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The Effect of Frequency-Dependent Soil Electrical Parameters on the Lightning Response of a 'Y' Shaped Composite Pylon for 400 kV Transmission Lines

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Abstract

In this paper, a novel composite pylon with 'Y' pattern for 400 kV transmission lines is introduced and its transient response to direct lightning strikes is investigated. The Donau and Eagle tower are also studied as a comparison. The paper focuses on the effect of the frequency-dependent soil model on the lightning response, including overvoltage stressed on the cross-arm (U_L) and ground potential rise (GPR) at both first and return strokes. The ground electrode is a vertical metal rod buried into a single or a multi-layer soil. The harmonic behavior of the soil ground impedance at a full-wave frequency is obtained by an accurate method of moment (MoM). The results show that Y-shaped composite pylon has lower U_L and GPR compared with the traditional towers when lightning strikes on the top of towers. This phenomenon is more evident for the soil with high resistivity. In addition, the length of the electrode rod can affect the inductive and capacitive characteristics, and a longer length rod would decrease the U_L and GPR level, especially when the soil resistivity is high. This research finding can provide a scheme to select ground rods under complex soil conditions.

1 Introduction

In recent years, the booming of renewable energy such as wind and solar power [1] stimulated the demand for new transmission lines [2-4]. Meanwhile, such transmission lines will realize the transmission and distribution of electric energy by cross-border transmission in Europe to decrease the generation costs and curtail CO_2 emission [3, 5]. Aiming to this transmission need growing, a new kind of transmission tower composed of composite materials is proposed for 400 kV transmission lines. The novel pylon has a 'Y' shaped appearance, and two bare conductors pass through the cross-arms and connect the shield wire with the steel cylindrical pylon body. The pylon with a compact structure can reduce the line corridor areas and the use of steel. It also benefits the component transportation and assembly in the process of construction. In addition to the economic advantages, this design embodies less visual impact with respect to the environmental impact [1, 6].

Lightning performance, such as lighting transient across the insulator (U_L) and ground potential rise (GPR) is one of the most concerning aspects for the reliability of the transmission tower operation, which directly affects the line protection design, human safety, and electromagnetic compatibility [7]. However, there is a lack of systematic research on the evaluation of the lighting performance of this composite pylon. As for this Y-shaped pylon, compared with the traditional tower, an evident advantage is the relatively low equivalent height of the pylon, which indicates the lower surge impedance of the shield wires and tower body [8]. In addition, there is less traveling time between the earth wire and the ground. However, there is also one potential downside that the radius of the downlead part inside the cross-arm is limited due to the cross-arm structure, which means a high surge impedance of the downlead. It is of great importance to evaluate the lightning performance of this kind of pylon.

Besides the configuration of the tower, the ground impedance is another critical factor influencing the lightning response [9]. Thus, when tower overvoltage simulation research is carried out, the rationality of the simulation ground model directly determines the accuracy of tower overvoltage. Frequency-dependentground model is an exact model which is based on experimental tests. This model can well present the variation of the capacitive or inductive characteristics along with frequency, which is proved to have a significant influence on the calculation error [10]. Moreover, it can also be used to simulate complicated soil conditions such as non-uniform soil [11]. Other soil parameters such as dielectric constant and moisture content are also considered simultaneously [12]. Thus, to evaluate the lighting performance of this composite pylon, the frequency-dependent model is a good candidate for precise estimation.

In this paper, a multi-story model is built, and a frequency-dependent soil model is adopted to analyze the overvoltage across the cross-arm and on the ground under first and subsequent lightning strikes. A contrastive study on the typical traditional Donau tower and Eagle tower is also conducted. The uniform and multi-layer soil with different resistivity and lengths of electrode rods are taken into consideration. In section 2, the surge impedance is determined by electromagnetic method and built in PSCAD. The frequency-dependent soil model is also expressed. Section 3.1 presents the ground impedance electrical behaviors as a function of frequency with different soil resistivity and electrode rod length. Then, there are comparison results regarding U_L and GPR shown in sections 3.2 and 3.3. The analysis is performed to demonstrate the synergistic effect of the soil characteristics and electrode length on the lightning response. Finally, section 4 summarizes the comparison results of lighting performance among Y-shaped pylon and traditional towers.

