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# Study on Influencing Factors of Insulators Flashover Characteristics on the 110 kV True Tower Under the Lightning Impulse

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**ABSTRACT** Lightning strike is the main reason for the transmission line tripping. Studies on the insulator flashover characteristics and the accurate flashover criteria under the lightning impulse are the basis for correctly evaluating the lightning resistance performance of the transmission line. In this paper, an experimental study on the flashover characteristics of the insulators with different materials was carried out on the 110-kV double-circuit transmission line tower. The insulators were hung on the umbrella-shaped tower and the drum-shaped tower in the test, and both the standard lightning impulse (1.2/50  $\mu$ s) and the short-tail lightning impulse (1/10  $\mu$ s) were used. The flashover test of a single composite insulator was also carried out for comparatively analyzing the influence of the true tower on the insulator flashover performance. According to the test results on the true tower, the lightning flashover criteria of the insulators with different materials are given. The influencing factors of the insulator flashover characteristics, including the impulse waveform, the insulator material, the tower type, and the insulator suspension position, were further compared and analyzed. Meanwhile, the results of the single insulator test proved that the true tower has great influence on the insulator flashover characteristics and that the flashover test on the true tower can reflect actual situation better and obtain more accurate results. In addition, based on the simulation analysis results of the electric-field distribution around the insulators, the difference of 50% impulse flashover voltage ( $U_{50\%}$ ) of the insulators in different conditions was partly explained.

**INDEX TERMS** The standard lightning impulse and the short-tail lightning impulse, 110 kV double-circuit transmission line, true tower, influencing factors of flashover characteristics,  $U_{50\%}$  and volt-second characteristics.

## I. INTRODUCTION

Lightning strike is the main cause of tripping in overhead transmission lines [1]. Relevant statistics show that the main form of lightning strikes on transmission lines below 220 kV is the lightning back-flashover, while the shielding failure is the main form on 220-500 kV transmission lines [2]. The lightning back-flashover of the double-circuit transmission line are more severe [3]–[6]. Moreover, a short-tail lightning impulse is formed across the insulator during back-flashover, while a standard lightning impulse is formed during shielding failure. Therefore, research on the insulator flashover characteristics and flashover criterions under the standard lightning impulse and the short-tail lightning impulse is the foundation

of the accurate evaluation on the lightning protection performance of transmission lines.

At present, some research on the flashover characteristics of the insulators with different materials and long air gaps under the standard and non-standard lightning impulses had been done. Through the flashover characteristic tests of the insulators with different materials at distinct voltage levels, the mathematical relationship between the  $U_{50\%}$  under the standard lightning impulse and the string length of the insulators were given [7]. However, the use scope and accuracy were limited by testing conditions, and related researches showed that the insulator material has a certain influence on the insulator flashover path [8]–[16], [29].

The insulator tests on AC/DC transmission lines under the short-tail lightning impulse were studied [17]–[20]. The waveforms with different wave front and tail were used in these tests and the voltage levels of the tests were 220 kV and above. Whether the test data were suitable for the lightning protection performance evaluation of 110 kV transmission lines and below remains to be verified. Wang *et al.* experimentally studied the flashover characteristics of 110 -500 kV insulators with different materials and the air gap under the standard lightning impulse and the short-tail lightning impulse. But the test object is a single insulator and the test was not carried out on the true tower. The influence of the tower body and crossarms on the insulator flashover characteristics were ignored [21], [22]. Yang *et al.* has experimentally studied the flashover characteristics of the glass insulators hung on the 220 kV wine-shape tower under short-tail lightning impulse. The test showed that the flashover characteristics of the insulator hung on the wine-shape tower were different from those of the single insulator and the air gap [23]. The above studies have facilitated the accurate analysis of the lightning resistance performance of transmission lines in diverse situations. However, various influencing factors will affect the results of the flashover characteristics test. It is necessary to carry out a more systematic experimental study on the flashover characteristics of the insulators hung on the true tower and to analyze the influencing factors and their influencing degree, from which the accurate lightning flashover criterions on 110 kV true tower can be proposed.

The aim of this paper is to study the influencing factors of the insulator flashover characteristics via the flashover tests and the electric-field simulation. The tests were conducted under the standard lightning impulse and the short-tail lightning impulse at an altitude of 2100 m. The short-tail impulse waveform on 110 kV tower is obtained by PSCAD simulation. The composite and glass insulators were hung on the umbrella-shape tower and the drum-shape tower. In order to prove the influence of the true tower in the insulator flashover characteristics and the necessity of using the true tower in the test, the flashover test of a single composite insulator was also carried out. Based on the test results, the influencing factors, including the impulse waveform, the insulator material, the tower type and the insulator suspension position, on the flashover characteristics are compared and analyzed. At the same time, based on the electric-field simulation around insulators, the difference of the insulator flashover characteristics is partly explained. This research provides a reference for improving the accuracy of the insulator flashover criterions.

