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Study on the Influence of Test Methods on AC and DC Pollution Flashover Performance of Different UHV Insulators

***Abstract**. This paper presents the flashover performance of three different insulators by using different test method. The results show that the influence of test method on the flashover performance of polluted insulators is significant. The average flashover voltage U_{av} obtained by even-raising the voltage method is 6.2% to 10.7% higher than the 50% breakdown voltage U_{50} obtained by the up-and-down method. The results also reveal a slight difference of pollution exponents obtained by different method which analyzed theoretically based on the Obenaus model.*

***Streszczenie.** W artykule przedstawiono porównanie odporności trzech typów izolatorów na zjawisko przeskoku, przy pomocy różnych metod badawczych. Wykazano duży wpływ rodzaju zastosowanej metody na wynik analizy przy występujących zanieczyszczeniach. Stwierdzono także różnice w znaczeniu zanieczyszczeń w modelu, w zależności od metody. (**Badanie odporności izolatora UHV na przeskoki AC i DC wynikające z zanieczyszczeń – porównanie wpływu metod badawczych na wynik**).*

Keywords: insulator, pollution flashover, UHV.
Słowa kluczowe: isolator, przeskok po zanieczyszczeniach, UHV.

Introduction

The history of artificial contamination tests on high voltage insulators spans from around 1939 to later than 1950, within which period a wide variety of test techniques was proposed [1]. The flashover caused by contamination on the surface of insulators mainly threatens the safe operation of power systems [2]. To maintain the high reliability of power delivery, the lines should be provided with adequate insulation [3]. The pollution flashover is the most dangerous for the power system compared with other flashovers cause by lighting, heavy rain, or ice [4]. Field performance data, although of great value, are extensive and difficult to gather before they are deemed reliable [5]. Consequently, to avoid or reduce the harm caused by the pollution flashovers of insulators on the transmission lines, reasonable artificial laboratory pollution tests are often used to assess insulator performance quickly. Laboratory tests are also useful for the optimization of insulator shapes, evaluation of new insulator designs and materials, establishment of acceptable insulation levels for new lines, and determination of modifications to upgrade existing ones [5].

In alternating current (AC) and direct current (DC) artificial pollution tests, the up-and-down method and the even-rising method are often used to assess the electrical characteristics of the insulator [6-8]. The procedure of the up-and-down method is more similar to the working state of the pollution insulators used in the power system [4]. Hence, the up-and-down method can better reflect the pollution breakdown voltage level of the operating insulators. Compared with the up-and-down method, the even-rising voltage method can obtain a large amount of data within a short time [4]. Therefore, the even-rising method has also been used by some researchers [4, 9].

Numerous investigations have been conducted by using the two test methods individually. Meanwhile, only a little of them studied the two methods together. Nowadays, several UHV transmission lines (both AC and DC) are on construction in China. In order to keep the safe operation of power systems, the pollution performance of UHV outdoor insulators must be estimated properly and efficiently. So three types of UHV insulators included ceramic insulators and SIR composite insulators were investigated in this paper. The test results indicate a clear difference in the flashover voltage of the same insulators by using different test methods. For all the insulators under AC and DC test, the average flashover voltages (U_{av}) obtained by using even-raising method are higher than the 50% flashover voltages (U_{50}) obtained by using up-and-down method. However, the results reveal only a slight difference between the two pollution exponents obtained by using different methods. Thereafter, it was also analyzed theoretically based on Obenaus model.

