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Research Article

Study on the Influencing Factors of Insulator on the Back-Flashover Lightning Withstand Performance of ±800 kV UHVDC Transmission Lines

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The current research results indicate that the insulator's insulation performance has a very important influence on the back-flashover lightning withstand performance of UHVDC transmission lines, especially for ±800 kV voltage level. However, it is not clear which factors will influence the insulation performance of the insulator, and the influencing mechanism is also not clear yet. To figure out this problem, the insulator's insulation performance under different conditions has been deeply analyzed and considered to reveal the influence mechanism in this paper, such as the surface hydrophobicity, pollution degree, and the string type. Firstly, the insulator's model is established using COMSOL software, and the lightning impulse voltage of insulator is calculated and verified with the corresponding experimental data. Then, the ±800 kV UHVDC transmission lines model is constructed using PSCAD software, and back-flashover lightning withstand level and back-flashover rate are calculated by considering the above lightning impulse voltage as the threshold of flashover. Finally, the back-flashover lightning withstand performance of ±800 kV UHVDC transmission lines is deeply analyzed based on different insulators. The simulation results demonstrate that the back-flashover lightning withstand performance of ±800 kV UHVDC transmission lines is obviously weakened with the increase of the pollution degree and slightly weakened with the decrease of the surface hydrophobicity. Considering the same pollution degree, the V-type string insulator has the least influence, while the II-type string insulator has the greatest influences on the back-flashover lightning withstand performance of ±800 kV UHVDC transmission lines. The research results are beneficial for providing theoretical basis for stable operation and reliable power supply of ±800 kV UHVDC transmission lines.

1. Introduction

The UHVDC power transmission is a large-scale long-distance transmission mode, which has the advantages of low transmission loss and large transmission capacity [1, 2]. It is very suitable for countries and regions with extremely uneven distribution of power resources and load, where the maximum voltage level of UHVDC transmission lines under actual operation in countries other than China is 500 kV, such as Russia, Italy, and Japan. In China, ±800 kV UHVDC transmission lines have been in actual operation for many years and play an important role in power transmission system, such as Xiangjiaba-Shanghai, Yunnan-Guangdong, Jinping-Suzhou, and Ha'mi-Zhengzhou transmission lines. In addition, there are several ±800 kV UHVDC transmission lines and one ±1100 kV UHVDC transmission line under construction in China.

However, the overhead lines of ±800 kV UHVDC transmission lines are very high, the terrain along the long-distance transmission lines is complicate, and it is easy to be disturbed by many natural factors, such as earthquake and lightning [3–5]. In order to reduce the probability of direct lightning strike on the transmission lines, the double-shielded wire is usually used in engineering applications, but it increases the probability of lightning strike on the shielded wire [6–8]. Therefore, it is necessary to explore the influence mechanism of insulator's insulation performance on the back-flashover lightning withstand performance of ±800 kV UHVDC transmission lines, which is beneficial for providing theoretical basis for stable operation and reliable power supply.

In China, there are many universities and research institutions engaged in ±800 kV UHVDC transmission lines, such as Chongqing University, Guangxi University, Xi'an Jiaotong University, and China Electric Power Research Institute. Many theoretical and experimental results have been achieved. In order to study the back-flashover lightning withstand performance of ±800 kV UHVDC transmission lines, the lighting impact flashover experimental testing of insulator is inevitable. However, the safety of experimental personnel and equipment will also be greatly threatened during this experimental testing. At the same time, there are also risks of power grid security and major property losses. Therefore, the relevant experimental testing has not been carried out until now. Therefore, the current research on the back-flashover lightning withstand performance of ±800 kV UHVDC transmission lines is still in the stage of theoretical calculation and analysis. The ±800 kV UHVDC transmission lines during actual operation in China are still adopting the conservative design method, which means there is enough design allowance/margins for lightning threat. This design method does not need to know which factors of insulator will influence the back-flashover lightning withstand performance of ±800 kV UHVDC transmission lines, and the influencing mechanism is also not clear yet. However, this design method will lead to high cost and waste of resources.

The current theoretical research results show that the back-flashover lightning withstand performance of ±800 kV UHVDC transmission lines is only related to these factors of grounding resistance, tower nominal height, insulator length, lightning current amplitude, etc [9–13]. The other influencing factors on the insulator's insulation performance and the ±800 kV UHVDC transmission lines are not under consideration. Actually, the insulator's insulation characteristics will be changed in different natural environments and string types, which will lead to changes in back-flashover lightning withstand performance of ±800 kV UHVDC transmission lines [14–21]. However, the existing mathematical model and analysis method are too complex, which also cannot carry out dynamical analysis and directly demonstrate the influencing mechanism of insulator with different parameters on the back-flashover lightning withstand performance of ±800 kV UHVDC transmission lines.

To solve the above problems, the advantages of COMSOL and PSCAD software will be combined to study the back-flashover lightning withstand performance of ±800 kV UHVDC transmission lines in this paper.

2. Simulation Models

At present, the commercial software which is usually used to simulate the back-flashover lightning withstand performance is COMSOL and PSCAD, where the former can construct accurate 3D model for different natural conditions but requires high hardware configuration when the model is too large, and lack of hardware configuration will cause the nonconvergence of simulation results. The latter does not require high hardware configuration, but it cannot directly simulate natural environment factors. Therefore, the advantages of COMSOL and PSCAD will be combined to study the back-flashover lightning withstand performance in our simulation model.

The simulation of the back-flashover lightning withstand performance of ±800 kV UHVDC transmission lines can be divided into the following four steps:

(1) Step 1: calculating the lightning impulse voltage of insulator using COMSOL software
(2) Step 2: calculating the back-flashover lightning withstand level of ±800 kV UHVDC transmission lines using PSCAD software
(3) Step 3: calculating the back-flashover rate of ±800 kV UHVDC transmission lines using standard methods
(4) Step 4: analyzing the influence mechanism of back-flashover lightning withstand performance of ±800 kV UHVDC transmission lines

2.1. Insulator Model. The boundary conditions of the simulation model under working voltage can be expressed as follows:

$$\begin{cases} U_+ = U_e, \\ U_- = 0, \end{cases} \tag{1}$$

where U_e is the rated voltage of transmission lines and U_+ and U_- are the upper value and lower value of the voltage, respectively.

The boundary conditions of the simulation model under impulse voltage can be expressed as follows:

$$\begin{cases} U_+ = U(t), \\ U_- = 0, \\ U(t) = U_m\left(e^{-\lambda_1 \cdot t} - e^{-\lambda_2 \cdot t}\right), \end{cases} \tag{2}$$

where U (t) is the instantaneous voltage and U_m is the amplitude of lightning impulse voltage; the value of λ_1 and λ_2 depends on the lightning current waveform.

$$\begin{cases} \lambda_1 = \dfrac{1}{T_1}, \\ \\ \lambda_2 = \dfrac{1}{T_2}, \end{cases} \tag{3}$$

where T_1 and T_2 are time constants of wave head and wave tail.

Using COMSOL software, 110 kV 3D model and ±800 kV 3D model of insulator are established, where the former is used to verify the accuracy of this modeling method and calculate the lightning impulse voltage. The theoretical and experimental data of 110 kV insulator can be easily accessed from other published literatures. The structural and material parameters of insulators are shown in Tables 1 and 2, respectively. The influence of the tower's cross arm and wires on the insulator is neglected in our simulation.

