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Calculation of overvoltage on nearby underground metal pipeline due to the lightning strike on UHV AC transmission line tower

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A B S T R A C T

Making use of EMTP, the transient simulation of the currents along the towers and ground wires is performed when the lightning strikes the tower of the power transmission line. The investigation shows that the currents along the towers and ground wires dramatically decrease and can be ignored after 5 spans. And the effect on them for different impulse ground impedances, lightning current injection locations, tower spans, lightning wave impedances and so on are obtained when lightning strike on tower. With the help of Fourier transform, the method of moment is adopted to calculate the transient coating stress voltage of the pipeline and total electric field in the earth when the underground pipeline runs parallel to or crosses the power transmission line. The approximate formulas of the maximum coating stress voltage along the pipeline are proposed for the situation of crossing, which involve the lightning current, soil resistivity, pipeline models, tower grounding structure sizes and separation distance between the pipeline and tower grounding structure. Then, the proposed method can be used to evaluate the safety distance between the pipeline and tower grounding structure with the lightning electrical strength of the anti-corrosion coating of the pipeline. Eventually, if actual distance is less than the calculated value, modeling and analysis of protection measures in the pipeline can be carried out to protect the coating.

1. Introduction

With the fast development of economy in China, energy demand is gradually pressing and the power transmission line and oil/gas pipeline are in the construction of rapid development. Ultra high voltage (UHV) and West-East gas projects are the national key projects in recent years. Because of the similarity of transmission path selectivity in the power industry and oil/gas industry, the situations of parallelism, oblique approach and crossing between the transmission line and pipeline have frequently happened. Therefore, the electromagnetic influence on oil/gas pipeline near the transmission line becomes increasingly prominent [1].

The pipeline is subject to interference arising from three parts, capacitive, inductive and resistive coupling [2]. Capacitive coupling only affects the aboveground pipeline since it has both a capacitance to the transmission line and to earth. And the pipeline buried below ground is shielded by the ground and cannot be affected by capacitive coupling. Inductive coupling is caused by the time-varying magnetic field produced by the transmission line currents. The induced voltage at the pipeline ends will vary as a function of length of parallelism, earth resistivity, distance between the pipeline and transmission line, and so on. Aerial and underground pipelines are both affected by inductive coupling. Resistive coupling between the transmission line and pipeline is only relevant during the grounding fault and lightning strike when significant level of current flows into the earth. And this will raise the potential of the tower base and of the neighboring soil with regard to the remote earth, and result in a considerable stress voltage across the coating of the pipeline, which can lead to arcing that damages the coating, or even the pipeline itself. When the lightning strikes the transmission line, both the inductive and resistive coupling will take place and put the pipeline at severe risk.

The electromagnetic influence on the underground pipeline near transmission line is chiefly concerned with the personal safety, pipeline safety, alternating current (ac) corrosion of pipeline and normally operating of pipeline cathodic protection system [1]. Some research work has been carried out and the limits of electromagnetic influence are released. Dangers for people touching a metallic pipeline subjected to the electromagnetic influence of high voltage transmission line are strongly linked to the magnitude and the duration of the current injected into the body. The admissible voltage limits of the human body for long duration and short duration are presented in [1–5]. Long term ac interference on buried metallic pipeline may cause corrosion due to an exchange of alternating current between the soil and the bare metal

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at unavoidable coating faults in the structure. The current density limits are proposed for the evaluation of ac corrosion likelihood in [6,7].

Many studies focus on the inductive and resistive coupling modeling during the normally operating and ground fault of the high voltage transmission line. The transmission line method is used to predict the voltage induced on gas transmission pipelines by 60 Hz ac power transmission lines and some useful mitigation techniques are presented for the reduction of induced voltages [8–10]. Both the circuit method and electromagnetic field method are presented for simulating complex realistic right-of-way problems accurately and to investigate the effects of both conductive and inductive interference for arbitrarily positioned above-ground and buried conductors [11,12]. A hybrid method employing finite element calculation and standard circuit analysis is put forward to calculate the induced voltage and current on a pipeline running in parallel to a faulted power transmission line and the influence of a multilayer soil structure is also investigated [13,14]. When the power transmission line is subjected to the lightning strike on the tower, the analysis of the voltage induced on the nearby pipeline is rarely performed. In [15,16], a circuit-based model has been used to investigate the relative importance of lightning and switching surges in terms of their likelihood of causing damage to a parallel pipeline or equipment connected to the pipeline for different soil resistivities and lengths of parallelism. It has also examined the impact of conductive coupling between a tower footing and a pipeline.

In this paper, firstly, the transient simulation of the currents along the towers and ground wires is performed by the electromagnetic transient program (EMTP) when the lightning strikes the tower of the power transmission line. Secondly, with the help of Fourier transform, the method of moment (MoM) [17] is used to calculate the transient coating stress voltage along the pipeline parallel to or across the power transmission line and the corresponding approximate formulas are proposed for the situation of crossing. Finally, with the lightning electrical strength of the anti-corrosion coating of the pipeline, the safety distance between the pipeline and tower grounding structure can be evaluated for different lightning current and soil resistivity. And if actual distance is less than the calculated value, the designed overvoltage mitigation can be used to protect the coating.

2. Lightning currents along ground wires and towers

Making use of EMTP, the transient simulation of the currents along ground wires and towers is carried out when the lightning strikes the tower of the 1000 kV vertical-double-circuit transmission line. As illustrated in Fig. 1, the EMTP simulation model includes 24-span ground wires and 25-base towers, which is symmetrical with regard to the lightning strike point. The ground wires are symmetrically numbered from 1 to 12 while the towers are from 0 to 12, where the No.0 tower represents the location of lightning current injection. During the simulation, the lightning current is with the amplitude of 100 kA, waveform of 2.6/50 μs and wave impedance of 300 Ω. The two ground wires are modeled as the overhead transmission lines using the J. Marti model of EMTP and with the mean height of 84 m, radius of 8.5 mm, separation distance of 43 m and tower span of 500 m. The soil resistivity equals 100 Ωm. The tower is modeled as the multi-wave impedance transmission lines with the speed of light [18]. Fig. 2 shows the geometric sizes and transmission line models of the tower. Table 1 lists the corresponding characteristic impedances of the different transmission line models in Fig. 2, and the values of them are computed by the method presented by Hara et al. [19]. With the action of the large impulse lightning current, the ground impedance takes on the nonlinear and time-varying characteristic. Therefore, the accurate modeling of the ground impedance is a complex work. In order to analyze the law, it simplifies as a resistance with a fixed value in the simulation. Then the impulse grounding impedances of the tower are respectively 10 Ω, 20 Ω, 30 Ω, 40 Ω and 60 Ω. One thing worthy of note is that the so-called back-flashover toward phase conductors is not involved during the simulation.

