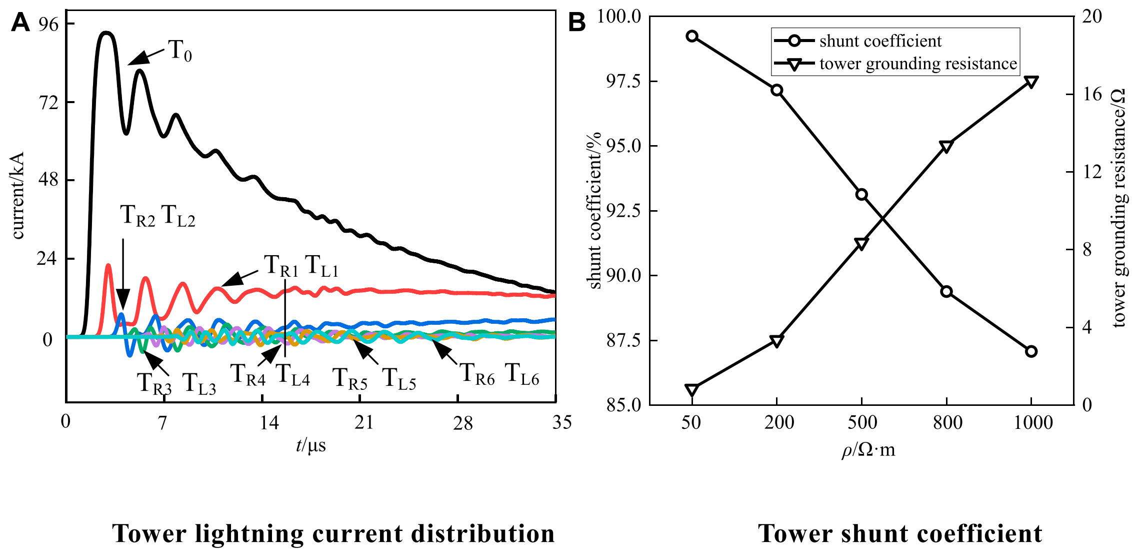

FIGURE 3 | Tower lightning current distribution. **(A)** Tower lightning current distribution **(B)** Tower shunt coefficient.

$$\beta = \frac{I_t}{I_z} \tag{5}$$

The grounding line shunt coefficient α is defined as the ratio of the current $\boldsymbol{I_{b1}} + \boldsymbol{I_{b2}}$ to the total lightning current $\boldsymbol{I_z}$. The $\boldsymbol{I_{b1}}$ and $\boldsymbol{I_{b2}}$ represent lightning current flowing through grounding lines on both sides of the tower.

$$\alpha = \frac{I_{b1} + I_{b2}}{I_z} \tag{6}$$

Grounding resistance directly affects the tower shunt coefficient. The soil resistivity is 50 Ω m, 200 Ω m, 500 Ω m, 800 Ω m, 1000 Ω m. The tower shunt coefficient is shown in **Figure 3B**. As the soil resistivity increases from 50 Ω m to 1000 Ω m, the tower grounding resistance increases from 0.84 to 16.7Ω. The tower shunt coefficient decreased from 99.2 to 87.1%. The reason is that with the decrease of soil resistivity, the lightning current is more likely to disperse in the soil, increasing the tower shunt coefficient.

PIPELINE OVERVOLTAGE UNDER MULTI-TOWERS LIGHTNING CURRENT DISPERSION

According to the lightning current distribution calculated in *Section Calculation of Lightning Current Shunt Among Multi-Tower Grounding Grids*, most of the lightning current flows through T_0 and T_{R1} as lightning strikes tower T_0 as shown in **Figure 1**. Hence, based on the lightning current distribution calculation results in *Section Calculation of Lightning Current Shunt Among Multi-Tower Grounding Grids*, the lightning