The simulation model of the insulator is shown in Figure 1, where 1(a) shows 110 kV insulator's model and 1(b) shows ±800 kV insulator's model, respectively. From Figure 1, one can see that the 110 kV insulator has no voltage-sharing ring, but the ±800 kV insulator has voltage-sharing ring. The outer diameter and tube radius of insulator's high-voltage part of the voltage-sharing ring are 232 mm and 32 mm, respectively. Moreover, the outer diameter and tube radius of insulator's low-voltage part of the voltage-sharing ring are 400 mm and 60 mm, respectively.

2.2. ±800 kV UHVDC Transmission Lines Model. Using PSCAD software, ±800 kV UHVDC transmission lines model is constructed, which is shown in Figure 2. From Figure 2, one can see that this model is mainly composed of the lightning current model, transmission line model, insulator flashover model, tower model, grounding resistance model, etc. These models are described separately below.

According to the standard of electric power industry in China, 2.6/50 μs double exponential wave is selected as the lightning current model in our simulation, which is shown in Figure 3.

In order to reflect the significant changes of inductance and capacitance effects during the lightning discharges process with high frequency and high current amplitude, the frequency-dependent model is chosen for transmission lines.

Insulator's flashover model is simulated by parallel connection of a voltage-controlled switch and a capacitor. The flashover threshold is calculated by COMSOL software.

The typical tower model is shown in Figure 4. When the lightning current occurs, the wave processes in different structures of tower are different, and the influence of tower height on wave impedance is also taken into account, and a multiwave impedance model is chosen in this paper.

The wave impedance of each structure is calculated as follows:

$$\begin{cases} Z_{\mathrm{TK}} = 60\left(\ln \dfrac{2\sqrt{2}\, h_k}{r_k} - 2\right), \quad k = 1,2,3, \\ Z_{AK} = 60\left(\ln \dfrac{2h_k}{r_{AK}}\right), \\ Z_{lk} = 9Z_{\mathrm{TK}}, \\ r_k = 2^{1/8}\left(r_{\mathrm{TK}}^{1/3} \cdot r_B^{2/3}\right)^{1/4} \cdot \left(R_{\mathrm{TK}}^{1/3} \cdot R_B^{2/3}\right)^{3/4}, \end{cases} \tag{4}$$

where Z_{TK}, Z_{AK}, and Z_{lk} indicate the main-frame wave impedance, cross-arm wave impedance, and stent wave impedance, respectively; r_{k} and r_{AK} indicate the equivalent radius of tower and cross arm, respectively; h_{k}, r_{TK}, R_{TK}, r_B, and R_B indicate the length of corresponding structure in Figure 4, respectively.

Table 1: The structural parameters of insulator.

Voltage level (kV)	Height (mm)	Arc distance (mm)	Creepage distance (mm)	Petticoat diameter (mm)
110	1240	1120	3440	145/120
±800	10600	10050	39800	226/176/130

Table 2: The material parameters of insulator.

Materials	Metal fittings	Petticoat	Mandrel	Air
Relative dielectric constant	5×10^5	3.5	5	1.0006
Conductivity (S/m)	1.5×10^7	1×10^{-12}	4×10^{-12}	5×10^{-14}

A nonlinear resistor model is chosen to indicate the grounding resistance, which varies with the lightning current amplitude. The expression is as follows:

$$\begin{cases} R_T = \dfrac{R_0}{\sqrt{1 + I/I_g}} \\ I_g = \dfrac{\rho \cdot E_0}{2\pi \cdot {R_0}^2} \end{cases} \tag{5}$$

where R_0 indicates the grounding resistance at power frequency (here $R_0 = 10\,\Omega$ and $E_0 = 400$ kV/m); I indicates the high-frequency impulse current; I_g indicates the ionization current threshold of soil; and ρ indicates the resistivity of soil (unit: Ω/m).

3. Parameter Calculation

3.1. The Lightning Impulse Voltage. From Figure 5, one can see that the potential difference is large between two ends of insulator, and the electric field distribution is U-shaped. The electric field at the insulator-air contact part is high, especially at the edge of petticoat. When the lightning impulse voltage is imposed at both ends of insulator, the potential distribution of insulator is shown in Figure 6.

To calculate the lightning impulse voltage, the flashover conditions are assumed as follows:

(1) When the flashover occurs, the average electric field intensity of leading channel is 550 kV/m [22].

(2) When the flashover occurs, the peak voltage of lightning is imposed to the insulator.

According to Figure 6 and the standard waveform of lightning current (Figure 3), one can see that the lighting impulse voltage reaches its maximum value at 8 μs, and the amplitude voltage is 844 kV, as shown in Figure 7.

From Figure 7, one can see that the average electric field intensity between the first petticoat is 550 kV/m when the amplitude of lightning impulse voltage is 844 kV. This conclusion is obtained based on the 1st hypothesis condition. Therefore, the lightning impulse voltage of 110 kV insulator is 844 kV.

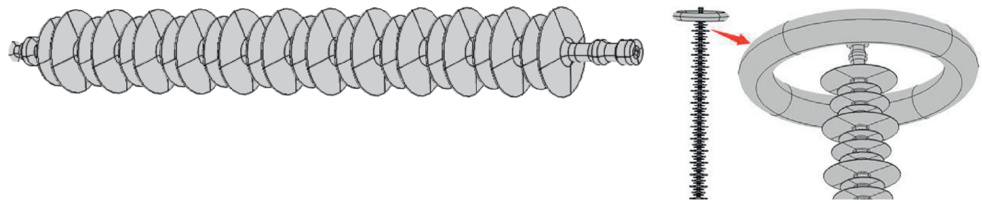


Figure 1: Two 3D models of insulator: (a) 110 kV and (b) ±800 kV Provide label for (a) and (b).

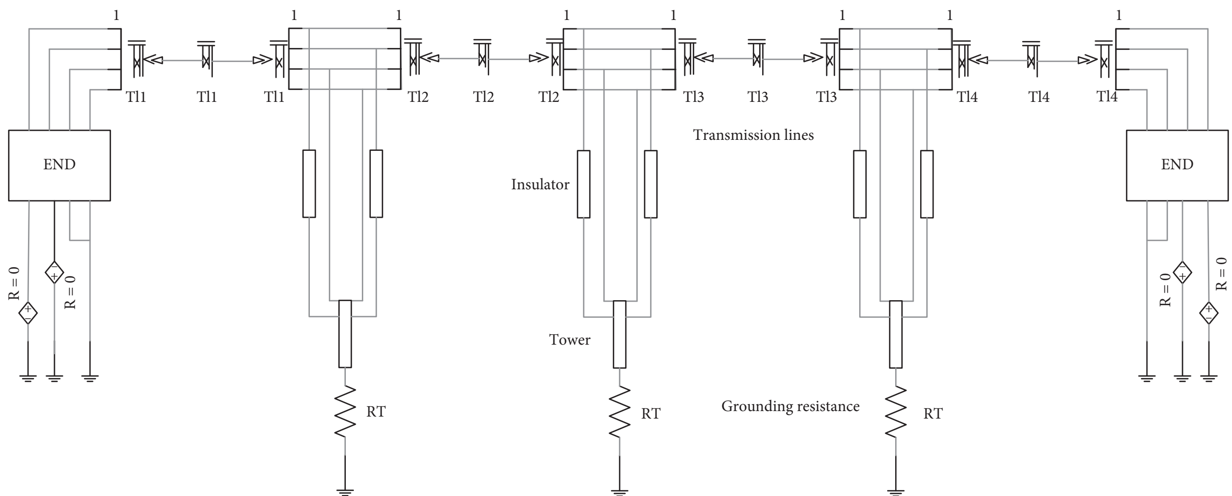


Figure 2: The model of ±800 kV UHVDC transmission lines.

