COMPARISON OF DC ICING FLASHOVE PERFORMANCES FOR PRE-POLLUTED SHORT SAMPLES OF COMPOSITE INSULATORS WITH DIFFERENT CONFIGURATION IN HIGH ALTITUDE AREA

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Abstract: DC icing flashover performance of seven types of pre-polluted short samples of composite insulators at low air pressure simulated by the multifunction artificial climate chamber was researched in this paper. The rationality of the minimum sample size of the improved U-type method used in the paper was proofed. The test results show that the relationship between DC icing flashover gradient and air pressure meets power function and the value of the exponent *n* describing the influence of air pressure is 0.397 to 0.711 for the 7 types of insulators. The influences of sheds configuration parameters, ice thickness, pollution and air pressure on icing flashover performance were analyzed. And the selection of sheds configuration of UHV DC composite insulators in high altitude was suggested

1. INTRODUCTION

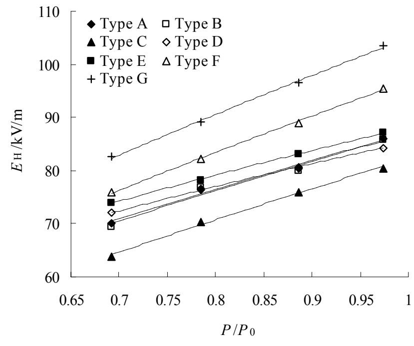
To the problem of how to select the external insulation for the UHV DC transmission project in high altitude and icing areas, there has no sophisticated design and practical operating experience to reference. This paper took the short samples of UHV dc composite insulator as research objective, investigated the samples' DC flashover performance in high altitude, pollution and icing conditions and analyzed the influence of sheds configuration on the flashover performance so as to provide technical reference for UHVDC transmission line design, construction and operation.

2. RESULTS AND DISCUSSION

As shown in ATTACHED TABLE 1, the test obtains the 50% DC icing flashover voltage under the condition that the simulating altitude is 232, 1000, 2000 m and 3000 m, and the pre-polluting *SDD* is 0.03, 0.05, 0.08 mg/cm^2 and 0.15 mg/cm^2, the equivalent thickness of monitoring cylinder is 10mm and 20mm, respectively. The minimum standard deviation of the test results calculated by equation (2) is 2.56% and the maximum value is 7.86%, respectively.

In order to compare the flashover performance of different specimens, the authors analyzed the E_H, where E_H is the 50% DC icing flashover voltage per arc distance. The relationship between E_H and P/P_0 was shown in Figure 1. According to the analysis of the test results, the relationship between the dc icing flashover gradient E_H of iced insulators and the air pressure is normally expressed as:

$$E_H = E_0\left(\frac{P}{P_0}\right)^n \qquad (1)$$



(a) d=10 mm, SDD=0.03 mg/cm^2

Figure 1: Relationship between E_H and P/P_0

(1) The influence of characteristic exponent *n*

The characteristic exponent *n* is related to the *SDD*, the generally trend is that the exponent *n* will decrease with the increase of the *SDD*.The characteristic exponent *n* is related to *d*, and *n* will decrease with the increase of *d*.The characteristic exponent *n* is related to the configuration parameters.

(2) The influence of flashover gradient

The flashover gradient E_H will decrease with the increase of *SDD*.E_H will decline with the increment of icing thickness and altitude, and the declining range has much to do with the shed configuration and parameters.The DC icing flashover gradient of the pre-polluted specimens is related to the configuration parameters k_1, k_2, k_3 and k_4.

3. CONCLUSIONS

(1)The distribution law of ice flashover follows the Gaussian distribution, and the samples mean value $\overline{U}$ also obey the Gaussian distribution

(2)DC icing flashover gradient E_H will decrease as the increase of ice equivalent thickness *d*, the increase of *SDD* before icing, and the decrease of air pressure.

(3)The exponent *n* is related to the sheds configuration of the specimens, *SDD* and *d* etc., and *n* will decrease with increase of *d* and *SDD*

(4)The DC icing flashover gradient of the pre-polluted specimens is related to the configuration parameters k_1, k_2, k_3 and k_4

4. REFERENCES

[1] SHU Yinbiao, LIU Zehong, et al. "A preliminary exploration for design of ±800 kV UHVDC project with transmission capacity of 6400MW". Power System Technology, Vol. 30, No.1, pp. 1-8, 2006 (in Chinese).

