Study of Pre-polluting Methods on Artificial Icing Flashover Characteristics of Composite Insulators

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Abstract—**Insulators icing is a special form of pollution. Generally speaking, pollution deposits onto the insulator surface before icing would cause insulator flashover at the voltage-applied. How to simulate and figure the effects of pollution on icing flashover is the foundation of designing anti-icing method. Based on the results of test carried out in the multi-functional artificial climate chamber, this paper discussed the effects of two different pollution manners, solid layer pollution manner(SLPM) and ice water conductivity manner(IWCM), on DC flashover performan- ce of composite insulators, and analyzed the relationship between the two different pollution manners. The test results show that: while considering the effects on icing flashover stress, two different pollution manners have a corresponding relationship between them; IWCM is more simple than SLPM, and have smaller dispersion than the latter; pollute manners have an effect on the flashover path of iced insulators, the flashover path propagates along the interface of ice layer and composite insulator pre-polluted by SLPM owing to hydrophobicity, and intermittent partial arcs between ice and insulator's surface can burn the insulator surface, which can cause hydrophobicity descend even disappear; Arc develops along the outer surface of ice layer while pre-polluted by IWCM so it will have smaller dispersion, and ICWM is simple and easily controlled. Therefore, ICWM should be recommended to simulate pollution.**

Index Terms—**Composite insulator, icing, flashover voltage, pollution manner; DC**

Ⅰ. Introduction

CHINA is one of the countries that have severe icing problems of transmission lines in the world. The south, north and middle corridors of the West-to-East Power Transmission project confront the threat of severe icing problems [1, 2]. Most part of southern China encountered the most serious ice and snow disaster in the meteorological record history in January and February 2008. Heavy losses of power grid were caused in East China, Central China, South China and Southwest China. During this large-scale ice disaster, thousands of towers (or poles) failure, wires fracture and icing flashover accidents caused over 100 billions RMB of direct economic losses [3,4,5]. And the disaster brought greater concerns about icing problems of power grid to Chinese power departments. In order to avoid similar losses in the future, it is very important and urgent to systematically investigate flashover performance of ice-covered insulators, anti-icing and deicing methods.

The flashover performance of ice-covered insulators is an important basis for the selection of external insulation of transmission lines in icing regions, and it has been extensively investigated by researchers in recent decades. But in the tests, the researchers have not reached an agreement on how to simulate the contamination effectively although they agree that the icing flashover is caused by contamination and the icing is a special form of contamination for insulators [6, 7]. For example, Canada, America, Sweden, Finland and other countries, as well as some of Chinese research institutions employ IWCM to simulate the contamination on insulators. But all Power Grid Corporations of China tend to use SLM because the pollution on line and substation insulators is relatively heavy and most of insulators have been contaminated before icing [6-9, 14]. The equivalent relation of the two pollution methods influencing the icing flashover stress of ice-covered insulators has not been obtained so far. Therefore, the test results of icing flashover voltage obtained by different methods are not comparable, which brings obfuscation to the external insulation design of transmission lines and substations in icing regions and also brings difficult problems to the establishment of standards of insulator icing test methods.

In the paper, the dc icing flashover performances of dc SIR composite long-rod insulators are investigated. Based on the test results, the equivalence of influence of the two methods on icing flashover stress is analyzed and researched. The results of the research can provide valuable references for engineering designs and the establishment of standards of icing test methods.

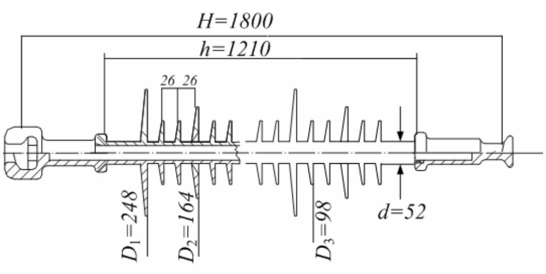
Ⅱ. Test Equipments, Specimens and Methods

A. Equipments and Tested Insulators

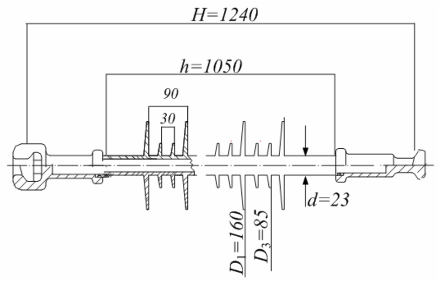
The experimental investigations were carried out in the multi-function artificial climate chamber with a diameter of 7.8 meters and a height of 11.6 meters, in which the power supply is led through a 330kV wall bushing. The minimum temperature in the chamber can be adjusted to -45±1°C, the air pressure can be controlled as low as 30kPa, and the wind velocity can be adjusted to 0~ 12m/s [8, 14, 18].