2 Tower and ground modeling

2.1 Tower structure

The composite pylon has a 'Y' structure, and two unibody cross-arms, each with a length of 12 m carrying a two circuit transmission lines. The angle between the cross-arm and horizontal line is 30°. Two shield wires are mounted on the tip of cross-arms, and each cross-arm holds three two-bundle conductors. The interval between phase conductors and upper phase conductor to shield wire are 3.4 m and 2.8 m, respectively [13]. Two bare conductors with radii of 1.75 cm going through the two cross-arms are connected together with the steel mast. Donau tower and Eagle tower are also studied for the purpose of comparison. The configuration of the composite, Donau towers, and Eagle tower are illustrated in Fig. 1. Table 1 shows the structure parameters of the three types of towers.

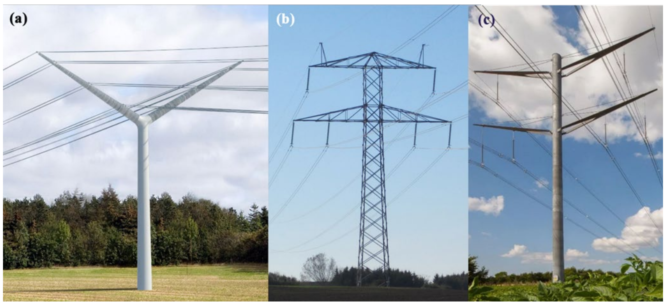

Fig. 1 The appearance of the (a) Y composite pylon, (b) Donau tower, and (c) Eagle tower.

Table 1 Structure parameters of Y pylon, Eagle, and Donau towers

Parameter	Y pylon	Eagle tower	Donau tower
Tower height [m]	22.5	43.10	41.67
Conductor height [m] Upper conductors	21.1	35.75	34.6
Middle conductors	19.3	24.03	25.8
Lower conductors	17.5	24.03	25.8
Tower base radius [m]	1	0.8	5
Radii of conductors and wires [m]	0.0175	0.0175	0.0175
Distances between shield wire to conductor [m]	2.8	3.2	3.2
Distances between conductors [m]	3.4	-	-
Span length [m]	250	300	300

2.2 Surge calculation

To build the multi-story model for towers. The surge performances of structure systems consisting of several straight metal cylinders or bracings should be determined. For the vertical cylinders, if the frequency is high enough, the surge impedance Z_v can be calculated by [14]

$$Z_v = 60\left[\ln\left(2\sqrt{2}h/r\right)-1\right] \quad (1)$$

Where h is the height of the tower and r denotes the radius of the cylinder. Due to the Donau tower's lattice structure, the surge impedance of the vertical body is reduced by about 10% by adding the bracings. Thus, the equivalent distributed parameter circuit for the Donau body needs to be connected in parallel with a surge impedance of bracings Z_b, and Z_b=9Z_v [8].

The surge impedance of the horizontal components such as metal cross-arm is given by [14]

$$Z_h = 60\ln\left(2h/r\right) \quad (2)$$

For the Y-shaped pylon, because the downlead inside the cross-arm has a tilting structure and composite housing, there is no available expression to describe its surge response. It is known that the surge impedance can be is equal to the square root of inductance/capacitance. Thus, we can obtain the inductance and capacitance of the downlead by the electromagnetic field theory. First, we simplify the downlead and divide it into four parts, as shown in Fig. 2. The inductance (L) and capacitance (C) inside the cross-arm can be written as the integral form:

$$L = \frac{\mu_0 l}{8\pi} + \frac{l}{2\pi}\left(\mu_1 \ln\frac{b}{a}\frac{2h-a}{2h-b} + \mu_0 \ln\frac{2h-b}{b}\right) \text{ H/m} \quad (3)$$

$$C = \frac{2\pi l}{\frac{1}{\varepsilon_1}\ln\frac{b}{a}\frac{2h-a}{2h-b} + \frac{1}{\varepsilon_0}\ln\frac{2h-b}{b}} \text{ F/m} \quad (4)$$