## II. TEST DEVICE AND RESEARCH METHOD

### A. TEST DEVICE AND SAMPLE

The test was carried out at the Kunming UHV Engineering Technology National Engineering Laboratory with an altitude of 2100 m. The test circuit consists of a surge voltage generator, a capacitive voltage divider and a test sample.

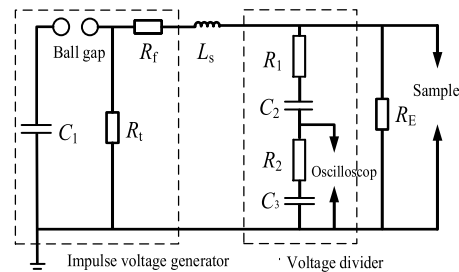


FIGURE 1. The experiment circuit.

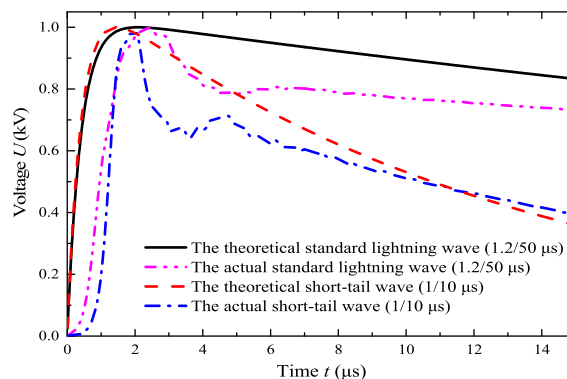


FIGURE 2. Comparison of the theoretical and the actual waveforms.

The impulse waveform used in the test had a critical impact on the accuracy of the test results. The standard lightning impulse has a front time of 1.2  $\mu\text{s}$  and a tail time of 50  $\mu\text{s}$ . At the same time, the electromagnetic transient simulation analysis of the 110 kV typical double-circuit transmission line subjected to lightning back flashover showed that the tail time of the insulator overvoltage under a back flashover was about 5-10  $\mu\text{s}$ , while the front time is about 0.2-2.0  $\mu\text{s}$ . Therefore, a short-tail lightning impulse with a front time of 1  $\mu\text{s}$  and a tail time of 10  $\mu\text{s}$  was selected for the following research [24]. In order to obtain the required waveform, the test circuit was designed as shown in Figure 1. Based on the 7200 kV impulse voltage generator with the rated capacity of 720 kJ, an external resistor  $R_E$  (264  $\Omega$ ) was utilized to reduce the tail time.

The theoretical and actual waveforms of the standard lightning impulse and short-tail lightning impulse are shown in Figure 2. There exists the phenomenon of overshoot and oscillation during the waveform tests. Reference to the overshoot calculation method in GBT 16927.1-2011 [27], it is known that the actual waveforms are within the allowable range of the 110 kV insulator lightning strike characteristics analysis.

The samples are composite and glass insulators which are hung on the 110 kV true tower. The insulator patterns are FXBW4-110/100 and XP-70 respectively. And the dry arc distances of two types of insulators are 1.12 m and 1.14 m, respectively. As shown in Figure 3, the left side is an umbrella-shape tower, and the lengths of its crossarms from

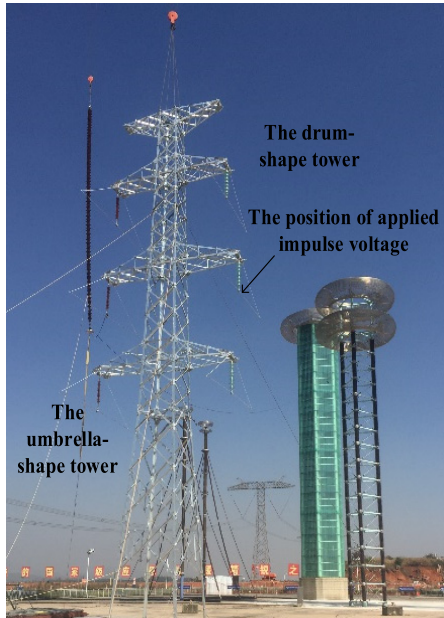


FIGURE 3. The true 110 kV double-circuit transmission line tower.

the up phase to the down phase are 2854.5 mm, 3150.0 mm, and 3450.0 mm, respectively. The right side is a drum-shape tower, and the lengths of its crossarms from the up phase to the down phase are 2854.5 mm, 3450.0 mm, and 3150.0 mm, respectively.