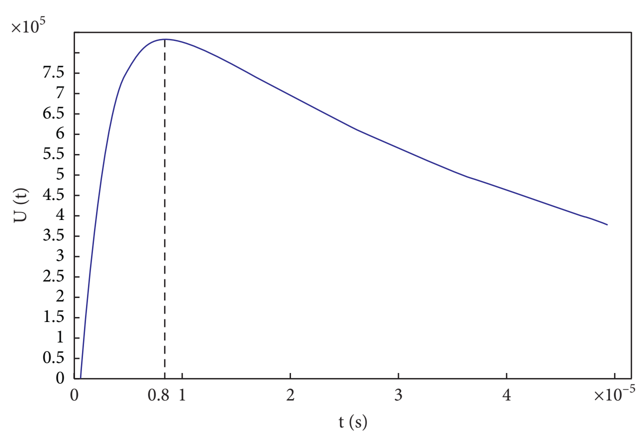


Figure 3: The standard waveform of lightning current.

In order to verify the accuracy of this simulation result, a large number of experimental data are consulted and compared with the simulation result, and the most representative references are [15, 16, 23, 24]. Because the data in reference [15, 23] are measured at high altitude region, the flashover voltage will be higher than standard atmospheric pressure. Compared with the average value of flashover voltage proposed in reference [16, 24, 25], the relative error is only 3.76%. Considering the dispersion characteristics of impulse voltage and the difference between simulation conditions and experimental conditions, we can infer that the simulation results are valid. Therefore, it is reasonable to calculate lightning impulse voltage using this method.

The above method is also used in calculating the lightning impulse voltage of ±800 kV insulator. Ignoring the influence of working voltage, the lightning impulse voltage is imposed at $t = 8\,\mu$s, and the potential distribution and electric field distribution of ±800 kV insulator are shown in Figures 8 and 9, respectively.

According to Figures 8 and 9, the impulse flashover voltage of ±800 kV insulator is calculated to be 5562 kV. However, the experimental data of ±800 kV insulator are not

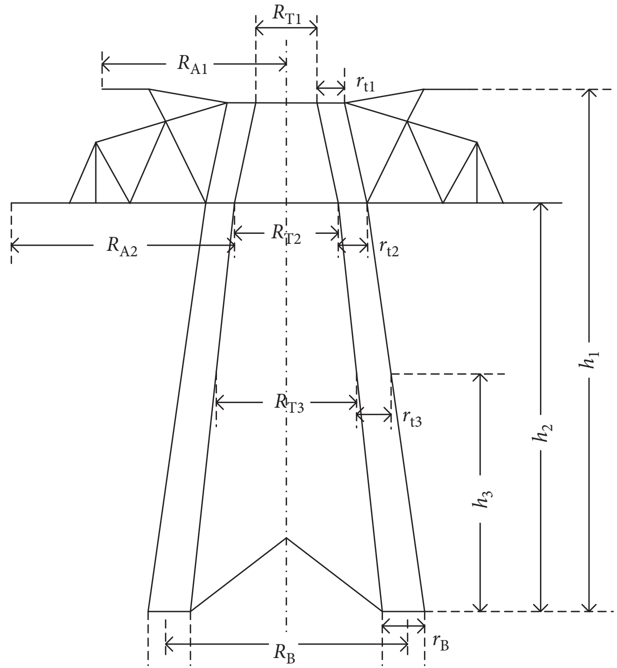


FIGURE 4: The structure of tower.

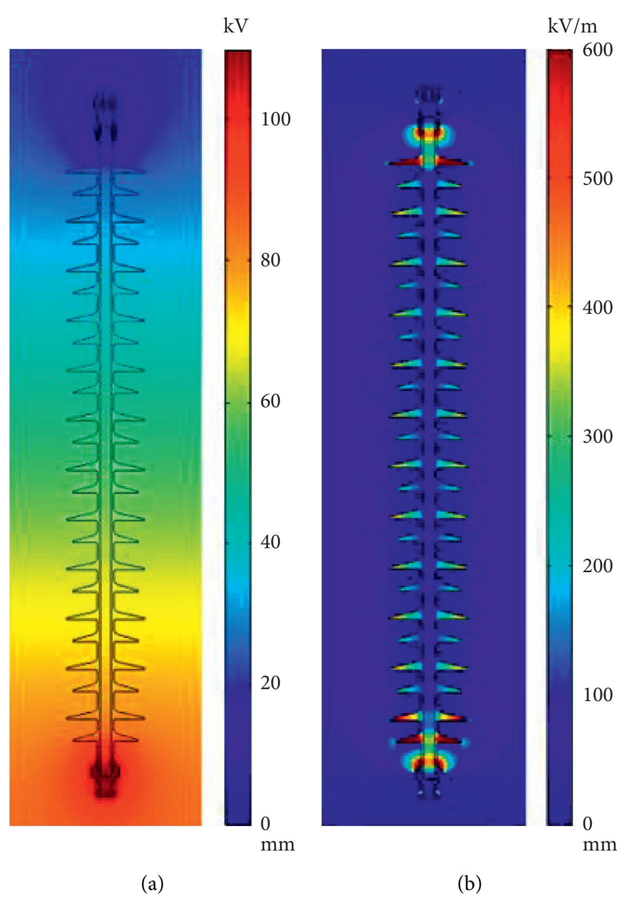


FIGURE 5: The potential distribution and electric field distribution of 110kV insulator under the working voltage: (a) potential distribution and (b) electric field distribution.

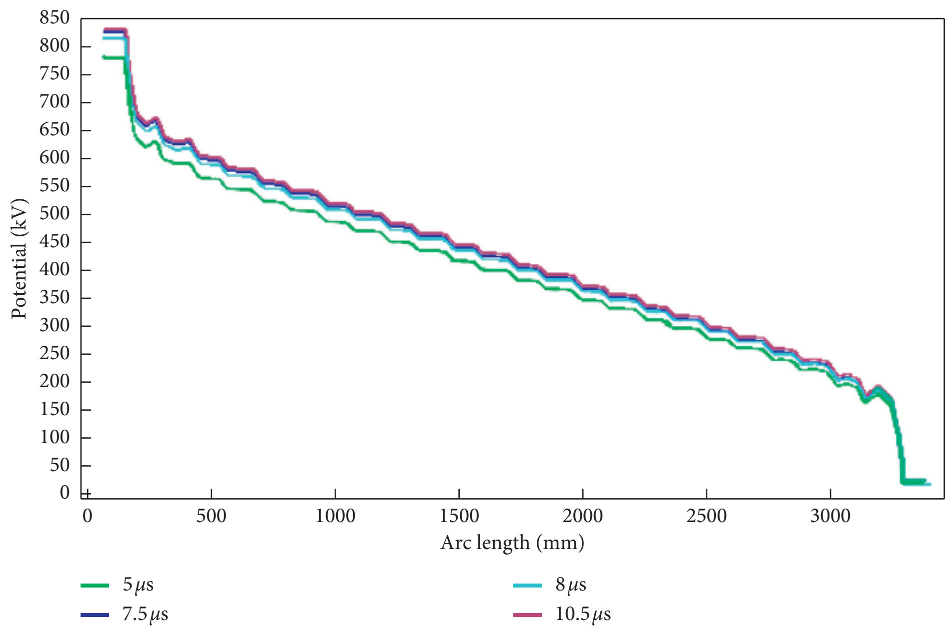


Figure 6: The potential distribution of 110 kV insulator under the impulse voltage.