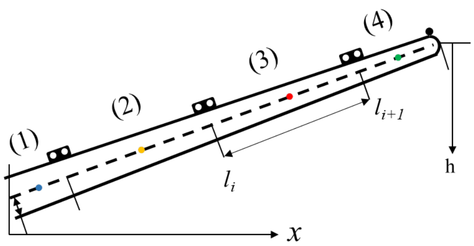

Fig. 2 The schematic of the composite cross-arm divided by four segments.

2.3 Footing resistance

The frequency-dependent soil model has been investigated in the past decades. The existing research presents the dynamic response of the soil model is well-matched with actual measurements with varied frequencies ranging from 1 kHz to

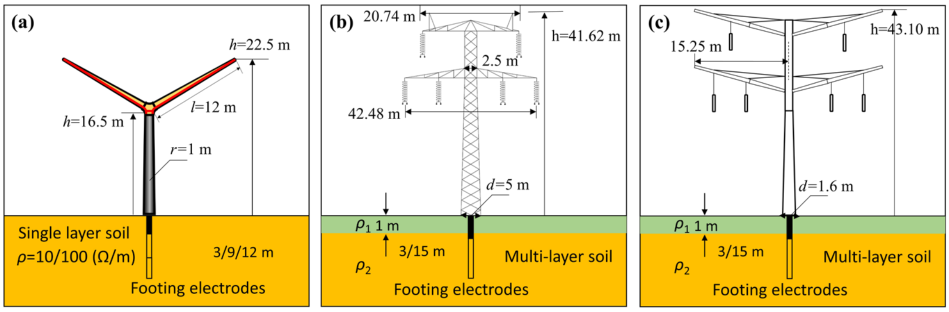

Fig. 3 The schematic of the ground system for (a) Y composite pylon buried in single-layer soil model, (b) Donau tower and (c) Eagle tower buried in two-layer soil model.

10 MHz. The analytical formulas derived from the method of moment are as follows [11]:

$$\varepsilon_r(f) = \varepsilon_\infty + \sum_{n=1}^{N} \frac{a_n}{1+(f/f_n)^2} \tag{5}$$

$$\frac{1}{\rho(f)} = \frac{1}{\rho_i} + 2\pi\varepsilon_0 \sum_{n=1}^{N} a_n f_n \frac{(f/f_n)^2}{1+(f/f_n)^2} \tag{6}$$

$$f_n = 10^{n-1}(M/10)^{1.28} \tag{7}$$

$$\rho_i = 125(M/10)^{-1.54} \tag{8}$$

Where ε_∞ is 5. ρ_i is the low-frequency soil resistivity; M is the moisture content of soil; a_n values are recommended in [11]. In this paper, vertical rods are selected as the electrodes and both single and multi-layer soil conditions are considered. For single-layer soil, the ρ_0 is homogenous and set to be 100 Ω/m and 1000 Ω/m. The ground systems for the three towers are shown in Fig. 3. For two-layer soil, the upper soil is 1 m depth, and there are three cases as shown in Table 2. The concentrated rod with a radius of 12.5 mm is adopted as an electrode and buried in the ground. The length of the electrode is varied to investigate the effect of electrode length on overvoltage in complex soil conditions.

Additionally, for comparison purposes, all towers adopt the same grounding system.

