Study on AC Flashover Performance for Different Types of Porcelain and Glass Insulators With Non-Uniform Pollution

Zhijin Zhang, Xiaohuan Liu, Xingliang Jiang, Jianlin Hu, and David Wenzhong Gao

Abstract—The ratio \( T/B \) of top to bottom surface salt deposit density (SDD) affects the ac pollution flashover performance of disk insulator strings. The ac pollution flashover stress was established for fifteen different combinations of SDD and T/B in a systematic study, making use of seven-unit suspension strings with six different disk profiles in this paper. Then a comparison was made of pollution performance for glass and porcelain disks with the same profile. The observed relation of ac flashover stress \( E_{L} \) to SDD and \( T/B \) followed an equation of the form \( E_{L} = c \cdot \text{SDD}^{b} \cdot (1 - A \cdot \log(T/B)) \). The values of \( c, b \) and \( A \) were fitted to test results for glass and porcelain disks of identical bottom-rib profile, and to four other bottom-rib and external-rib profiles. A reduction in the ratio \( T/B \) from 1/1 to 1/15 gave a median 26% ± 8% increase in flashover strength, corresponding to the calculated increase in overall pollution layer resistance. Extrapolation of results for the seven-unit strings to UHV dimensions suggests that some reduction in leakage distance can be accepted in areas where there is frequent natural washing of the top surfaces of disk insulators.

Index Terms—Alternating current, correction factor, flashover voltage, insulator, salt deposit density, non-uniform contamination.

I. INTRODUCTION

The pollution on the surface of an insulator will pick up moisture under weather conditions that increase humidity such as fog, dew, and rain. Thus, its surface conductance and leakage current will increase greatly under an applied voltage, which may lead to the degradation of the surface electrical performance of polluted insulators and may even cause the occurrence of flashover.

Flash-over of insulators caused by pollution on their surfaces happens from time to time in China, and around the world. These flash-over can lead to blackouts of the grid system. [1], [2]. According to the statistics, the number of power grid flashovers is second only to that by lightning [3]. Therefore, a lot of studies on the performance and mechanism of pollution flashover have been done in many countries as well as in China to prevent pollution flashover [1]–[33].

Experimental results show that the flashover voltage will decrease as pollution increases. Taking the pollution as an independent parameter, the mathematical relationship between the flashover voltage \( U \) and the equivalent salt deposit density (ESDD) can be expressed as follows:

\[
U = a \cdot S^{-b}
\]

where \( a \) is a constant related to the profile and material of insulator, atmospheric pressure and the type of voltage; \( S \) is the ESDD on the surface of insulator and \( b \) is the exponent characterizing the influence of pollution. Research indicates that the value of \( b \) is not constant as shown by the following studies:

The result of a study on dc pollution flashover performance of 14 different types of insulators showed that the value of \( b \) ranges from 0.3 to 0.33 and different insulators have different values of \( b \) [4].

According to the study on the dc pollution flashover performance of 12 different types of post type insulators, the values of \( b \) is not the same for different post type insulators and it ranges from 0.32 to 0.41 [5].

Based on the laboratory research on ac and dc pollution flashover performance, the value of \( b \) ranges from 0.17 to 0.30 for ac and 0.30–0.37 for dc [6]–[12].

Another experiment results showed that: with ac voltage applied, the values of porcelain and glass insulators is in the range of 0.22–0.31 and for composite insulators \( b \) is in the range of 0.19–0.27 [13]–[16].

The round-robin test on the dc pollution flashover of 5-unit insulator strings of standard, anti-polluting, post type insulators was made in Japan, Brazil, Sweden, Canada, America and Italy alternately and the results showed that the values of \( b \) is 0.33 for negative dc [17].

The study on the dc pollution flashover of various types of insulators showed that the \( b \) value of suspension insulators ranges from 0.32 to 0.33 and for post insulators it is in the range of 0.35–0.37 under the action of negative dc [18].