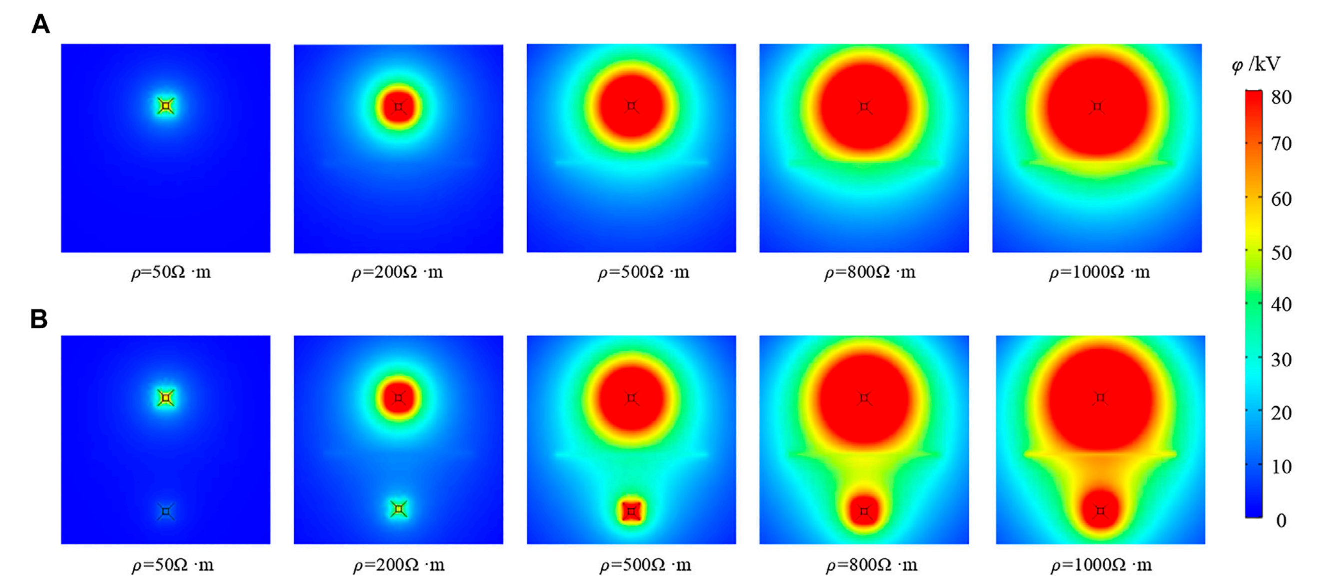

FIGURE 4 | Grounding grids, pipeline, and surrounding soil potential distribution.

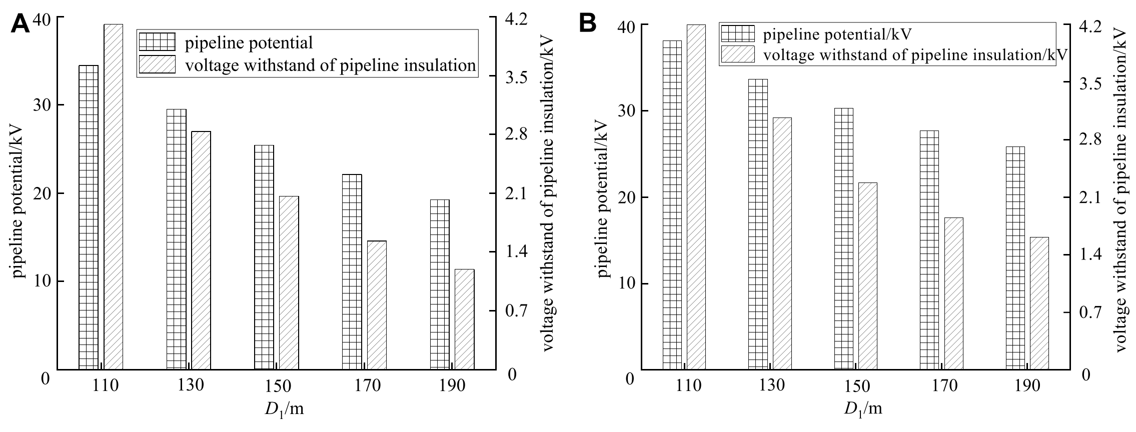

FIGURE 5 | Influence of D_1 on pipeline potential and insulating layer voltage. **(A)** shows the overvoltage of the grounding grid of the T_0 tower to the adjacent pipeline. **(B)** shows the overvoltage of the adjacent pipeline due to the common dispersion of the T_0 and T_{R1} tower grounding grids.

current of the T_0 tower grounding grid is obtained by the T_0 tower shunt coefficient $\boldsymbol{\beta}$. The lightning current of the T_{R1} tower grounding grid is obtained by fitting.