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Comparison Of DC Icing Flashover Performances For Pre-polluted Short Samples Of Composite Insulators With Different Configuration In High Altitude Area

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***Abstract*: In order to find out the optimal configuration of composite insulator under high altitude, pollution and icing conditions, the DC icing flashover performance of seven types of pre-polluted short samples of composite insulators at low air pressure simulated by the multifunction artificial climate chamber was researched in this paper. The rationality of the minimum sample size of the improved U-type method used in the paper was proofed. The test results show that the relationship between DC icing flashover gradient and air pressure meets power function and the value of the exponent *n* describing the influence of air pressure is 0.397 to 0.711 for the 7 types of insulators. The influences of sheds configuration parameters, ice thickness, pollution and air pressure on icing flashover performance were analyzed. And the selection of sheds configuration of UHV DC composite insulators in high altitude was suggested.**

Keywords-High altitude; pollution; icing; dc; shed-configuration; improved U-type method; flashover-gradient

I. INTRODUCTION

DC transmission project is one of the important ways to solve the problems of high voltage, great capacity, Long-distance transmission and power network interconnection. China is vast in territory, but the distribution of energy and load centers are very uneven. Therefore, for the purpose of solving this problem, developing UHV transmission technology is the necessary choice to China. With the implementation of "west-east power transmission, south-north interconnection, nationwide power networking", two UHV DC transmission lines, Yun—Guang ±800kV and Xiangjiaba—Shanghai ±800kV, have been established and put into production, in addition, another UHV DC transmission line, Jingping—Sunan ±800kV, is under construction. According to the development program of State Grid Corporation of China, a number of UHVDC transmission lines have been listed in the construction plan [1, 2]. The capacity of these bipolar systems is as high as 5000 to 7200 MW, and such a large capacity of power transmission put forward extremely high requirement to the reliability of the dc transmission system [3]. Moreover, due to the complex geographic and climatic features in China, the transmission line network would be inevitably faced with insulation problems under the conditions of high altitude and complex environment. As shown in experimental researches, electrical performance of insulators will be reduced significantly under high altitude, pollution and icing conditions [5-10]. However, to the problem of how to select the external insulation for the UHV DC transmission project in high altitude and icing areas, there has no sophisticated design and practical operating experience to reference. Therefore, it is difficult to choose the external insulation for the UHV DC transmission lines under high altitude and icing conditions at the present time, and the further study of external insulation of UHVDC project is significant to ensure the reliability, safe and stable operation of UHVDC transmission system.

This paper took the short samples of UHV dc composite insulator as research objective, investigated the samples' DC flashover performance in high altitude, pollution and icing conditions and analyzed the influence of sheds configuration on the flashover performance so as to provide technical reference for UHVDC transmission line design, construction and operation.

II. TEST FACILITIES, SPECIMENS AND TEST PROCEDURE

A. *Test Facilities*

The experimental investigations were carried out in the artificial chamber, which has a diameter of 7.8m and a height of 11.6m[10]. The minimum pressure in the chamber can be as low as 30kPa and the temperature in it can be decreased to −45℃. The test power supply is introduced by the 330kV wall porcelain bushing built on the side of the artificial chamber. The ±600kV/0.5A DC test power supply satisfies the requirements commended by IEC [11]. Due to the silicon-controlled voltage-doubling rectifying circuit with a voltage-current double-feedback system, the dynamic voltage drop is less than 5% when the load current is 0.5 A, and the ripple coefficient is less than 3% when the flashover is occurring.

B. *Test Specimens*

The specimens studied here are seven types of composite insulators short sample, their configuration parameters and profiles are shown as from TABLE 1 to

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TABLE 3.

TABLE 1. Sheds configuration parameters of specimens

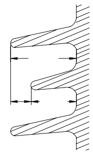
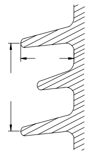
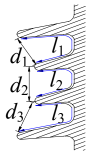
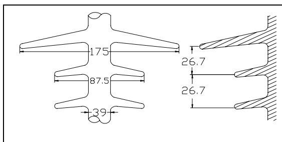
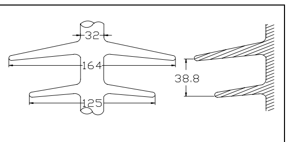
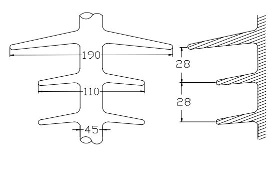
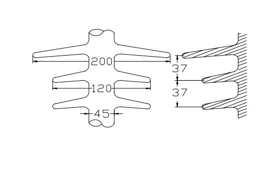
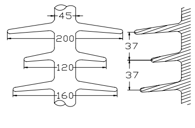
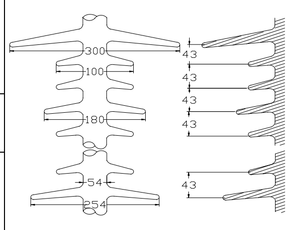
parameters	k_1	k_2	k_3	k_4
expressions	$k_1=\Delta p/p_1$	$k_2=s/p$	$k_3=\sum l_i/\sum d_i$	$k_4=L/H$
sketch diagram				

TABLE 2. Parameters of tested specimens

Type	*H*	*L*	*φ*	k_1	k_2	k_3	k_4	*Note*
A	2195	7395	39	0.643	1.178	2.247	3.369	±500 kV
B	2290	7588	32	0.295	1.176	3.180	3.314	±500 kV
C	3600	13100	45	0.552	1.228	2.654	3.639	±800 kV
D	3980	13570	45	0.516	1.432	2.329	3.410	±800 kV
E	3980	13900	45	0.516	1.910	2.693	3.492	±800 kV
F	3600	9994	54	0.813	2.048	2.059	2.776	±500 kV
G	3600	10132	54	0.813	2.048	2.032	2.814	±500 kV