In order to reflect the practical operating situation of insulators more accurately, the pollution accumulation experiments of field operating insulators were studied in some countries. The pollution accumulation of ESDD from the top to bottom surface of insulators can be expressed as a ratio of T/B. Experiment results indicate that the pollution deposition on bottom surface...
is more serious than that on top surface [19]–[23]. According to the operation experience of Chinese grids, the ratio (T/B) of porcelain and glass insulators is usually in the range of 1.5–1.10 and the maximum value is 1:20 [24].

The flash-over of an insulator has a direct relationship to the non-uniform distribution of pollution from the top to the bottom of the insulator. The pollution withstand voltage will increase by approximately 30% when the T/B ratio is lowered from 1:1 to 1:5 and increase by approximately 50% when the T/B ratio is lowered from 1:1 to 1:10 [25]. Based on the salt deposit density (SDD) of upper surface, the correction factor \( K \) for the influence on the dc pollution flashover voltage of porcelain and glass insulators is presented as follows [26]:

\[
K = \frac{U_2}{U_1} = 1 - A \times \log \left( \frac{T}{B} \right)
\]

where \( U_1 \) is the dc pollution flashover voltage of insulators with non-uniform pollution and \( U_2 \) is the dc pollution flashover voltage of insulators with uniform pollution; T/B is the ratio of the ESDD of top surface with respect to that of bottom surface; the value of coefficient \( A \) ranges from 0.29 to 0.47 with a mean value of 0.38. A study about the influence of non-uniform pollution distribution on the dc flashover voltage of composite insulators was carried out in [24]; and the result indicated that the value of \( A \) of composite insulators ranges from 0.141 to 0.156, which is lower than that of porcelain and glass insulators.

In [27], another research was done to study on the influence of non-uniform pollution distribution on ac flashover voltage of standard suspension insulators and found that the (2) is also applicable in ac case and the value of \( A \) was obtained as 0.31.

So far, much effective work on pollution flashover has been done around the world and the related results are applied in insulation coordination by designers. But the accident of pollution flashover of insulators has never disappeared in China since the 1990s. This means that the safe operation of Chinese power grid is still threatened by large scale pollution flashover [28].

The construction and development of UHV ac and dc transmission engineering projects is well under way in China and a number of large-tonnage porcelain and glass insulators will be used in some transmission lines. The external insulation design and selection in pollution regions is one of the most key technologies in the construction of Chinese UHV transmission engineering [29]. In this paper, the ac pollution flashover performance of different types of large diameter porcelain and glass insulators is studied to reveal the influence of non-uniform pollution distribution on pollution flashover performance and our research results will provide significant references for the external insulation design and selection of UHV ac transmission project.

II. TEST FACILITIES, SPECIMENS AND TEST OPERATING PROCEDURE

A. Test Facilities

The artificial pollution tests were carried out in the multifunction artificial climate chamber in the State Key Laboratory of Power Transmission Equipment & System Security and New Technology, Chongqing University. The artificial climate chamber, with a diameter of 7.8 m and a height of 11.6 m, can simulate complex atmospheric environments such as fog, rain, ice and high altitude [6], [7].

The power was supplied by the YDTW-500-kV/2000-kVA pollution test transformer. The major technical parameters are as follows: rated capacity 2000 kVA, rated current 4 A and short-circuit impedance less than 6% under a rated voltage of 500 kV and the short circuit current 75 A at flashover. The tested circuit and the principle were detailed in [9].

B. Test Specimens

The specimen insulators studied are six types of porcelain, glass insulators. Their profiles and dimensions as well as some of the parameters are shown in Table I and Fig. 1, in which \( D \) is the disc diameter, \( H \) is the configuration height, \( L \) the creepage distance, \( U_1 \) the dry flashover voltage and \( U_2 \) the wet flashover voltage for a clean insulator.