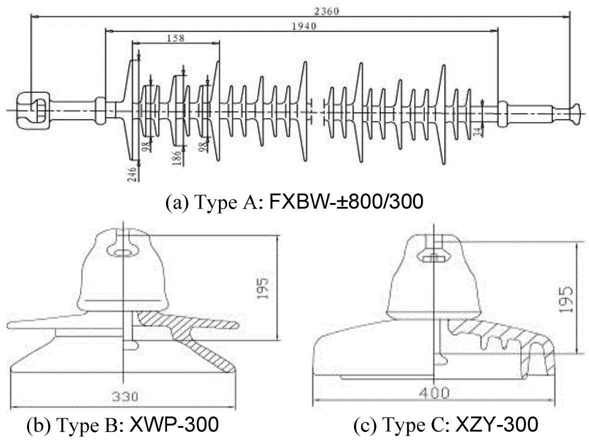
Test Facilities and Procedure

A. Test Facilities

The experimental investigations were carried out in a multifunctional artificial climate chamber with a diameter of 7.8 m and a height of 11.6 m. The AC power is supplied by a pollution test transformer (YDTW 500 kV/2000 kVA). The major technical parameters are seen in [9]. The DC power supply is supplied by a cascade rectifier circuit (±600 kV/0.5 A), and its detail was illustrated in [8]. Due to polarity effect, the positive flashover voltage is higher than the negative flashover voltage. In order to study most severe case, the negative polarity DC voltage is always applied in this work. For simplification, all of the negative flashover voltages in this paper are presented in positive numbers.

B. Specimens

The specimens are short sample of FXBW-±800/300 composite insulator and two types of disc ceramic insulator used for UHV outdoor insulation. The characteristics and configuration of the specimens are shown in Fig.1 as well as Tables 1 and 2.



(a) Type A: FXBW-±800/300

(b) Type B: XWP-300 (c) Type C: XZY-300

Fig.1. Configuration of the tested insulators

Table 1. Parameters of SIR composite insulator

Type	Configuration height H [mm]	Dry arc distance h [mm]	Leakage distance L [mm]	Shed diameter D [mm]	Rod diameter d [mm]
A	2360	1940	8205	246(D_1)/186 (D_2)/98(D_3)	34
Note: D_1-the diameter of large shed, D_2-diameter of the middle one, D_3-diameter of the small one.					

Table 2. Parameters of ceramic insulators

Type	Shed diameter D [mm]	Configuration height H [mm]	Leakage distance L [mm]	Surface area A [cm^2]	Dry arc distance of 7 units [mm]
B	330	195	485	3860	1530
C	400	195	635	5298	1565

C. Test Procedures

According to the corresponding test standards [10, 11], the procedures for preparing the specimen adopted in this study can be described as follows:

Preparation and Pollution:

Before the tests, all specimens were carefully cleaned using trisodium phosphate to ensure the removal of all traces of dirt and grease, and then dried under normal laboratory conditions. Thereafter, the surfaces of the specimens were contaminated with the suspension of sodium chloride and kieselguhr. In this study, the salt deposit densities (SDD) are 0.03, 0.05, 0.10, 0.15, and 0.20 mg/cm^2, meanwhile the ratio of SDD to NSDD is 1:6. In this study, the SDD and NSDD of the upper and lower surfaces of the insulators are uniform.

Arrangement:

After drying for 24 h in room temperature, the specimens are suspended vertically from the hoist at the center of the chamber. The minimum clearance between any part of the samples and any earth objects satisfies the requirements [8].

Wetting:

The polluted insulators were wetted by steam fog generated by a boiler (1.5 t/h). The nozzles are arranged perpendicular to the axis of the test insulators at the bottom of the artificial climate chamber. The clearance between the insulator and the ground is more than 3.5 m. The input rate of steam fog is 0.05 ± 0.01 kg/h·m^3. The temperature in the chamber was controlled between 30 ºC and 35 ºC.

D. Electrical Performance Evaluated Method

Different electrical performance evaluation methods result in different performance levels of contaminated insulators [8]. To investigate the effect of the test method on the results of polluted insulators under AC and DC voltage, two typical test methods, the even-rising method or average flashover voltage (U_{av}) and the up-and-down method or 50% breakdown voltage (U_{50}) have been adopted in this study.

1) Method A: Even-rising voltage method

The even-rising voltage method is also called the average flashover voltage method. Its step up rate is 3 kV/s. Flashover tests were carried out on 4-5 strings of insulators and each one were performed for 4-5 times at the same pollution degree. The flashover voltages, with deviations of less than 10% compared with the mean value of those flashover voltages, are defined as valid flashover voltages (or valid test). The minimum number of valid tests required is 20 under a certain pollution degree. The average value of valid tests is defined as the average flashover voltage of the insulator string, U_{av}, at that pollution degree.