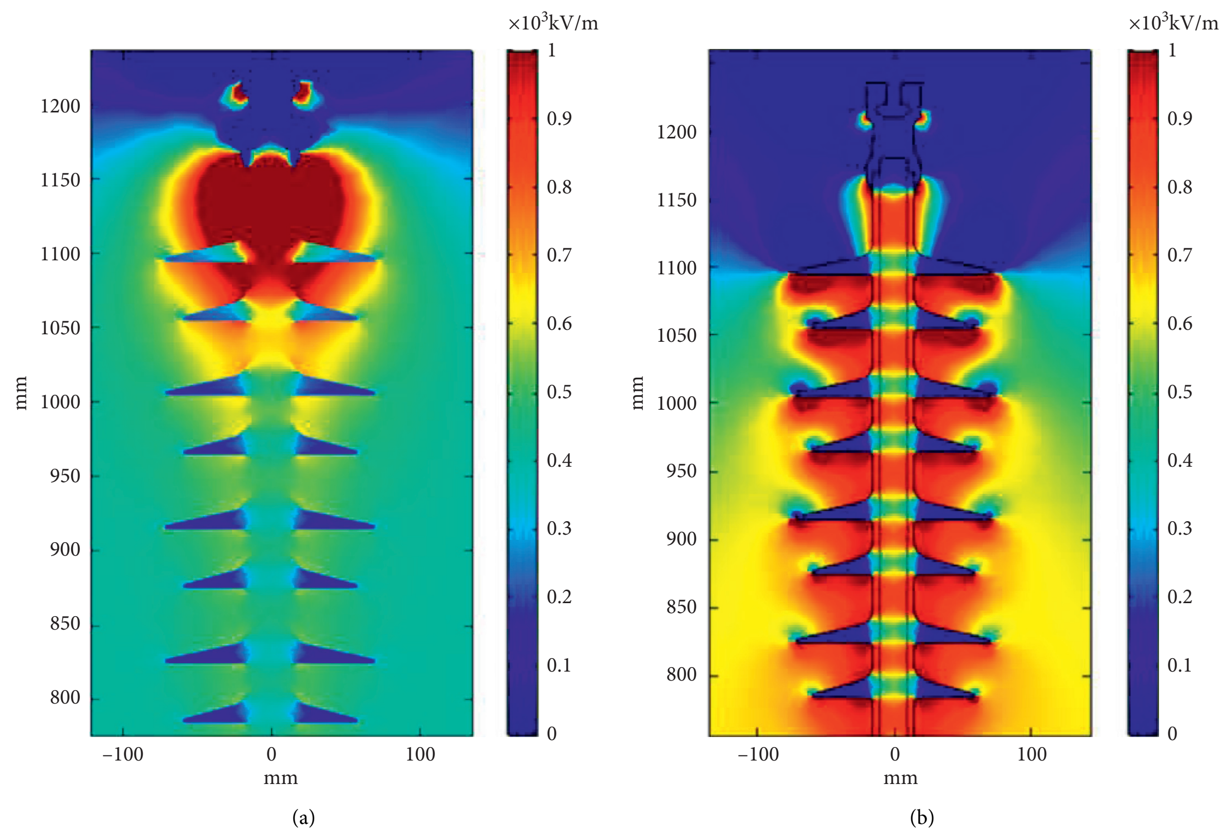


Figure 7: The electric field distribution of 110 kV insulator under the impulse voltage (t = 8 μs): (a) without flashover and (b) with flashover.

readily available, so the above simulation results are compared with two common discriminant methods to further verify the validity and rationality of this method. The expressions of the volt-time characteristic ($V_{s\text{-}t}$) and 50% breakdown voltage ($U_{50\%}$) of insulators are as follows [15, 26, 27]:

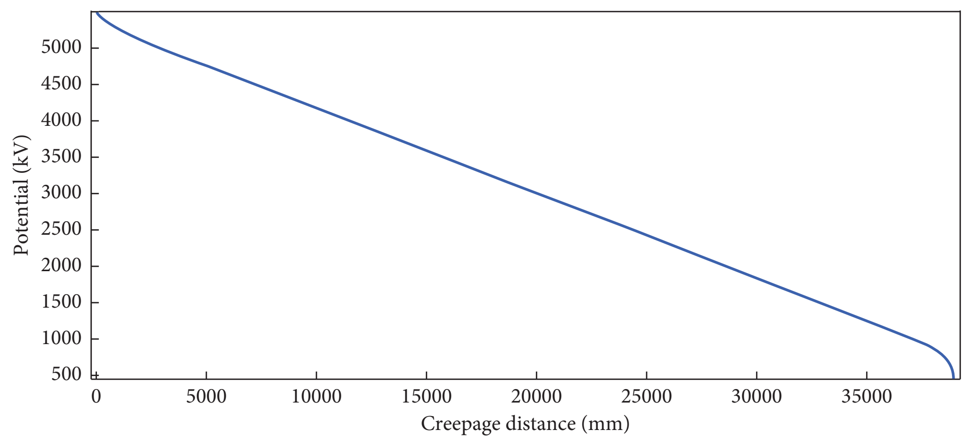


Figure 8: The potential distribution of ±800 kV insulator under the impulse voltage.

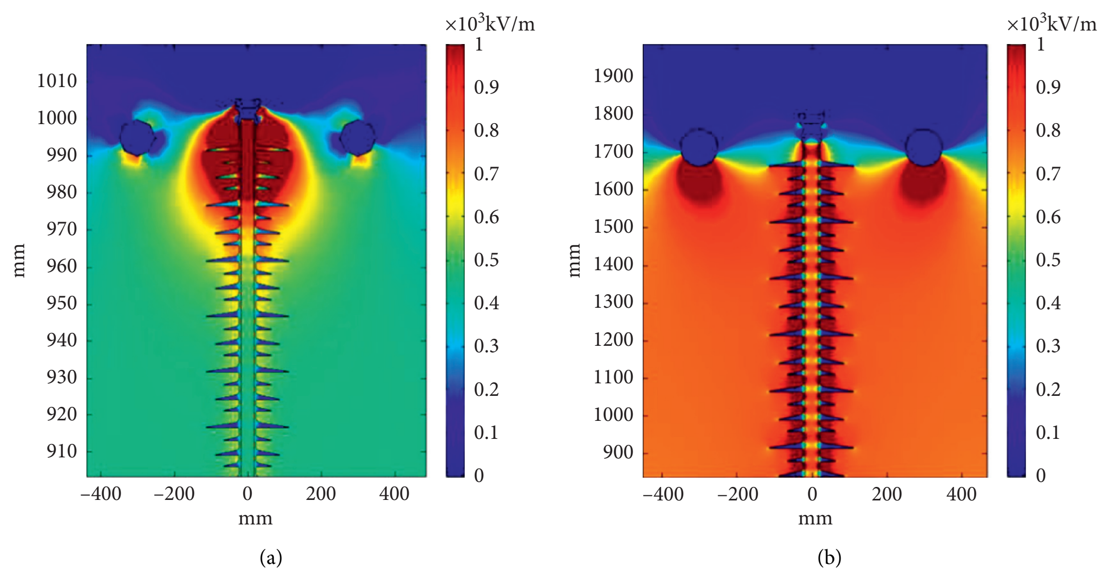


Figure 9: The electric field distribution of ±800 kV insulator under the impulse voltage (t = 8 μs): (a) without flashover and (b) with flashover.

$$\begin{cases} V_{s-t} = 400 \cdot L + \dfrac{710 \cdot L}{t^{0.75}}, \\ U_{50\%} = 533 \cdot L + 132, \end{cases} \quad (6)$$

where L indicates the length of insulator string (unit: m) and t indicates the time from lightning striking (unit: μs).