Specially, k_1 is the ratio of shed spread, where *Δp* is the difference value of the distance of the rod to the maximum shed edge (p_1) to the distance of the rod to minimum shed edge (p_2), namely $k_1=\Delta p/p_1$; k_2 is the ratio of shed spacing *s* and shed spread *p*, where *s* is the vertical distance of two identical sheds in the same group and *p* is the distance of the rod to the maximum shed edge in this group of sheds, namely $k_2=s/p$; k_3 is the ratio of creepage distance $\sum l_i$ and sheds spacing $\sum d_i$, where d_i is the direct air distance of two points on the insulate portion or the direct air distance of one point on the insulate portion to the other point on the fitting, l_i is the creepage distance between these two points, namely $k_3=\sum l_i/\sum d_i$; k_4 is the creepage factor which is the ratio of creepage distance and arc distance, *φ* is the diameter of rod, the measurements are in mm.

TABLE 3. Configuration of tested specimens

	
A	B
	
C	D
	
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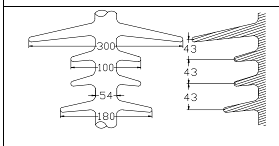
	
G	F

C. Test Procedure

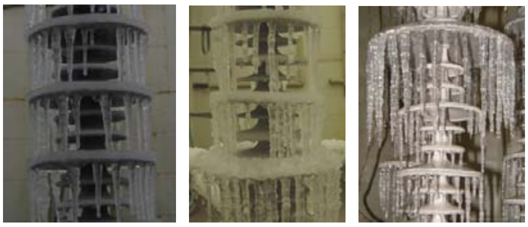
(1)Pre-polluting of specimens

Based on the running experience and accidents surveys, it is shown that most icing flashover of insulator strings of the transmission line in China results from the pollution on insulators before icing [12-16]. Therefore, the most dangerous situation which affects the safe operation of the transmission line's external insulation is taken into account in this paper according to the concrete condition in china, and the solid layer pollution method [17] was adopted in the pre-polluting procedure to simulate the pollution situation of insulators before icing.

(2)Artificial ice-coating procedure

The specimens which had been pre-polluted and dried in the shade for 24 hours were suspended vertically on the electric hoist in the central top of the artificial climatic chamber, and the rotational speed of the hoist is one rpm. While the preparation work complete, reduced the temperature in the climatic chamber to the preset value. The surface of the specimens was wetted by the sprayer and covered with a thin layer of ice to make sure the pollution layer not to be cleared away. In this paper, the spraying system was used to form wet-grown ice on insulators without service voltage. The minimum clearances between any part of the specimens and the spraying system were larger than 3.8 m, the droplets size was 80~100 μm, the spray flux was about 60~80 $L \cdot h^{-1} \cdot m^{-2}$, the wind speed was 3.0~5.0 m/s, the temperature in the climate chamber was -10.0°C~-7.0 °C, and the density of the ice deposit is about 0.80~ 0.90 g/cm^3. The icing instance of some specimens which satisfied the icing conditions above were shown in Figure.1.

The freezing water conductivity was 100μS/cm, In order to make the freezing-water in climate chamber as similar as the supercooling water in natural conditions; the freezing-water was pre-cooled to 4-5°C before spray [11].



(a) Type D (b) Type E (b) Type F

Figure 1. Icing instance of some specimens in the artificial climate chamber

(3) Characteristics defining the icing degree

The average thickness of ice on the insulators was checked by measuring the thickness d of the ice accumulated on a monitoring cylinder with a diameter of 28 mm, a length of 600mm and rotating at one rpm.. The standard and arrangement of the monitoring meet the demand of IEEE STD 1783-2009. The monitoring cylinders were placed on the upper, middle and lower position closed to the insulator. By measuring the three positions' thickness, the average thickness d can be obtained to reflect the icing thickness of insulators.

(4) Flashover test method of icing insulators

The correct U-type method summarized by the authors in long-term experimental investigation was used to obtain the 50% DC flashover voltage of the icing insulators in this paper, the test method can be summarized as follows:

a) When the ice amount accreted on the tested specimens approached a predetermined amount, the droplets spray was turned off and frozen about 15 minute. Then opening the airtight door of the chamber, letting warm air outside in to rise the temperature in the chamber so as to make the ice accreted thaw naturally and gradually, and the rising speed of temperature in the chamber was controlled at 2 °C/h~3 °C/h.

b) When the ice started to melt and the air pressure reached the target value, a series of flashover tests were carried out on each iced specimen with even-rising voltage method every 3-5 minutes until all the ice on the insulator sheded. The flashover voltage and current were measured in every flashover test, and the flashover phenomenon was observed. To make sure each flashover event independent of others, the time interval between two adjacent flashover tests should be 3~5 min.