Table 1
Characteristic impedances of transmission line models.

k	ZAk (Ω)	ZTk (Ω)	ZLk (Ω)
1	307	142	1278
2	313	135	1215
3	298	117	1053
4	280	80	720

Table 2
Amplitudes of transient currents along towers for different impulse grounding impedances (kA).

R	No.0	No.1	No.2	No.3	No.4	No.5
10 Ω	91.8	17.8	5.5	2.9	1.9	1.3
20 Ω	84.7	17.9	7.3	3.8	2.2	1.4
30 Ω	78.6	18.9	8.2	4.5	2.8	1.8
40 Ω	73.4	19.1	8.8	5.0	3.2	2.1
60 Ω	64.7	19.5	9.5	5.6	3.7	2.5

Table 3
Amplitudes of transient currents along ground wires for different impulse grounding impedances (kA).

R	No.1	No.2	No.3	No.4	No.5
10 Ω	20.0	9.0	4.3	1.7	1.1
20 Ω	24.9	13.0	7.9	5.1	3.6
30 Ω	27.6	15.6	9.9	6.8	4.9
40 Ω	29.3	17.4	11.5	8.1	5.9
60 Ω	31.4	19.9	13.9	10.1	7.7

Tables 2 and 3 list the amplitudes of transient currents along the towers and ground wires for different impulse grounding impedances of the tower. The results show that the variance of currents along the ground wires and towers is obviously lower than the variance of ground impedance. Therefore, for the regularity study, simplifying the grounding impedance as a resistance mentioned above is effective and can be used in the engineering. Fig. 3 shows the corresponding transient current responses when the impulse grounding impedance of the tower *R* equals 10 Ω. It can be seen that the currents along the towers and ground wires dramatically decrease and can be ignored after 5 spans for all the impulse grounding impedances under consideration. Almost 60–90% of the total intruding lightning current is discharged through the No.0 tower, where the lightning strike occurs. The higher the impulse grounding impedance of the tower *R*, the greater the currents along the ground wires, and the smaller the currents along the towers. Due to the reflections of the multi-wave impedance tower model, some high-frequency oscillations appear for the transient current responses.

Table 4
Amplitudes of transient currents along towers for different lightning current injection locations (kA).

x (m)	No.0	No.1	No.2	No.3	No.4	No.5
0	91.8	17.8	5.5	2.9	1.9	1.3
50	88.1	17.4	5.8	2.9	2.1	1.5
100	79.6	15.7	5.2	2.4	1.8	1.3
150	69.7	13.6	4.6	2.2	1.6	1.3
200	60.3	11.8	4.3	2.1	1.4	1.2
250	51.5	11.7	3.9	2.1	1.4	1.1

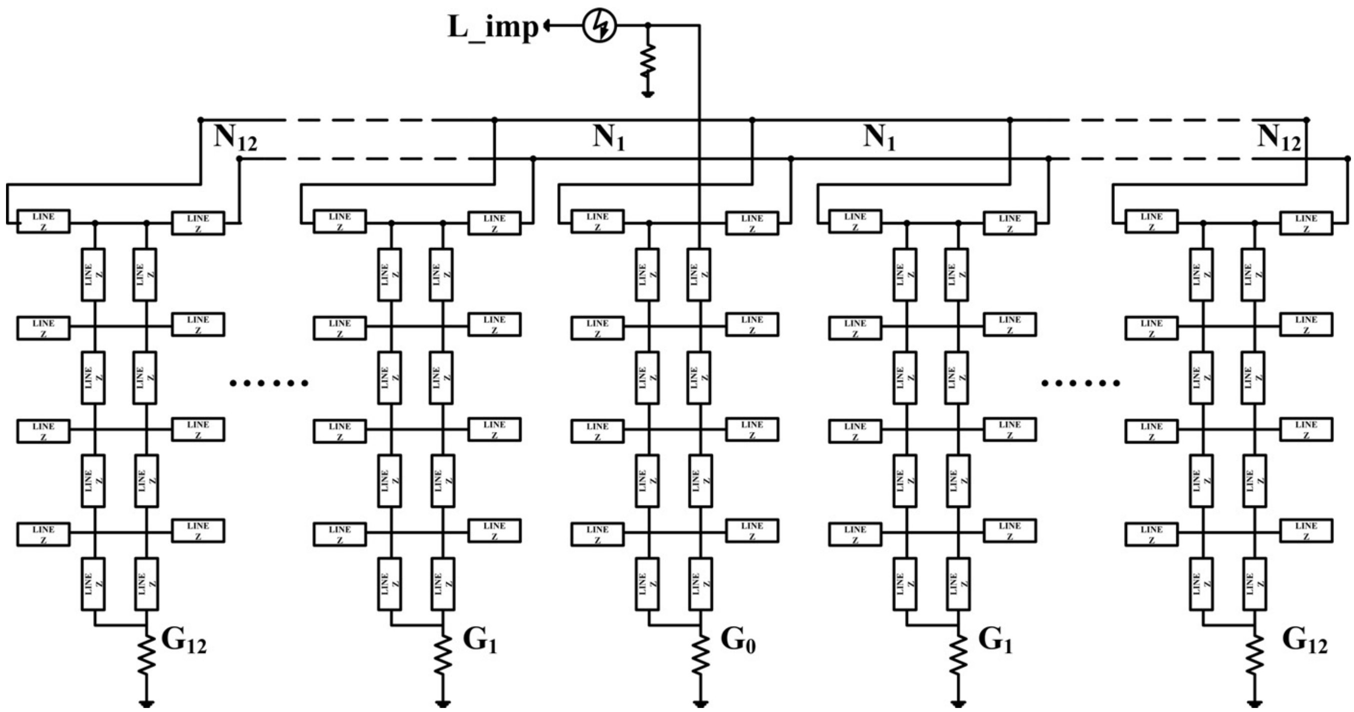

Fig. 1. Simulation model for EMTP.

