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Influence of Test Methods on DC Flashover Performance of Ice-covered Composite Insulators

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Abstract: Operational statistics and studies home and abroad show that, the reducing of insulation characteristics of transmission line insulator caused by icing is one of the critical reasons. Now, there have not been uniform standards of icing test of insulator. Therefore the study on the methods on icing insulator test is significant. The test objects of this paper are two types of composite insulators, FXBW-±800/530 short like and FXBW-110/100. The influence of various test method on flashover performance of insulator are studied in the artificial climate chamber. The results shown that, the impact of various test method on flashover performance of composite insulator is significant and the experimental results obtained by using different test methods are discrepant. The average flashover voltage(U_{av}) obtained by using average flashover voltage method is highest, the 50% withstand voltage($U_{50\%}$) obtained by using up and down method is the second, the lowest flashover voltage($U_{f.min}$) obtained by using U-curve method is the third, and the maximum withstand voltage(U_{ws}) obtain by the maximum withstand voltage method is the lowest. The U_{av}, $U_{50\%}$ and $U_{f.min}$ are higher than U_{ws} about 18.8%, 12.7%, and 3.5% respectively. There is a intrinsical relationship among the test results obtained by various test method. Therefore, the appropriate test method can be selected according to the testing specific circumstances.

Keywords: test method; composite insulator; DC; ice flashover performance; icing; conductivity of icing water

1 INTRODUCTION

The safe operation of electric power system is threatened seriously by the flashover performance of ice-covered insulators. From the first ice accident of Transmission Line occurred in United States in 1932[1-2], flashover problems of HV and EHV transmission lines have been widely reported in many countries such as the disastrous ice storm of 1998 in Canada, in which 1,300 high voltage transmission line towers and 35,000 distribution line structures were destroyed, more than 170 million people were interrupted power supply cumulative up to a week, the direct economic loss of Quebec reached to 10 billion Canadian dollars[3]. In China, the first recorded ice accident of transmission line occurred in 1954, and from then on, icing failures are occurred continuously. In February 2005, serious icing was occurred on power grid facilities in Hubei, Hunan, Jiangxi, Henan, Chongqing and Guizhou. The towers of high-voltage transmission line were collapsed, transmission lines were trip frequently, and the grid structure was severely damaged and suffered serious losses[2-6].

From January to February in 2008, a disaster caused by unusual cold weather with glaze ice took place in most provinces in the south of China. The disaster made a bad effect on the safe performance of the power system, and caused a large-scale outage. The statistics shown that the ice disaster(in 2008) was one of the most serious disaster of power network in China since 1937 and the economic loss reached 7.9 billion US dollars, reported by Chinese State Department. Therefore, icing is a serious natural disaster in China power grid. With the implementation of “west-east power transmission, nationwide power networking”, more and more DC UHV transmission line will cross the ice region. Insulator (string) icing will become one of the major restricting factors of the safe operation of power system. The study of the flashover characteristics of ice-covered insulators is very important for the designing of insulation used in ice-area, and is special theoretical and practical significance.

The flashover characteristics of ice-covered insulators is long-term researched at home and abroad[1-8]. But so far, there is still no uniform standard test method for testing the electrical characteristics of ice-covered insulators at home and abroad. Artificial icing tests have been widely used as an important means for researching the characteristics of ice-covered insulators for a long time. A number of countries have conducted the study of

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artificial icing test of insulators continuously, and many test manners had been proposed to achieve different study goals [2-12]. However, the differences in test conditions, equipments, and process of different research institutes at home and abroad would lead to different test results. Moreover, those institutes just study the flashover performance of ice-covered insulators based on current test methods. Paper[9] introduces and summarizes ice Electrical test methods, but doesn't make deep comparison and research on the differences between pollution flashover performances under various test manners.

Domestic research institutions adopt Even-raising method, U-type Curve method, Up and Down method and Maximum Withstand method. But they are carried out under different conditions, so there is no comparability among them. Composite insulators have been widely used in the field of high voltage external insulation with the advantages of light weight, high strength, good tolerance to contamination, easy operation and maintenance, etc. Paper[6] analyzes the influence of test methods on AC flashover characteristics of icing insulator. Paper[11] analyzes the influence of test methods on DC pollution flashover performance of composite insulator. So far, institutes at home and abroad haven't make deep comparison and research on the differences between DC icing flashover characteristics under various test methods. This paper try to explore intrinsic link of the DC icing flashover voltage test results of the composite insulators under various test methods. The research results are of great practical significance and reference value to guide the artificial test of icing insulators.

