AC flashover performance of different shed configurations of composite insulators under fan-shaped non-uniform pollution

Zhijin Zhang1, Xinhan Qiao1, Yi Zhang1, Liang Tian1, Dongdong Zhang1, Xingliang Jiang1

1 State Key Laboratory of Power Transmission Equipment and System Security and New Technology School of Electrical Engineering, Chongqing University No. 174, Shazheng Street Shapingba District, Chongqing 400044, People’s Republic of China
E-mail: zhangzhijing@cqu.edu.cn

Abstract: Currently, it is founded that under unidirectional wind and certain landform, composite insulators are always fan-shaped non-uniformly polluted. In this paper, artificial pollution tests on three types of composite insulators with different shed configurations and under various fan-shaped non-uniform pollution conditions were carried out. Then the flashover performances of composite insulators, porcelain insulators and glass insulators were compared. Results indicate that there is a big difference between ac flashover performance of composite insulators under non-uniform pollution and uniform pollution. The flashover voltage of composite insulator is largely influenced by salt deposit density (SDD), the ratio of SDD of windward side to leeward side (W/L), the occupation ratio of leeward side k and the shed configurations. The relationship between SDD and U90 still meets negative power function when composite insulator is fan-shaped non-uniform polluted. There is a reduction of 17.8–27.6% in the flashover strength when the ratio W/L of SDD decreases from 1/1 to 1/15. The shed configurations of composite insulators have great effects on the flashover performance. Composite insulators always have better withstand property compared to glass and porcelain insulators under either uniform pollution or fan-shaped non-uniform pollution.

1 Introduction

In recent years, the extra and ultra-high-voltage transmission systems in China have been developed rapidly due to the growth of native economy. Simultaneously, the environmental pollution issue is still outstanding, and the pollution induced flashover of transmission lines is still threatening the safety operation of power grid [1–4]. Composite insulators have been widely applied in transmission lines for their favourable resistance to pollution flashover [5, 6]. Plenty of researches about flashover performance of composite insulators have been conducted at home and abroad, and the results have been applied in transmission lines for the purpose of promoting power system’s stability [7–19]. Numerous factors which might have effects on the flashover performance of polluted insulators have been taken into consideration, such as humidity, altitude, components of contamination. However, the issues of pollution flashover have not been completely figured out yet.

The vast majority of previous researches in non-uniform pollution insulators are concentrated on the non-uniform distribution contamination between top and bottom surface. Researchers from different countries have conducted plenty of experiments to study the effects of non-uniform contamination between the top and the bottom surfaces on insulator flashover performance [7, 10, 11]. Researchers from China found that for glass and porcelain insulators, the ratio of contaminations between the top and the bottom surfaces is generally in the range of 1:5 to 1:10, besides the ratio could reach to 1:20 in particular situation. The flashover voltage of polluted glass insulators increases by nearly 50% compared to the insulators under uniform contamination when T/B is 1:10 [12], where T/B is the ratio of SDD of top surface to bottom surface.

Electric Power Research Institute (EPRI) proposed a formula for the correction of dc flashover voltage under non-uniform pollution as follows [13]:

\[
K = \frac{U_1}{U_2} = C \times \log \left(\frac{T}{B}\right)
\]

where K is the correction coefficient, \(U_1\) is the pollution flashover voltage when the pollution distribution is non-uniform, \(U_2\) is the pollution flashover voltage when the contamination distribution is uniform and \(T/B\) is as above. \(C\) is a factor with a value of 0.29–0.47, and with an average of 0.38. In [14], the influence of non-uniform pollution distribution on ac flashover voltage of standard suspension insulators was studied, which turned out that the formula of EPRI is also applicable in ac case and the value of \(C\) was calculated as 0.31.

Composite insulators have worse self-cleanness compared to porcelain and glass insulators, which leads to contamination accumulated in composite insulators is 1.5–2 times worse than the porcelain and glass insulators in the same pollution area [15–17]. The ratio of contaminations between the top and the bottom surfaces of composite insulators is 1:3 to 1:10, which is similar to porcelain and glass insulators. A formula for the correction of dc flashover voltage of composite insulators under non-uniform pollution has been proposed, and the correction coefficient \(C\) was calculated as 0.208 which is smaller compared to the porcelain and glass insulators.

As a matter of fact, the non-uniform pollution of insulators is diverse. Sundararajan [18] revealed that the non-uniform distributions of contamination accumulated in insulators could be divided into three different types, the distribution between the top and bottom surfaces, along the insulators string, and the traverse direction. Different kinds of non-uniform contamination accumulated in the insulators have various influences on the pollution flashover. So the results obtained through artificial tests on insulators with uniform pollution cannot accurately represent the flashover performance of transmission line insulators with non-uniform pollution.