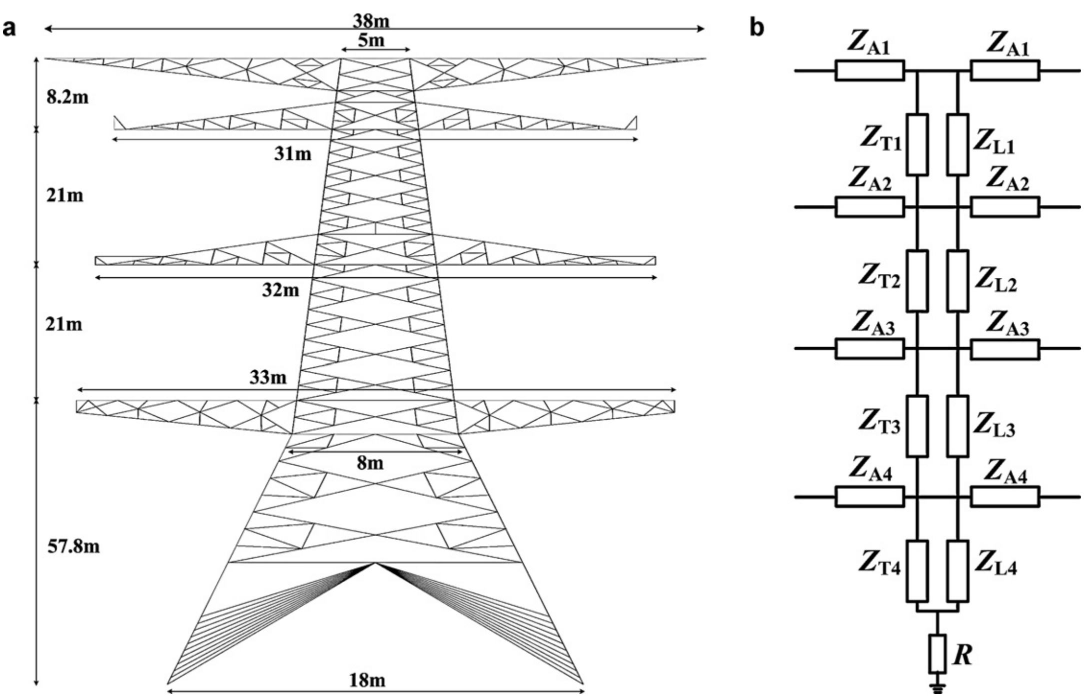

Fig. 2. Geometric sizes and multi-wave impedance TL models of the tower.

Table 5
Amplitudes of transient currents along ground wires for different lightning current injection locations (kA).

x (m)	No. x	No.1	No.2	No.3	No.4	No.5
0	–	20.0	9.0	4.3	1.7	1.1
50	89.5	22.7	9.5	4.9	2.9	2.1
100	77.9	20.1	8.6	4.4	2.4	1.8
150	66.6	17.9	7.9	3.9	2.1	1.5
200	58.0	16.4	7.4	3.7	1.9	1.4
250	49.0	14.6	6.9	3.5	1.7	1.3

Tables 4 and 5 list the amplitudes of transient currents along the towers and ground wires for different lightning current injection locations. Variable x is the distance from the lightning current injection point to the nearest tower which is numbered as the No.0 tower. The ground wire from the lightning current injection point to the No.0 tower is numbered as the No.x ground wire in Table 5. And the impulse grounding impedance of the tower R equals 10 Ω. It can be seen that the currents along the towers and ground wires vary greatly when the lightning current injection points change from the tower top to the center of the ground wire. The currents

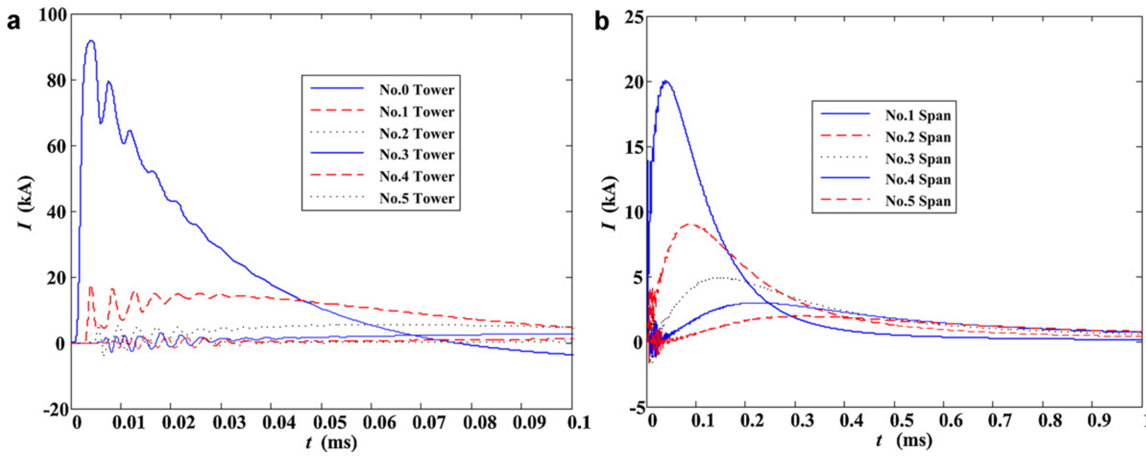

Fig. 3. Transient responses of currents along the towers and ground wires.

Table 6
Amplitudes of transient currents along towers for different tower spans (kA).

L (m)	No.0	No.1	No.2	No.3	No.4	No.5
400	91.3	17.8	6.1	3.3	2.6	1.6
450	91.6	17.8	5.8	3.1	2.1	1.4
500	91.8	17.8	5.5	2.9	1.9	1.3
550	91.8	17.7	5.3	2.6	1.8	1.2
600	91.8	17.7	5.3	2.4	1.8	1.2

Table 7
Amplitudes of transient currents along ground wires for different tower spans (kA).

L (m)	No.1	No.2	No.3	No.4	No.5
400	21.6	10.3	5.6	2.5	1.2
450	20.7	9.6	4.9	2.0	1.2
500	20.0	9.0	4.3	1.7	1.1
550	19.4	8.5	3.9	1.5	1.0
600	18.8	8.1	3.4	1.4	0.9

Table 8
Amplitudes of transient currents along towers for different lightning wave impedances (kA).

Z (Ω)	No.0	No.1	No.2	No.3	No.4	No.5
100	86.1	14.3	5.4	2.6	1.5	1.0
200	90.3	16.8	5.5	2.7	1.8	1.2
300	91.8	17.8	5.5	2.9	1.9	1.3
400	92.5	18.3	5.6	3.0	2.0	1.4
500	93.0	18.7	5.6	3.1	2.1	1.4

along the towers and ground wires are almost the same when *x* is less than 50 m which is often encountered in practical engineering situations. Consequently the lightning strike on the tower top is considered for further study. Tables 6–9 list the amplitudes of transient currents along the towers and ground wires for different tower spans and lightning wave impedances when the impulse grounding impedance of the tower *R* equals 10 Ω. It can be seen

Table 9
Amplitudes of transient currents along ground wires for different lightning wave impedances (kA).

