Research Article

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

Wenbo Jiang,1,2 Chunlin Tang,1,2 and Bo Zhou1,2

1School of Electrical Engineering and Electronic Information, Xihua University, Chengdu 610039, China
2Sichuan Provincial Key Laboratory of Signal and Information Processing, Xihua University, Chengdu 610039, China

Correspondence should be addressed to Wenbo Jiang; caswenbojiang@gmail.com

Received 3 February 2020; Revised 22 March 2020; Accepted 4 April 2020; Published 30 April 2020

Academic Editor: Michele Guida

Copyright © 2020 Wenbo Jiang et al. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

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 H-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’i-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:

\[
\begin{align*}
U_x &= U_e, \\
U_z &= 0,
\end{align*}
\]

where \(U_e\) is the rated voltage of transmission lines and \(U_x\) and \(U_z\) 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:

\[
\begin{align*}
U_x &= U(t), \\
U_z &= 0, \\
U(t) &= U_m(e^{-\lambda_1 t} - e^{-\lambda_2 t}),
\end{align*}
\]

where \(U(t)\) is the instantaneous voltage and \(U_m\) is the amplitude of lightning impulse voltage; the value of \(\lambda_1\) and \(\lambda_2\) depends on the lightning current waveform.

\[
\begin{align*}
\lambda_1 &= \frac{1}{T_1}, \\
\lambda_2 &= \frac{1}{T_2},
\end{align*}
\]

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 volt-
age-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 di-
ameter 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, in-
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:

\[
Z_{TK} = 60 \left( \ln \frac{2\sqrt{2} h_k}{r_k} - 2 \right), \quad k = 1, 2, 3,
\]

\[
Z_{AK} = 60 \left( \ln \frac{2h_k}{r_{AK}} \right),
\]

\[
Z_{ik} = 9Z_{TK},
\]

\[
r_k = 2^{1/8} \left( \frac{r_{1/3}^{1/3} \cdot r_B^{2/3}}{R_{TK} \cdot R_B} \right)^{1/4} \cdot \left( R_{1/3}^{1/3} \cdot R_{2/3}^{2/3} \right)^{3/4},
\]

where \(Z_{TK}, Z_{AK}, Z_{ik}\) 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; \(h_k, r_{1/3}, r_{2/3}, r_B, R_{1/3}\),
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 x 10^3       | 3.5       | 5       | 1.0006 |
| Conductivity (S/m) | 1.5 x 10^7     | 1 x 10^-12| 4 x 10^-12| 5 x 10^-14|

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

\[
R_T = \frac{R_0}{\sqrt{1 + 1/I_g^2}}
\]

\[
I_g = \frac{\rho \cdot E_0}{2\pi \cdot R_0^2}
\]

where \(R_0\) indicates the grounding resistance at power fre-
quency (here \(R_0 = 10 \Omega\) and \(E_0 = 400 \text{kV/m}\); \(I\) indicates
the high-frequency impulse current; \(I_g\) indicates the ioniza-
current threshold of soil; and \(\rho\) 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, espe-
cially 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 condi-
tion. Therefore, the lightning impulse voltage of 110 kV
insulator is 844 kV.
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.
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 ($V_{t}$) and 50% breakdown voltage ($U_{50\%}$) of insulators are as follows [15, 26, 27]:

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 ($t = 8 \mu s$): (a) without flashover and (b) with flashover.
\[ V_{s-t} = 400 \cdot L + \frac{710 \cdot L}{t^{0.75}} \]
\[ U_{50\%} = 533 \cdot L + 132, \]

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

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

\[
\begin{align*}
    n &= N_s \cdot \eta \cdot g \cdot P, \\
    N_s &= N_g \left( \frac{28h^{0.6} + b}{10} \right), \\
    N_g &= 0.0237^{1.3}, \\
    \lg P &= -I/88,
\end{align*}
\]

where \( N_s \) indicates the number of lightning striking per hundred kilometers per year in this area; \( \eta \) 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 \( \pm800 \) kV UHVDC transmission lines; \( N_g \) 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 \( \pm800 \) 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 \( \pm800 \) 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 \( \pm800 \) 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 \( \rho_{ESDD} \) is located at 0.0007–0.19 mg cm\(^{-2}\), which indicates that the surface of insulators with good hydrophobicity will be more resistant to contamination.

Table 3: The parameters of \( \pm800 \) 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) | \( r_{IK} \) (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.
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.

| $\rho_{ESDD}$ (mg·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|

**Figure 11:** Three kinds of water contamination on insulator's surface: (a) small droplet, (b) large droplet, and (c) water film.
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 $\rho_{ESDD} = 0.2 \text{ mg cm}^{-2}$ 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:
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

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

(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
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.