After we observed the insulator strings in the power lines, we finally discovered that under unidirectional wind and certain landform, composite insulators are always fan-shaped non-uniformly polluted. So the contamination tests of composite insulator in wind tunnel were carried out. The contamination distribution of the insulators surfaces after the test is as shown in Fig. 1. Compared to the contamination on the windward side of insulators, the pollution layer in leeward side of insulators is much thicker, and it occupies a minor area of the whole insulator.
In [19, 20], researches of flashover performance on the porcelain and glass insulators under ac and dc voltage have been conducted thoroughly, which concluded that insulator pollution flashover voltage decreases with the increase of fan-shaped pollution non-uniformity. However, the flashover performance of composite insulators under fan-shaped non-uniform pollution has not been studied yet. For the purpose of investigating the pollution flashover performance of composite insulators under fan-shaped non-uniform pollution, ac pollution tests of three types of composite insulators have been carried out in the multifunction artificial chamber. During the tests, artificial pollution method was used to imitate various pollution degrees at windward and leeward sides of composite insulators. Test results can provide reference for the external insulation selection of transmission lines.

2 Sample, experimental setup and procedure

2.1 Sample

As shown in Fig. 2, the test samples are three different types of long rod composite insulators, which are numbered by Type A, Type B, Type C, respectively. The relevant technical parameters are shown in Table 1, in which \( D_1 \), \( D_2 \) is shed diameter, \( D_0 \) is the rod diameter, \( L \) is the creepage distance, \( H \) is the insulation height, \( L/H \) is the creepage factor which is illustrated in [21–23].

2.2 Experimental setup

The pollution flashover experiments were conducted in a multifunction artificial climate chamber which has a height of 11.6 m and a diameter of 7.8 m. The artificial tests on complex climate atmospheric environments can be carried out in the climate chamber, such as ice, rain, fog, and low barometric pressure. The power of pollution tests was supplied by the YDTW-500 kV/2000 kVA test transformer, and the short-circuit current of the transformer is up to 75 A. The power supply meets the requirement of the artificial pollution test [24].

The test circuit is shown in Fig. 3. In the test circuit, T1 is the 10 kV/2000 kVA voltage regulator, T2 is the 500 kV/2000 kVA ac testing transformer, R0 (10 kΩ) is a current limiting resistor, C1 (10 pF) and C2 (0.1 μF) are the capacitors of the capacitor divider \( F \) (10,000:1), \( H \) is a wall bushing (330 kV), \( r \) (1 Ω) is a current sampling resistor, \( G \) is a protective discharge tube (voltage rating 5 V), \( E \) represents the artificial climate chamber.

2.3 Test procedure

2.3.1 Preparation: At the beginning of the tests, all the samples were carefully cleaned by cleaning cloth with \( \text{Na}_2\text{PO}_3 \) solution, so that all traces of dirt and grease were removed. Then, the samples were thoroughly rinsed with tap water, and let to dry naturally indoor to avoid dust or other pollution. During the tests, the solid
Table 1  Profile parameters of insulators

| Type  | $D_0, \text{mm}$ | $D_1/D_2, \text{mm}$ | $L, \text{mm}$ | $H, \text{mm}$ | $L/H$ |
|-------|-----------------|----------------------|-------------|-------------|-------|
| type A | 25              | 150/90               | 450         | 235         | 1.91  |
| type B | 24              | 129/89               | 546         | 230         | 2.37  |
| type C | 25              | 105/78               | 586         | 226         | 2.59  |

2.3.2 Wetting: After the samples were polluted as mentioned above, they were dried naturally for 24 h, and then the samples were suspended vertically in the climate chamber with arrangement of I-shape. In this paper, water spray method was adopted to confirm the hydrophobicity class before test. Hydrophobicity class of insulator was HC4 before the test. The steam fog which was produced by a 1.5 t/h boiler was used for wetting the surface of polluted insulators. The nozzles which hold a distance of 3.5 m to the insulators were set vertically to the axis of the samples. The input rate of the steam fog was 0.05 ± 0.01 kg/h·m$^3$. During the tests, the temperature of the climate chamber was maintained between 30 and 35°C by the refrigerating system, and the atmospheric pressure was kept at 98.6 kPa.

2.3.3 Flashover test: The flashover test was conducted simultaneously when the pollution layers of samples were fully wetted to prevent water on the umbrella skirt of polluted insulators from dropping into ground.