2 TEST FACILITES AND PROCEDURE

2.1 Test facilites and power supplies

The experimental investigations were carried out in the multifunction artificial climate chamber with a diameter of 7.8 m and a height of 11.6 m, as shown in figure 1(a). It mainly consists of a refrigeration system, a vacuum-pumping system, a spraying system, and a wind velocity regulating system. The minimum temperature in the chamber can be adjusted to -45℃, which is adapt to the fundamental conditions of icing test. The air pressure can be controlled as low as 30 kPa, and the wind velocity can be adjusted to 0-12m/s. The spraying system consists of two row of fog nozzles customized according to IEC standard and can form environmental conditions of wet grown icing which was the most serious icing type. The power supply is leaded in through a 330kV wall bushing.

The DC power supply is a ±600 kV/0.5A cascade rectifying circuit controlled by a thyristor voltage-current feedback system, which ensures that the voltage ripple factor is less than 3.0% when load current is 0.5 A, as shown in figure 1(b). The test electrical principles of layout diagram are shown in reference[4].

2.2 Test speciemens

The specimens are short samples of FXBW- 800/530 DC SIR composite long-rod insulators (type A) and FXBW1-110/100 DC SIR composite (type B). The parameter and configuration are provided in Table 1 and Figure 2. In the table 1 the H is structure height; h is arc distance; L is leakage distance; D_1 is big umbrella diameter; D_2 is middle umbrella diameter; D_3 is small umbrella diameter; d is rod diameter. The aspect of ice-covered insulator strings with artificial ice is displayed in Figure 3.

2.3 Test procedures and method

2.3.1 Cleaning of specimens

Before the tests, all of the specimens were carefully cleaned with trisodium phosphate or alcohol to ensure the removal of all traces of dirt and grease and then dried naturally.

2.3.2 Simulation of contamination

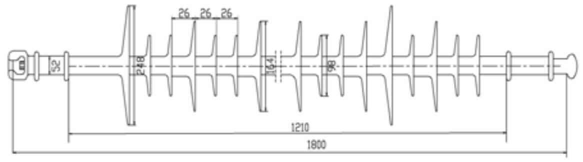
Insulators in service may be contaminated before and during the icing. External insulation characteristics of ice-covered insulator were influenced significantly by the contamination. The solid-layer method is often used to simulate pollution before icing, and the icing-water conductivity method is used to simulate pollution during icing. There is a equivalent influence on flashover performance of ice-coved insulator between solid-layer method and icing-water conductivity method[4]. Therefore, this paper adopts the icing-water conductivity method to simulate the contamination. The test insulators were iced with freezing water with a specified electrical conductivity. In this investigation, the conductivities of freezing water(γ_{20}) were 80, 200, 360, 630 μS/cm, and 1000 S/cm, respectively(20℃).

(a) Multifunction artificial climate chamber (b) DC ±600 kV/0.5A power supply

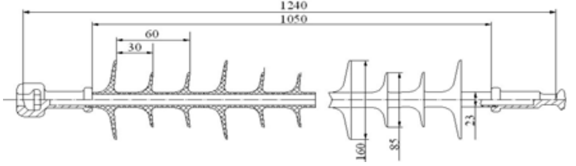
Figure 1. Test facilities

Table 1. Parameters of tested composite insulators

Insulator	H/mm	h/mm	L/mm	D/mm	d/mm
Type A	1800	1210	4260	248(D_1)/164(D_2)/98(D_3)	52
Type B	1240	1050	3350	160(D_1) /85(D_3)	23