### B. TEST METHOD

The flashover tests, including the  $U_{50\%}$  test and the volt-second characteristic test, were carried out in accordance with the standard of IEC 60060 [25], [26]. And the up-and-down method was used to test the  $U_{50\%}$ . The rise-and-fall level of the voltage is 3% of the expected voltage.

The test voltage started from the  $U_{50\%}$  and increased to 1.05, 1.10, 1.20, 1.30, 1.40, 1.6, 1.8, 2.0, 2.2, 2.4, 3.0, 3.3, 3.6 times of the  $U_{50\%}$ . Due to the rated voltage limit of the impulse voltage generator, the test voltage under the short-tail lightning impulse is up to 2.4 times of the  $U_{50\%}$ . The data of the volt-second characteristic test is fitted using the volt-second characteristic description function recommended in [25], as in (1):

$$U = A \times L + \frac{B \times L}{t^C} \quad (1)$$

Where  $L$  is the gap length (m);  $t$  is the flashover time ( $\mu\text{s}$ );  $A$ ,  $B$ , and  $C$  are the coefficients to be determined.

### C. SIMULATION ANALYSIS METHOD

The instantaneous electric-field distribution around the insulator has an effect on the generation and development of the following discharge/flashover process.

In order to explore the influences of insulator material, tower type and the relative position of the three-phase crossarms on the electric-field distribution around the

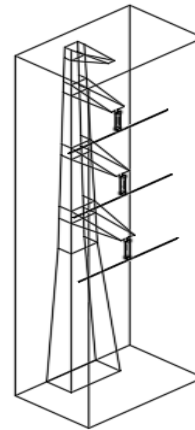


FIGURE 4. The 3-D simulation model.

insulator, and to explain the resulting difference in flashover characteristics, the three-dimensional (3-D) model of the tower and insulator were established and the electrostatic field simulation was carried out based on COMSOL Multiphysics. The simulation model is shown in Figure 4.

The structural parameters of the tower are in accordance with the actual towers in the test. The typical electric-field distribution around the insulator and the electric-field uneven coefficients were compared and analyzed. The electric-field uneven coefficient is the ratio of the maximum field strength and the average field strength in the possible discharge path around the insulator. In the gap discharge theory, the uneven coefficient represents the electric-field non-uniformity of the discharge gap. Under the switching and lightning impulses, the more uneven the electric field is., the more obvious the polarity effect of the  $U_{50\%}$ . Therefore, in two gaps with the same length, the positive  $U_{50\%}$  of the gap with larger uneven coefficient will be lower, while the negative  $U_{50\%}$  will be higher [9], [29]. The detailed modeling method and part of the results can be found in [29].

### D. THE SINGLE INSULATOR TEST

In order to prove the influence of the true tower on the insulator flashover characteristics and the necessity of using the true tower in the test, the flashover test of a single insulator was also carried out. The upper end of the insulator was connected to the high voltage wire, and the lower end was connected by two grounding wires. Due to the limitation of the impulse voltage generator (in door) in this test, the actual output impulse is with a front time of 0.84  $\mu\text{s}$  and a tail time of 50  $\mu\text{s}$ . The parameter deviation is within the allowable range of the standard lightning impulse. The test layout are shown in Figure 5.

## III. RESULTS OF TESTS AND SIMULATION

### A. TEST RESULTS

Based on the test device and method above, impulse flashover tests of the insulators for 110 kV double-circuit transmission lines were conducted. The  $U_{50\%}$  and volt-second

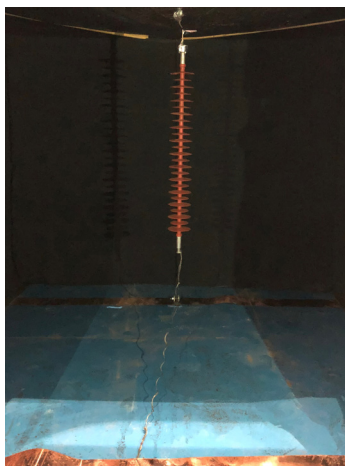


FIGURE 5. The layout of the single insulator test.

TABLE 1. The  $U_{50\%}$  of the insulators on the true tower under the standard lightning impulse.

| Type of tower            | Type of insulator | The phase | Positive (kV) | Negative (kV) |
|--------------------------|-------------------|-----------|---------------|---------------|
| The umbrella-shape tower | Composite         | upper     | 763           | 815           |
|                          |                   | middle    | 758           | 821           |
|                          |                   | down      | 769           | 821           |
|                          | Glass             | upper     | 754           | 777           |
|                          |                   | middle    | 763           | 776           |
|                          |                   | down      | 773           | 794           |
| The drum-shape tower     | Composite         | upper     | 751           | 822           |
|                          |                   | middle    | 751           | 821           |
|                          |                   | down      | 761           | 827           |
|                          | Glass             | upper     | 769           | 800           |
|                          |                   | middle    | 780           | 806           |
|                          |                   | down      | 766           | 820           |

characteristics of the three-phase composite and glass insulators hung on the umbrella-shape and drum-shape tower under the standard lightning impulse and the short-tail lightning impulse were respectively obtained.