For a iced specimen, the relationship between the flashover voltage $U_f(i)$ (i=1, 2, ···, N) obtained by above procedures and the number of flashovers or melting time can be expressed as U-type curve. The lowest point on the U-type curve stands for the minimum flashover voltage. Therefore, the minimum flashover voltage of the iced insulator is

$$U_{fm} = Min(U_{\mathrm{f1}}, U_{\mathrm{f2}}, U_{\mathrm{f3}}, ..., U_{\mathrm{fi}}, ..., U_{\mathrm{fn}}) \quad (1)$$

According to above test procedure, more than ten effective U_{fm} should be obtained for each kind of insulator. And the 50% icing flashover voltage U_{50} and its standard deviation can be expressed as:

$$\begin{cases} U_{50} = \dfrac{\sum_{i=1}^{N} U_{\mathrm{fm}}(i)}{N} \\ \sigma = \sqrt{\dfrac{\sum_{i=1}^{N}\left(U_{\mathrm{fm}}(i) - U_{50}\right)^2}{N}} \end{cases} \quad (2)$$

where $U_{fm}(i)$ is the minimum flashover voltage obtained from the test in the i time, kV; N is the total times of the effective test, $N \geq 10$; σ(%) is the standard deviation of the test result.

III. The Minimum Sample Size of The Correct U-Type Method

A. *Test Results*

The DC icing flashover performance of 7 different shed configurations of polluted composite insulators at low air pressure simulated by the multifunction artificial climate chamber has been researched in this paper. The test numbers of each species specimen is more than 10 strings. The test obtains the 50% DC icing flashover voltage under the condition that the simulating altitude is 232, 1000, 2000 m and 3000 m, and the pre-polluting *SDD* is 0.03, 0.05, 0.08 mg/cm^2 and 0.15 mg/cm^2, the equivalent thickness of monitoring cylinder is 10mm and 20mm, respectively. The minimum standard deviation of the test results calculated by (2) is 2.56% and the maximum value is 7.86%, respectively.

B. *Analysis of The Minimum Sample Size of The Correct U-type Method*

In order to verify the rationality of the sample size chosen in the test procedure, the minimum sample size of the correct U-type method is analyzed in this paper. Taking the flashover test on the same specimen for N times and there will obtain n valid data, namely there is one sample of the flashover voltage of that specimen which was obtained from the test, and the sample size is n. Define the sample mean as $\overline{U}$, the sample standard deviation as δ. Because every icing flashover test was carried out under nearly the same conditions, the data obtained is independent to each others and the distribution law of the flashover voltage follows Gaussian distributions [19, 20]. Therefore, in spite of the size of the sample, the sample mean $\overline{U}$ also follow Gaussian distributions. When take $\overline{U}$ as the estimated value of the 50% flashover voltage U_{50}, the sampling error, namely the deviation between the estimated value and the actual value U_{50} is also required. So the confidence interval of U_{50} needs to be analyzed. Presuming all of the random variable $U_{\mathrm{fm}}(i)$ follow Gaussian distributions, normal population U_{50}~$N(\mu,\delta^2)$, where δ^2 is given parameter. {$U_{\mathrm{fm}}(1)$, $U_{\mathrm{fm}}(2)$, …, $U_{\mathrm{fm}}(n)$} is one sample from the normal population, and the sample size is n. if the given confidence is (1-α), the confidence interval of μ can be expressed as:

$$\left(\overline{U} - \mu_{1-\frac{\alpha}{2}} \cdot \frac{\delta}{\sqrt{n}}, \overline{U} + \mu_{1-\frac{\alpha}{2}} \cdot \frac{\delta}{\sqrt{n}}\right) \quad (3)$$

The test times selecting is related to the test accuracy. Define the statistical error accuracy of the DC icing flashover voltage of the pre-polluted specimens as e_s, the accuracy which is the ratio of half of confidence interval which is stay to be estimated and the median of this confidence interval can be expressed as:

$$e_s = \frac{\left(\overline{U} + \mu_{1-\frac{\alpha}{2}} \cdot \frac{\delta}{\sqrt{n}}\right) - \left(\overline{U} - \mu_{1-\frac{\alpha}{2}} \cdot \frac{\delta}{\sqrt{n}}\right)}{\left(\overline{U} + \mu_{1-\frac{\alpha}{2}} \cdot \frac{\delta}{\sqrt{n}}\right) + \left(\overline{U} - \mu_{1-\frac{\alpha}{2}} \cdot \frac{\delta}{\sqrt{n}}\right)} = \frac{\mu_{1-\frac{\alpha}{2}} \cdot \frac{\delta}{\sqrt{n}}}{\overline{U}} \tag{4}$$

The test data should be satisfied (4) to guarantee the relative deviation, namely the sampling error e_s between the estimated value U_{50} and the actual U_{50} less than a certain allowable value e. When the sampling error e_s is less than 3.0%, the deviation can meet the demand of the engineering. Suppose e_s can be expressed as:

$$e_s = \frac{\mu_{1-\frac{\alpha}{2}} \cdot \frac{\delta}{\sqrt{n}}}{\overline{U}} \le e \tag{5}$$

So:

$$n \ge \left(\frac{\delta \cdot \mu_{1-\alpha/2}}{\overline{U}}\right)^2 \tag{6}$$

The purpose of analyzing the minimum sample size of the correct U-type method is to verify the rationality of deducing the whole characteristic by the part performance. The minimum sample size derived form (6) can be expressed as:

$$n = \left(\frac{\delta \cdot \mu_{1-\alpha/2}}{\overline{U} \cdot e}\right)^2 \tag{7}$$