(1) $$U_{av} = \left(\sum_{i=1}^{N} U_i \right) / N$$

(2) $$\sigma\% = \frac{\sqrt{\sum_{i=1}^{N} \left(U_i - U_{av}\right)^2 / (N-1)}}{U_{av}} \times 100\%$$

where U_{av} - flashover voltage, kV; U_i - pollution flashover voltage for the i time, kV; N - number of valid test, σ% - relative standard deviation.

2) Method B: Up-and-down method

The up-and-down method is also called the 50% breakdown voltage method. The insulator was subjected to at least 10 “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 one. Only the individual test and at least 9 following individual tests were taken as useful tests to be considered to determine.

(3) $$U_{50} = \frac{\sum \left(n_i V_i\right)}{N}$$

(4) $$\sigma\% = \frac{\sqrt{\sum_{i=1}^{N} \left(V_i - U_{50}\right)^2 / (N-1)}}{U_{50}} \times 100\%$$

where U_{50} - 50% breakdown voltage, kV; V_i - applied voltage, kV; n_i - test number under applied voltage V_i; N - total number of “valid” tests; σ% - relative standard deviation.

Test results and analysis

A. Test results

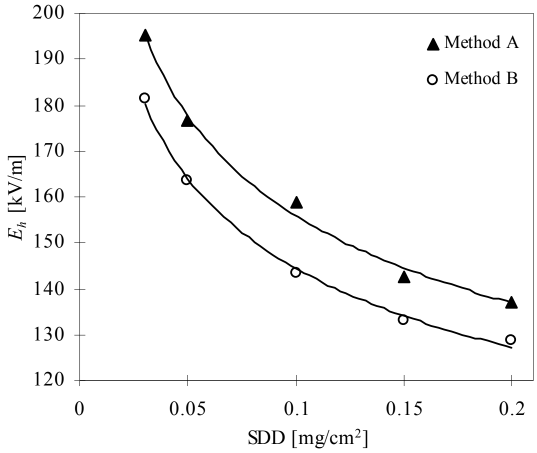
AC pollution flashover tests were carried out on type A and type B insulators in the climate chamber, meanwhile DC pollution flashover tests were carried out on type A and type C insulators. The test results of these samples under different test method are presented in Tables 3 and 4. The insulators’ string dry arc distance flashover gradient was defined as the ratio of pollution flashover voltage U_f to the dry arc distance of the insulators (string) h, which are listed in Tables 1 and 2, namely $E_h = U_f/h$. The E_h of these insulators investigated in this paper are shown in Fig.3-Fig.6, according to the results presented in Table 3 and 4.

Table 3. Test results of polluted insulators under AC voltage

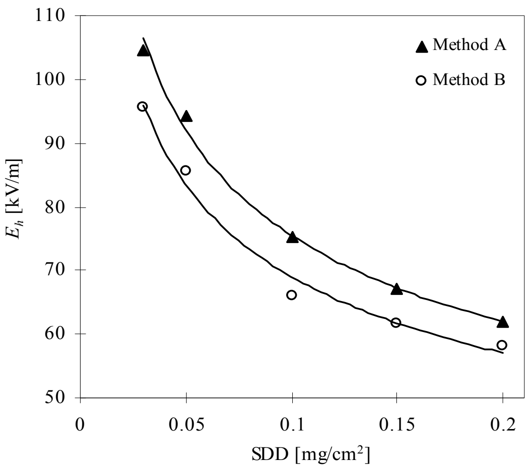
Type	SDD (mg/cm^2)	Method A		Method B	
		U_{av} [kV]	σ [%]	U_{50} [kV]	σ [%]
A	0.03	379.1	4.2	352.2	4.5
	0.05	342.8	3.8	317.0	4.9
	0.10	308.5	5.0	278.5	5.3
	0.15	276.5	4.5	258.4	4.3
	0.20	265.7	5.2	249.5	5.7
B	0.03	160.2	4.2	146.2	4.9
	0.05	144.3	4.7	131.0	4.9
	0.10	115.0	4.1	101.2	5.1
	0.15	102.5	3.1	94.3	4.5
	0.20	94.6	2.4	89.1	5.2