During the tests, the temperature was between 10.1° to 26.8°, the relative humidity was between 19.4% to 72.6%, and the air pressure was between 78.73 kPa to 79.86 kPa. The data were corrected to the standard atmospheric conditions according to the g-parameter method provided in the standard GB/T 16927.1-2011 [27]. The  $U_{50\%}$  and their standard deviations are shown in Table 1, Table 2, Table 3, and Table 4. Due to the great linearity relationship between the insulator flashover voltage and their length in the range of 1-3 m [7], the results are unified to the length of the composite insulator of 1.12 m for comparison.

The  $U_{50\%}$  test results of single insulator under the standard lightning impulse are shown in Table 5.

Since the volt-second characteristic data is large, it is given separately in the discussion of Part IV.

**B. SIMULATION RESULTS**

Based on the 3-D electrostatic field simulation model above, the electric-field distributions and uneven coefficients around

TABLE 2. The  $U_{50\%}$  of the insulators on the true tower under the short-tail lightning impulse.

| Type of tower            | Type of insulator | The phase | Positive (kV) | Negative (kV) |
|--------------------------|-------------------|-----------|---------------|---------------|
| The umbrella-shape tower | Composite         | upper     | 1016          | 1032          |
|                          |                   | middle    | 963           | 1048          |
|                          |                   | down      | 948           | 1020          |
|                          | Glass             | upper     | 1007          | 1032          |
|                          |                   | middle    | 1010          | 1031          |
|                          |                   | down      | 945           | 996           |
| The drum-shape tower     | Composite         | upper     | 1071          | 1114          |
|                          |                   | Middle    | 1052          | 1101          |
|                          |                   | Down      | 1009          | 1065          |
|                          | Glass             | Upper     | 1068          | 1113          |
|                          |                   | Middle    | 1045          | 1083          |
|                          |                   | Down      | 995           | 1065          |

TABLE 3. The comparison of the standard deviation of the  $U_{50\%}$  of the insulators on the true tower under the standard lightning impulse.

| Type of tower            | Type of insulator | The phase | Positive (%) | Negative (%) |
|--------------------------|-------------------|-----------|--------------|--------------|
| The umbrella-shape tower | Composite         | upper     | 6.26         | 7.78         |
|                          |                   | middle    | 2.79         | 8.28         |
|                          |                   | down      | 4.32         | 4.66         |
|                          | Glass             | upper     | 7.01         | 9.26         |
|                          |                   | middle    | 6.24         | 7.23         |
|                          |                   | down      | 5.31         | 6.21         |
| The drum-shape tower     | Composite         | upper     | 6.82         | 7.47         |
|                          |                   | middle    | 11.96        | 6.82         |
|                          |                   | down      | 6.26         | 7.78         |
|                          | Glass             | upper     | 2.79         | 8.28         |
|                          |                   | middle    | 4.32         | 4.66         |
|                          |                   | down      | 7.01         | 9.26         |

TABLE 4. The comparison of the standard deviation of the  $U_{50\%}$  of the insulators on the true tower under the short-tail lightning impulse.

| Type of tower            | Type of insulator | The phase | Positive (%) | Negative (%) |
|--------------------------|-------------------|-----------|--------------|--------------|
| The umbrella-shape tower | Composite         | upper     | 18.63        | 14.44        |
|                          |                   | middle    | 7.73         | 9.98         |
|                          |                   | down      | 19.12        | 17.16        |
|                          | Glass             | upper     | 6.02         | 8.10         |
|                          |                   | middle    | 7.44         | 9.12         |
|                          |                   | down      | 7.32         | 7.75         |
| The drum-shape tower     | Composite         | upper     | 9.98         | 10.03        |
|                          |                   | middle    | 15.56        | 16.27        |
|                          |                   | down      | 8.25         | 5.21         |
|                          | Glass             | upper     | 11.47        | 9.97         |
|                          |                   | middle    | 7.22         | 9.67         |
|                          |                   | down      | 10.56        | 14.23        |