During the tests, the up and down method was adopted [24], which mean that at least 15 ‘valid’ tests were carried out on the same type sample. There are 15 for each type of insulators and the insulator was replaced after flashover to avoid the effect of the changing of pollution layer on the insulator. The flashover voltages changed based on the up and down method. The voltage step was set at about 5% of expected $U_{50}$; $U_{50}$ was calculated by the individual test and the following 14 individual tests. The $U_{50}$ and relative standard deviation error ($\sigma$) were calculated by the equation as follows:

$$U_{50} = \frac{\sum(U_{ni})}{N}$$

$$\sigma = \sqrt{\frac{\sum(U_i - U_{50})^2}{(N - 1)/U_{50} \times 100\%}}$$

where $U_i$ is an applied voltage, $n_i$ is the number of tests which were carried out at the applied voltage $U_{ic}$ and $N$ is the number of the number of the whole ‘valid’ tests.

3  Result and analysis

3.1 Ac flashover test’s results

Tests on three types of composite insulators with different shed configurations were conducted by the procedure mentioned above, and the results are shown in Tables 2–4. It can be concluded as follows:

(i) The relative deviation is <6%. The dispersion degree of the flashover voltage is acceptable, which means that the method taken in the tests is rational.

(ii) Regardless of the value W/L and $k$, the ac flashover voltage of all three types of composite insulators decreases with the increase of SDD. For example, the flashover voltage of Type A composite insulator under uniform pollution is 23.9, 19.7 and 16.5 kV, respectively, when SDD is 0.05, 0.01 and 0.15 mg/cm$^2$, respectively. Compared to flashover voltage of 0.05 mg/cm$^2$, the flashover voltage of 0.10, 0.15 mg/cm$^2$ decreases by 17.6 and 31.0% separately.
The flashover voltage of composite insulators is related to the non-uniform pollution at the windward and leeward sides of composite insulators. To be specific, $U_{50}$ decreases gradually with the decreasing of $W/L$. For example, the $U_{50}$ of Type C composite insulator is 22.8, 19.9, 17.9 and 16.7 kV separately when SDD is 0.10 mg/cm$^2$, k is 10% and W/L is 1/1, 1/3, 1/8 and 1/15. The result shows that there is a decrease of 12.7, 21.5 and 27.1% on the $U_{50}$ when the W/L change from 1/1 to 1/3, 1/8 and 1/15.

The ratio of leeward side area to the whole area of the composite insulators also has effects on the flashover voltage. To be specific, there is a slight decrease on the flashover voltage when $k$ increases gradually. Taking composite insulator of Type B for example, when SDD is 0.10 mg/cm$^2$, W/L is 1/8 and $k$ is 10, 20, 30%, the $U_{50}$ is 18.1, 17.3 and 16.9 kV correspondingly, which indicates that the $U_{50}$ decreases by 6.6% when $k$ increases from 10 to 30%.

The flashover voltages of composite insulators with different shed configurations are different under fan-shaped non-uniform pollution. Compared to Type B composite insulator, Type C has longer creepage distance. However, $U_{50}$ of Type C insulator is 13.4 kV when SDD is 0.15 mg/cm$^2$, $k$ is 20% and W/L is 1/15, which is lower than the corresponding $U_{50}$ of Type B.

### 3.2 Influence of SDD on $U_{50}$ under fan-shaped pollution

The relationship between $U_{50}$ and SDD has been studied for quite a long time. Previous researches show that there is a negative power function between pollution flashover voltage and SDD as follows [25]:

$$U_{50} = a \cdot SDD^{-n}$$  (5)

where $a$ is constant which is up to the structure of insulator, air pressure, materials and so on. Besides, $n$ is the characteristic index of pollution on the insulator.

With given $a$, $n$, the pollution flashover voltage under certain SDD can be calculated in (5). The values of $a$ and $n$ of different insulators under uniform pollution have been calculated by researchers. However, the relationship between SDD and $U_{50}$ under fan-shaped non-uniform pollution has not been studied by