From (7), we can see that if the confidence coefficient 1-α is identical, the test times n demanded in the experiment is directly proportional to the square of the relative dispersion coefficient of the measured value and inversely proportional to the square of the reciprocal of the accuracy. Therefore, we can estimate the value of n by the given 1-α and e. Take the confidence coefficient 1-α as 0.95 in this paper, namely α is 0.05, $\mu_{1-\alpha/2}$=1.96. The DC icing flashover voltage and standard deviation of the specimens was obtained under the conditions that the altitude was 232m, 1000m, and 300m, the icing thickness was 5, 10, 15, 20 mm and 25mm, and the *SDD* is 0.05 mg/cm^2 and 0.15 mg/cm^2, respectively. Calculate the minimum sample size n of the specimens A~G by the correct U-type method according to (7), where e_1=1%, e_2=2%, e_3=3%. The results are shown in ATTACHED TABLE.1.

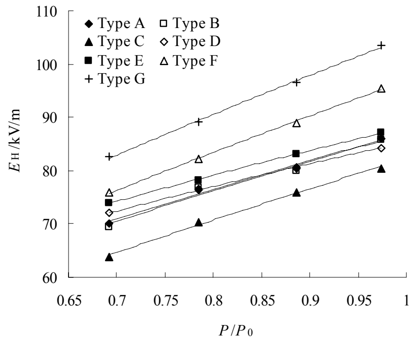
According to ATTACHED TABLE.1, we can see that the minimum sample size of different composite insulators by the correct U-type method is different, and of the same insulators, the minimum sample size is also different under different icing thickness, *SDD* and air pressure. So we take the mean value of those minimum sample sizes of the same sampling error as the minimum sample size which could deduce the characteristic of the whole specimens. While the sampling error e is 3%, 2% and 1%, the mean value of those minimum sample sizes n is 3, 6 and 23, respectively. Therefore, take the minimum sample size as $n\geq10$ is sufficient to obtain the performance of those insulators, and the value also take account of the accuracy of the test as well as reducing the workload of the experiment and the wear of the test facilities.

IV. Analysis of Experimental Results

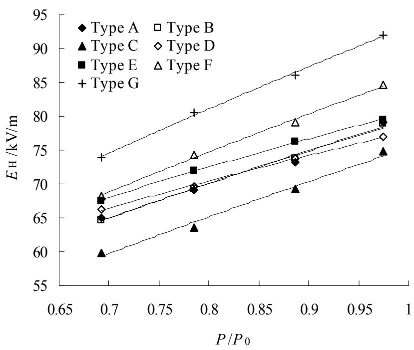
In order to compare the flashover performance of different specimens, the authors analyzed the E_H, where E_H is the 50% DC icing flashover voltage per arc distance. The relationship between E_H and P/P_0 was shown in Figure 2. According to the analysis of the test results, the relationship between the dc icing flashover gradient E_H of iced insulators and the air pressure is normally expressed as [10, 11, 21]:

$$E_H = E_0 \left(\frac{P}{P_0}\right)^n \tag{8}$$

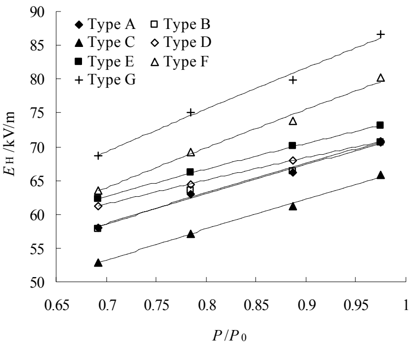
where E_H and E_0 are the dc icing flashover gradient of specimens at air pressure P (high altitude) and pressure at sea level P_0 (101.3 kPa) respectively; n is the exponent describing the influence of air pressure on E_H.