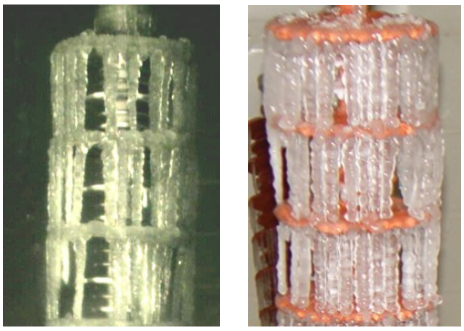


(a) A type



(b) B type

Figure 2. Sketch maps of the tested insulators



Type A Type B

Figure 3. Aspect of ice-covered insulator

2.3.3 The procdure of ice deposit

Both field and laboratory experiments shown that the most dangerous type of ice was the wet-grown ice with highest probability of flashover [1, 2]. Before icing, the specimens were hanged on the test stand in the climate chamber so as to keep the temperature of the insulators was corresponded to the temperature around the insulator. In order to ensure the formation of wet-grown ice on the test insulators, the experimental parameters shown in Table 2 were introduced in this investigation. And the test insulators were heavily covered with ice, namely the sheds of insulators were bridged completely by icicles (Figure 3). In such case, the ice densities on the insulators were 0.84~0.89 g/cm^3. The consistency of ice amounts was kept by a monitoring cylinder with a diameter of 25 mm and rotating at 1 r.p.m., and the actual ice amounts deposited on the insulators were measured and compared in each experiment. Thus, the differences in ice amounts on the same type of insulators were relatively small. The weight of ice on the four different types of insulators is shown in Table 3.

Table 2. Experimental parameters of ice deposit

Droplet /μm	Spraying speed/ (mm/h)	Air temperature /°C	Wind velocity/(m/s)	Icing duration /h
100~120	10	-5~-7	5	5~6

Note: pre-cooling the freezing water to1~2°C before starting icing.

Table 3. Ice amount covered on the tested insulators

Insulator	Ice amount W /gram per string	Ice thickness on top/below surface /mm	Ice thickness on reference cylinder/mm
Type A	3500±200	8.0/1.5	10
Type B	2300±160	8.0/1.5	10

2.3.4 Flashover performance evaluation method

Presently, there is not standard test method for electrical characteristics of icing insulators at home and abroad. According to the experience and with reference to IEC507, IEEE Std 4 which recommend contaminated insulator testing methods, this paper uses the following ways[2,9,11-12,15,17].

(1) Even-raising Method

After icing, the temperature of the artificial climate chamber is controlled to -2～-1℃. When the conductive water film was formatted on the insulator surface, the voltage was applied on the insulator uniformly until flashover taken place. After every flashover test, in order to make ice frozen again, the temperature was lower and the interval is about 5 minute. Each iced insulator string was tested to flashover 3～4 times. When the test times up to 12, the average flashover voltage is obtained as follow:

$$\begin{cases} U_{av} = \left(\sum_{i=1}^{N} U_i \right) / N \\ \sigma = \sqrt{\sum_{i=1}^{N} \left(U_i - U_{av} \right)^2 / (N-1)} \end{cases} \tag{1}$$

where U_{av}(kV) is the average flashover voltage of iced insulator; U_i(kV) is the value of applied voltage of test; N is the total number of useful tests.

(2) Up and Down Method

In this study, the up-and-down method was used to determine the 50% flashover voltage ($U_{50\%}$) of ice-covered insulators in ice-melting period. The test procedures are described as follows:

Water spray was stopped when the ice accretion on the reference cylinder reached its target value, and ice was hardened for 15 minutes at the icing temperature.

When the preparation phase was finished, the sealed door of the climate chamber was opened to raise the temperature at a rate of 1~2°C/h.When the temperature in climate room rose to -2~0°C, the voltage was applied to the insulator and raised to the test level (U_y). Applied voltage was then kept at this level for 15min or until flashover. Each iced insulator string was only tested to flashover once.

The up-and-down method was used to determine the $U_{50\%}$ of iced insulators with steps of 10% of U_y. At each test, the estimated test value, U_y, was respectively increased or decreased by one step depending whether the last test result was withstand or flashover. The first test showing a different result from the last one (from flashover to withstand or vice versa), as well as the following tests, is defined as the 'useful test'. For the ice-covered insulators with the same ice amount and the same pollution degree, at least 15 "useful tests" were carried out. Then the $U_{50\%}$ (kV) and its standard deviation (σ) can be calculated by equation (2):

$$\begin{cases} U_{50\%} = \dfrac{\sum(n_i U_i)}{N} \\ \sigma = \sqrt{\sum\limits_{i=1}^{N} (U_i - U_{50\%})^2 / (N-1)} \end{cases} \tag{2}$$

(3) U-type Curve Method

The improved U-type method summarized by the authors from long-term experimental investigations was used to obtain the 50% DC flashover voltage of the iced specimens in this paper. And the test method can be summarized as follows:

(a) The spraying was stopped when the ice amount reached the target value, the ice was frozen about 15 minute or longer to guarantee complete hardening of the ice and equalization of specimen and ice temperature. Then the airtight door of the chamber was opened to rise the temperature in chamber to -2 to 0 ℃ at a speed of 2-3 ℃/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. During the tests, the temperature in the chamber was strictly controlled within -2 to 0 ° C to avoid the early melting and non-melting of the ice on the insulators.