C. Test Procedure

1) Preparation and Method of Pollution: Before the tests, all the samples were carefully cleaned so that all traces of dirt and grease were removed and the samples were let to dry naturally. The insulators were polluted by quantitative coating using pasting method [33]. Sodium chloride and kieselguhr were used to simulate conductive and inert materials respectively. Firstly,
the required amount of sodium chloride and kieselguhr were calculated and weighed according to the specified salt deposit density (SDD), non-soluble deposit density (NSDD) and the surface areas of the specimens. The errors of the weight of sodium chloride and kieselguhr were less than ±1% and ±10%, respectively. The ratio of SDD to NSDD was 1/6 in all the tests. Then, sodium chloride and kieselguhr were mixed to slurry with appropriate volume of deionized water ($\sigma_{20} < 10 \mu S/cm$). In an hour after the preparing, the specimens were polluted by fully stirred suspension. After 24 hours of natural drying, the specimens were suspended into the climate chamber.

In order to produce the non-uniform pollution distribution on the top and the bottom surfaces of the insulator, both the average salt deposit density and the non-soluble density, which can be presented as SDD, should satisfy the condition during the artificial pollution produce process as follows:

$$SDD = \frac{SDD_B \cdot S_T + SDD_T \cdot S_B}{S_B + S_T}$$  \hspace{1cm} (3)

$$T/B = \frac{SDD_T}{SDD_B}$$  \hspace{1cm} (4)

where $SDD_T$ represents the salt deposit density of the top surface with a surface area of $S_T$, $SDD_B$ represents the salt deposit density of the bottom surface with a surface area of $S_B$. Therefore during the tests with various $T/B$, the total soluble materials on the insulator string are kept unchanged.

2) **Arrangement:** The minimum clearances between any part of the samples and any earthed objects met the requirements of [30], [31].

3) **Wetting:** The polluted insulators were wetted by steam fog. The steam fog was generated by a 1.5 t/h boiler; the nozzles were perpendicular to the axis of the test insulator; and the distance between them was greater than 3.5 m. The input rate of fog was 0.05 $+ 0.01 \text{ kg}/\text{h} \cdot \text{m}^2$, and the temperature in the chamber was controlled between 30°C and 35°C through the refrigeration system and the atmospheric pressure is 98.6 kPa in all the experiments.

4) **Evaluation:** In this test, up and down method was adopted [6]–[11]. The insulator was subjected to at least 15 “valid” individual tests at a specified degree of contamination. The applied voltage level in each test was varied according to the up-and-down method and the voltage step was approximately 5% of the expected $U_{50}$.

The first “valid” individual test was selected as being the first one that yields a result different from the preceding ones. Only the individual test and at least 14 following individual tests were taken as useful tests to be considered to determine $U_{50}$. The $U_{50}$ and relative standard deviation error ($\sigma$) could be calculated as follows:

$$U_{50} = \frac{\sum(n_i V_i)}{N}$$  \hspace{1cm} (5)

$$\sigma = \sqrt{\frac{\sum(V_i - U_{50})^2}{N - 1}} \times \frac{U_{50}}{100\%}$$  \hspace{1cm} (6)

where $V_i$ is an applied voltage level, $n_i$ is the number of tests carried out at the same applied voltage $V_i$, and $N$ is the total number of “valid” tests.

III. EXPERIMENTAL RESULTS AND ANALYSIS

A. Experimental Results

The experiment on the pollution flashover performance of various types of insulator strings with 7 units was conducted as described above and the experimental results are presented in Table II.

The relative standard deviations of all experimental results is less than 7%, which means that the dispersion degree of pollution flashover performance of insulators acquired by this experiment method is very small.

The $U_{50}$ of the various types of insulators decreases with the increase of their SDD. For example, when $T/B = 1$ and the value of SDD is 0.03 mg/cm$^2$, 0.08 mg/cm$^2$, and 0.20 mg/cm$^2$, the $U_{50}$ of A-type insulator string with 7 units is 152.1 kV, 112.3 kV and 82.1 kV, respectively. From the data above we can see that the $U_{50}$ decreases by 26.2% and 46.0% respectively when the SDD increases from 0.03 mg/cm$^2$ to 0.08 mg/cm$^2$ and 0.20 mg/cm$^2$ respectively.