Through comparison of lightning impulse voltage, we find that the relative error between the simulated result using COMSOL in this paper and the calculated data of volt-second characteristic is 4.47%, and the relative error between the simulated data and the 50% breakdown voltage is only 3.79%. The error is within a reasonable range, and this method can be used to calculate the lightning impulse voltage of ±800 kV insulator. The calculated value will be set as the threshold of insulator's flashover model when the ±800 kV UHVDC transmission lines model is constructed using PSCAD software.

3.2. The Back-Flashover Lightning Withstand Level. The parameters of ±800 kV UHVDC transmission lines and tower are shown in Tables 3 and 4.

According to these data, the line-voltage variation of two poles of ±800 kV UHVDC transmission lines can be simulated by changing the amplitude of lightning current continuously. Through observation, it is found that there is a sharp change between 391 kA and 392 kA, which is shown in Figure 10.

From Figure 10(a), one can see that the potential distribution is continuous when the amplitude of lightning current is 391 kA, which indicates that the flashover of insulators did not occur. From Figure 10(b), one can see that the voltage curve on positive decreases sharply when the amplitude of lightning current is 392 kA, which indicates that the flashover of insulators occurs. Therefore, the back-flashover lightning withstand level of ±800 kV UHVDC transmission lines is determined to be 391 kA.

Table 3: The parameters of ±800 kV UHVDC transmission lines.

Parameters	Length	Capacity	Span distance	Thunderstorm day	Splitting number
Values	500 (km)	5k (MW)	500 (m)	80 (days)	6

Table 4: The parameters of tower.

Parameters	R_{TK} (m)	r_{tK} (cm)	h_k (m)	R_A (m)
Values	4/5/6	7/8/16	34/44/55	10.1/21.7

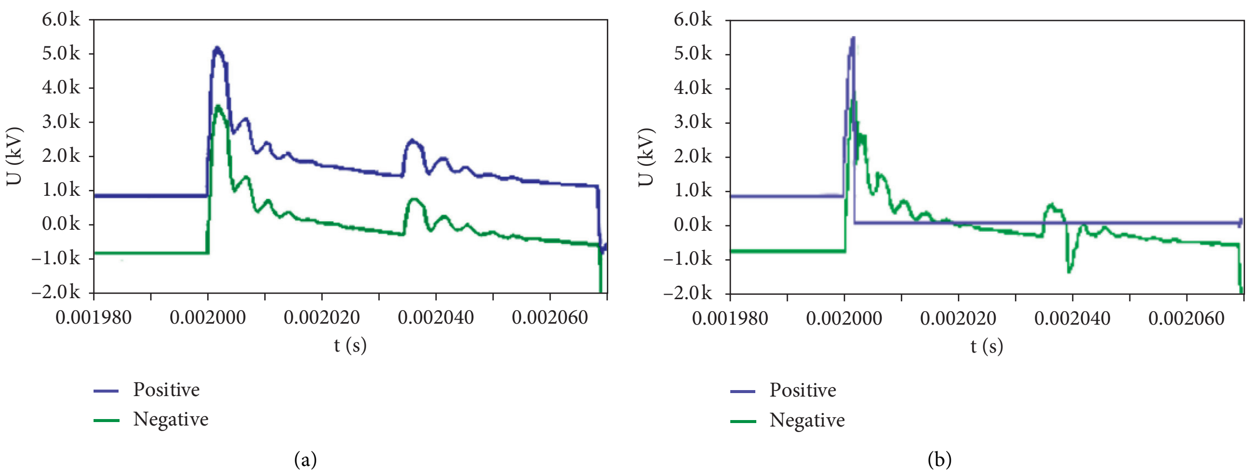


Figure 10: The line voltage of the two poles of transmission lines: (a) without flashover and (b) with flashover.

3.3. The Back-Flashover Rate. Using the standard method, the expression of the back-flashover rate n can be expressed as follows:

$$\begin{cases} n = N_s \cdot \eta \cdot g \cdot P, \\ N_s = N_g\left(\dfrac{28h^{0.6} + b}{10}\right), \\ N_g = 0.023T_d^{1.3}, \\ \lg P = -I/88, \end{cases} \quad (7)$$

where Ns indicates the number of lightning striking per hundred kilometers per year in this area; η indicates the arc-establishing rate; g indicates the lightning striking rate on poles; P indicates the probability that the lightning current amplitude is larger than the flashover current of ±800 kV UHVDC transmission lines; Ng indicates the number of thunder falls per 100 square kilometers per year in this area; h indicates the height of tower (unit: m); b indicates the spacing between shield lines (unit: m); T_d indicates the number of thunderstorm day; and I indicates the flashover current (unit: kA).

Suppose the arc-establishing rate equals 1, the lightning striking rate on poles equals 1/6, and the thunderstorm day is 80 days, then the back-flashover rate of ±800 kV UHVDC transmission lines is calculated to be 0.0006 times/(100 km·year).

Through the above simulation calculation, the back-flashover lightning withstand level and the back-flashover rate of ±800 kV UHVDC transmission lines can be obtained without considering the natural water and water pollution on the insulator's surface (I-type), which are 391 kA and 0.0006 times/(100 km·year), respectively.