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

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.

Acknowledgments

This study was supported by the National Natural Science Foundation of China under grant nos. 61875166 and 61307063 and Sichuan Provincial Academic and Technical Leader Training Plan and Xihua Scholars Training Plan of Xihua University. Wenbo Jiang would also like to acknowledge the Overseas Training Plan of Xihua University (09/2014–09/2015, University of Michigan, Ann Arbor, US).

References

[1] Z. Y. Liu, Q. P. Zhang, C. Dong et al., “Efficient and security transmission of wind, photovoltaic and thermal power of large-scale energy resource bases through UHVDC projects,” Proceeding of the CSEE, vol. 34, no. 16, pp. 2513–2522, 2014.
[2] H. Zhou, W. Q. Qiu, K. Sun et al., Ultra-high Voltage AC/DC Power Transmission, Springer Press, Berlin, Germany, 2018.
[3] H. R. Zhao and S. Guo, “Risk evaluation on UHV power transmission construction project based on AHP and FCE method,” Mathematical Problems in Engineering, vol. 2014, Article ID 687568, 1 pages, 2014.
[4] M. Zhang, G. F. Zhao, and J. Li, “Nonlinear dynamic analysis of high-voltage overhead transmission lines,” Mathematical Problems in Engineering, no. 1-35, p. 1247523, 2018.
[5] K. Yao and J. Qian, “Study on seismic reliability of UHVDC transmission systems,” Mathematical Problems in Engineering, vol. 2019, no. 9, Article ID 4131609, 2019.
[6] Z. G. Datsios and P. N. Mikropoulos, “Modeling of lightning impulse behavior of long air gaps and insulators including pre-discharge current: implications on insulation coordination of overhead transmission lines and substations,” Electric Power Systems Research, vol. 139, pp. 37–46, 2016.
[7] M. S. Banjanin, “Application possibilities of special lightning protection systems of overhead distribution and transmission lines,” *International Journal of Electrical Power & Energy Systems*, vol. 100, pp. 482–488, 2018.

[8] P. Chiradeja and A. Ngsopitakkul, “Classification of lightning and faults in transmission line systems using discrete wavelet transform,” *Mathematical Problems in Engineering*, vol. 2018, Article ID 1847968, 14 pages, 2018.

[9] S. Visacro and F. H. Silveira, “Lightning performance of transmission lines: methodology to design grounding electrodes to ensure an expected outage rate,” *IEEE Transactions on Power Delivery*, vol. 30, no. 1, pp. 237–245, 2015.

[10] R. Shariatinasab, J. Gholinezhad, K. Sheshyekani, and M. R. Alemi, “The effect of wide band modeling of tower-footing grounding system on the lightning performance of transmission lines: a probabilistic evaluation,” *Electric Power Systems Research*, vol. 141, pp. 1–10, 2016.

[11] Y. Liu, G. Sheng, Y. Hu et al., “Identification of lightning strike on 500-kV transmission line based on the time-domain parameters of a traveling wave,” *IEEE Access*, vol. 4, pp. 7241–7250, 2016.

[12] P. Sarajcev, J. Vasilj, and D. Jakus, “Method for estimating back-flashover rates on HV transmission lines based on EMTP-ATP and curve of limiting parameters,” *Electric Power and Energy Systems*, vol. 78, pp. 127–137, 2015.

[13] M. Qian, D. Zhao, J. Ma, L. Zhu, R. Ju, and M. Chen, “Operation characteristics of DC transmission system with large-scale renewable energy integration,” *The Journal of Engineering*, vol. 2019, no. 16, 2019.

[14] S. Kumara, S. Alam, I. R. Hoque, Y. V. Serdyuk, and S. M. Gubanski, “DC flashover characteristics of a polymeric insulator in presence of surface charges,” *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 19, no. 3, pp. 1084–1090, 2012.

[15] Y. Hao, Y. Han, L. Tang, C. Mao, and L. Li, “Leader propagation models of ultrahigh-voltage insulator strings based on voltage/time curves under negative lightning impulses at high altitude,” *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 22, no. 2, pp. 1186–1192, 2015.

[16] Q. Hu, S. Wang, L. Shu, X. Jiang, J. Liang, and G. Qiu, “Comparison of AC icing flashover performances of 220 kV composite insulators with different shed configurations,” *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 23, no. 2, pp. 995–1004, 2016.