Another factor that affects the $U_{50}$ of insulator is its profile. The configuration height, disc diameter and leakage distance of B-type, D-type and F-type insulators are exactly the same, but their profiles are different. The $U_{50}$ of B-type insulators is higher than that of D-type and F-type insulators under the same pollution condition. For example, the $U_{50}$ of B-type, D-type and F-type insulator strings with 7 units is 132.2 kV, 125.1 kV and 114.8 kV respectively when $T/B = 1$ and SDD = 0.08 mg/cm$^2$. The data indicate that the $U_{50}$ of B-type glass insulators is 5.4% and 13.2% higher than that of D-type and F-type porcelain insulators, respectively.

The non-uniformity of pollution of the upper and lower surface of insulators has significant influence on $U_{50}$. Moreover, the lower the $T/B$ ratio, the greater the $U_{50}$ of insulators. For example, the $U_{50}$ of A-type insulators is 112.3 kV, 120.1 kV, 125.9 kV, 132.1 kV, 125.2 kV and 130.2 kV respectively when SDD = 0.08 mg/cm$^2$ and the $T/B$ ratio is 1/1, 1/3, 1/5, 1/8 and 1/15 respectively. The data indicate that there is an increase of 6.9%, 12.1%, 17.7% and 23.1% of the $U_{50}$ of insulators respectively when the $T/B$ ratio is decreased from 1/1 to 1/3, 1/5, 1/8 and 1/15.

B. Analysis on Differences of the AC Pollution Flashover Performance of Various Types of Insulators

The insulators’ string length flashover gradient was defined as the ratio of $U_{50}$ with respect to the length of insulator h, namely $E_h = U_{50}/h$ and the insulators’ creepage flashover gradient was defined as the ratio of $U_{50}$ with respect to the creepage distance L, namely $E_L = U_{50}/L$ [10]. According to the test results and the basic technical parameters of the insulators presented in Table I, the $E_h$ and $E_L$ of various types of polluted insulators are shown in Table III and IV.

The values of $E_h$ of the tested insulators are in the range of 55–165 kV/m and they are dependant upon many factors, such as the profile and material of insulators, the pollution and the
non-uniformity of pollution distribution. Furthermore, the less pollution or the lower the $T/B$ ratio, the larger the value of $E_h$. The value of $E_h$ of A-type insulators is the highest and that of E-type insulators is the lowest under the same pollution condition. This means that the pollution flashover voltage of A-type insulator strings is the highest and that of E-type insulator strings is the lowest for the insulator strings with same structure height.

The $E_L$ of the tested insulators are in the range of 18–63 kV/m and $E_L$ value is also dependant upon the profile and material of insulators, the pollution, the $T/B$ and so on. In addition, the less pollution or the greater the non-uniformity of pollution, the larger the value of $E_L$. Under the same pollution condition, the $E_L$ values of A-type and C-type insulators are the highest while that of D-type and F-type insulators are the lowest. This
indicates that the effective utilization rates of creepage distance of A-type and C-type insulators are higher than others. It is now clear that the pollution flashover voltage of insulators with larger disc diameter and longer creepage distance are not always higher. For the various types of insulators that were tested, the anti-pollution property of unit structure height of the A-type insulators is the best and the effective utilization rate of creepage distance of the C-type insulators is the highest. Therefore, the ideal \( L/D \) value of insulator is in the range of 1.528–1.56.

**IV. INFLUENCE OF T/B ON POLLUTION FLASHOVER VOLTAGE AND CORRECTION**

**A. Relationship Between Pollution Flashover Voltage and T/B**

The \( T/B \) on the top and bottom surface of insulators affects its pollution flashover voltage and the relationship between them is shown in Fig. 2. From it we can see that the influence of the \( T/H \) on various types of insulators is different. For the 6 types of insulators that were tested, the effect of the \( T/B \) on E-type porcelain insulators is the greatest and that on A-type insulators is the smallest.