Table 2 Soil resistivity and electrode parameters

		Upper soil (ρ_1)	Down soil (ρ_2)	Length of rod (m)
Single soil	Case 1	10 Ω/m		3 /9 /12
	Case 2	100 Ω/m		
Two-layer soil	Case 3	10 Ω/m	1000 Ω/m	3 /15
	Case 4	100 Ω/m	1000 Ω/m	
	Case 5	1000 Ω/m	10 Ω/m	

2.4 First and subsequent lightning

Normally, lightning is composed of multiple discharges denoted by first and subsequent return strokes. The mean time of the interstroke interval is about 45 μs. Thus, there is no front wave overlap between the first and return lightning. The waveforms can be represented using Heidler's functions, defined as (9)-(10) [11]:

$$I = (I_0/\eta)\left((t/\tau_1)^n / 1 + (t/\tau_1)^n\right) e^{-t/\tau_2} \tag{9}$$

Where η is expressed as:

$$\eta = e^{-(\tau_1/\tau_2)(n\tau_1/\tau_2)^{-n}} \tag{10}$$

The parameters of the typical first stroke and a subsequent return stroke are given in Table 3. It should be noted that the subsequent stroke is represented using the sum of two Heidler's functions.

Table 3 Lightning waveform parameters

Lightning waveform	I_0 (kA)	τ_1 (μs)	τ_2 (μs)
First stroke	28	1.8	95
Subsequent stroke	10.7/6.5	0.25/2	2.5/230

2.5 PSCAD simulation

The whole process of the simulation is exhibited in the flow chart (Fig. 4). First, according to the electrode and soil parameters, the harmonic impedance is obtained by the method of moment [11], and then, generating the txt data of soil impedance amplitude and phase as a function of frequency. These files are put into the FDNE module in the PSCAD to establish the ground system. The tower structure above the ground is built by multi-story model [8]. The self-assembling lightning current model and injecting it on one shield wire can generate the U_L and GPR.

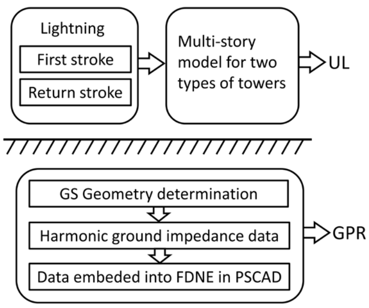

Fig. 4 The process of the simulation to obtain the results of U_L and GPR.

3 Results and discussion

3.1 Harmonic grounding impedance

As shown in Fig. 5, the footing impedance assumes the inductive effect and increases with the frequency. When ρ_0=100 Ω/m and frequency lower than 1 MHz, the magnitude of the footing impedance is unchanged and then starts growing considerably. Increasing the length of the electrode rod can lead to the reduction of the initial |Z| at low frequency, being such reduction relatively more pronounced for higher ρ_0 [9].

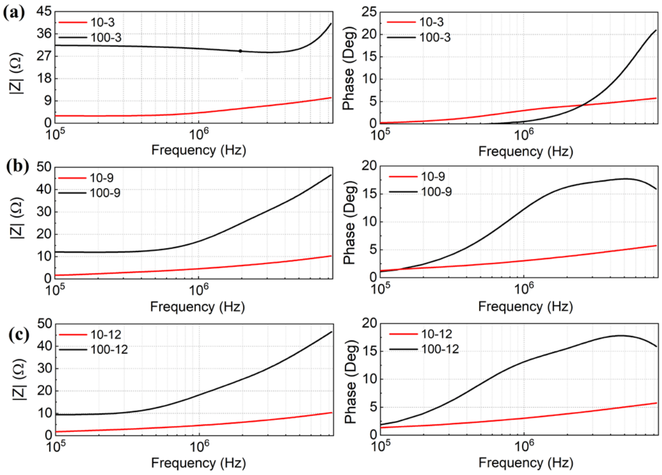

Fig. 5 Magnitude and phase of the single-layer grounding impedance ρ=10 Ω/m and ρ=100 Ω/m with different electrode length: (a) 3 m, (b) 9 m and (c) 12 m.