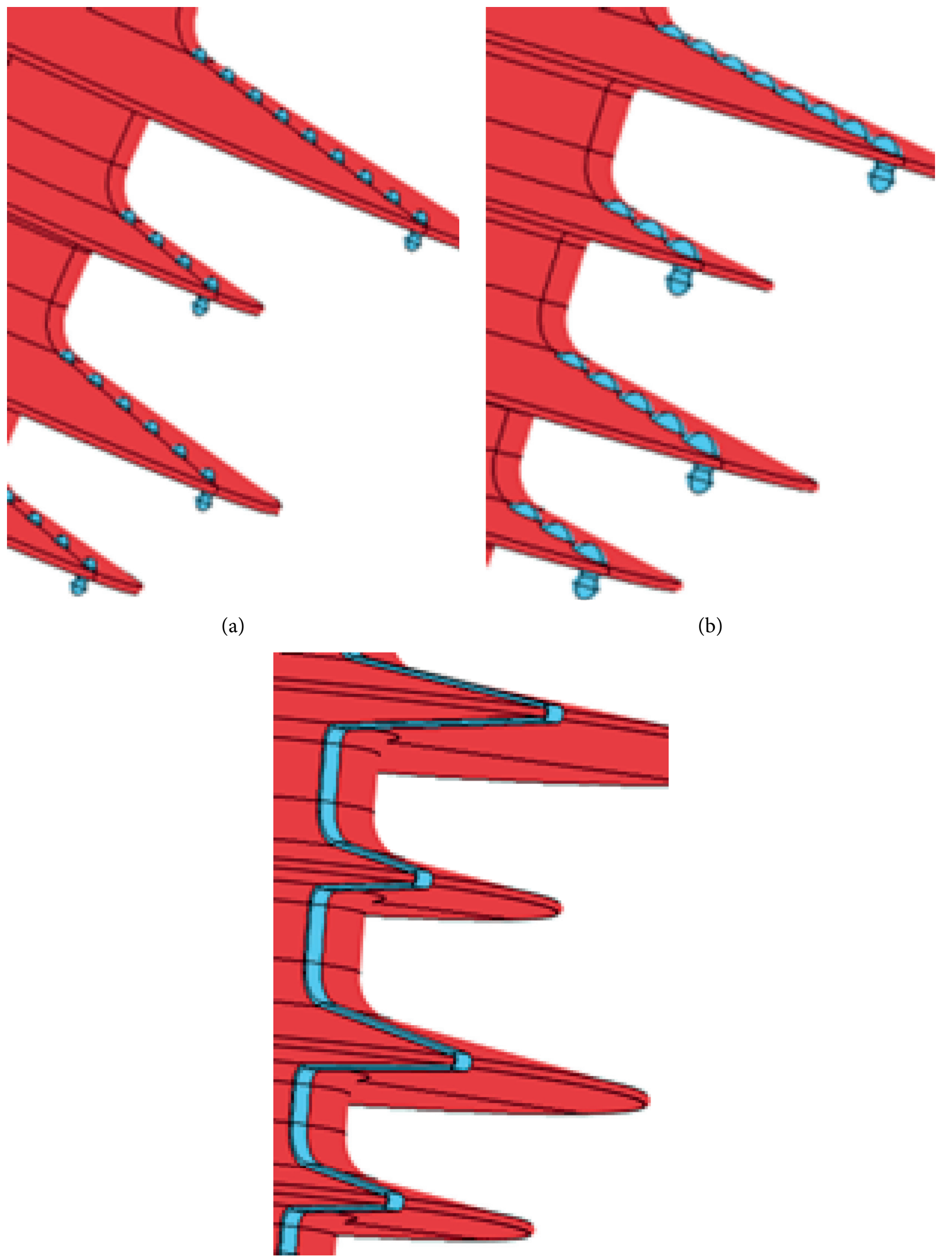
4. Analysis of Influencing Factors

The back-flashover lightning withstand performance of UHVDC transmission lines is mainly indicated by two parameters, the back-flashover lightning withstand level and back-flashover rate. In general, the back-flashover lightning withstand level is higher and the back-flashover rate is lower; then, the back-flashover lightning withstand performance is better. The insulator's influencing mechanism with different conditions on the back-flashover lightning withstand performance of ±800 kV UHVDC transmission lines will be deeply analyzed in this section.

4.1. The Surface Hydrophobicity and Pollution Degree of Insulator. With the increase of operation time under natural conditions, the surface of insulators will suffer varying degrees of contamination, which is generally expressed by equivalent salt density (unit: mg·cm^{-2}) and conductivity (unit: S/m). Literature [21, 28] collects more than 800 samples of UHVDC insulators and finds that the range of ρ_{ESDD} is located at 0.0007–0.19 mg cm^{-2}, which indicates that the surface of insulators with good hydrophobicity will

Table 5: The relationship between the equivalent salt density and conductivity.

ρ_{ESDD} ($mg \cdot cm^{-2}$)	Natural water	0.05	0.10	0.15	0.20
Conductivity (S/m)	0.001	0.010	0.021	0.033	0.041



(a) (b) (c)

Figure 11: Three kinds of water contamination on insulator's surface: (a) small droplet, (b) large droplet, and (c) water film.

adhere to small droplets (static contact angle is more than 90°), while the surface of insulators with loss of hydrophobicity will adhere to large droplets (static contact angle is less than 90°). In severe cases, it is very likely to form water film [29–31]. After the contamination dissolves in the water film, it will improve its conductivity and reduce the insulation performance of insulators.

Table 5 shows the corresponding relationship between equivalent salt density and conductivity.

In order to explore the influence mechanism of insulator with different pollution degrees on lightning withstand performance of ±800 kV UHVDC transmission lines, three simulation models are constructed, which are small droplet, large droplet, and water film, as

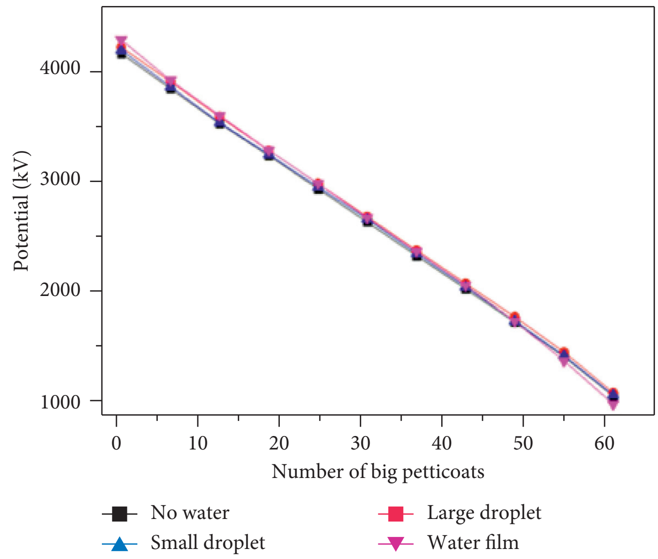


Figure 12: The relationship between different kinds of water contamination and surface potential.

shown in Figures 11(a)–11(c), where the radii of small droplet and large droplet are 2 mm and 4 mm, and the distance between contact surface and vertex of small droplet and large droplet is 2.5 mm and 3 mm. Moreover, the width and thickness of water film are 4 mm and 1 mm, respectively.

It is considered that the water droplets are uniformly distributed and the water film is uniform and uninterrupted, and the deformation influence of the water droplets/film on the potential and electric field distribution is neglected, which is caused by the wind and gravity. The relationship between different forms of water contamination and surface potential distribution of big petticoat when $\rho_{ESDD} = 0.2\ mg\cdot cm^{-2}$ can be simulated, as shown in Figure 12.

From Figure 12, one can see that the water film has the greatest influence on potential distribution, which means that it has the greatest influence on insulation performance of insulator. In addition, water film with contamination will also distort the electric field distribution on the insulator's surface, which leads to changes in lightning withstand performance of UHVDC transmission lines.

Figure 13 indicates the relationship between different forms of water contamination and the electric field distribution, and Table 6 shows the back-flashover lightning withstand performance of ±800 kV UHVDC transmission lines with three different kinds of water contamination under different pollution degrees.

4.2. The String Type of Insulator. Three types of insulator string are usually used in UHVDC transmission lines, such as I-type, II-type, and V-type. Different types of insulator string have different insulation performances, which leads to different lightning withstand performances [32–35]. Therefore, the suitable insulator's string type should be selected according to the actual needs and operating conditions of UHVDC transmission lines.

In order to explore the influence mechanism of different types of insulator string on lightning withstand performance of ±800 kV UHVDC transmission lines, three simulation models are constructed, where I-type is shown in Figure 1 and II-type and V-type are shown in Figure 14.

Considering the water film formation on insulator's surface, the electric field distribution of II-type and V-type is shown in Figures 15(a) and 15(b).

Because II-type string has one more discharge channel than I-type string, the lightning impulse voltage is reduced, which means that it has lower lightning withstand performance of UHVDC transmission lines using II-type string. When the gap length is the same, the V-type string is longer than I-type string, and the discharge channel is formed by the air gap with more uniform electric field distribution, so its lightning impulse voltage is higher, which means that it has better lightning withstand performance of UHVDC transmission lines using V-type insulator string [32–35].

The lightning withstand performance of ±800 kV UHVDC transmission lines with three string types of insulator under different pollution degrees is shown in Table 7.