### Table 2 Tests results of Type A composite insulator

| k, % | SDD, mg/cm$^2$ | W/L | $U_{50}$, kV | $σ$% | $U_{50}$, kV | $σ$% | $U_{50}$, kV | $σ$% | $U_{50}$, kV | $σ$% |
|------|----------------|-----|-------------|------|-------------|------|-------------|------|-------------|------|
| 10   | 0.05           | 23.9| 2.5         | 22.1 | 4.5         | 20.8 | 0.6         | 19.9 | 1.1         | 18.7 |
|      | 0.10           | 19.7| 0.8         | 18.1 | 1.3         | 17.1 | 1.4         | 16.2 | 3.5         | 15.3 |
|      | 0.15           | 16.5| 0.3         | 15.2 | 2.9         | 14.5 | 2.7         | 13.7 | 5.8         | 12.8 |
| 20   | 0.05           | 23.9| 2.5         | 21.5 | 4.6         | 19.9 | 3.1         | 19.1 | 4.2         | 18.7 |
|      | 0.10           | 19.7| 0.8         | 17.5 | 5.1         | 16.4 | 2.7         | 15.6 | 2.5         | 15.3 |
|      | 0.15           | 16.5| 0.3         | 14.9 | 0.8         | 13.9 | 0.5         | 13.1 | 2.8         | 12.8 |
| 30   | 0.05           | 23.9| 2.5         | 21.1 | 1.5         | 19.5 | 0.4         | 18.7 | 2.5         | 18.4 |
|      | 0.10           | 19.7| 0.8         | 17.2 | 5.2         | 16.1 | 4.3         | 15.3 | 2.7         | 15.1 |
|      | 0.15           | 16.5| 0.3         | 14.6 | 3.6         | 13.6 | 3.1         | 12.8 | 4.3         | 12.4 |

### Table 3 Tests results of Type B composite insulator

| k, % | SDD, mg/cm$^2$ | W/L | $U_{50}$, kV | $σ$% | $U_{50}$, kV | $σ$% | $U_{50}$, kV | $σ$% | $U_{50}$, kV | $σ$% |
|------|----------------|-----|-------------|------|-------------|------|-------------|------|-------------|------|
| 10   | 0.05           | 27.3| 1.5         | 24.9 | 5.4         | 22.9 | 2.8         | 21.6 | 5.6         | 20.3 |
|      | 0.10           | 21.5| 2.7         | 19.7 | 0.7         | 18.1 | 3.7         | 17.1 | 0.7         | 16.5 |
|      | 0.15           | 18.3| 1.1         | 16.6 | 3.8         | 15.3 | 4.1         | 14.5 | 3.5         | 14.2 |
| 20   | 0.05           | 27.3| 1.5         | 24.1 | 4.2         | 21.9 | 5.1         | 20.7 | 0.9         | 20.3 |
|      | 0.10           | 21.5| 2.7         | 19.1 | 2.7         | 17.3 | 2.2         | 16.5 | 2.8         | 16.1 |
|      | 0.15           | 18.3| 1.1         | 16.2 | 1.5         | 14.7 | 4.1         | 13.8 | 5.1         | 13.5 |
| 30   | 0.05           | 27.3| 1.5         | 23.4 | 4.2         | 21.4 | 2.1         | 20.3 | 3.5         | 20.0 |
|      | 0.10           | 21.5| 2.7         | 18.4 | 5.1         | 16.9 | 1.6         | 16.1 | 4.1         | 15.8 |
|      | 0.15           | 18.3| 1.1         | 15.7 | 3.3         | 14.3 | 0.5         | 13.6 | 1.3         | 13.2 |

### Table 4 Tests results of Type C composite insulator

| k, % | SDD, mg/cm$^2$ | W/L | $U_{50}$, kV | $σ$% | $U_{50}$, kV | $σ$% | $U_{50}$, kV | $σ$% | $U_{50}$, kV | $σ$% |
|------|----------------|-----|-------------|------|-------------|------|-------------|------|-------------|------|
| 10   | 0.05           | 28.2| 1.5         | 24.8 | 4.7         | 22.4 | 0.5         | 20.5 | 4.7         | 19.8 |
|      | 0.10           | 22.5| 2.7         | 19.9 | 3.2         | 17.9 | 2.3         | 16.3 | 3.1         | 15.8 |
|      | 0.15           | 19.1| 1.1         | 16.9 | 5.6         | 15.2 | 4.1         | 13.9 | 2.3         | 13.4 |
| 20   | 0.05           | 28.2| 1.5         | 24.2 | 3.4         | 22.9 | 5.4         | 19.7 | 1.6         | 19.3 |
|      | 0.10           | 22.5| 2.7         | 19.4 | 4.1         | 17.5 | 3.7         | 16.1 | 1.9         | 15.8 |
|      | 0.15           | 19.1| 1.1         | 16.5 | 1.3         | 14.9 | 2.6         | 13.4 | 4.2         | 13.0 |
| 30   | 0.05           | 28.2| 1.5         | 23.4 | 4.5         | 21.1 | 5.1         | 19.2 | 1.3         | 18.8 |
|      | 0.10           | 22.5| 2.7         | 18.7 | 6.0         | 16.9 | 3.7         | 15.4 | 3.6         | 15.1 |
|      | 0.15           | 19.1| 1.1         | 15.9 | 3.6         | 14.3 | 3.5         | 13.0 | 1.9         | 12.6 |
now, which indicates that there is no existing expression for composite insulators to predict flashover voltage. The fitting curves of SDD and $U_{50}$ have been obtained with the tests results in Tables 2–4. The fitting curves of three kinds of composite insulators are shown in Fig. 5 when $k$ is 10%. Besides $a$, fitting degree $R^2$ and the influence of pollution characteristics index $n$ of three kinds of composite insulators with different value of W/L were calculated and is shown in Table 5.