[17] Y. Han, Y. Zhang, Y. Ruan et al., “Study on influencing factors of insulators flashover characteristics on the 110 kV true tower under the lightning impulse,” *IEEE Access*, vol. 6, pp. 66536–66544, 2018.

[18] G. Shanmugam and S. Karakkad, “Influence of the insulator geometry on the streamer propagation characteristics in polymeric insulators under positive polarity lightning impulse voltages,” *IET Science, Measurement & Technology*, vol. 12, no. 8, pp. 1082–1088, 2018.

[19] Z. Zhang, J. Zhao, D. Zhang et al., “Study on the DC flashover performance of standard suspension insulator with ring-shaped non-uniform pollution,” *High Voltage*, vol. 3, no. 2, pp. 133–139, 2018.

[20] T. Li, S. H. Wang, H. J. Liu et al., “Comparison of natural contamination accumulation characteristics between composite rod insulators and standard suspended insulator strings,” *The Journal of Engineering*, vol. 2019, no. 16, pp. 1027–1032, 2019.

[21] X. Qiao, Z. Zhang, X. Jiang, and T. Liang, “Influence of DC electric fields on pollution of HVDC composite insulator short samples with different environmental parameters,” *Energies*, vol. 12, no. 12, p. 2304, 2019.

[22] R. T. Waters, “Leader and space charge characteristics derived from fluxmeter results,” *Electra*, vol. 35, pp. 77–85, 1974.

[23] Y. Q. Zhang, L. C. Li, Y. X. Han et al., “Flashover performance test and flashover criterion study of insulators in a 110kV true type tower at high altitude areas,” *Power System Technology*, vol. 43, no. 1, pp. 340–348, 2019.

[24] Z. J. Zhang, X. L. Jiang, J. L. Hu et al., “Analysis on electric performance variation of 110 kV composite insulators being operated,” *Power System Technology*, vol. 32, no. 3, pp. 35–40, 2008.

[25] Y. Q. Zhang, L. C. Li, Y. X. Han et al., “Flashover performance test with lightning impulse and simulation analysis of different insulators in a 110 kV double-circuit transmission tower,” *Energies*, vol. 11, no. 3, pp. 1–13, 2018.

[26] W. Song, W.-W. Shen, G.-J. Zhang et al., “Aging characterization of high temperature vulcanized silicone rubber housing material used for outdoor insulation,” *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 22, no. 2, pp. 961–969, 2015.

[27] H. Motoyama, “Experimental study and analysis of breakdown characteristics of long air gaps with short tail lightning impulse,” *IEEE Transactions on Power Delivery*, vol. 11, no. 2, pp. 972–979, 1996.

[28] I. Ahmad-Joneid, A. A. Shayeegani-Akmal, and H. Mohseni, “Leakage current analysis of polymeric insulators under uniform and non-uniform pollution conditions,” *IET Generation, Transmission & Distribution*, vol. 11, no. 11, pp. 2947–2957, 2017.

[29] P. Hu and M. Farzaneh, “Two dimensional modeling of the ice accretion process on transmission line wires and conductors,” *Cold Regions Science and Technology*, vol. 46, no. 2, pp. 132–146, 2006.

[30] Z. H. Liu, “Accreted Ice and Preventive Treatment on Conductor of UHVDC Transmission Lines,” pp. pp10–24, China Electric Power Press, Beijing, China, 2012.

[31] Q. Hu, S. Wang, L. Shu, X. Jiang, G. Qiu, and H. Li, “Influence of shed configuration on icing characteristics and flashover performance of 220 kV composite insulators,” *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 23, no. 1, pp. 319–330, 2016.

[32] I. Gallimberti, G. Bacchioga, A. Bondiou-Clergerie, and P. Lalande, “Fundamental processes in long air gap discharges,” *Comptes Rendus Physique*, vol. 3, no. 10, pp. 1335–1359, 2002.

[33] F. A. M. Rizk, “Modeling of proximity effect on positive leader inception and breakdown of long air gaps,” *IEEE Transactions on Power Delivery*, vol. 24, no. 4, pp. 2311–2318, 2009.

[34] W. Chisholm, “New challenges in lightning impulse flashover modeling of air gaps and insulators,” *IEEE Electrical Insulation Magazine*, vol. 26, no. 2, pp. 14–25, 2010.

[35] Y. F. Zhang, E. C. Zhang, and J. L. Gu, “Evaluation of horizontal electric field from the lightning channel by electromagnetic field equations of moving charges,” *Mathematical Problems in Engineering*, vol. 2019, Article ID 4091586, 8 pages, 2019.