When ρ_0 is equal to 100 Ω/m, and the length of the rod is 3 m, the footing impedance exhibits a resistive behavior at low frequency and inductive characteristic at a higher frequency. For other 100 Ω/m cases, with the increase of the frequency, the inductive behavior of the ground impedance becomes more dominant. When ρ_0=100 Ω/m, the longer the electrode, the more apparent the inductive effect is shown on the ground impedance, especially at high frequency. In contrast, for lower soil resistivity ρ_0, the lower inductive effect is shown.

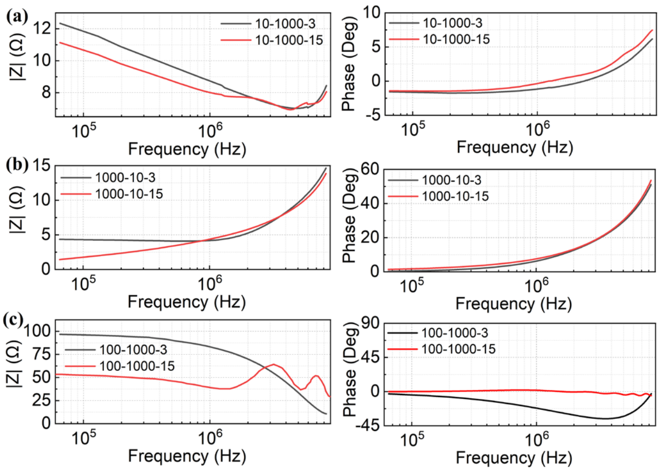

Fig. 6 Magnitude and phase of the two-layer grounding impedance with different lengths of the electrodes. (a) ρ_1=10 Ω/m, ρ_2=1000 Ω/m, (b) ρ_1=1000 Ω/m, ρ_2=10 Ω/m and (c) ρ_1=100 Ω/m, ρ_2=1000 Ω/m.

For the two-layer soil model shown in Fig. 6, if the resistivity of one layer in the soil model is low, the behavior of the soil presents the inductive characteristic. As the frequency increases, the inductive effect becomes more evident. Additionally, the layer position of the high resistivity soil has a significant impact on the footing resistance variations. If the lower soil ρ_0 is equal to 1000 Ω/m, |Z| decreases along with the frequency increasing. Conversely, when the upper layer soil is high resistivity, |Z| shows the opposite trend in the frequency range of interest. Once the frequency content above the switching frequency about 1 MHz, the impedance is on the transition from capacitive to inductive behavior, and we can observe the magnitude shows an upward trend. On the contrary, the high-frequency for 1000-10 Ω/m case indicates a worse grounding performance due to the inductive effect [11].

When the two-layer soil resistivity is 100 Ω/m and 1000 Ω/m, respectively, the soil presents a capacitive effect, especially for the rod length of 15 m. The electrode rod with a longer length can cause an evident reduction in the lower frequency resistivity. This phenomenon is the same as the case in single-layer soil. For all cases, the increase of the rod length can cause the transition of the footing resistance from capacitive behavior to inductive behavior. This is especially true when the soil resistivity is very high.

3.2 Lightning response under the first stroke

3.2.1 Single layer soil model

Under the first stroke, U_L for the Y-shaped tower is the lowest among the three kinds of towers. Donau tower shows the U_L is slightly higher than that of the Y-shaped pylon. This phenomenon becomes more pronounced when the soil resistivity is 100 Ω/m. For GPR, the three towers show similar levels and strong dependence on soil resistivity. The increase of the rod length plays a prominent role in reducing the U_L and GPR when ρ is 100 Ω/m. But for 10 Ω/m, the impact of rod length is minimal.