For a iced specimen, a series of flashover voltage obtained by above procedures are expressed as U_{f1}, U_{f2}, ···, U_{fn} (n is the number of flashovers), then the minimum flashover voltage of the iced insulator is

$$U_{f.\min} = \min\left(U_{f1}, U_{f2}, \cdots, U_{fn}\right) \tag{3}$$

(4) Maximum Withstand Method

The spraying was stopped when the ice amount reached the target value, the ice was frozen about 10-15 minute or longer to guarantee complete hardening of the ice and equalization of specimen and ice temperature. Then the airtight door of the chamber was opened to rise the temperature in chamber to -2 to 0 ℃ at a speed of 2-3 ℃/h. The test procedure was shown in table 4. That is to say, when the U_2 applied to the insulator 3 out of 4 times, the applied voltage was withstand and U_3 (higher than U_2 by 5%)applied to the insulator, two times of flashover taken place, U_2 was consider to be the maximum withstand voltage. The relation can be shown as $U_{ws}=U_2$.

Due to the positive polarity flashover voltage is higher than the negative polarity flashover voltage of the icing insulator, so the insulators were applied negative polarity voltage when the tests were carried out.

Table 4. The procedure of the maximum withstand method

Withstand voltage	1st time	2nd time	3rd time	4th time
U_1=0. 95U_2	Withstand	Withstand	Withstand	/
U_2	Withstand	Flashover	Withstand	Withstand
U_3=1. 05U_2	Flashover	Flashover	/	/

3 TEST RESULTS AND ANALYSIS

3.1 Test result of ice-covered insulator

This paper obtained the average flashover voltage(U_{av}), 50% withstand voltage ($U_{50\%}$), minimum flashover voltage($U_{f.min}$) and maximum withstand voltage(U_{ws}) by using Even-raising method, Up and Down method, U-type Cure method and Maximum withstand voltage method respectively. The test results and standard deviation are shown in table 5.

From the table 5, it is easy to know that, the standard deviation of icing flashover test results is very small by using icing water conductivity method. The range of the standard deviation is 2.1% to 5.9%.

Table.5 The results of DC flashover Voltage of the composite insulator by using various test method

γ_{20}(μS/cm)		80	200	360	630	1000
Type A	U_{av} (kV)	187.3	157.0	130.7	113.0	98.0
	σ%	4.9	5.9	5.4	4.3	2.1
	$U_{50\%}$(kV)	176.9	149.2	123.2	107.4	93.1
	σ%	5.1	3.7	3.4	5.0	2.5
	$U_{f.min}$(kV)	164.6	138.8	112.6	97.7	85.4
	U_{ws}(kV)	157.5	133.9	108.2	94.8	83.5
Type B	U_{av} (kV)	172.3	146.8	121.8	104.9	87.9
	σ%	3.3	4.5	5.7	4.2	3.8
	$U_{50\%}$(kV)	163.7	138.9	115.7	98.7	82.5
	σ%	4.9	4.3	2.9	3.6	4.2
	$U_{f.min}$(kV)	150.2	127.4	104.3	90.7	76.1
	U_{ws}(kV)	145.3	122.3	101.8	88.2	73.6

3.2 Influence of conductivity of icing water on flashover voltage

No matter which method is selected, the icing flashover voltage decreases with the increase of the conductivity of the icing water, and the empirical equation is as follow:

$$U_f = A\gamma_{20}^{a} \tag{4}$$

where A is the coefficient which is related to the configuration and icing amount of the insulator; *a* is the characteristic exponent characterizing the influence of conductivity of the applied water on U_f. Base on the test results in the table 5, according to the equation (4), the relationship between flashover voltage and the conductivity of applied water was obtained by using cure fitting, and the fitting curve was shown as figure 4～figure 5. The fitting coefficient A, *a* and correlation coefficient R^2 were shown in table 6.

Table 6 indicates that the effect of test method and configuration of insulator is not remarkable on contamination index. The value of *a* is about 0.259 to 0.271, and the mean value is 0.265. Further more the correlation coefficient R^2 is higher than 0.94.