It can be concluded from Table 5 and Fig. 5 that:

The correlation coefficients $R^2$ of all fitting curves are >0.9, which indicates that the $U_{50}$ and SDD under fan-shaped non-uniform pollution fit power function well. Coefficient $a$ is influenced by the ratio of leeward side area $k$ and W/L. Coefficient $a$ decreases with the increasing of $k$ and the decreasing of W/L. Taking composite insulator of Type B as an example, when $k$ is 10%, W/L is 1/1, 1/3, 1/8 and 1/15, respectively, the corresponding value of $a$ is 9.26, 8.37, 7.78 and 7.37, which means that the average value of $a$ is 0.33, which indicates that the relative error is −0.4, −0.1, −0.1 and 0.4%. It can be concluded that fan-shaped non-uniform pollution have little influence on the value of $n$, which means that the fan-shaped non-uniformity has independent influence on the flashover voltage from the SDD.

In [19], the values of $a$, $n$ and $R^2$ have been calculated minutely after researches carried out on several kinds of glass and porcelain insulators under ac voltage. The values of $n$ ranged from 0.281 to 0.329 are smaller than those of composite insulators, which indicate that pollution has greater influence on the composite insulators compared to glass and porcelain insulators.

### 4 Analysis on the flashover performance under different shed configurations of composite insulators

The shed configurations of composite insulators have great effects on the ac pollution flashover. Shed spacing and shed diameter are the several configuration parameters considered when analysing. Besides, the creepage factor $L/H$ is another significant configuration parameter which is related to the flashover performance.

| K | Type | W/L | 1/1 | 1/3 | 1/8 | 1/15 | 1/3 | 1/8 | 1/15 | 1/3 | 1/8 | 1/15 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| A | A | 8.95 | 8.17 | 7.95 | 7.34 | 8.05 | 7.66 | 7.01 | 7.88 | 7.49 | 6.83 |
| N | 0.331 | 0.335 | 0.323 | 0.335 | 0.330 | 0.322 | 0.338 | 0.331 | 0.322 | 0.339 |
| R\(^2\) | 0.984 | 0.987 | 0.989 | 0.992 | 0.993 | 0.989 | 0.988 | 0.994 | 0.987 | 0.987 |
| B | A | 9.26 | 8.37 | 7.78 | 7.37 | 8.26 | 7.47 | 6.99 | 7.95 | 7.22 | 6.91 |
| N | 0.362 | 0.366 | 0.364 | 0.360 | 0.359 | 0.360 | 0.365 | 0.361 | 0.364 | 0.361 |
| R\(^2\) | 0.998 | 0.996 | 0.997 | 0.997 | 0.997 | 0.998 | 0.993 | 0.999 | 0.997 | 0.996 |
| C | A | 9.88 | 8.85 | 7.89 | 7.19 | 8.64 | 7.77 | 7.09 | 8.27 | 7.42 | 6.67 |
| N | 0.352 | 0.346 | 0.350 | 0.351 | 0.345 | 0.348 | 0.344 | 0.349 | 0.350 | 0.351 |
| R\(^2\) | 0.996 | 0.995 | 0.996 | 0.996 | 0.997 | 0.985 | 0.996 | 0.995 | 0.994 |

**Fig. 5** Relationships between $U_{50}$ and SDD

(a) Type A, (b) Type B, (c) Type C
performance of composite insulators [22]. For the purpose of comparing the flashover voltages of composite insulators with different shed configurations under fan-shaped non-uniform pollution, two parameters were defined in this paper, one of which is the insulation height flashover gradient defined as the ratio of $U_{50}$ to insulation height $H$, namely $E_H = U_{50}/H$, the other parameter is the creepage flashover gradient of insulators defined as the ratio of $U_{50}$ to the creepage distance $L$, namely $E_L = U_{50}/L$. The $E_H$ and $E_L$ of three types of composite insulators under different combinations of $W/L$, SDD and $k$ were calculated with given technical parameters of composite insulators and test results shown in Tables 2–5. In this paper, the corresponding results of $E_H$ and $E_L$ when SDD is 0.10 mg/cm$^2$ and $k$ is 10, 20 and 30%, respectively, were presented in Figs. 6 and 7.