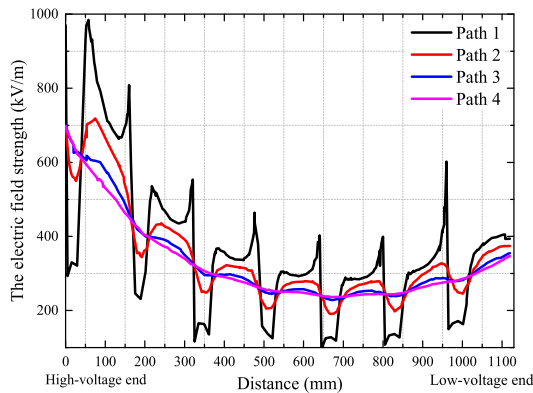
TABLE 5. The  $U_{50\%}$  of single insulator under the standard lightning impulse.

| Type of insulator | Positive (kV) | Negative (kV) |
|-------------------|---------------|---------------|
| Composite         | 747           | 881           |

the three-phase insulator in the umbrella-shape and the drum-shape towers are obtained. Part of the simulation results are demonstrated as examples. The electric field distribution

**TABLE 6.** The electric-field uneven coefficients around the insulators on the true tower.

| Type of tower            | The phase | Uneven coefficients |       |
|--------------------------|-----------|---------------------|-------|
|                          |           | Composite           | Glass |
| The umbrella-shape tower | upper     | 3.15                | 2.09  |
|                          | middle    | 3.24                | 2.13  |
|                          | down      | 3.10                | 2.06  |
| The drum-shape tower     | upper     | 3.12                | 2.10  |
|                          | middle    | 3.11                | 2.08  |
|                          | down      | 3.14                | 2.13  |



**FIGURE 6.** The electric field distribution around the upper-phase glass insulator.

around the upper-phase glass insulator hung on the umbrella-shape tower is shown in Figure 6. The electric-field uneven coefficients along Path 2 of the three-phase composite and glass insulators hung on different towers are shown in Table 6.

#### IV. DISCUSSION AND ANALYSIS OF INFLUENCING FACTORS

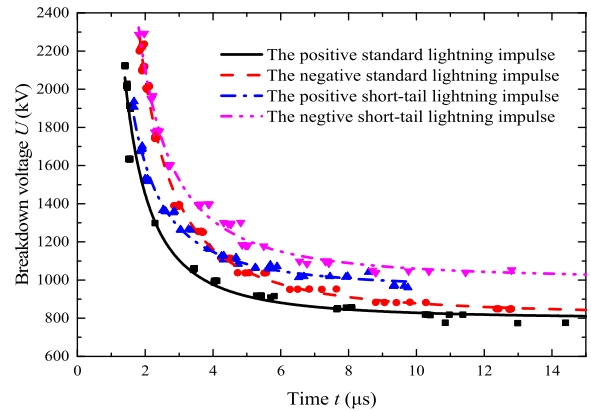
According to the test results, the influencing factors on the flashover voltage of the insulator, including the impulse voltage waveform, the insulator material, the tower types, and the suspension positions of the insulator, are all analyzed in the following.

##### A. THE IMPULSE WAVEFORM

Comparing with the data in Table 1 and Table 2, the  $U_{50\%}$  under the short-tail lightning impulse are about 20%-40% higher than those under the standard lightning impulse. Because the front time and tail time of the short-tail lightning impulse are both short, it is not easy to reach the threshold of the discharge delay. Therefore, a higher voltage is required to allow the discharge to continue.

As shown in Table 3 and Table 4, the  $U_{50\%}$  under the short-tail lightning impulse is more dispersive than those under the standard lightning impulse. And the standard deviations of  $U_{50\%}$  under the short-tail lightning impulse are even more than 3 times higher than those under the standard lightning impulse in some working conditions.

Taking the composite insulator hung on the down phase of the umbrella-shape tower as an example, the volt-second



**FIGURE 7.** The volt-second characteristics curves of the insulators under different impulse voltage waveforms.

characteristic curves of the insulator under different impulse voltage waveforms are illustrated in Figure 7.