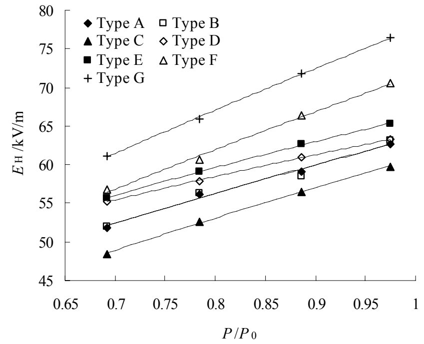
(a) d=10 mm, SDD=0.03 mg/cm^2



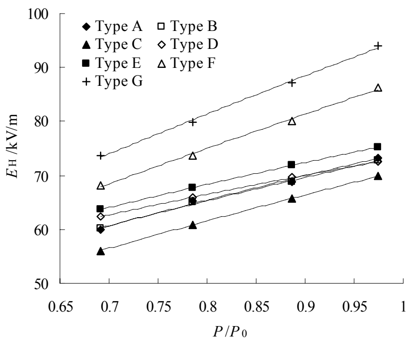
(b) d=10 mm, SDD=0.05 mg/cm^2



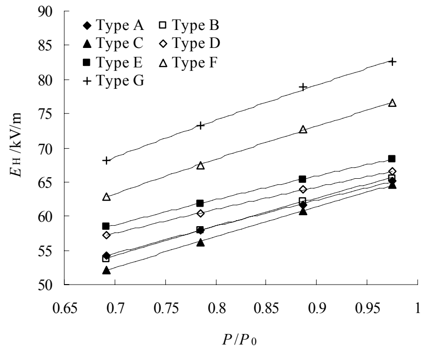
c) d=10 mm, SDD=0.08 mg/cm^2



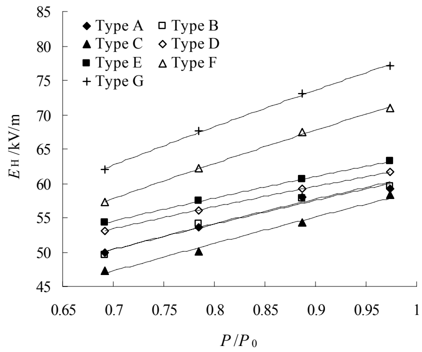
(d) d=10 mm, SDD=0.15 mg/cm^2



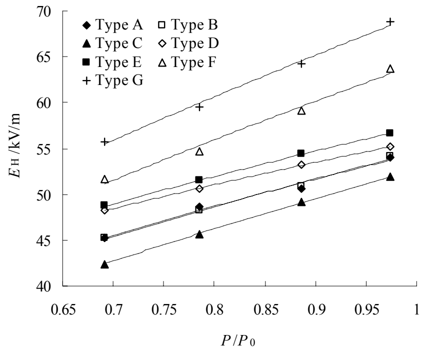
(e) d=20 mm, SDD=0.03 mg/cm^2



(f) d=20 mm, SDD=0.05 mg/cm^2



(g) d=20 mm, SDD=0.08 mg/cm^2



(h) d=20 mm, SDD=0.15 mg/cm^2

Figure 2. Relation ship between E_H and P/P_0

Fitting value of E_0 and n according to the test results in Figure 2 with (8), and the results are shown in TABLE 4, the entire square of the correlation coefficient R^2 are more than 0.95.

According to Figure 2 and TABLE 4, it is known that: the DC icing flashover gradient E_H is affected by the air pressure characteristic exponent n, which ranges from 0.399~0.711. Compared with the results from [22], it is known that the value of air pressure characteristic exponent n for the specimens of type A, B and C under the condition of icing flashover is lower than that under the condition of pollution flashover.

TABLE 4. Fitting value of E_0 and n according to the test results of Figure 2 with (8)

Type	***d*(mm)**		***SDD*(mg/cm^2)**			
			0.03	*0.05*	*0.08*	*0.15*
A	10	E_0	87.1	79.4	71.4	63.5
		n	0.576	0.562	0.558	0.538
	20	E_0	74.3	65.9	60.8	54.4
		n	0.568	0.533	0.526	0.499
B	10	E_0	86.9	79.6	71.7	63.4
		n	0.587	0.570	0.566	0.537
	20	E_0	73.7	66.6	61.1	54.6
		n	0.545	0.582	0.539	0.518
C	10	E_0	82.2	75.4	66.6	60.8
		n	0.674	0.651	0.631	0.611
	20	E_0	71.0	65.4	58.8	52.8
		n	0.639	0.629	0.614	0.592

D	10	E_0	85.3	77.7	71.5	63.9
		n	0.460	0.440	0.423	0.399
	20	E_0	73.4	67.3	62.3	55.8
		n	0.442	0.442	0.433	0.395
E	10	E_0	88.1	80.6	74.0	66.2
		n	0.479	0.474	0.469	0.465
	20	E_0	76.2	69.1	63.9	57.3
		n	0.487	0.458	0.448	0.442
F	10	E_0	96.9	85.8	81.0	71.6
		n	0.669	0.616	0.663	0.648
	20	E_0	87.5	77.8	72.4	64.2
		n	0.689	0.580	0.632	0.615
G	10	E_0	104.9	93.3	87.5	77.6
		n	0.659	0.628	0.657	0.656
	20	E_0	95.4	84.1	78.7	69.5
		n	0.711	0.568	0.638	0.612

A. The Influence of Characteristic Exponent n

(1) The characteristic exponent n is related to the *SDD*. The generally trend is that the exponent n will decrease with the increase of the *SDD*. Namely the more sever contaminated of the specimens before icing, the weaker influence of the P/P_0 on E_H. For example, to the specimens of type C, when d=10 mm, *SDD* is 0.03, 0.05, 0.08 mg/cm^2 and 0.15 mg/cm^2, n is 0.674, 0.651, 0.631 and 0.611, respectively. For the reason of that when the pollution degree becomes heavier, due to the crystallization effect, conductive ions repelled to the ice layer surface increase at a great speed and strengthen the critical flashover current, leading to the reduction of the utilization ratio of creepage distance and critical flashover arc distance, and finally giving rise to the influence of air pressure on flashover gradient is on the decline.