Table 4. Test results of polluted insulators under DC voltage

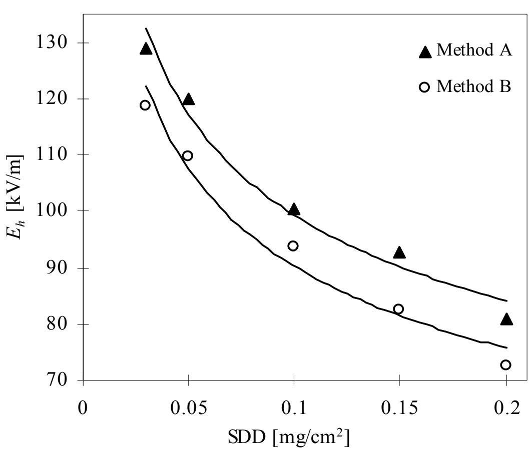
Type	SDD (mg/cm^2)	Method A		Method B	
		U_{av} [kV]	σ [%]	U_{50} [kV]	σ [%]
A	0.03	250.0	4.9	230.1	5.5
	0.05	233.3	5.0	213.2	5.2
	0.10	195.4	3.9	182.4	4.5
	0.15	180.7	4.3	160.3	4.8
	0.20	157.1	4.6	141.0	4.8
C	0.03	145.4	4.0	134.2	3.9
	0.05	124.6	4.8	113.5	5.1
	0.10	100.4	3.8	92.3	4.7
	0.15	92.1	4.6	86.6	4.4
	0.20	86.9	5.2	81.2	5.6



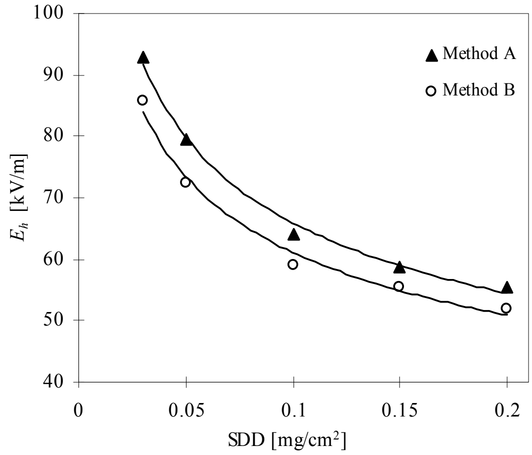
(a) AC flashover voltage gradient of type A insulator



(b) AC flashover voltage gradient of type B insulator string



(c) DC flashover voltage gradient of type A insulator



(d) DC flashover voltage gradient of type C insulator string

Fig. 2. Flashover voltage gradient of dry arc distance E_h of various insulators versus *SDD* under different test methods

Fig.3 - Fig.6 show that both AC and DC pollution flashover voltage of the insulators decrease with the increase of SDD. It also easy to find out that, the E_h of composite insulators was higher than the ceramic insulators significantly, which mean the composite insulators have good anti-pollution flashover performance. For the same composite insulator (type A), the AC flashover voltage was higher than DC flashover voltage.

B. Influence of Test Methods on the Flashover Performance of Polluted Insulators

From Tables 3 and 4, the flashover voltages of insulators (strings) decrease with the increasing of SDD for both two test methods. Results were fitted with empirical equations of the form: [8,16]:

$$U_f = A \cdot SDD^{-\alpha} \tag{5}$$

where A – coefficient, α - characteristic exponent

Through the curve fitting, the relationship between flashover voltages and *SDD* could be expressed as follows:

For type A insulators applied AC voltage

$$U = \begin{cases} 196.1 SDD^{-0.188} & \text{Method A} \\ 182.4 SDD^{-0.186} & \text{Method B} \end{cases} \tag{6}$$

For type B insulators applied AC voltage

$$U = \begin{cases} 59.83 SDD^{-0.286} & \text{Method A} \\ 56.76 SDD^{-0.272} & \text{Method B} \end{cases} \tag{7}$$

For type A insulators applied DC voltage

$$U = \begin{cases} 111.6 SDD^{-0.238} & \text{Method A} \\ 98.38 SDD^{-0.251} & \text{Method B} \end{cases} \tag{8}$$