Through similar simulation calculation as shown in Sections 3.1–3.3, the back-flashover lightning withstand level and back-flashover rate of ±800 kV UHVDC transmission lines using II-type string can be calculated without considering natural water and water pollution on insulator's surface, which are 367 kA and 0.00011 times/(100 km·year), respectively. Meanwhile, the back-flashover lightning withstand level and back-flashover rate of ±800 kV UHVDC transmission lines using V-type string can be calculated without considering natural water and water pollution on insulator's surface, which are 434 kA and 0.00018 times/(100 km·year), respectively.

4.3. Discussion. Through analyzing the data in Table 6, the following conclusions can be drawn:

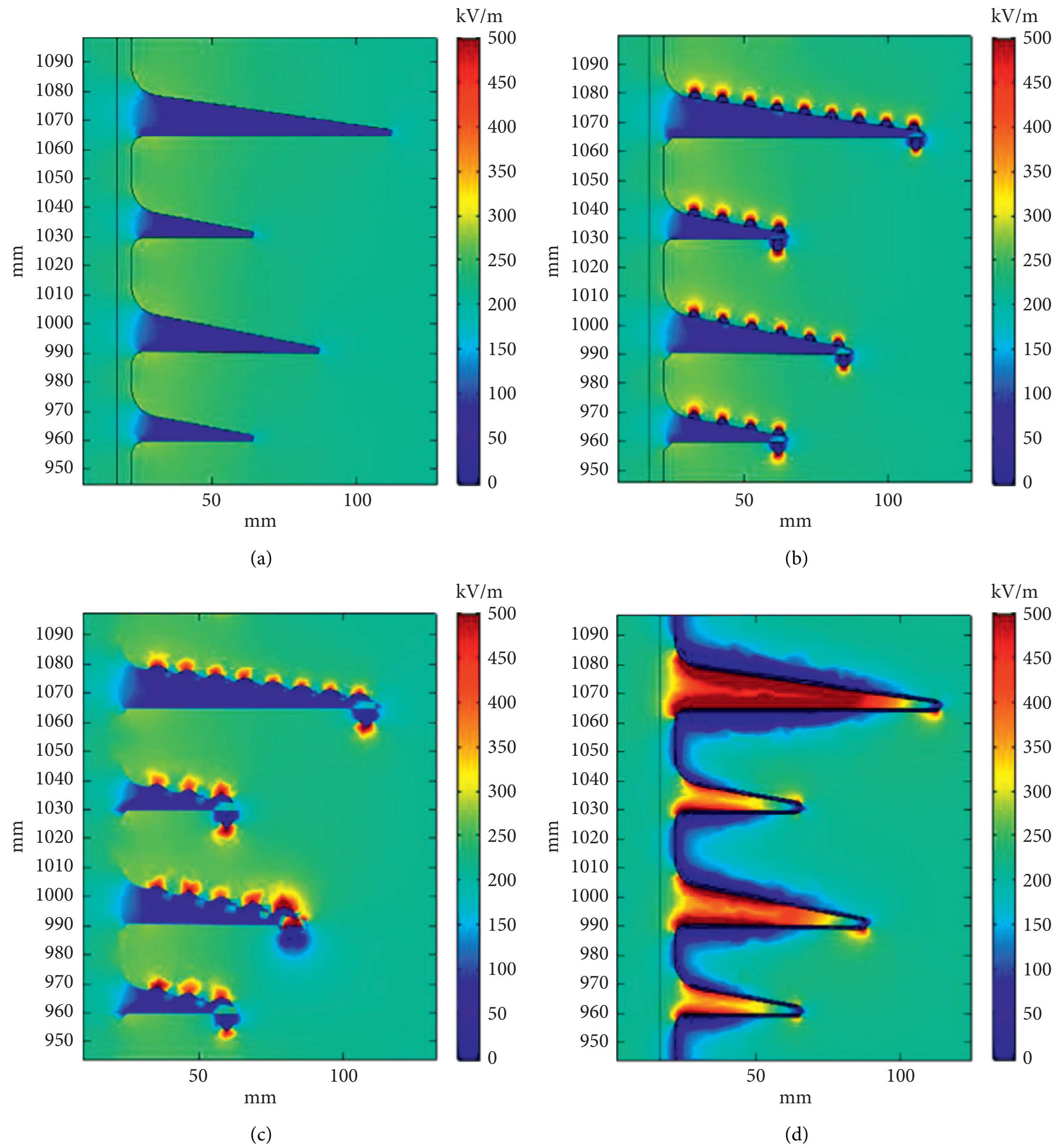
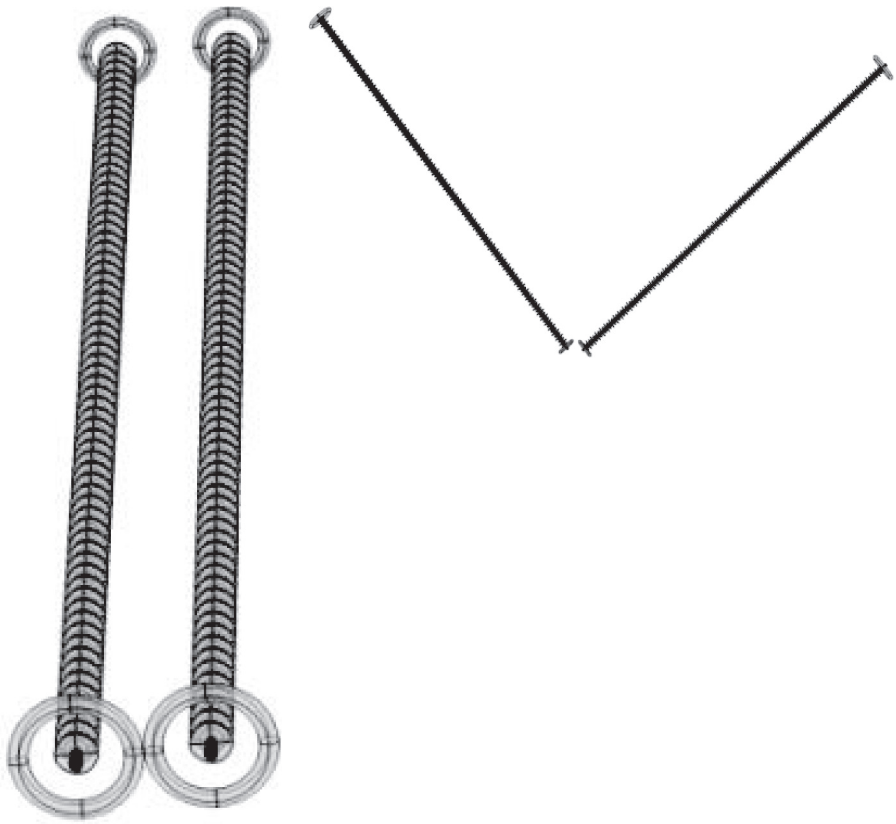


Figure 13: The relationship between different kinds of water contamination and electric field: (a) droplet, (b) small droplet, (c) large droplet, and (d) water film.

Table 6: Comparison of back-flashover lightning withstand performance of ±800 kV UHVDC transmission lines with three different kinds of water contamination under different pollution degrees.