Z (Ω)	No.1	No.2	No.3	No.4	No.5
100	19.4	8.8	4.2	1.7	0.9
200	19.9	8.9	4.3	1.7	1.0
300	20.0	9.0	4.3	1.7	1.0
400	20.1	9.0	4.3	1.8	1.1
500	20.2	9.0	4.4	1.8	1.1

Coating Stress Voltage for Parallelism.

that the tower spans and lightning wave impedances have slight effect on the lightning currents along the towers and ground wires.

Additionally, the EMTP modeling including100-span ground wires is also performed. The simulated results show that the above 24-span ground wires model can give almost the same results to those of 100-span ground wires model and consequently can meet the actual project needs. Especially, for the situations of parallelism or oblique approach between the power line and pipeline, both the inductive and resistive coupling are considered, and the simplified model is suggested due to the rapid decrease of the lightning currents along the towers and ground wires, which only includes 5 spans on each side of the lightning current injection point (10 spans in total). While for the situation of crossing, only the resistive coupling of the current in the earth through two towers adjacent to the pipeline is considered and the inductive coupling of the current along the overhead ground wires can be ignored during the simulation.

3. Coating stress voltage for parallelism

As illustrated in Fig. 4, the underground pipeline runs parallel to the overhead power transmission line for a length of 5 km, and then extends beyond the parallel routing without earthing. The simulation model for the method of moment includes 10-span ground wires and 11-base towers. The parameters of the steel ground wires are the same in Section 2. The tower is approximately modeled by 4 vertical thin conductors each with the resistivity of 1.66×10^{-7} Ωm, equivalent radius of 2 cm and relatively magnetic permeability of 636. Fig. 5 shows the configuration of the tower grounding structure, and 41 observation points are selected with the interval of 0.5 m, depth of 0.6 m along the Line 1. The buried conductors made of steel are with the radius of 6 mm, resistivity of 1.66×10^{-7} Ωm,

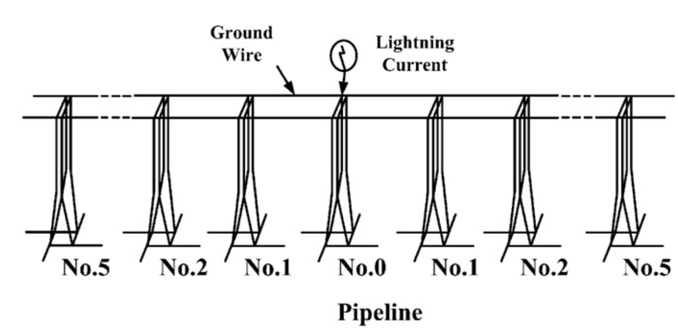

Fig. 4. Simulation model for the method of moment.

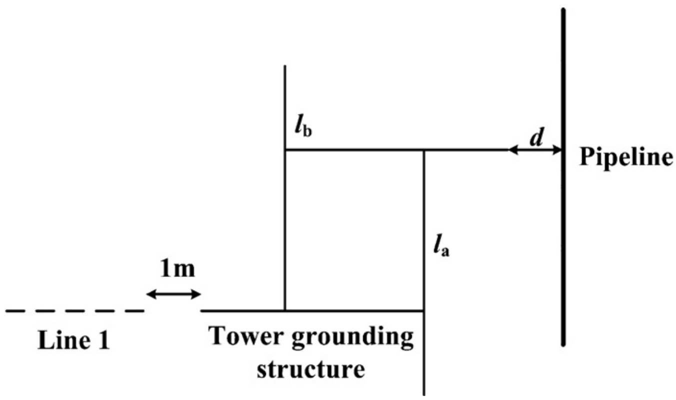

Fig. 5. Configuration of the pipeline and tower grounding structure.

relatively magnetic permeability of 636 and depth of 0.6 m. The lengths of side and outer lead of the square are, respectively 17.5 m and 5 m. The soil resistivity is 100 Ωm. The underground pipeline is with the depth of 1.7 m, inner radius of 485 mm, outer radius of 505 mm, resistivity of 1.66×10^{-7} Ωm, relatively magnetic permeability of 300. The anti-corrosion coating of the pipeline is with the thickness of 3 mm, relatively dielectric constant of 2.3 and insulating resistivity of 10^5 Ωm^2, which is an important parameter for evaluating the pipeline corrosion and can be expressed as the volumetric resistivity times the coating thickness.

For the ground network in Fig. 5 consisting of bare thin cylindrical conductors connected together (for instance the towers, ground wires and tower grounding structures) and insulated pipeline (the coating can be taken into account by applying the appropriate boundary conditions at the conductor/coating interfaces), a numerical frequency-domain method called the method of moment (MoM) based on the electromagnetic field theory proposed by Dawalibi [21] can be used in this paper. Before any computations are made, all conductors are subdivided into segments of length "small enough" with respect to both wavelength and overall length of the ground network. Although it is recognized that the selection of an optimum segment length is not at all a trivial task, the term "small enough" is taken to mean that the subdivision process is such that it will satisfactorily lead to the desired engineering accuracy. As a result the whole ground system is analyzed as a network of short conductors. Suppose that there are a total of n segments in the network, each characterized by its internal impedance and its coating leakage admittance, if any. If the longitudinal currents flowing in each segment are selected as the unknowns, a set of simultaneous linear equations can be achieved and solved based on the fundamental electromagnetic field equations. Then the field theory can be used to determine the potentials and fields resulting in points in the earth or on the conductors due to the leakage currents flowing from each segment. It is evident that the accuracy of the solution will depend on the number n of the whole ground network segments and on the degree of the polynomial used to represent the distribution of the longitudinal current within a conductor segment. In this paper the first-order polynomial is used to represent the longitudinal current distribution of each conductor segment. And the pipeline is subdivided into 1000 segments each with the length of 5 m, while the tower grounding system is subdivided each with the length of 1 m.