For type C insulators applied DC voltage

$$U = \begin{cases} 54.73 SDD^{-0.275} & \text{Method A} \\ 52.06 SDD^{-0.264} & \text{Method B} \end{cases} \tag{9}$$

Based on equations (6)-(9), the exponent α is related to the profile and material of the insulator as well as the type of test voltage. For AC flashover voltage, α is about 0.18-0.28, and α of composite insulator is less than that of ceramic insulator. It proves that the composite insulator has more excellent anti-pollution flashover performance than ceramic insulators once more. For DC flashover voltage, the value of α is about 0.24-0.28, and these values are more closed to each other. The exponent α of composite insulator is also less than that of ceramic insulator string. Based on the analysis, it is easy to make a conclusion that the composite insulator has more excellent anti-pollution flashover performance which is in line with other researchers [6, 7, 14]. Furthermore, it is worth to mention that the exponents α of two different methods are closed to each other under the same condition. Hence, the influence of test methods on the exponent α is not apparent. According to equations (6)-(9), the pollution characteristic exponent α of insulators under different situation are summarized in Table 5, which demonstrated that difference of α between two different methods is relatively small.

Table 5. Pollution characteristic exponent of insulators

Insulators	Type A (AC)	Type B (AC)	Type A (DC)	Type C (DC)
Method A	0.188	0.286	0.238	0.275
Method B	0.186	0.272	0.251	0.264
Difference	-0.002	-0.014	0.013	0.011

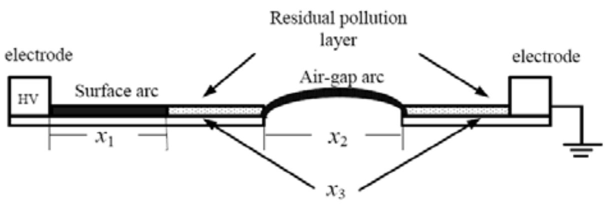
Based on the data in Tables 3 and 4 as well as Fig.3 - 6, the influence of test methods on the flashover performance of polluted insulators is remarkably. According to the Tables 3 and 4, all U_{av} obtained by means of method A are higher than U_{50} by means of method B at the same contamination level with the amplitudes about 6.2%-10.7%. The difference of the test results by means of two methods can be defined as follow:

(10) $$\Delta\beta\% = \frac{U_{av} - U_{50}}{U_{50}} \times 100\%$$

The calculated differences were summarized in Table 6, which shown that the difference was various with insulator's type, the type of applied voltage as well as the contamination levels. However, the mean values of different insulators were closed to each other (from 8.1 to 9.4). The average flashover voltage (U_{av}) is higher than the 50% withstand voltage (U_{50}) about 8.6% (the mean value of all the differences).

Table 6. Difference of test results by different methods (in percent)

Insulators	SDD (mg/cm^2)					means
	0.03	0.05	0.10	0.15	0.20	
Type A(AC)	7.6	8.1	10.8	7.0	7.1	8.1
Type B(AC)	9.6	10.2	10.4	8.7	6.2	9.0
Type A(DC)	8.9	9.4	7.1	10.7	11.1	9.4
Type C(DC)	8.3	9.8	8.8	6.4	7.0	8.1



x_1: length of surface arc, x_2: length of air-gap arc, x_3: length of residual pollution layer

Fig. 3 pollution discharge model of insulator

C. Analysis of Pollution Characteristic Exponent (α)

Base on the Obenaus model, a developing model was illustrated in Fig. 3, which consider the influence of the air-gap arc. This model is applicable to any type, any length, and any material of insulators [8].

According to the model illustrated in Fig.7 and the basic equation of *U-I* characteristics of air-gap arc and surface arc, the voltage balance equation can be given as follow:

(11) $$U = A_1 \cdot I^{-n_1} \cdot x_1 + A_2 \cdot I^{-n_2} \cdot x_2 + r_p \cdot I \cdot x_3 + U_0$$

where: U - voltage applied to the insulator, I - leakage current, r_p - resistance of the remaining pollution layer, A_1, n_1 - constants of the surface arc characteristics, A_2, n_2 - constants of the air-gap arc characteristics, U_0 - electrode fall voltage.