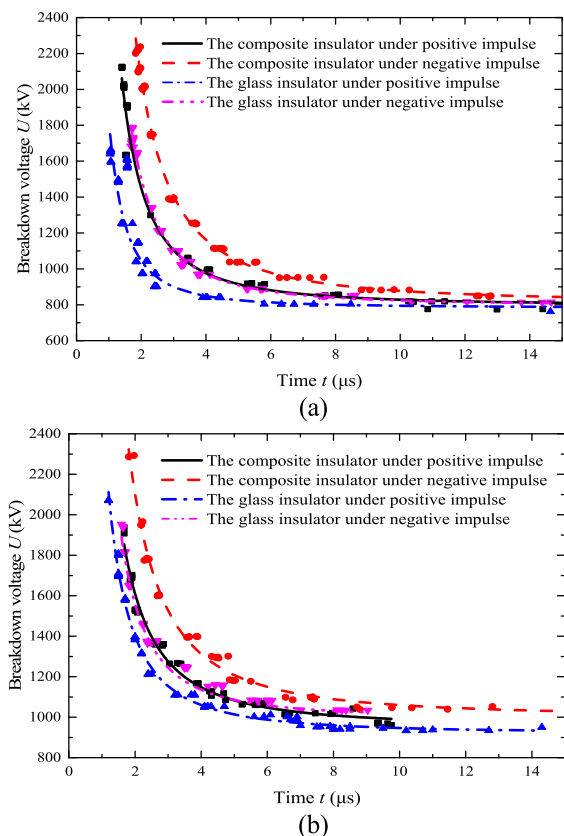
Figure 7 shows that the volt-second characteristic curves under the short-tail lightning impulse are above the curves under the standard lightning impulse. The breakdown voltages under the short-tail lightning impulse are about 100-300 kV higher than those under the standard lightning impulse when the time is after 6  $\mu$ s. This value is close to the  $U_{50\%}$  difference between the short-tail lightning impulse and the standard lightning impulse. From 3  $\mu$ s to 0  $\mu$ s the volt-second characteristic curves under different impulses get closer gradually. It means that the flashover characteristics under the two impulses are similar when the flashover occurs on the wave front. And when the flashover occurs on the wave tail, the differences under the two impulses are large. The two impulse waveforms have a half-peak time difference of about 40  $\mu$ s, while the difference in the wave front is only about 0.2  $\mu$ s. So the main difference in the volt-second characteristics caused by the impulse waveform become obvious when the breakdown time is after 3  $\mu$ s.

##### B. THE MATERIAL OF INSULATOR

The material of the insulator has a certain influence on the flashover characteristics, and the influences under the standard lightning impulse and the short-tail lightning impulse differ sharply.

From the test data in Table 1, it can be seen that under the standard lightning impulse of 1.2/50  $\mu$ s, the positive  $U_{50\%}$  of the glass insulators are slightly larger than those of the composite insulators of the corresponding phase. The difference is within 2%. However, the negative  $U_{50\%}$  of the glass insulators are about 0.85%-5.48% smaller than those of the composite insulators. There exists a significant polarity effect. While under the short-tail lightning impulse, as shown in Table 2, in most cases, the  $U_{50\%}$  of the composite insulators is slightly larger than the glass insulator, and the difference is less than 5%. The polarity effect is not clear.

According to simulation results of the electric-field uneven coefficients around the insulators of different materials shown



**FIGURE 8.** The volt-second characteristics curves of the insulators with different materials. (a) Under the standard lightning impulse. (b) Under the short-tail lightning impulse.

in Table 3, it can be observed that the electric-field uneven coefficients around the glass insulator is smaller than those around the composite insulator (4%-33%). That is to say, the flashover of the composite insulator has a greater polarity effect than that of the glass insulator. Thus, under the standard lightning impulse, the positive  $U_{50\%}$  of the glass insulators are larger and the negative  $U_{50\%}$  are smaller than those of the composite insulators of the corresponding phase. While under the short-tail lightning impulse, the tail time is much smaller than the standard lightning impulse, and the electrostatic-field analysis result is no longer applicable. It has to be explained by the simulation analysis of the dynamic discharge process.

Taking the down-phase insulators of the umbrella-shape tower as an example, the influence of the insulator materials on the volt-second characteristics is analyzed, as shown in Figure 8.

Figure 8 shows that the volt-second characteristic curves of the composite insulator are higher than those of the glass insulator. When the breakdown time is before  $10 \mu$ s, the voltage differences of the volt-second characteristic curves of two types of the insulators are large. Because the flashover of the glass insulator is along the surface and the coronas start at the edges of multiple insulator pieces, its discharge leaders develop and interconnect simultaneously with many short gaps between the closer insulator pieces. While the

flashover of the composite insulator is in the air far away from the insulator surface and its discharge leaders start the two ends of the insulator. So the discharge development time of the glass insulator is shorter than that of composite insulator under the same breakdown voltage [30]. When the time is after than  $10 \mu$ s, there is a larger dispersion of breakdown time at the same voltage. And the differences on the breakdown voltage of different insulators are small. The range is within 150-100 kV.

### C. THE TOWER TYPE AND THE INSULATOR SUSPENSION POSITION

It can be seen from Table 1 that the  $U_{50\%}$  of insulators hung on the two types of towers have no obvious influencing law. However the  $U_{50\%}$  differences under the standard lightning impulse are less than 4%, and that under the short-tail lightning impulse is 5%-8%.