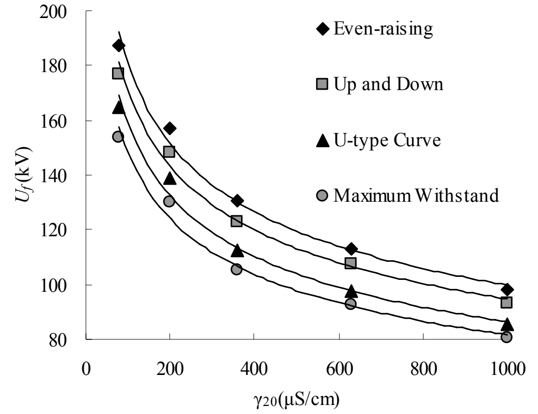


Figure 4. The relationship between Voltage U_f of composite insulator type A and conductivity of icing water γ_{20}

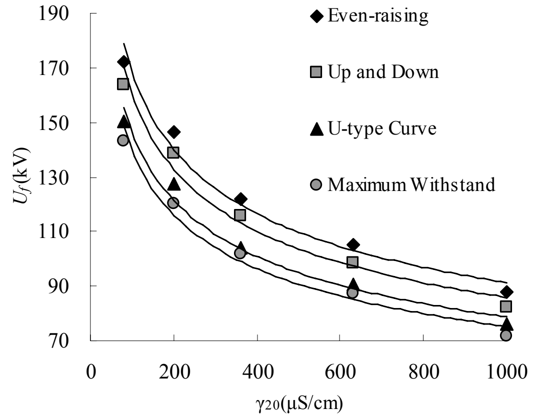


Figure 5. The relationship between Voltage U_f of composite insulator type B and conductivity of icing water γ_{20}

Table 6. Constant *A* and special exponent *a* gained by regression according to formula

Type	Test method	*A*	*a*	*R*^{2}
Type A	Even-raising	597.6	0.259	0.985
	Up and Down	568.9	0.260	0.969
	U Type Curve	540.9	0.265	0.987
	Maximum withstand	499.9	0.258	0.956
Type B	Even-raising	587.2	0.271	0.948
	Up and Down	558.5	0.271	0.970
	U Type Curve	507.3	0.270	0.983
	Maximum withstand	488.1	0.269	0.957

Table 7. Relative flashover voltage errors with various test methods

γ_{20}(μS/cm)		80	200	360	630	1000	Mean value
Type A	$\Delta\alpha$	5.9	5.2	6.1	5.2	5.3	5.5
	$\Delta\beta$	-7.0	-7.0	-8.6	-9.0	-8.3	-8.0
	$\Delta\eta$	-11.0	-10.3	-12.2	-11.7	-10.3	-11.1
Type B	$\Delta\alpha$	5.3	7.7	5.3	6.3	6.5	5.8
	$\Delta\beta$	-8.2	-8.3	-9.9	-8.1	-7.8	-8.4
	$\Delta\eta$	-11.2	-12.0	-12.0	-10.6	-10.8	-11.3

3.3 The effect of test method on the icing flashover voltage of composite insulator

As shown in figure 4~5, the test methods play an evident impact on the DC ice flashover voltage of composite insulators. The average flashover voltage U_{av} obtained by the average flashover method is the largest, followed by the $U_{50\%}$ which is corresponding to the uniform increase voltage method, and the third one is lowest flashover voltage $U_{f.min}$ obtained by the U-curve method, at last, the maximum withstand voltage U_{ws} obtained by the maximum withstand voltage method ranks the last place. To compare with the difference among the test voltages, based on the $U_{50\%}$, relative error can be defined:

$$\begin{cases} \Delta\alpha = \dfrac{U_{av} - U_{50\%}}{U_{50\%}} \times 100\% \\ \Delta\beta = \dfrac{U_{f.\min} - U_{50\%}}{U_{50\%}} \times 100\% \\ \Delta\eta = \dfrac{U_{ws} - U_{50\%}}{U_{50\%}} \times 100\% \end{cases} \tag{5}$$

According to the test results of Table 5, the relative error satisfied with different test methods can be calculated in the form of equations (5), as shown in Table 7.