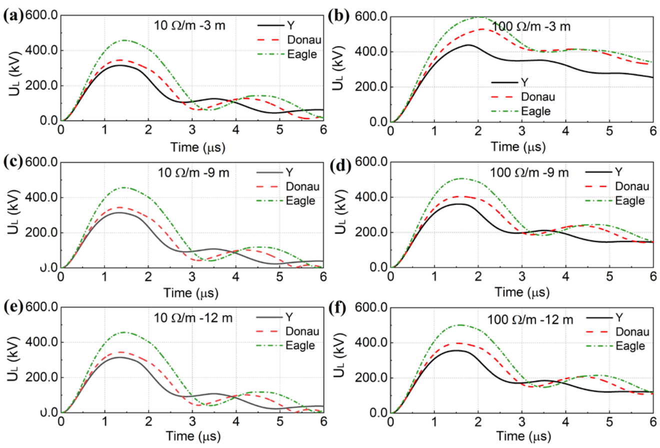

Fig. 7 U_L of the vertical electrode of length l=3/9/12 m buried in a single layer soil with 10 Ω/m and 100 Ω/m subjected to first striking lightning.

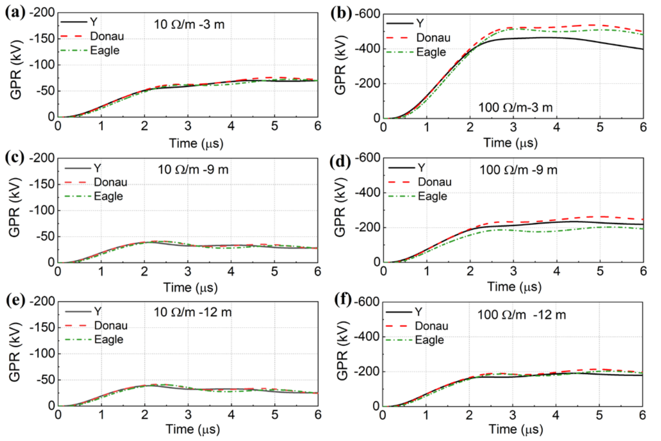

Fig. 8 GPR of the vertical electrode of length l=3/9/12 m buried in a single layer soil with 10 Ω/m and 100 Ω/m subjected to first striking lightning.

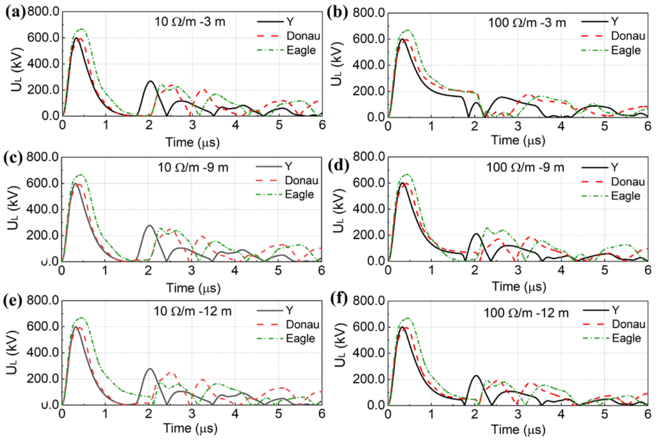

Fig. 9 U_L of the vertical electrode of length l=3/9/12 m buried in a single layer soil with 10 Ω/m and 100 Ω/m subjected to subsequent striking lightning.

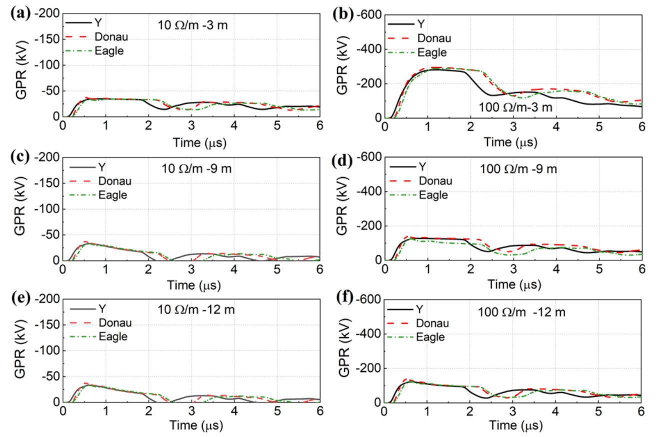

Fig. 10 GPR of the vertical electrode of length l=3/9/12 m buried in a single layer soil with 10 Ω/m and 100 Ω/m subjected to subsequent striking lightning.