Due to the phenomenon of arc levitation, discharge path may not be strictly in accordance with leakage path. So the total length of the local arc and remaining pollution layer may unequal to the creepage distance of insulator (string). That is

(12) $$x_1 + x_2 + x_3 = k_1 NL$$

where: k_1 - ratio of the length of actual discharge path to creepage distance of the insulators string, N the insulators units, L the creepage distance of one insulator.

Supposing $x = x_1$, $x_2/x_1 = k_2$, then $x_3 = k_1NL\text{-}(1+k_2)x$, the equation (11) can be expressed as follow:

(13) $$\begin{aligned} U &= A_1 \cdot I^{-n_1} \cdot x + k_2 \cdot A_2 \cdot I^{-n_2} \cdot x \\ &\quad + r_p \cdot I \cdot [k_1 \cdot N \cdot L - (1+k_2) \cdot x] + U_0 \\ &\approx A_3 \cdot I^{-n_3} \cdot x + r_p \cdot I \cdot [k_1 \cdot N \cdot L - (1+k_2) \cdot x] \end{aligned}$$

where: A_3 ,n_3 - constants determined by A_1, n_1, A_2, n_2 and k_2.

The electrode fall voltage U_0 was also ignored, because comparing to the total flashover voltage, it is a small part.

By using $dU/dx=0$, and $dU/dI=0$, the critical current I_c and critical surface arc length x_c can be obtained.

(14) $$I_c = \left(\frac{A_3}{r_p \cdot (1+k_2)} \right)^{\frac{1}{n_3+1}}$$

(15) $$x_c = \frac{k_1 \cdot N \cdot L}{(1+k_2) \cdot (1+n_3)}$$

Substituting equation (14) and (15) into equation (13), the critical flashover voltage U_c can be obtained.

(16) $$U_c = \left(\frac{A_3}{(1+k_2)} \right)^{\frac{1}{n_3+1}} k_1 \cdot N \cdot L \cdot r_p^{\frac{n_3}{1+n_3}}$$

According to the literatures [8], the relationship between the surface conductivity and SDD of the pollution layer of the insulators can be expressed as follows:

(17) $$r_p \propto= SDD \quad \text{or} \quad r_p = \eta \cdot (SDD)^{-1}$$

where: η - coefficient

So the equation (16) can be changed as:

(18) $$U_c = \left(\frac{A_3}{(1+k_2)} \right)^{\frac{1}{n_3+1}} \cdot \eta^{\frac{n_3}{1+n_3}} k_1 \cdot N \cdot L \cdot (SDD)^{-\frac{n_3}{1+n_3}}$$

Comparing the equation (5) and equation (18), the pollution characteristic exponent α can be express as follow:

$$\alpha = \frac{n_3}{1+n_3} \tag{19}$$

Equation (19) shows that the pollution characteristic exponent α only relates to the compositive exponent n_3. And the n_3 is influenced by n_1, n_2, and k_2. Because n_1 and n_2 are constant, so they do not depend on the test method. However the k_2 will be influence by test method to some extent, because the different method may influence formation of dry band on the surface of the insulator, and this may change the length of surface arc and air-gap arc as seen Fig.3. Different k_2 will result different n_3. This can explain why the different test method influences the pollution characteristic exponent α to some extent as seen Table 5. The change of k_2 may be relative small, so that the change of exponent α is also relative small.

Conclusions

The influence of test method on the flashover performance of polluted insulators is significant. Under similar conditions, average flashover voltage (U_{av}) obtained by Method A is higher by about 6.2% to 10.7% than 50% flashover voltage (U_{50}) obtained by Method B. And the average value is 8.6%. Through the theoretic analysis based on Obenaus model, different test method may result different length of surface arc and air-gap arc, this will cause small difference of pollution exponent α. However, due to the small change of k_2, the influence of test methods on the exponent α is not apparent.

Acknowledgment

This work was supported by National Basic Research Program of China (973 program) (2009CB724503) and National Science Foundation for Young Scientists of China (Grant NO.51107151).

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