(2) The characteristic exponent n is related to d, and n will decrease with the increase of d. Namely the influence of P/P_0 on E_H is more sensitive when the ice thickness is thinner. For example, to the specimens of type C, when *SDD*=0.03 mg/cm^2, d=10 mm and d=20 mm, n=0.674 and n=0.639, respectively. It can be explained that: when the icing degree is relatively light, the shed cluster will not be bridged by ice slush, then the air gap between ice slush and shed cluster can distort the electrical field [23], making the air pressure plays a significant part in the flashover voltage; with the accumulation of icing, the flashover voltage tends to saturation after the insulator has been bridged entirely, and the influence of air pressure on characteristic exponent become smaller.

(3) The characteristic exponent n is related to the configuration parameters. According to TABLE 2 and TABLE 4, it is known that the influence of the configuration parameter k_4 on n is sensitive, and the generally trend is that n will increase with the increase of k_4. This is because that the larger k_4 is, the more number of shed clusters in the unit of arc distance will be, therefore, it is easy for shed clusters to be bridged by ice slush and the influence of air pressure exponent decreases. In addition, the factors of k_1, k_2 and k_3 also exert effect on n, but there is no evident law to obey due to the intense fluctuation.

B. The influence of flashover gradient

(1) The flashover gradient E_H will decrease with the increase of *SDD*. The reason is that: with the increment of pollution, the ions repelled to the ice layer surface will multiply by times due to the crystallization effect, which brings about the increase of water film conductivity on the ice layer surface, decreasing the flashover gradient.

(2) E_H will decline with the increment of icing thickness. It can be interpreted that the rise of thickness will accelerate the growth of ice slush, making shed clusters bridged easily, thus, shortening the discharge path and leading to the drop of E_H.

(3) E_H will decrease with the increase of altitude, and the declining range has much to do with the shed configuration and parameters.

(4) The DC icing flashover gradient of the pre-polluted specimens is related to the configuration parameters k_1, k_2, k_3 and k_4:

a). Generally speaking, if the angle of inclination of sheds is not horizontal or too large, k_1 is not an important parameter separately. However, the flashover gradient will decrease greatly when k_1 is relatively small for the reason that shed clusters are easy to be bridged under the icing condition. Therefore, larger k_1 is beneficial to the safe operation of the insulator strings which setting vertically in snow and ice weather. As seen from specimens A to G, k_1 concerning type F and G is the largest and the flashover gradient related to that is the highest as well.

b). k_2 is important to avoid the failure of the creepage distance owing to the bridge of the electric arc between sheds. When the value of k_2 is lower, the density of shed cluster in unit arc distance will be on the rise. Thus, the flashover gradient will decline because the shed clusters can be bridged easily even in the light icing condition. Among the specimens from A~G, the value of k_2 corresponding to type A, B, and C is relatively small, and the flashover gradient related to that is relatively the lowest. Therefore, large k_2 is useful to the safe operation of the insulator strings under icing, contamination and high altitude conditions;

c). k_3 is a parameter which could check the bridge risk of the electric arc due to dry region or non-uniform hydrophobic of insulators. If k_3 is too large, the security of the insulators will be decreased because the sheds could be bridged by ice easily when the icing degree is relatively light. Consequently, relatively small k_3 is helpful to improve the DC icing flashover gradient;

d). k_4 is a parameter which could check the validity of the insulator's creepage distance completely. Trough the analysis of E_H concerned with specimens A ~ G, the value of k_4 regarding type C is the largest, but the flashover gradient referring to that is the smallest; on the other hand, type F has the minimum k_4 but with the maximum E_H. It can be seen that relatively small k_4 is helpful to improve E_H. Generally, if k_1, k_2 and k_3 are satisfied with the favorable conditions of E_H, k_4 will meet the favorable conditions automatically.

V. Conclusion

(1) The distribution law of ice flashover follows the Gaussian distribution, and the samples mean value $\overline{U}$ also obey the Gaussian distribution. When taking the confidence coefficient 1-α as 0.95 and the deviation *e* as 3%, 2%, 1%, we can obtain the specimens' average minimum samples *n* equal to 3, 6 and 22 respectively. For the practical engineering, the value of *e* which is lower than 3.0% can be satisfied with the demand. Therefore, the minimum number of samples selected in this paper can not just meet the test accuracy but also reduce the workload of experiments and the loss of facilities.

(2) DC icing flashover gradient E_H will decrease as the increase of ice equivalent thickness *d*, the increase of *SDD* before icing, and the decrease of air pressure.

(3) The exponent *n* is related to the sheds configuration of the specimens, *SDD* and *d* etc., and *n* will decrease with increase of *d* and *SDD*. The value of characteristic exponent *n* for the specimens of type A, B and C under the condition of icing flashover is lower than that under the condition of pollution flashover.

(4) The DC icing flashover gradient of the pre-polluted specimens is related to the configuration parameters k1, k2, k3 and k4. Among the seven types of specimens used to conduct experiment in this paper, it is shown that type G is characterized by the best insulation performance under the high altitude, pollution and icing conditions for the relatively larger value of k1, k2 and the smaller value of k3, k4. Therefore, the authors suggest that taking the shed configuration k1, k2, k3 and k4 as one of the technical factors to select composite insulators under complex environments. Especially, the insulator which has relatively large k1, k2 and small k3, k4 at the same time should be selected primarily in the UHV DC transmission project.