Effect of Soil Resistivity

To study the effect of soil resistivity on grounding characteristics of grounding devices (Heimbach and Grcev, 1997; Grcev, 2009; Visacro, 2018; Salarieh et al., 2019), the soil resistivity is taken as 50 Ω m, 200 Ω m, 500 Ω m, 800 Ω m, 1000 Ω m. The applied lightning current amplitude I_0 = 100 kA. The "pipeline-line" distance $D_1 = D_2$ = 150 m. Two individual cases are considered as only grounding grid of T_0 tower and two grounding grids of T_0 and T_{R1} tower. The potential distribution of grounding grids, pipelines, and surrounding soil are shown in **Figure 4**.

As the soil resistivity increases, the effective current dispersion region of the tower grounding grid gradually increases in both cases. The reason for this is that the increasing soil resistivity prevents the tower grounding grid current from flowing into the surrounding soil resulting in that most of the current diffuses the far end through the extended electrode.

It can be seen from **Figure 4** that in one case, only considering the grounding grid of the T_0 tower, as the soil resistivity increases from 50 Ω m to 1000 Ω m, the pipeline potential increases from 2.71 to 47.50 kV, while the pipeline insulation layer withstands voltage increase from 0.72 to 2.39 kV. In the other case, considering both grounding grids of T_0 and T_{R1} tower, as soil resistivity increases from 50 Ω m to 1000 Ω m, the pipeline potential increases from 3.22 to 57.41 kV. The pipeline

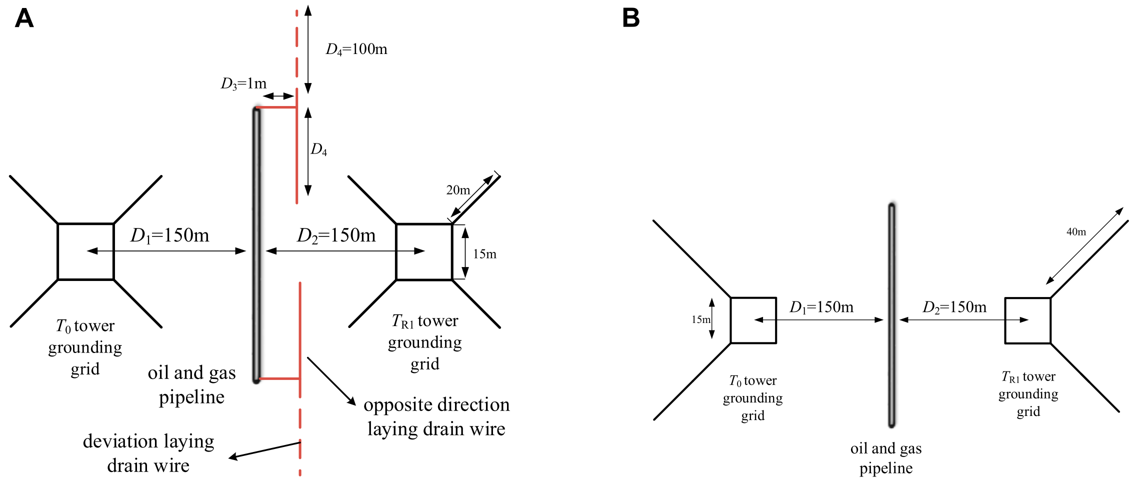

FIGURE 6 | Pipeline overvoltage protection methods. **(A)** shows the schematic diagram of drain wire in pipeline overvoltage protection measures. **(B)** shows the schematic diagram of forced commutation in pipeline overvoltage protection measures.

TABLE 1 | Influence of methods on pipeline potential/kV.

Methods	I_0 = 100 kA	I_0 = 85 kA	I_0 = 70 kA
No protection method	30.28	25.81	21.20
Opposite direction laying drain wire	29.75	25.39	20.87
Deviation laying drain wire	24.83	21.22	17.44
Forced commutation	27.36	23.28	19.15

insulation layer withstands a voltage increase from 0.80 to 2.67 kV. The pipeline potential and the voltage of the pipeline insulation layer is larger in the second case.