The pollution flashover performances of composite, porcelain and glass insulators are totally different because of the imparities of material and structure. However, it has not been studied that the difference of pollution flashover performance among composite, porcelain and glass insulators under fan-shaped non-uniform pollution yet. The ac flashover performances of five kinds of porcelain and glass insulators have been studied in [19]. In this chapter, the $E_L$ and $E_H$ under uniform pollution and fan-shaped non-uniform pollution of composite, porcelain and glass insulators are compared.

4.1 Analysis on the $E_L$ of various types of composite insulators

The $E_L$ values of three types of composite insulators range from 0.222 to 0.531 kV/cm. The values of $E_L$ are influenced by several factors which include SDD, shed configuration, $W/L$ and $k$. In addition, the value of $E_L$ decreases with the increasing of $W/L$. 
SDD or \( k \). As shown in Fig. 6a, the \( E_L \) values of Type B composite insulator is 0.394, 0.361, 0.332 and 0.313 kV/cm, respectively, when the value of W/L ranges from 1/1 to 1/15, which indicates that there is a decrease of 20.5% for Type B composite insulator with the variation of W/L from 1/1 to 1/15. The ratio of leeward area to the whole surface area of composite insulator also has effects on the value of \( E_L \), which is smaller than the W/L does.

It is clearly shown in Fig. 6 that the \( E_L \) value of Type A composite insulator is always bigger compared to Type B and Type C composite insulators, which indicates that the effective utilisation rate of creepage distance of Type A composite insulator is higher than the others. So there is an obvious connection between the \( L/H \) value of composite insulators and \( E_L \), which is the \( E_L \) of composite insulator with a bigger \( L/H \) is smaller than that of composite insulator with a smaller \( L/H \). Besides, the decline rates of \( E_L \) when W/L ranging from 1/1 to 1/15 are also effected by the shed configuration parameter of composite insulators \( L/H \). Taking \( k = 10\% \) for an example, the \( E_L \) decline rates of three types of composite insulators are 17.8, 20.5 and 27.6%, respectively, when the W/L ratio decline from 1/1 to 1/15, which indicates composite insulator with a bigger \( L/H \) was tempted to be more seriously influenced by fan-shaped non-uniform pollution.

The \( E_L \) of five type's porcelain and glass insulators analysed in [18] ranged from 0.266 to 0.301 kV/cm under SDD is 0.10 mg/cm² uniform pollution, whereas the \( E_L \) of them varied from 0.206 to 0.231 kV/cm when SDD is 0.10 mg/cm². \( k = 20\% \) and W/L is 1/15. It is obvious that the values of \( E_L \) of composite insulators always bigger than glass and porcelain insulators under both uniform and fan-shaped non-uniform pollution, which indicates that composite insulators always have better effective utilisation rate of creepage distance under either uniform or fan-shaped non-uniform pollution.

### 4.2 Analysis on the \( E_H \) of various types of composite insulators

The calculated results of \( E_H \) of three types of composite insulators range from 0.545 to 1.248 kV/cm, and it is also effected by several factors, such as the fan-shaped non-uniformity of pollution W/L, \( k \), SDD and shed configurations of composite insulators. Specifically speaking, the heavier pollution or the lower value of W/L, the lower value of \( E_H \) is. As shown in Fig. 6, the \( E_H \) value of Type C composite insulator is always higher at any value of SDD under uniform pollution compared to Type A and Type B. This is mainly because the creepage distance of Type A and Type B is relatively small. However, it is totally different when three types of composite insulators are under fan-shaped non-uniform pollution. Taking \( k = 20\% \), W/L is 1/15 and SDD is 0.10 mg/cm² for an example, the \( E_H \) values of three types of composite insulators (Type A, Type B and Type C sequentially) are 0.664, 0.717 and 0.712 kV/cm, respectively, which reveals that the \( E_H \) of Type C insulator drops most quickly to a lower value compared to Type B composite insulator. It is clear that the \( E_H \) values of three types of composite insulators are influenced differently by the fan-shaped non-uniform pollution.

As shown in Fig. 7a, when W/L is 1/1, the \( E_H \) of Type C composite insulator is the largest among three types of insulators, which indicates that the insulator height effective utilisation rate of composite insulators with larger shed configuration parameter \( L/H \) under uniform pollution is higher than the others. When W/L is 1/15, the \( E_H \) value of Type B is larger than Type C, which means that the composite insulator with larger \( L/H \) does not always has larger \( E_H \) under fan-shaped non-uniform pollution.