There is no recognizable law about the influence of the suspension positions of three-phase insulators on  $U_{50\%}$ . The  $U_{50\%}$  difference of the three-phase insulators is 0.67%-2.58% under the standard lightning impulse, while that is 3.58%-7.31% under the short-tail impulse, as shown in Table 1.

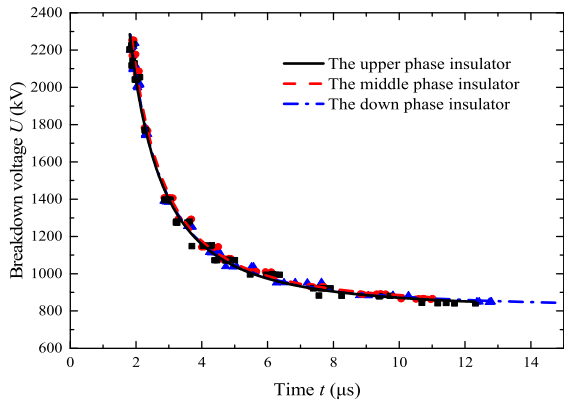
The results of the electric-field simulation show that the tower type and the insulator suspension position have little impact on the electric-field distribution and uneven coefficients. The difference on the electric-field uneven coefficients of the three-phase insulators hung on the umbrella-shape tower is less than 4.5%. And the difference on the electric-field uneven coefficients of the three-phase insulators hung on the drum-shape tower is less than 0.9%. Therefore, both the test and simulation results show that under the standard lightning impulse, the tower type and the insulator suspension position have little influence on the  $U_{50\%}$ . However, the test results reveal that the  $U_{50\%}$  difference resulted from the tower type and the insulator suspension position under the short-tail impulse is large, and the electrostatic-field simulation cannot explain this phenomenon.

Considering the voltage across the insulator is the negative standard lightning impulse during the shielding failure and the positive short-tail lightning impulse during the back flashover, the volt-second characteristic curves of the three-phase composite insulators hung on the umbrella-shape tower are given in Figure 9 under the two kinds of the lightning impulse mentioned above.

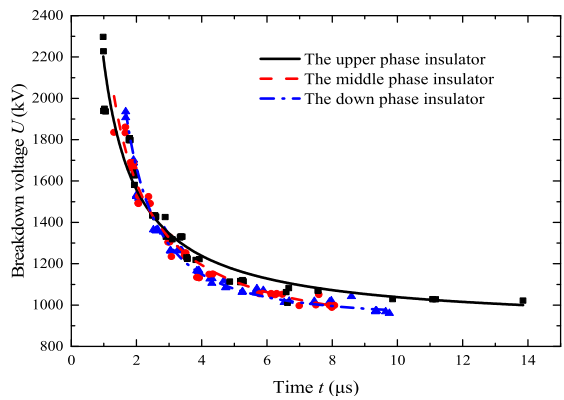
It is found that the influence on the volt-second characteristic resulted from the tower type and the insulator suspension position under the standard lightning impulse is small, and that under the short-tail lightning impulse is slightly larger. However, the influence degree is smaller than that resulted from the impulse waveform and insulator material.

### D. THE TRUE TOWER

Comparing the corresponding  $U_{50\%}$  of the single insulator and the insulators hung on the true tower in Table 1, Table 2, and Table 5, it is found that there is a polarity effect. The



(a)



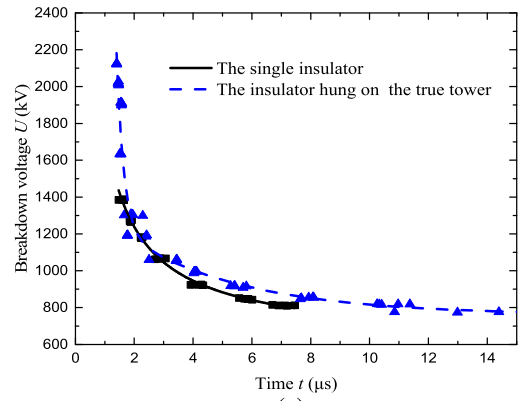
(b)

**FIGURE 9.** The volt-second characteristics curves of the three-phase composite insulators. (a) Negative standard lightning impulse. (b) Positive short-tail lightning impulse.