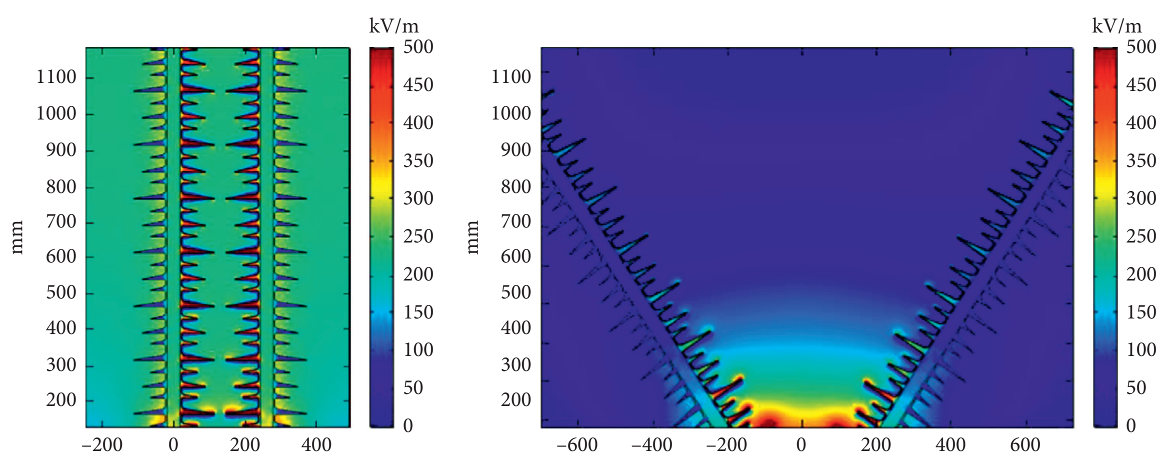
ρ_{ESDD} (mg·cm^{-2})		Natural water	0.05	0.10	0.15	0.20
Small droplet	Lightning withstand level (kA)	387	381	375	370	366
	Back-flashover rate (times/(100 km·year))	6.4×10^{-4}	7.4×10^{-4}	8.7×10^{-4}	9.9×10^{-4}	11×10^{-4}
Large droplet	Lightning withstand level (kA)	384	374	365	361	356
	Back-flashover rate (times/(100 km·year))	6.8×10^{-4}	8.9×10^{-4}	11×10^{-4}	13×10^{-4}	14×10^{-4}
Water film	Lightning withstand level (kA)	380	366	351	337	327
	Back-flashover rate (times/(100 km·year))	7.6×10^{-4}	11×10^{-4}	16×10^{-4}	24×10^{-4}	31×10^{-4}

(1) When the surface contamination of insulators is not considered, the surface hydrophobicity has little effect on the back-flashover lightning withstand level of ±800 kV UHVDC transmission lines. When the surface hydrophobicity is good (e.g., only small droplets are attached to the surface), the back-flashover lightning withstand level is only reduced by 1.02%, and the back-flashover rate is increased by



(a) (b)

Figure 14: Two string types of insulator: (a) II-type and (b) V-type.



(a) (b)

Figure 15: The electric field distribution of insulator with water film: (a) II-type and (b) V-type.

6.67% compared with no droplets. When the surface hydrophobicity is lost and water film is formed, the back-flashover lightning withstand level is only reduced by 2.81%, and the back-flashover rate is increased by 26.67% compared with no droplets.

(2) When the surface contamination of insulators is considered, the back-flashover lightning withstand performance of ±800 kV UHVDC transmission lines decreases obviously with increase of the contamination on insulator's surface. When the surface hydrophobicity of insulators is good (e.g., only small

Table 7: Comparison of lightning withstand performance of ±800 kV UHVDC transmission lines with three different string types of insulator under different pollution degrees.

ρ_{ESDD} (mg·cm^{-2})		Natural water	0.05	0.10	0.15	0.20
I-type string	Lightning withstand level (kA)	380	366	351	337	327
	Back-flashover rate (times/(100 km·year))	7.6×10^{-4}	11×10^{-4}	16×10^{-4}	24×10^{-4}	31×10^{-4}
V-type string	Lightning withstand level (kA)	427	410	393	381	372
	Back-flashover rate (times/(100 km·year))	2.2×10^{-4}	3.5×10^{-4}	5.4×10^{-4}	7.4×10^{-4}	9.4×10^{-4}
II-type string	Lightning withstand level (kA)	354	339	322	308	295
	Back-flashover rate (times/(100 km·year))	15×10^{-4}	22×10^{-4}	35×10^{-4}	50×10^{-4}	69×10^{-4}

droplets are attached to the surface) and $\rho_{\mathrm{ESDD}} = 0.2\,\mathrm{mg{\cdot}cm^{-2}}$, the back-flashover lightning withstand level is reduced by 6.39% and the back-flashover rate is increased by 83.33% compared with no droplets. When the surface hydrophobicity is lost and water film is formed and $\rho_{\mathrm{ESDD}} = 0.2\,\mathrm{mg{\cdot}cm^{-2}}$, the back-flashover lightning withstand level is reduced by 16.37% and the flashover rate is increased by 416.67% compared with no droplets.

Through analyzing the data in Table 7, the following conclusions can be drawn:

(1) When the water pollution on insulator's surface is not considered, the back-flashover lightning withstand level of ±800 kV UHVDC transmission lines using I-type string is decreased by 9.91% compared with V-type string but increased by 6.54% compared with II-type string. And the back-flashover rate is increased by 233.33% compared with V-type string but decreased by 45.45% compared with II-type string.

(2) When the water pollution on insulator's surface is considered, the water pollution has the least influence on lightning withstand performance of ±800 kV UHVDC transmission lines using V-type string, while it has the greatest influence on lightning withstand performance of ±800 kV UHVDC transmission lines using II-type string.

(3) The back-flashover lightning withstand performance of ±800 kV UHVDC transmission lines using V-type string ($\rho_{\mathrm{ESDD}} = 0.2\,\mathrm{mg{\cdot}cm^{-2}}$) is decreased by 14.29%, while the back-flashover rate is increased by 422.22% compared with the case of $\rho_{\mathrm{ESDD}} = 0\,\mathrm{mg{\cdot}cm^{-2}}$; the back-flashover lightning withstand performance of ±800 kV UHVDC transmission lines using II-type string ($\rho_{\mathrm{ESDD}} = 0.2\,\mathrm{mg{\cdot}cm^{-2}}$) is decreased by 19.62%, while the back-flashover rate is increased by 527.27% compared with the case of $\rho_{\mathrm{ESDD}} = 0\,\mathrm{mg{\cdot}cm^{-2}}$.

5. Conclusions

The research results demonstrate that the insulator's condition has great influence on the back-flashover lightning withstand performance of ±800 kV UHVDC transmission lines, which cannot be neglected in practical engineering applications. In order to ensure stable operation and reliable power supply of ±800 kV UHVDC transmission lines, some special precaution measures should be taken, such as regularly cleaning up the surface contamination of insulator and timely replacement of the insulator with serious surface damage and loss of surface hydrophobicity. On the premise of meeting budget, V-type string insulator should be preferred for ±800 kV UHVDC transmission lines in some heavy pollution regions.

The proposed method will provide the theoretical foundation and significant guiding role for experimental testing. However, the influencing factors are not considered comprehensively in our simulation model, which leads to some differences between the simulation situation and the actual operating state of ±800 kV UHVDC transmission lines. In addition, the contradiction between improving the back-flashover lightning withstand performance of ±800 kV UHVDC transmission lines and reducing the operating cost is also not fully considered in this paper. The future work will be focused on conducting joint experimental research with research institutions with experimental conditions so as to further verify the rationality and correctness of this proposed model and research method.

Data Availability

The data supporting the conclusions of this study are included within the article, such as insulator's parameters, UHVDC transmission line's parameters, and tower's parameters.

Conflicts of Interest

We declare that we have no financial and personal relationships with other people or organizations that can inappropriately influence our work, and there is no professional or other personal interest of any nature or kind in any product, service, and/or company that could be construed as influencing the position presented in or the review of our work submitted.

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