The \( E_H \) of five type's porcelain and glass insulators are analysed in [19] ranged from 0.613 to 0.83 kV/cm under SDD is 0.10 mg/cm² uniform pollution, besides the \( E_H \) of them varied from 0.464 to 0.634 kV/cm when SDD is 0.10 mg/cm², \( k = 20\% \) and W/L is 1/15. It is obvious that the values of \( E_H \) of composite insulators always bigger than glass and porcelain insulators under both uniform and fan-shaped non-uniform pollution, which indicates that composite insulators always have better effective utilisation rate of insulation height under any circumstances. Moreover, the values of \( E_{HE} \) and \( E_{HL} \) are also diverse with same material when the structures of insulators are different, which indicates that the pollution flashover performance is also effected by the structure of insulators.

It can be obtained from the analysis above that there is a negative correlation between \( E_L \) and the value of \( L/H \), which indicates that the effective utilisation rate of creepage distance of composite insulator with lower \( L/H \) is always larger than the others. Besides, it can also be found out that the composite insulator with larger \( L/H \) always has higher \( E_H \) under uniform pollution. However, it is quite different when the composite insulator is under fan-shaped non-uniform pollution. The decline rate of \( E_H \) of composite insulator with larger \( L/H \) Type C is bigger than others when W/L decreases from 1/1 to 1/15, which indicates that composite insulator with a bigger \( L/H \) was tempted to be more seriously influenced by fan-shaped non-uniform pollution. Furthermore, the antipollution flashover property of composite insulator with larger \( L/H \) Type C is not as excellent as Type B composite insulator when the W/L is 1/15. Compared to glass and porcelain insulators, composite insulators always have better performance under either uniform or fan-shaped non-uniform pollution.

### 5 Conclusion

Influences of fan-shaped non-uniform pollution on the ac flashover performances of three kinds of composite insulators with different shed configurations are presented in this paper. The conclusions can be drawn as follows:

(i) The ac flashover voltage of composite insulator is influenced by SDD, W/L and \( k \) when the composite insulator is under fan-shaped non-uniform pollution. Besides, the flashover voltage of composite insulator is always decrease with the increase of the non-uniformity of pollution.

(ii) There is a power function between SDD and \( U_{50} \) which can be presented as \( U_{50} = aSDD^b \) under uniform pollution and fan-shaped non-uniform pollution. There is a great influence of W/L on the value of ‘\( a \)’. With the increase of fan-shaped non-uniformity of pollution, the value of ‘\( a \)’ decrease sharply.

(iii) The flashover voltage is also influenced by the shed configuration of composite insulators. Composite insulator with larger creepage distance does not mean better effective utilisation rate of creepage distance. Composite insulator with a bigger \( L/H \) was tempted to be more seriously influenced by fan-shaped non-uniform pollution. However, the fan-shaped non-uniformity of pollution is high enough to 1/15, the value of \( E_{HI} \) of composite insulator with lower \( L/H \) is even higher than that of composite insulator with bigger \( L/H \).

(iv) Fan-shaped non-uniform pollution has a great effect on the flashover performance of insulators not matter it is composite insulator, glass insulator or porcelain insulator. Composite insulators always have better flashover performance under uniform and fan-shaped non-uniform pollution compared to glass and porcelain insulators.

### 6 Acknowledgments

This work was supported by Science and Technology Foundation of National Key R&D Plan (grant no. 2016YFB0900904). The authors gratefully acknowledge the contributions of J. You, W. Zhang, C. Li and J. Zhu for their work on the experiments.

### References

[1] Zhang, Z., Zhao, J., Zhang, D., et al.: ‘Study on the dc flashover performance of standard suspension insulator with ring-shaped non-uniform pollution’, *IEEE Trans. Dielectr. Electr. Insul.*, 2016, 23, (5), pp. 2840–2849

[2] Zhang, C., Wang, L.: ‘Experimental investigation on pollution flashover performance of multiple parallel suspension insulators’, *IEEE Trans. Dielectr. Electr. Insul.*, 2016, 23, (5), pp. 2840–2849
Zhang, D., Zhang, Z., Jiang, X., et al.: ‘Study on the flashover performance of various types of insulators polluted by nitrates’, IEEE Trans. Dielectr. Electr. Insul., 2017, 24, (1), pp. 167–174

Zhang, Z., Jiang, X., Chao, Y., et al.: ‘Influence of low atmospheric pressure on AC pollution flashover performance of various types of insulators’, IEEE trans. Dielectr. Insul., 2010, 17, (2), pp. 425–433

Madi, A., He, Y., Jiang, L.: ‘Design and testing of an improved profile for silicone rubber composite insulators’, IEEE Trans. Dielectr. Electr. Insul., 2017, 24, (5), pp. 2930–2936

Kone, G., Volat, C., Ezzaidi, H., et al.: ‘Experimental investigation of internal defect detection of a 69-kV composite insulator’. IEEE Electrical Insulation Conf., Canada, June 2016, pp. 206–263