In order to obtain the transient voltage on nearby underground pipeline when the lightning strikes on the tower top of the UHV AC power transmission lines, firstly the lightning transient current is expanded into its frequency components by the fast Fourier transform (FFT). A finite number of currents consisting of the representative sample of the frequency spectrum are selected. Then the frequency domain voltage responses of the underground pipeline are evaluated using the MoM for each one of the selected currents. Once the voltage responses of the underground pipeline to all the single frequency sources have been computed, corresponding time domain behavior generated by the lightning transient current can be obtained simply by the inverse fast Fourier

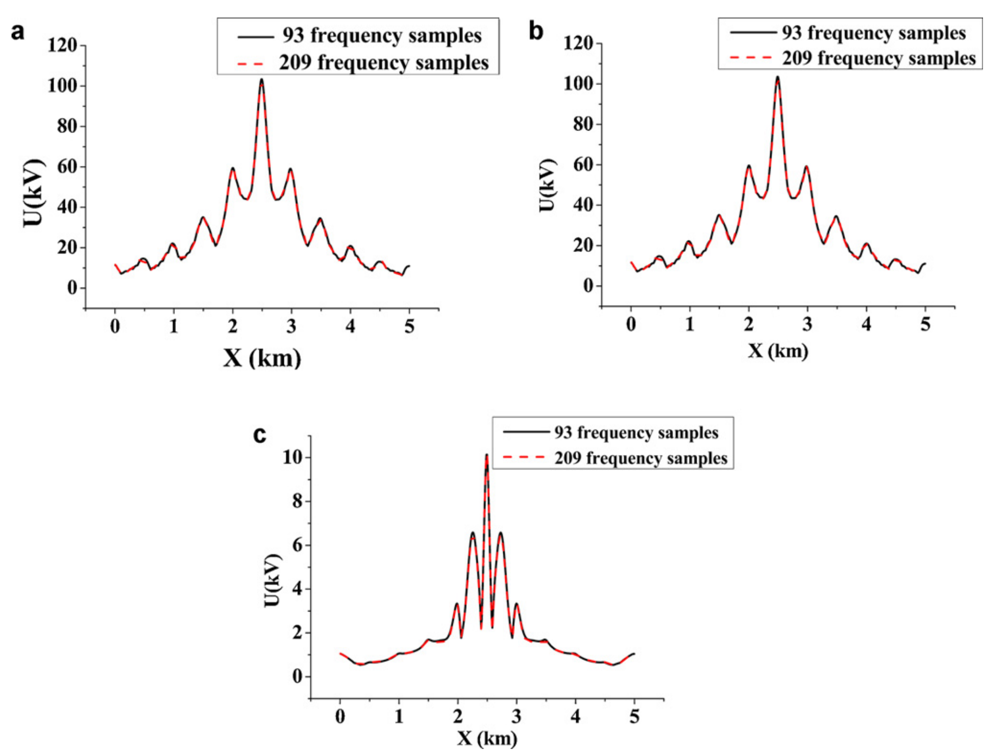

Fig. 6. Amplitude distribution of transient responses of pipeline voltage.

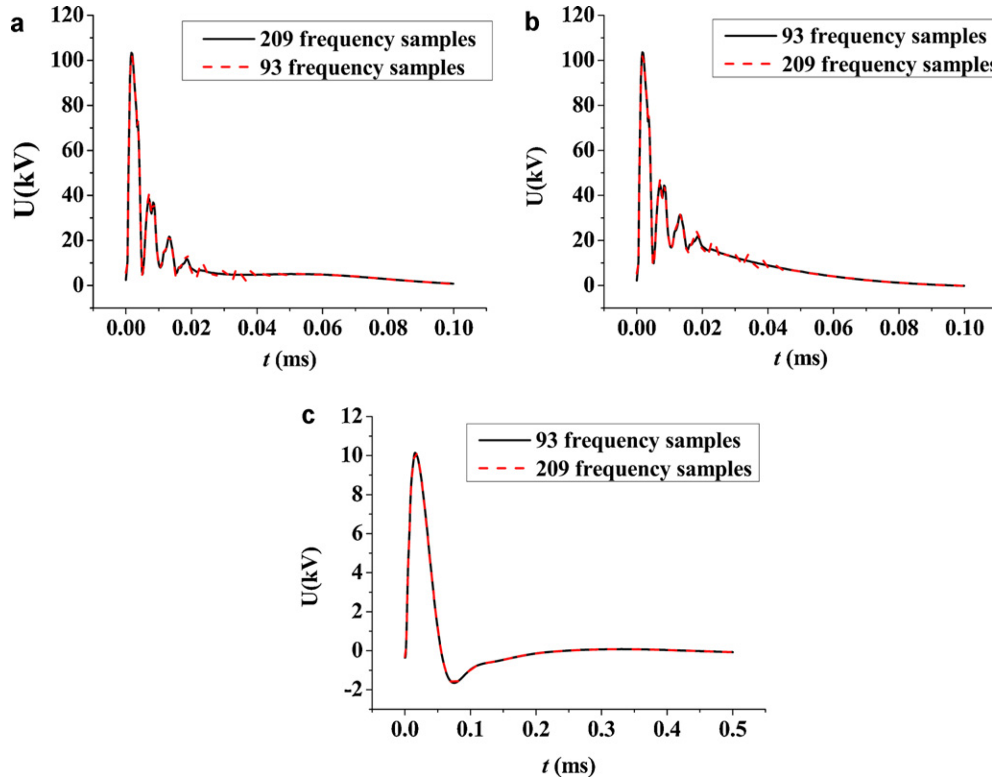

Fig. 7. Transient voltage responses at the midpoint of the pipeline.

transform (IFFT). In order to reduce computation time, appropriate interpolation method is used to minimize the size of the sample necessary to accurately represent the frequency spectrum. In this paper the main frequency spectrum of lightning transient current is considered to be less than 4 MHz and the calculations were done using both 93 and 209 frequency samples. As a result, the transient responses of the metal pipeline potential and coating potential are calculated. Actually, only the coating stress voltage is concerned with the pipeline's coating safety, which equals the difference between the metal pipeline potential and coating potential with regard to the remote reference earth. The parameters of lightning transient current are the same in Section 2. The distance *d* between the pipeline and the edge of the tower grounding structure is 50 m.

Fig. 6 shows respectively the amplitude distribution of transient responses of the metal pipeline potential, coating potential and coating stress voltage along the pipeline when the number of frequency samples equals 93 and 209, respectively. It can be seen that the simulated results of 93 frequency samples are almost the same to those of 209 frequency samples and can lead to the desired engineering accuracy. Consequently 93 frequency samples are adopted for the following simulation. The maximum values of the metal pipeline potential, coating potential and coating stress voltage along the pipeline appear at the midpoint of the pipeline, which is the nearest position of the pipeline to the lightning strike point. The metal pipeline potential and coating potential are very similar in the amplitude and slightly different in the waveform. Fig. 7 shows the transient responses of the metal pipeline potential, coating potential and coating stress voltage at the midpoint of the pipeline. It can be seen that the peak value of the coating stress voltage is about 10.1 kV, which is much less than those of the metal pipeline potential and coating potential. Fig. 8 shows the amplitude distribution of transient responses of the coating stress voltage along the pipeline for different approach distance *d*. It can be seen that the maximum coating stress voltages along the pipeline decrease rapidly with the increase of the approach distance *d*.