In the case of subsequent striking, the lightning response waveform on the U_L and GPR present a steep rise front. The overvoltage level on the insulator of Eagle tower is the most serious, and the other towers show almost no difference on the overvoltage U_L across the unibody cross-arm no matter how long the electrode rod is and how much the value of the soil resistivity. Similarly, the GPR for the three towers is also nearly identical. GPR is obviously reduced due to the growth of rods when the ρ is high. It should be noted that the GPR is lower compared with the first stroke case, but U_L is sharply higher in the subsequent stroke case.

3.2.2 Two-layer soil model

For the first stroke, in the case of two-layer soil with higher resistivity, the values of GPR and U_L are highest. Especially for the Eagle tower, the GPR value for 100/1000 Ω/m case is four times as the 1000/10 Ω/m case with the rod length of 3 m. By having one layer of the soil with a relatively low ρ such as 10 Ω/m, the transient overvoltage would not be severe. In addition, the characteristics of each soil layer have a significant influence on the effect of the rods. When the down layer resistivity is high, the length of the rod cannot decrease the GPR and U_L. This phenomenon is the same as that of the single-layer soil.

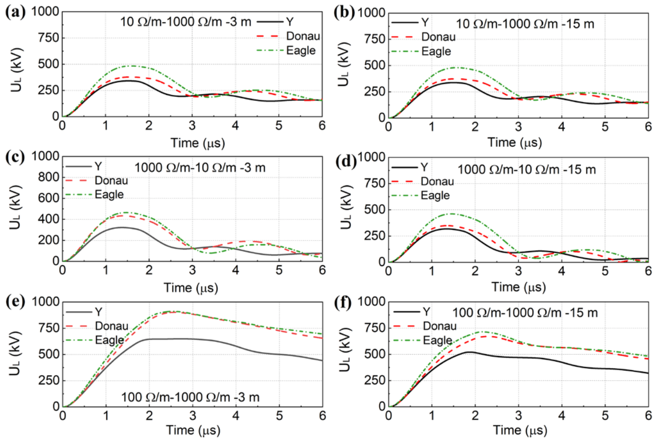

Fig. 11 U_L of the vertical electrode of length l=3/15 m buried in a multi-layer soil with (a)-(b) ρ_1=10 Ω/m, ρ_2=1000 Ω/m, (c)-(d) ρ_1=1000 Ω/m, ρ_2=10 Ω/m and (e)-(f) ρ_1=100 Ω/m, ρ_2=1000 Ω/m subjected to first striking lightning.

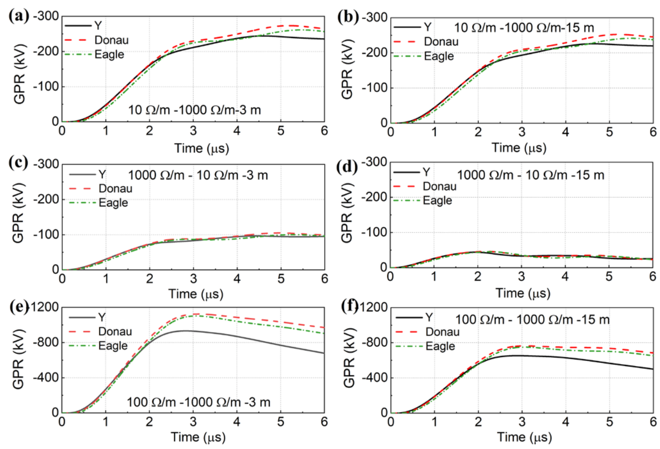

Fig. 12 GPR of the vertical electrode of length l=3/15 m buried in a multi-layer soil with (a)-(b) ρ_1=10 Ω/m, ρ_2=1000 Ω/m, (c)-(d) ρ_1=1000 Ω/m, ρ_2=10 Ω/m and (e)-(f) ρ_1=100 Ω/m, ρ_2=1000 Ω/m subjected to first striking lightning.