Equations (3) and (4) indicate that \( SDD_B > SDD \) and \( SDD_C < SDD \) when \( T/H < 1 \). For the insulators polluted by NaCl is even in the artificial pollution tests, their surface pollution layer conductivity (\( SPLC \)) is directly proportional to the \( SDD \) when they are at the same temperature and saturated sufficiently [32]. In other words, the resistance of the top surface pollution layer will increase and that of the bottom surface pollution layer will decrease as the non-uniformity of pollution distribution increases.

The relationship among the form factor of insulator \( f \), the conductivity of pollution layer \( \gamma \), the surface conductance \( G \) and the resistance of pollution layer \( R \) is as follows:

\[
\gamma = f \times G = \frac{1}{R} f. \tag{7}
\]

The relationship between the form factor of insulator and its profile is as follows:

\[
f = \int_{L} \frac{dl}{\pi D(l)} = \int_{0}^{L_T} \frac{dl}{\pi D(l)} + \int_{L_T}^{L} \frac{dl}{\pi D(l)} = f_T + f_B \tag{8}
\]

where \( L \) is the creepage distance along the surface of insulator, \( L_T \) is the creepage distance along the top surface of insulator, \( dl \) is the increment of creepage distance, \( D(l) \) is the diameter at distance \( dl \), \( f_T \) and \( f_B \) is the form factor of the top and bottom surface of insulator respectively and \( f \) is the total form factor of insulator.

From (7) and (8), the following equation is obtained:

\[
\gamma_{eq} = \frac{f}{f_B/\gamma_B + f_T/\gamma_T} \tag{9}
\]

where \( \gamma_{eq} \) is the equivalent conductivity of the whole insulator surface; \( \gamma_T \) is the conductivity of top surface and \( \gamma_B \) is that of bottom surface.

Because the \( SPLC \) of insulator is directly proportional to its \( SDD \), from (3) and (7)–(9), the ratio of the equivalent value of conductivity \( k \) of the whole insulator surface \( (\gamma_{eq}) \) with non-uniform pollution distribution to the surface conductivity \( (\gamma_1) \) with uniform pollution distribution can be expressed as follows:

\[
k = \frac{\gamma_{eq}}{\gamma_1} = \frac{f \cdot SDD_T \cdot SDD_B}{SDD \cdot (f_B \cdot SDD_T + f_T \cdot SDD_B)}. \tag{10}
\]

The related technical parameters of insulators calculated according to Table I and standard [33] are shown in Table V.

According to (3), (4), (10) and the parameters in Table V, the values of \( k \) of various types of insulators with non-uniform pollution distribution are obtained, and they are shown in Table VI.

From Table VI we can see that, the more uneven the pollution distribution on the top and bottom surface of insulator, the smaller the mean pollution surface conductivity along the whole surface of insulator. For example, the \( k \) of A-type insulator is 0.85, 0.67, 0.50 and 0.31 respectively when \( T/B \) decreases from 1 to 1/3, 1/5, 1/8 and 1/15, which means that the
TABLE V
THE RELATED PARAMETERS OF DIFFERENT INSULATORS

<table>
<thead>
<tr>
<th>Types</th>
<th>$f_B$</th>
<th>$f_C$</th>
<th>$f$</th>
<th>$S_B$</th>
<th>$S_C$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.619</td>
<td>0.226</td>
<td>0.845</td>
<td>2050</td>
<td>1124</td>
</tr>
<tr>
<td>B</td>
<td>0.845</td>
<td>0.255</td>
<td>1.070</td>
<td>2996</td>
<td>1820</td>
</tr>
<tr>
<td>C</td>
<td>0.535</td>
<td>0.225</td>
<td>0.760</td>
<td>2766</td>
<td>1499</td>
</tr>
<tr>
<td>D</td>
<td>0.796</td>
<td>0.217</td>
<td>1.013</td>
<td>3309</td>
<td>1989</td>
</tr>
<tr>
<td>E</td>
<td>0.495</td>
<td>0.332</td>
<td>0.827</td>
<td>1710</td>
<td>1810</td>
</tr>
<tr>
<td>F</td>
<td>0.926</td>
<td>0.460</td>
<td>1.386</td>
<td>2750</td>
<td>2860</td>
</tr>
</tbody>
</table>