4. Coating stress voltage for crossing

As discussed above, when the pipeline crosses the power transmission line, only the resistive coupling of the current in the earth through the two towers adjacent to the pipeline needs to be considered during the simulation. Especially, when the pipeline is very close to one of the two towers, the resistive coupling of the current in the earth through the other tower can also be ignored. According to the grounding requirements for ac electrical installations in power system [5], the sizes of the tower grounding structure are distinct for different soil resistivity ρ. Table 10 lists the sizes, power frequency of 50 Hz grounding resistances R_{50} and impulse

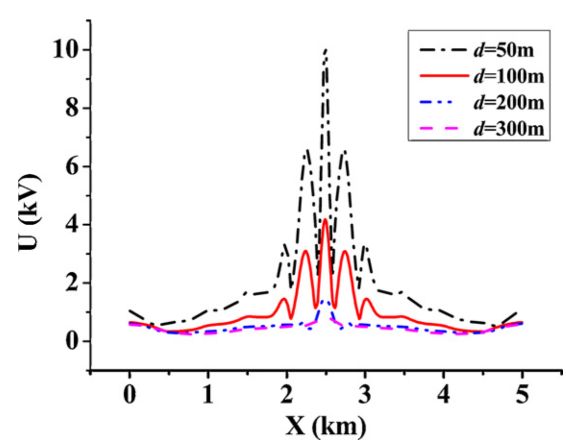

Fig. 8. Amplitude distribution of transient responses of the coating stress voltage along the pipeline for different approach distances.

Table 10
Sizes and grounding resistances of typical tower grounding structure.

	l_a (m)	l_b (m)	ρ (Ωm)	R_{50} (Ω)	R_t (Ω)	I_0 (kA)
Case 1	17.5	5	50	1.4	3.4	93
Case 2			100	2.8	5.1	93
Case 3		15	200	4.2	6.5	93
Case 4			300	6.3	8.3	93
Case 5		35	400	5.5	7.6	93
Case 6			500	6.9	8.7	92
Case 7		60	700	6.6	8.3	92
Case 8			1000	9.5	10.4	92

Table 11
Sizes of typical oil/gas pipelines.

Pipeline model	R_1 (mm)	R_2 (mm)	t (mm)
Model 1	54	49	1.8
Model 2	109.5	103.1	2.0
Model 3	203	196.7	2.2
Model 4	330	322.1	2.5
Model 5	406.5	395.5	3.0
Model 6	508	490.5	3.0

grounding resistances R_t of the typical tower grounding structure for different ρ. l_a and l_b are respectively the lengths of side and outer lead of the square in Fig. 5. When the lightning with the amplitude of 100 kA strikes on the tower top of the power transmission lines, the amplitude I_0 of transient current through the tower where the lightning strike occurs is also listed in Table 10. As a result, when the transient current with amplitude I_0 flows through the tower, a quarter of it will be incident at each corner of the grounding structure. The pipeline is with the length of 2 km and subdivided into 400 segments each with the length of 5 m, while the tower grounding system is subdivided each with the length of 1 m. Other parameters needed for the simulation are given below.

In order to investigate the total electric field in the earth, 41 observation points are selected with the interval of 0.5 m, depth of 0.6 m along the Line 1 in Fig. 5. The minimum distance between the observation points and the tower grounding structure is 1 m. With the pipeline removed, the transient responses of the total electric field in the earth along Line 1 are simulated and corresponding amplitudes are shown in Fig. 9 for different soil resistivity cases in Table 10. It can be seen that the total electric field in the earth dramatically decreases with the distance between the observation point and the tower grounding structure for all the soil resistivity cases under consideration. When the soil resistivity is 1000 Ωm, the peak value of the total electric field in the earth at the No.1 observation point (with the distance of 1 m to the tower grounding structure) is about 61.7 kV/m and much less than the breakdown electric field of 300 kV/m [20] of the soil.

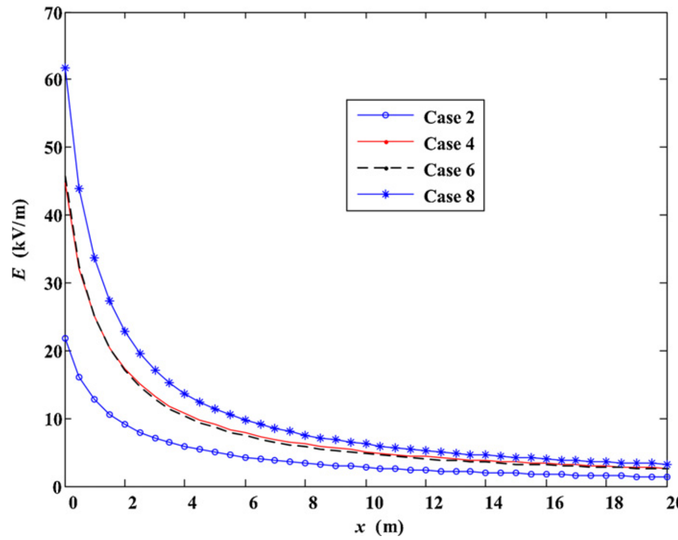

Fig. 9. Amplitudes of transient responses of the total electric field in the earth along Line 1 (Fig. 5) for different soil resistivity cases.

Table 11 lists the sizes of typical oil/gas pipelines including the inner radius R_1, outer radius R_2 of the pipeline and coating's thickness t. The anti-corrosion coatings of the different pipeline models are all with the insulating resistivity of 10^5 Ωm^2 and relatively dielectric constant of 2.3. With regard to the pipeline model 6 in Table 11, Fig. 10 shows the amplitude curves of transient responses of the coating stress voltage at the midpoint of the pipeline versus the separation distance d in Fig. 5 for different soil resistivity cases in Table 10. It is evident that the maximum coating stress voltage along the pipeline appears at the midpoint of the pipeline. It can be seen that the maximum coating stress voltages along the pipeline decrease rapidly with the increase of the separation distance d for all the sizes of the tower grounding structure in Table 10.

With respect to other five pipeline models in Table 11, the transient responses of the coating stress voltages along the pipeline are also investigated for different cases. By fitting the simulated results

Table 12
Coefficients A, B and C for typical pipelines and tower grounding structures.