Douar, M.A., Mekhaldi, A., Bonzidi, M.C.: ‘Flashover process and frequency analysis of the leakage current on insulator model under non-uniform pollution conditions’, IEEE Trans. Dielectr. Electr. Insul., 2010, 17, (4), pp. 1284–1297

He, L., Gorur, R.S.: ‘Source strength impact analysis on polymer insulator flashover under contaminated conditions and a comparison with porcelain’, IEEE Trans. Dielectr. Electr. Insul., 2016, 23, (4), pp. 2189–2195

Ahmadi-Jonidi, I., Shayegani-Akmal, A.A., Mohseni, H.: ‘Leakage current analysis of polymeric insulators under uniform and non-uniform pollution conditions’, IET Gener. Transm. Distrib., 2017, 11, (11), pp. 2947–2957

Jiang, X., Wang, S., Zhang, Z., et al.: ‘Investigation of flashover voltage and non-uniform pollution correction coefficient of short samples of composite insulator intended for ±800-kV UHVDC’, IEEE Trans. Dielectr. Electr. Insul., 2010, 17, (1), pp. 71–80

Jiang, Z., Liu, X., Jiang, X., et al.: ‘Study on AC flashover performance for different types of porcelain and glass insulators with non-uniform pollution’, IEEE Trans. Power Deliv., 2013, 28, (3), pp. 1691–1698

Liu, X.: ‘Study on the Pollution Accumulation and AC Pollution Flashover Performance of Insulators with Typical Sheds’. MSc thesis, CQU University, 2013

EPRI: ‘HVDC transmission line insulation performance: report EL24618’, USA, EPRI, 1986

Sima, W., Yuan, T., Yang, Q., et al.: ‘Effect of non-uniform pollution on the withstand characteristics of extra high voltage (EHV) suspension ceramic insulator string’, IET Gener. Transm. Distrib., 2010, 4, (3), pp. 445–455

Jiang, X., Yuan, J., Zhang, Z., et al.: ‘Study on pollution flashover performance of short samples of composite insulators intended for 800-kV UHVDC’, IEEE Trans. Dielectr. Electr. Insul., 2007, 14, (5), pp. 1192–1200

Jiang, X., Yuan, J., Shu, L., et al.: ‘Comparison of DC pollution flashover performances of various types of porcelain, glass, and composite insulators’, IEEE Trans. Power Deliv., 2008, 23, (2), pp. 1183–1190

Jiang, X., Yuan, J., Zhang, Z., et al.: ‘Study on ac pollution flashover performance of composite insulators at high altitude sites of 2800–4500 m’, IEEE Trans. Dielectr. Electr. Insul., 2009, 16, (1), pp. 123–132

Sundaranjan, R., Gorur, R.S.: ‘Effect of insulator profiles on DC flashover voltage under polluted conditions. A study using a dynamic arc model’, IEEE Trans. Dielectr. Electr. Insul., 1994, 1, (1), pp. 124–132

Zhang, Z., You, J., Zhang, D., et al.: ‘AC flashover performance of various types of insulators under fan-shaped non-uniform pollution’, IEEE Trans. Dielectr. Electr. Insul., 2016, 23, (3), pp. 1760–1768

Zhang, Z., Zhang, D., You, J., et al.: ‘Study on the DC flashover performance of various types of insulators with fan-shaped non-uniform pollution’, IEEE Trans. Power Deliv., 2015, 30, (4), pp. 1871–1879

Jiang, X., Chao, Y., Zhang, Z., et al.: ‘DC flashover performance and effect of sheds configuration on polluted and ice-covered composite insulators at low atmospheric pressure’, IEEE Trans. Dielectr. Electr. Insul., 2011, 18, (1), pp. 97–105

Zhang, F., Wang, L., Guan, Z., et al.: ‘Influence of composite insulator shed design on contamination flashover performance at high altitudes’, IEEE Trans. Dielectr. Electr. Insul., 2011, 18, (3), pp. 739–744

Hu, Q., Wang, S., Shu, L., et al.: ‘Influence of shed configuration on icing characteristics and flashover performance of 220 kV composite insulators’, IEEE Trans. Dielectr. Electr. Insul., 2016, 23, (1), pp. 319–330

Sun, J., Gao, G., Zhou, L., et al.: ‘Pollution accumulation on rail insulator in high-speed Aerosol’, IEEE Trans. Dielectr. Electr. Insul., 2013, 20, (3), pp. 731–738

Farzaneh, M., Farokhi, S., Chisholm, W.A.: ‘Electrical design of overhead power transmission lines’ (McGraw-Hill Professional, New York, 2013)