TABLE VI
THE VALUE OF $T/B$ OF INSULATORS WITH NON-UNIFORM POLLUTION

<table>
<thead>
<tr>
<th>Types</th>
<th>$T/B$</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>1/1</td>
</tr>
<tr>
<td>A</td>
<td>0.20</td>
</tr>
<tr>
<td>B</td>
<td>0.08</td>
</tr>
<tr>
<td>C</td>
<td>0.03</td>
</tr>
<tr>
<td>D</td>
<td>0.20</td>
</tr>
<tr>
<td>E</td>
<td>0.08</td>
</tr>
<tr>
<td>F</td>
<td>0.03</td>
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<tr>
<td></td>
<td>0.20</td>
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<td></td>
<td>0.08</td>
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<td></td>
<td>0.03</td>
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<td>0.20</td>
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<td>0.08</td>
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<td>0.03</td>
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<td>0.20</td>
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<td>0.08</td>
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<td>0.03</td>
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<td></td>
<td>0.20</td>
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<td></td>
<td>0.08</td>
</tr>
<tr>
<td></td>
<td>0.03</td>
</tr>
</tbody>
</table>

Some mathematical methods and the fitting analysis based on (13) were adopted for the data in Table II, and a group of equations are obtained as follows:

\[ E_L = \begin{cases} 
97.0 \cdot SDD^{-0.325} & \text{Type A,} \\
93.1 \cdot SDD^{-0.361} & \text{Type B,} \\
103.8 \cdot SDD^{-0.310} & \text{Type C,} \\
76.4 \cdot SDD^{-0.365} & \text{Type D,} \\
78.5 \cdot SDD^{-0.465} & \text{Type E,} \\
70.7 \cdot SDD^{0.373} & \text{Type F,} 
\end{cases} \]

(15)

The relative errors of the values of pollution flashover voltage of different insulators between the actual values and the values calculated by (15) are shown in Table VII.

V. CONCLUSIONS

From the above tests and analysis, some conclusions are obtained as follows:

1) The relative errors of the ac pollution flashover voltage of insulators between the results calculated by (13) and the actual values are within 6%; so it is acceptable to express the relationship between the pollution and $T/B$ of insulators and the ac pollution flashover voltage of insulators by (13), which is similar to the dc experimental results.

2) The effects of the $T/B$ on the ac pollution flashover voltage of various types of insulators are different. The value of $A$ of the 6 various types of insulators is 0.181, 0.200, 0.193, 0.236, 0.293 and 0.275, respectively, but they are all smaller than that of the porcelain insulators with dc voltage applied [24], [26].
1) The ac pollution flashover voltage \(U_f\) of large tonnage porcelain and glass insulators are influenced by their surface \(SDD\) and \(T/B\); and the effects of the \(SDD\) and \(T/B\) on various types of insulators are different.

2) The relationship among the ac pollution flashover stress \(E_f\), \(SDD\) and \(T/B\) of large tonnage porcelain and glass insulators is shown as follows:

\[
E_f = c \cdot SDD^{1-b} \left[ 1 - A \cdot \log \left( \frac{T}{B} \right) \right].
\]

For the 6 various types of porcelain and glass insulators that were tested in this paper, the value of \(b\) is in the range of 0.30–0.41 and the value of \(A\) is in the range of 0.18–0.30.

3) The insulator with bigger disc diameter and longer creepage distance does not always have a higher ac pollution flashover voltage. It is found that the insulators tested in this paper with \(I/D\) values between 1.528 and 1.563 have better anti-pollution properties of unit structure height and higher effective utilization rates of creepage distance.

4) The more uneven the pollution distribution on the top and bottom surface of insulators, the smaller the mean pollution surface conductivity along the whole surface of insulators.

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REFERENCES


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