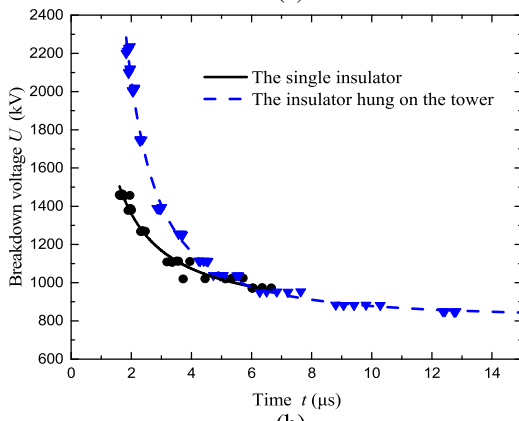
positive  $U_{50\%}$  of the single insulator is lower than those of the insulators hung on the true tower (within 2.8%). And the negative  $U_{50\%}$  of the single insulator is higher than those of the insulators hung on the true tower (within 6.7%). By preliminary analysis, it may be caused by the two grounding wires at the lower end of the single insulator. Due to the layout of the grounding wires, the electric-field distribution around the insulator becomes an asymmetrical distribution from a symmetrical distribution at the beginning, and the uneven degree in the single insulator test is bigger than that in true tower test.

For the purpose of analyzing the influence of the true tower on the insulator flashover characteristics, the volt-second characteristic curves of the single insulator and the down-phase composite insulator hung on the umbrella-shape tower under the standard lightning impulse are all illustrated in Figure 10.

As shown in Figure 10, the differences of the volt-second characteristic curves under the positive and negative lightning impulses are big. Under the positive standard lightning impulse, when the breakdown voltage is lower than 1000 kV, the breakdown time of the single insulator is obvious shorter than those of the insulators hung on the true tower under the same breakdown voltage; while under the negative



(a)



(b)

**FIGURE 10.** The volt-second characteristic curves comparison. (a) Positive standard lightning impulse. (b) Negative standard lightning impulse.

standard lightning impulse, the same situation happens when the breakdown voltage is higher than 1000 kV. The difference under the negative impulse is apparently greater.

Therefore, the flashover test of the insulators hung on the true tower can reflect actual situation better and obtain more accurate results than that of the single insulator.

Combined with the analysis of the influencing factors above, it can be concluded that the true tower is essential in the flashover test. Based on the true tower test, the impulse waveform has the greatest influence on the insulator flashover characteristics, followed by the insulator material; while the tower type and the insulator suspension position have the least influence. Thus, in the analysis of lightning protection performance of overhead transmission lines, when the shielding failure happens on the transmission line, the influence of the insulator material on the flashover characteristics needs to be taken into consideration; while the  $U_{50\%}$  difference caused by the insulator suspension position is within 3%, which is negligible. Meanwhile, when the back flashover happens on the transmission line, the influences of both the impulse waveform and insulator material on the flashover characteristics should be mainly considered.

## V. CONCLUSION

The flashover characteristics tests of the composite and glass insulators hung on the 110 kV true tower were carried

out in this paper. The different influencing factors of the flashover characteristics and the influence degree were studied. Combined with the electrostatic-field simulation, reasons for the difference were partly explained. The following are the conclusions.

(1) Through the insulator flashover test on the true tower, the data of the  $U_{50\%}$  and the volt-second characteristics with different impulse waveforms, different insulator materials, different tower shapes, and different insulator suspension position are given. The test results can be used in the lightning protection calculation and analysis of the 110 kV double-circuit transmission lines.

(2) The impulse waveform is one of the main influencing factors that affect the insulator flashover characteristics. The  $U_{50\%}$  under the short-tail lightning impulse are about 20%-40% higher and more dispersive than those under the standard lightning impulse. The principle difference in the volt-second characteristics due to the impulse waveform is obvious when the breakdown time is longer than 3  $\mu$ s.

(3) The  $U_{50\%}$  differences caused by the insulator material under the standard lightning impulse and the short-tail lightning impulse differ sharply. The  $U_{50\%}$  of the glass and composite insulators have significant polarity effects under the standard lightning impulse; while under the short-tail lightning impulse, the  $U_{50\%}$  of the composite insulator are substantially larger than those of the glass insulator (within 5%). The volt-second characteristic curves of the composite insulator are higher than those of the glass insulator. It is caused by the faster development of the glass insulator discharge channel at the same breakdown voltage.

(4) Under the different lightning impulses, the factors of the tower type and the insulator suspension position have different effects on the  $U_{50\%}$  and the volt-second characteristics. The influence of the tower type and the insulator suspension position is small under the standard lightning impulse, but the influence is obvious under the short-tail lightning impulse.

(5) Whether the insulator is hung on the true tower or not directly affects the authenticity of flashover test and the accuracy of experimental results. And the effect of the true tower on the volt-second characteristic curve is greater than that on the  $U_{50\%}$ .

(6) By the analysis on the influencing factors of the insulator flashover characteristics, it is indicated that the influences of the impulse waveform and the insulator material need to be considered in the calculation of lightning protection performance when shielding failure or back flashover happens on the transmission lines.

Due to the testing objects are the 110 kV insulators, the applicability of the above conclusions to the insulators with other voltage levels is to be further verified.

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