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ATTACHED TABLE. 1 The minimum sample size of different $\delta/\overline{U}$

Type	*d* (mm)	*P (kP)*	SDD=0.05 mg/cm2					SDD=0.15 mg/cm2				
			$\overline{U}$	δ	*e (%)*			$\overline{U}$	δ	*e (%)*		
					3	**2**	**1**			**3**	**2**	**1**
					n_1	n_2	n_3			n_1	n_2	n_3
A	10	70.1	142.7	4.81	5	11	44	113.9	3.95	6	12	47
		79.5	151.5	4.54	4	9	35	123.3	3.54	4	8	32
		89.8	160.7	4.52	4	8	31	129.8	3.36	3	7	26
		98.7	173.8	3.24	2	4	14	137.6	3.14	3	6	21
	20	70.1	119.1	3.65	5	10	37	99.2	3.07	5	10	37
		79.5	127.1	2.98	3	6	22	106.9	2.86	4	7	28
		89.8	135.3	3.18	3	6	22	111	2.56	3	6	21
		98.7	143.1	2.39	2	3	11	118.7	2.69	3	5	20
B	10	70.1	148.2	4.83	5	11	41	119	3.16	4	7	28
		79.5	158.7	3.42	2	5	18	128.9	3.77	4	9	33
		89.8	168.7	3.42	2	4	16	133.9	2.98	3	5	20
		98.7	180.8	3.65	2	4	16	144.5	2.97	2	5	17
	20	70.1	123.1	2.94	3	6	22	103.5	3.58	6	12	46
		79.5	132.6	2.89	3	5	19	110.4	2.92	3	7	27
		89.8	142.4	3.16	3	5	19	116.4	2.65	3	5	20
		98.7	150.2	3.52	3	6	22	124.1	2.74	3	5	19
C	10	70.1	215.5	5.26	3	6	23	174.5	3.99	3	6	21
		79.5	228.7	4.52	2	4	16	189.5	3.75	2	4	16
		89.8	249.3	6.86	4	8	30	203.5	4.33	2	5	18
		98.7	269.1	5.54	2	5	17	215.2	3.88	2	4	13
	20	70.1	187.9	5.82	5	10	37	152.7	4.68	5	10	37
		79.5	202.1	4.62	3	6	21	164.5	5.21	5	10	39
		89.8	218.6	3.94	2	4	13	177.2	3.1	2	3	12
		98.7	232.8	7.86	5	11	44	186.8	6.38	5	12	45
D	10	70.1	263.6	6.12	3	6	21	219.9	4.65	2	5	18
		79.5	277.4	5.86	2	5	18	230.4	6.61	4	8	32
		89.8	293.2	5.99	2	5	17	242.4	4.79	2	4	16
		98.7	306.3	4.94	2	3	10	252	5.31	2	5	18
	20	70.1	227.7	4.13	2	4	13	192	5.67	4	9	34
		79.5	240.6	4.56	2	4	14	201.4	3.99	2	4	16
		89.8	254.1	4.92	2	4	15	211.7	4.55	2	5	18
		98.7	264.8	6.15	3	6	21	219.7	4.24	2	4	15
E	10	70.1	269	5.94	3	5	19	221.7	5.79	3	7	27
		79.5	286.5	5.61	2	4	15	235.3	5.12	3	5	19
		89.8	303.2	6.32	2	5	17	249.1	4.31	2	3	12
		98.7	316.4	7.26	3	6	21	259.9	5.94	3	6	21
	20	70.1	232.5	5.62	3	6	23	193.9	5.12	3	7	27
		79.5	246.2	5.21	2	5	18	204.9	4.45	3	5	19
		89.8	260.3	4.69	2	4	13	216.4	5.46	3	7	25
		98.7	272	7.82	4	8	32	225.5	6.92	5	10	37
F	10	70.1	245.7	5.36	3	5	19	204.1	5.85	4	8	32
		79.5	267.2	6.21	3	6	21	218.2	4.96	3	5	20
		89.8	285	6.14	2	5	18	239	5.33	3	5	20
		98.7	304.5	6.65	3	5	19	253.8	5.25	2	5	17
	20	70.1	226.4	5.36	3	6	22	185.8	3.94	2	5	18
		79.5	242.6	5.19	2	5	18	197	4.65	3	6	22
		89.8	261.8	4.16	2	3	10	212.9	3.87	2	4	13
		98.7	275.5	6.11	3	5	19	229.5	5.65	3	6	24
G	10	70.1	265.9	6.52	3	6	24	220.2	5.87	4	7	28
		79.5	290	6.55	3	5	20	237.1	3.98	2	3	11
		89.8	310	4.61	1	3	9	258.7	4.68	2	4	13
		98.7	330.8	6.51	2	4	15	275	4.85	2	3	12
	20	70.1	245.1	5.43	3	5	19	200.8	4.65	3	6	21
		79.5	263.7	5.65	2	5	18	214.4	5.52	3	7	26
		89.8	283.9	6.55	3	6	21	231.4	4.69	2	4	16
		98.7	297.1	5.47	2	4	14	247.7	4.51	2	4	13