Same with the single-layer soil, the two-layer soil condition has a limited impact on the U_L under the subsequent stroke. The GPR shows lower values and a similar trend with the cases under the first stroke. Compared with the first stroke, serious overvoltage is transferred from the ground to the cross-arm with the fast front time striking. Interestingly, when the upper soil with high resistivity, U_L is the highest compared with other cases.

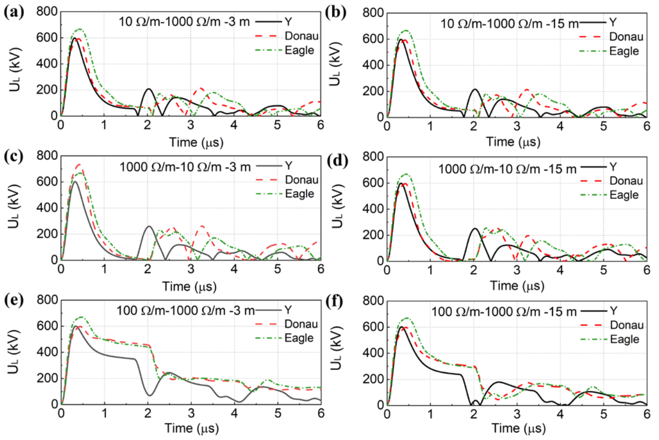

Fig. 13 U_L of the vertical electrode of length l=3/15 m buried in a multi-layer soil with (a)-(b) ρ_1=10 Ω/m, ρ_2=1000 Ω/m, (c)-(d) ρ_1=1000 Ω/m, ρ_2=10 Ω/m and (e)-(f) ρ_1=100 Ω/m, ρ_2=1000 Ω/m subjected to subsequent striking lightning.

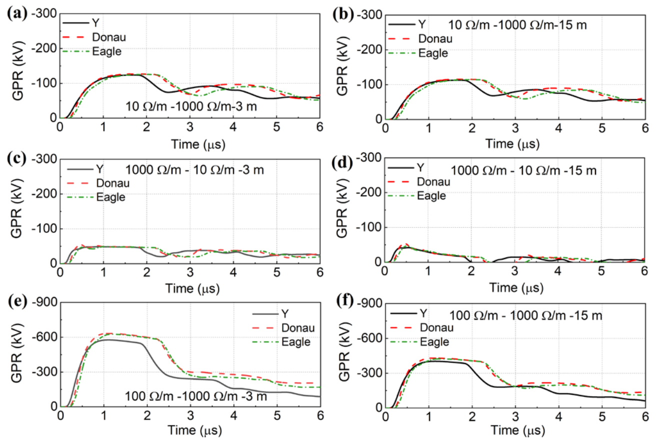

Fig. 14 GPR of the vertical electrode of length l=3/15 m buried in a multi-layer soil with (a)-(b) ρ_1=10 Ω/m, ρ_2=1000 Ω/m, (c)-(d) ρ_1=1000 Ω/m, ρ_2=10 Ω/m and (e)-(f) ρ_1=100 Ω/m, ρ_2=1000 Ω/m.

4 Conclusion

This paper presents the work on the transient lightning response of the Y-shaped composite tower under the frequency-dependent soil model. GPR and U_L are the main factors of interest, and typical traditional Doanu and Eagle towers are investigated as a comparison. It is a common conclusion that GPR and U_L have different sensitivities on the first and subsequent strokes. For the first stroke with slow front time, the GPR is relatively high, but when the tower stroke by fast front lightning such as return stroke, overvoltage on U_L becomes serious. In addition, the longer length of the electrode rod can obviously reduce the overvoltage only when the soil resistivity is high. We found that the Y-shaped pylon has better lightning performance compared with the traditional towers, especially when the soil resistivity is high. Thus, this composite pylon has advantages when it is built on mountainous regions and frozen ground areas where the soil resistivity is high.

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