Pipeline model	Coefficients	l_a = 17.5 m l_b = 5 m	l_a = 17.5 m l_b = 15 m	l_a = 17.5 m l_b = 35 m	l_a = 17.5 m l_b = 60 m
Model 1	A	−0.034	0.007	0.024	0.028
	B	11.77	8.22	5.02	3.10
	C	11.71	12.94	13.29	12.70
Model 2	A	−0.053	0.002	0.023	0.025
	B	11.54	7.44	4.43	2.74
	C	11.53	12.02	12.48	12.27
Model 3	A	−0.029	0.003	0.020	0.023
	B	10.11	6.87	4.03	2.39
	C	10.52	11.82	12.24	11.73
Model 4	A	−0.047	0.002	0.012	0.020
	B	10.42	6.59	3.75	2.13
	C	11.09	11.75	12.01	11.27
Model 5	A	−0.046	0.002	0.019	0.020
	B	10.35	6.57	3.73	2.12
	C	11.03	11.72	11.97	11.21
Model 6	A	−0.042	0.001	0.017	0.018
	B	10.12	6.23	3.51	1.95
	C	10.98	11.58	11.72	10.88

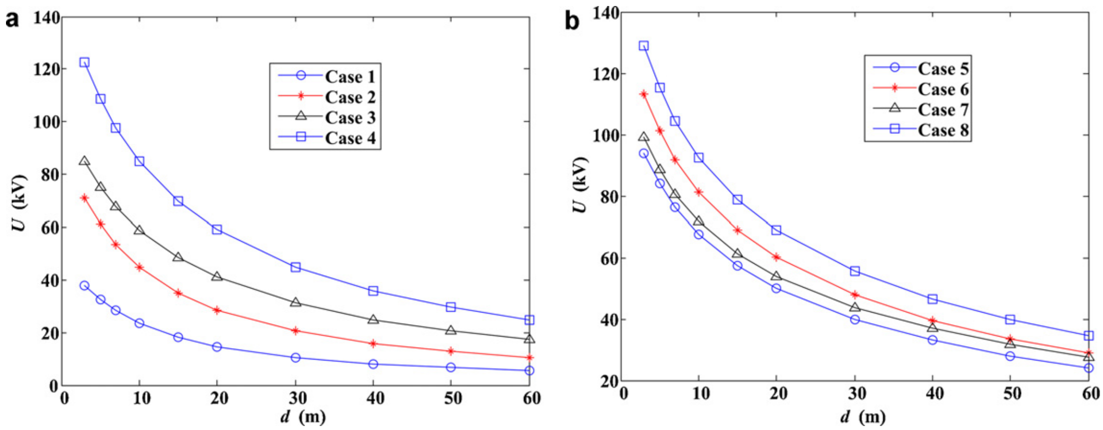

Fig. 10. Amplitudes of transient responses of the coating stress voltage at the midpoint of the pipeline for different ρ and d.

of the maximum coating stress voltage for different soil resistivity ρ, different separation distances d and different pipeline models, the corresponding approximate formula can be achieved

$$U_{\max} = \frac{Ad + B}{100(d + C)} I_0 \rho \tag{1}$$

where $U_{\max}$ is the amplitude of maximum coating stress voltage along the pipeline and with the unit of kV; I_0 is the amplitude of transient current incident at the tower grounding structure and with the unit of kA, which is slightly less than the total intruding lightning transient current; ρ is the soil resistivity and with the unit of Ωm; d is the separation distance between the pipeline and the edge of the tower grounding structure in Fig. 5, and with the unit of m. The coefficients A, B and C are listed in Table 12 for typical pipeline models and tower grounding structure sizes. Table 13 lists the maximum relatively differences between the simulated results using the MoM and the fitting results by (1) for different separation distances d. It can be seen that the maximum relatively difference is below 5%. As an application, Eq. (1) can be used to evaluate whether the pipeline's coating is in potential danger or not in practical engineering situations. Additionally with the lightning electrical strength of the anti-corrosion coating of the pipeline, the safety distance between the pipeline and the edge of tower grounding structure can also be evaluated approximately for different cases.

5. Mitigation of coating stress voltage

External pipeline coating can be subjected to stress voltage during the lightning strike on the nearby overhead power transmission lines. Properly designed mitigation (i.e., grounding) can reduce the coating stress voltage to protect the coating from disbandment or puncture. This, in effect, also protects the pipeline wall from arc burns and puncture, as the tolerable coating stress voltages are always lower than the conditions reported to cause damage to steel pipeline wall. The process of lightning mitigation is one of providing a path to earth from the pipeline to discharge the surge energy in such a way as to minimize the risk to personnel and the damage to pipeline and ancillary equipment. In general, the lower the resistance of these paths, the lower will be the voltage on the pipeline. It will usually be necessary to consider the effect of lightning protection on the cathodic protection design. Generally the direct current (DC) decoupling device which allows the flow of AC in both directions and stops or substantially reduces the flow of DC may be needed in series with the low-impedance path. Conductors used for bonding or for connections to grounding facilities shall have good mechanical strength and adequate conductivity. Generally copper conductor with some section is recommended for the practical engineering design.

As illustrated in Fig. 11, the pipeline is very close to the tower grounding facilities where the lightning transient current with the amplitude of 100 kA is injected. In order to mitigate the coating stress voltage of the pipeline, the bare copper conductor is connected to the pipeline through the DC decoupling devices with the resistance of 10 mΩ. The separation distance between the pipeline and tower grounding facilities is 5 m. The pipeline is with the length of 5 km. The soil resistivity is 100 Ωm. Other parameters needed for the simulation are the same in Section 3. The bare

Table 13
Relatively differences between simulated results and fitting results (%).