Table 7 indicates that the effect of icing water conductivity on $\Delta\alpha$, $\Delta\beta$ and $\Delta\eta$ is not significant. For the A composite insulator, U_{av} is 5.2%～6.1% higher than $U_{50\%}$, $U_{f.min}$ is 7.0%～9.0% lower than $U_{50\%}$, and the mean value is 8.0%; U_{ws} is 10.3%～12.2% lower than $U_{50\%}$ and its mean value is 11.3%. For the B composite insulator, U_{av} is 5.3%～7.7% higher compared with $U_{50\%}$ and its mean value is 5.8%; $U_{f.min}$ is 7.8%～9.9% lower than $U_{50\%}$, and the mean value is 8.4%; compared with $U_{50\%}$, U_{ws} is 10.6%～12.6% lower and its mean value is 11.3%. $U_{f.min}$ and U_{ws} are approximate, and 10% lower than $U_{50\%}$. On the basis of analysis above, the influences of test methods on test results are apparent. Moreover, the influence mechanism of test methods on the result is coincident, and the insulator shape plays little impact on this mechanism.

The ice flashover voltage of icing insulators obeys the normal distribution, namely the ice flashover voltage $U_f \sim N(\mu,\sigma^2)$, μ is $U_{50\%}$, σ stands for the standard deviation, therefore, $U_{\alpha\%}$,which is corresponding to the discharge probability $\alpha\%$, can be obtained:

$$U_{\alpha\%}=U_{50\%}\,(1+K_{\alpha\%}\sigma\%) \tag{6}$$

In equation (6), $K_{\alpha\%}$ is the random variable satisfied with the probability $\alpha\%$ in the standard normal distribution. $K_{\alpha\%}$ is negative owing to $\alpha\%<50\%$ and $U_{\alpha\%}< U_{50\%}$. According to the recommendation of IEC/IC28, taking the standard deviation as 10% and based on the standard normal distribution, $K_{10\%}$=-1.282, then:

$$\begin{aligned} U_{10\%} &= U_{50\%}(1+K_{10\%}\sigma\%) \\ &= U_{50\%}(1-1.282\sigma\%) \\ &= 0.872U_{50\%} \end{aligned} \tag{7}$$

From equation (5):

$$\Delta\zeta = \frac{U_{10\%} - U_{50\%}}{U_{50\%}} \times 100\% = 12.8\% \tag{8}$$

From table 6:

$$\Delta\eta = \frac{U_{ws} - U_{50\%}}{U_{50\%}} \times 100\% = 11.3\% \tag{9}$$

Within the allowable error limit, $\Delta\eta\approx\Delta\zeta$, and in terms of equation (80) and (9):

$$U_{ws}=U_{10\%} \tag{10}$$

The maximum withstand voltage equals the ice flashover voltage which has the 10% flashover probability

Based on the analysis above, there exists certain equivalency among the ice flashover voltages of composite insulators with different test methods. According to particular cases, appropriate test methods can be chosen when conducting artificial icing tests. The maximum withstand method and 50% withstand method both have the disadvantages of long test period and high cost, but the two ways are coincidence with the practical running situations, therefore, their results are more reliable and are capable of meeting the engineering application. Although the uniform increase voltage method is opposite to the practical running state, it is easy to be carried out and to obtain test results in a short time. The minimum flashover voltage $U_{f.min}$ reflects the electrical performances of icing insulators in the melting period. Furthermore the minimum flashover voltage is close to the maximum withstand voltage.

4 CONCLUSIONS

a) The effect of test method on the ice flashover voltage of composite insulators is significant. The average flashover voltage U_{av} obtained by the average flashover method is the largest, followed by the $U_{50\%}$ which is corresponding to the uniform increase voltage method, and the third one is lowest flashover voltage $U_{f.min}$ obtained by the U-type curve method, at last, the maximum withstand voltage U_{ws} obtained by the maximum withstand voltage method ranks the last place.

b) Due to the internal relation of the DC ice flashover voltage of icing composite insulators with different test methods, appropriate test methods can be chosen according to the test situations. Since $U_{f.min}$ is 3% greater than U_{ws}, which is fairly close, U-curve method can be employed to conduct the composite insulator DC ice flashover test, and the test results can be corrected with a standard deviation when the dispensability in test is taken into consideration.

c) The test shows that the ice flashover voltage of icing composite insulators obtained by the maximum withstands voltage method has the 10% flashover probability.

d) The maximum withstand method, 50% withstand method, average flashover method and “U” curve method can all be employed as the test methods of the icing insulator electrical performance. In addition, “U” curve method plays a positive role in the icing test of short insulator strings. For the icing test of long insulator strings, more investigation need be done. This paper recommends 50% withstand method and U-type curve method.

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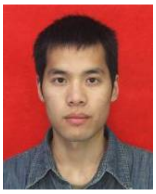

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