Effect of "Pipeline-Line" Distance D_1

To study the effect of "pipeline-line" distance D_1 on the pipeline overvoltage, distance D_1 is taken as 110, 130, 150, 170, and 190 m with D_1+D_2 = 300 m. The soil resistivity is 500 Ω m and the lightning current amplitude is I_0 = 100 kA. Pipeline potential and insulating layer voltage are as shown in **Figure 5**. In both cases, the pipeline potential and the withstand voltage of the pipeline insulation layer decreases with distance D_1.

Effect of Lightning Current Amplitude I_0

To study the effect of lightning current amplitude I_0 on the pipeline overvoltage, the lightning current amplitude I_0 is taken as 40, 55, 70, 85, and 100 kA. The soil resistivity is 500 Ω m and the "pipeline-line" distance D_1 = D_2 = 150 m. Pipeline potential and insulating layer voltage are calculated. When only considering grounding current dispersion of T_0 tower, the pipeline potential and the withstand voltage of the pipeline insulation layer increases with the lightning current amplitude I_0. When the lightning current amplitude I_0 increases from 40 to 100 kA, the pipeline potential increases from 10.18 to 25.45 kV, and the pipeline insulation layer withstand voltage increases from 0.83 to 2.06 kV. When considering grounding current dispersion of both the T_0 and T_{R1} tower, the pipeline potential and the withstand voltage of the pipeline insulation layer increases with the lightning current amplitude I_0. When the lightning current amplitude I_0 = 100 kA, the pipeline potential and the voltage of the pipeline insulation layer are the largest as 30.28 and 2.28 kV respectively. Compared with only considering the grounding current dispersion of T_0 tower, pipeline potential and pipeline insulation withstand voltage increases by 4.83 and 0.22 kV respectively.

Pipeline Overvoltage Protection Measures

Currently, most of the lines near the pipeline overvoltage protection methods are as shown in **Figure 6A**, where D_3 is the distance between the copper wire and oil and gas pipeline, D_4 is the length of copper wire. In this paper, a novel grounding current dispersion method of the "forced commutation" method is proposed for pipeline overvoltage protection, as shown in **Figure 6B**. This method is to connect the epitaxial rays of the grounding grid near the pipeline side to the other side. The epitaxial rays of grounding grids away from the pipeline side increased from 20 to 40 m.

To study the effect of drain wire and forced commutation on pipeline overvoltage, a simulation was conducted. During the simulation, the soil resistivity was 500 Ω m, and the lightning current amplitude I_0 was 70, 85, and 100 kA. The "pipeline-line" distance D_1 = D_2. The simulation results are shown in **Table 1**.

It can be seen from **Table 1** that laying drain wire and adopting forced commutation can reduce pipeline potential. When the lightning current amplitude I_0 is 70, 85, and 100 kA. The deviation laying drain wire makes the pipeline potential decrease 3.76, 4.59, and 5.45 kV respectively. The forced commutation makes the pipeline potential decrease 2.05, 2.53, and 2.92 kV respectively, even though the effect of lowering pipeline potential is weaker than deviation laying drain wire. If 200 m of copper is too expensive, and need to dig 200 m of channel, construction complex and difficult. In contrast, "forced commutation" requires lower engineering costs, and the construction is simple.

CONCLUSION

This paper focuses on the overvoltage problem affecting transmission lines near a pipeline, and examined the influence of the lightning current dispersion of multi-towers on adjacent pipeline overvoltage. In this paper, a novel grounding current dispersion method of "forced commutation" is proposed Based on the above research, the conclusions are as follows:

1) The tower grounding resistance and tower shunt coefficient were greatly affected by soil resistivity.
2) Considering lightning current through the multi-tower grounding grids, pipeline overvoltage is much larger than that of a one with a single tower. When the soil resistivity is 1000 Ω m, lightning current amplitude is 100 kA, and "pipeline-line" distance $D_1 = D_2$. Compared with single tower grounding dispersion, the pipeline potential increased by 10 kV.
3) Although deviation laying drain wire has the best protection effect on pipeline overvoltage, the forced commutation method is more economical and convenient.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding authors.

AUTHOR CONTRIBUTIONS

SH: conceptualization, writing-original draft preparation, simulation; YH: CDEGS software simulation: ATP-EMTP software and grounding test; JW: Assist with software simulation; YA: software; GL: project administration and data arrangement; ZL: supervision; YC: supervision and proofreading.

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