The power supply is a ±600kV/0.5A thyristor-controlled voltage-current feedback dc pollution test source with ripple factor less than 3.0%, and its voltage drop less than 5.0% when the load current is 0.5A [7, 19].

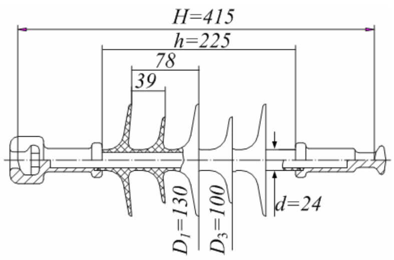
The specimens are short samples of FXBW-±800/530 (800kV) dc SIR composite long-rod insulators (Type A), and FXBW$_4$-110/100 (110kV) dc SIR composite long-rod insulators (Type B), as well as FXBW-10/70 (10kV) dc SIR composite rod insulator (Type C). Their profiles and parameters are shown in Fig.1 and Tables I.



(a) Type A



(b) Type B



(c) Type C

Fig.1 Sketch maps of the tested insulators

TABLE I
PARAMETERS OF SIR COMPOSITE LONG-ROD INSULATORS

No.	Type	Material	H/mm	h/mm	L/mm	D/mm	d/mm
A	FXBW-±800/530	SIR	1800	1210	4260	248(D_1) 164(D_2) 98(D_3)	52
B	FXBW4-110/100	SIR	1240	1050	3350	160(D_1)/ 85(D_3)	23
C	FXBW-10/70	SIR	415	225	590	130(D_1)/ 100(D_3)	24

Note: D -Shed diameter, D_1-the diameter of large shed, D_2-diameter of the middle one, D_3-diameter of the small one, H -Configuration height, h -Dry arc distance, L -Leakage distance, d-Rod diameter.

B. Test Procedures and Methods

1) Solid Layer Pollution Manner (SLPM): Before the tests, the all specimens were carefully cleaned to ensure the removal of all traces of dirt and grease and then dried naturally. The surfaces of composite insulators were coated with a very thin layer of dry kieselguhr to destroy the hydrophobicity to the degree of HC4 or HC5. Since the layer of kieselguhr was very thin, the effect of the kieselguhr on a nonsoluble deposit density (*NSDD*) could be neglected [12]. In one hour after aforementioned preparation, the surfaces of specimens were contaminated with the suspension of sodium chloride and kieselguhr which simulate the electric and inert materials respectively [12, 19-21]. In present investigation, the salt deposit densities (*SDD*) were 0.03, 0.05, 0.08, 0.12 mg/cm^2 and 0.15 mg/cm^2 respectively, and the ratio of *SDD* to *NSDD* was 1/6. After 24 hours of natural drying, the specimens were suspended vertically from the hoist at center of the chamber, and the water with a conductivity of 80±5 μS/cm (at 20°C) was sprayed to the insulators to ice. At the beginning of icing, the surface of the insulator was wetted by a sprayer manually and covered with a layer ice of 1~2 mm to prevent the pollution layer from being washed away. Then the automatic spraying system was used to form wet-grown ice on the insulators without service voltage [8,14].

2) Ice Water Conductivity Manner (IWCM): Before the icing, tap water is used to clean the surface of the insulator to remove the dirt and grease at first, and then de-ionized water with an electrical conductivity lower than 10μS/cm is used to wash it again. After 24h natural drying, the test insulators were iced with freezing water with a certain electrical conductivity [16-21]. The conductivities of freezing water (corrected to the values at 20°C, and the conductivities mentioned below are all corrected to the values at 20°C) in present investigation were 80, 200, 340, 640 μS/cm and 1000μS/cm respectively.