Pipeline model	Soil Resistivity ρ (Ωm)							
	50	100	200	300	400	500	700	1000
Model 1	0.9	0.9	1.0	1.0	0.7	0.7	1.4	1.5
Model 2	0.6	0.6	1.0	1.0	0.7	0.8	2.1	2.2
Model 3	2.4	2.5	1.2	1.2	1.1	1.1	3.0	3.2
Model 4	1.0	0.7	1.8	1.8	1.6	1.6	3.8	4.1
Model 5	0.8	0.9	1.8	1.9	1.6	1.7	3.8	4.1
Model 6	1.1	1.1	2.1	2.2	1.8	1.8	4.2	4.7

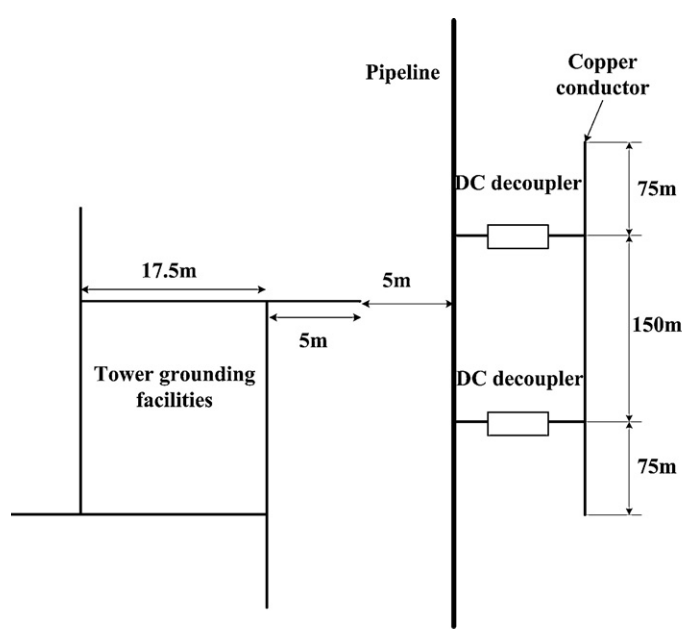

Fig. 11. Arrangement of the DC decouplers connected to the pipeline.

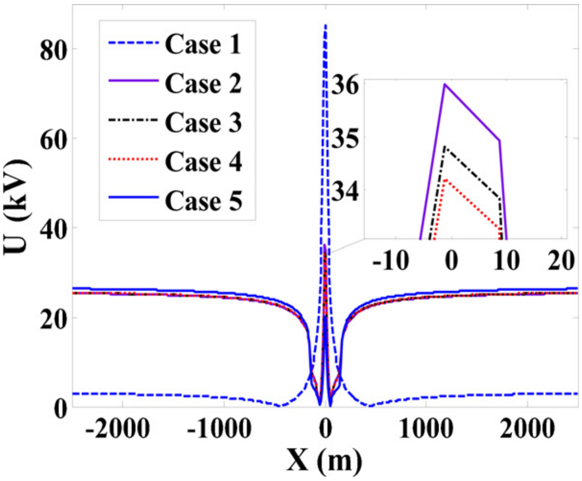

Fig. 12. Amplitude distribution of transient responses of coating stress voltage along the pipeline for different cases.

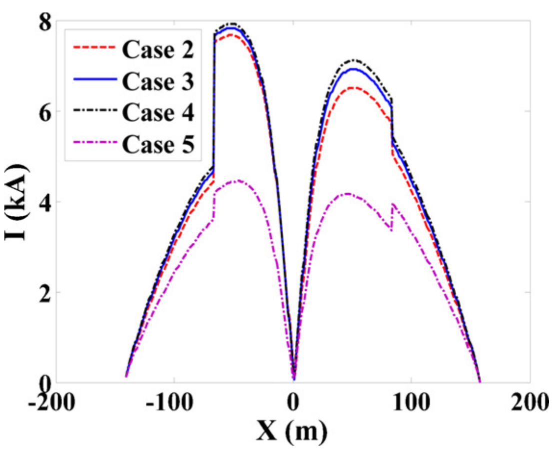

Fig. 13. Amplitude distribution of transient responses of current flowing in the copper conductor for different cases.

copper conductor is with the total length of 300 m and depth of 2.3 m, and located at the right side of pipeline with the separation distance of 1 m.

Fig. 12 and Fig. 13 respectively show the amplitude distribution of transient responses of coating stress voltage along the pipeline and current flowing in the copper conductor for different cases. In Figs. 12 and 13, the cases under consideration are as follows. Case 1: without the mitigation measure; Case 2: one copper conductor with the section area of 15 mm^2; Case 3: one copper conductor with the section area of 35 mm^2; Case 4: one copper conductor with the section area of 55 mm^2; Case 5: two copper conductors each with the section area of 35 mm^2 and located at the both sides of the pipeline. It can be seen that the maximum coating stress voltages along the pipeline for case 1–5 are respectively 85.1 kV, 36.0 kV, 34.8 kV, 34.2 kV and 26.4 kV, which appear at the midpoint of the pipeline. And the maximum currents flowing in the copper conductor for case 2–5 are respectively 7.6 kA, 7.8 kA, 7.9 kA and 4.4 kA. Clearly, the coating stress voltage can be greatly reduced if the pipeline is connected to the bare copper conductor through the DC decouplers. And coating stress voltages and currents flowing in the copper conductor are different for different cases, so we should carefully consider choosing appropriate types of copper conductors for different current-carrying capacity based on actual conditions.

6. Conclusion

With the example of the 1000 kV UHV AC vertical-double-circuit transmission line, the electromagnetic interference and mitigation on the nearby underground metal pipeline are researched when the lightning strikes on the tower in this paper. Making use of EMTP, the transient simulation of the currents along ground wires and towers is carried out for different impulse grounding impedances of the tower, lightning current injection locations, tower spans and lightning wave impedances. The results show that the currents along the towers and ground wires dramatically decrease and can be ignored after 5 spans. Almost 60–90% of the total intruding lightning current is discharged through the No.0 tower, where the lightning strike occurs. Additionally the impulse grounding impedances of the tower and lightning current injection locations have great effect on the currents along the towers and ground wires.

For the ground network consisting of the towers, ground wires, tower grounding structures and insulated pipeline, the method of moment is used to calculate the metal pipeline potential, coating potential and coating stress voltage when the underground pipeline runs parallel to the overhead power transmission lines. The simulation results show that the coating stress voltage is much less than both the metal pipeline potential and coating potential. Additionally the maximum coating stress voltage along the pipeline decreases rapidly with the increase of the approach distance, which appears at the nearest position of the pipeline to the lightning strike point.

Based on the method of moment, the transient responses of the coating stress voltage of the pipeline and total electric field in the earth are calculated when the underground pipeline crosses the overhead power transmission line. The investigation shows that the total electric field is much less than the breakdown electric field of the soil. The approximate formula of the maximum coating stress voltage along the pipeline is put forward, which involves the lightning current, soil resistivity, pipeline model and the separation distance between the pipeline and tower grounding structure. The simulation results show that the coating stress voltage can be greatly mitigated with the bare copper conductor connected to the pipeline through the DC decoupling devices. Additionally, we should carefully consider choosing appropriate types of copper conductors for different current-carrying capacity based on actual conditions.

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