3) Ice-Deposit: Glaze with icicles is known as the most dangerous type of ice associated with a high probability of flashover on insulators [9-11, 16-17]. In order to ensure the formation of wet-grown ice on the test insulators, the experimental parameters showed in Tab. II were introduced in this investigation. And the test insulators were heavily covered with ice, namely, the sheds of insulators were bridged completely by icicles (Fig.8). In such case, the ice densities on the insulators were 0.84~0.89 g/cm^3.

TABLE II
EXPERIMENTAL PARAMETERS OF ICE DEPOSIT

Droplet (μm)	Spray speed (mm/h)	Air temperatur e (°C)	Wind velocity (m/s)	Icing duration (h)
40~120	10	-5~-7	5	8.0

Note: pre-cooling the freezing water to 3~4 °C before starting icing.

The consistency of ice amounts was kept by a monitoring cylinder with a diameter of 25 mm and rotating at 1 r.p.m. [7], and the actual ice amounts deposited on the insulators were measured and compared in each experiment. Besides, the environmental parameters such as spraying speed, droplet size, wind velocity, air temperature, as well as the duration of icing were all strictly controlled and kept constant. Thus, the differences in ice amounts on the same type of insulators were relatively small. The weight of ice on the three different types of insulators is shown in Tab. III.

TABLE III
ICE AMOUNT COVERED ON THE TESTED INSULATORS

Insulator	Ice amount W(g/string)	Ice thickness on top/below surface/mm
Type A	3500±200	8.0/1.5
Type B	2300±160	8.0/1.5
Type C	400±50	5.0/1.0

C. *Determination of 50% Flashover Voltage*

According to experiences in field investigations, the flashover of an iced insulator usually occurs during the ice melting [8, 10, 15]. 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 [13]. The test procedures are described as follows:

Stop spraying water when the ice amount reaches to target value, and keep freezing for 15min to ensure complete hardening of the ice and equalization of insulator and ice temperatures [7-9]. And then the ice-covered insulator is photographed and measured, which lasts less than 10min.

When the preparation work is finished, open the sealed door of climate chamber to raise the temperature at the rate of 1~2°C/h.When the temperature in climate room rises to -2~0°C, the voltage is applied to the insulator and raised to the estimated voltage (U_y). Voltage is then kept at this level for 15min or until flashover. Each flashover test is performed on only one iced insulator.

The up-and-down method is 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, is respectively increased or decreased by one step depending whether the last test result is 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, are defined as the “useful tests”. For the ice-covered insulators with the same ice amount and the same pollution degree, at least 15 “useful tests” were carried out [12, 13, 15]. Then the U_{50}(kV) and its standard deviation (σ), as well as flashover stress E_{50} (kV/m) can be calculated by eqn (1):

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

where U_i is the value of applied voltage of useful tests; N is the total number of useful tests; h is the dry arc distance of insulator.

III. TEST RESULTS AND ANALYSIS

D. *Influence of Ice Amount on U_{50}*

No matter which method is selected, the 50% dc icing flashover voltage decreases with the increase of ice amount, and the downtrend of U_{50} becomes flat when the ice amount reaches to a certain degree [8, 14, 17, 18]. In this study, the $FXBZ_4$-110/100 SIR composite long-rod insulators (Type B) polluted with IWCM (conductivity of applied water γ_{20}=340μS/cm) were used as specimens to investigate the relationship between U_{50} and ice weight W (g/string). Fig.3 shows the relationship between U_{50} and W, and the empirical equation was as follows:

$$U_{50} = CW^{-c} = 1876.6W^{-0.3435} \quad (2)$$

The correlation coefficient of regression equation (2) is greater than 0.9. Fig.2 shows that the U_{50} decreases with the increase of the ice weight, and the downtrend becomes flat when the ice weight reaches to 5.0 kg/string. At this time, ice deposit almost reaches to saturation. Not only are the sheds completely bridged by icicles, but also the insulators are completely enwrapped by ice layer (Fig.8). Thereafter, the U_{50} decreases slightly as ice weight further increases.

When the icing is slight, the icicles are not long enough to bridge the sheds, i.e. there are still relatively large air gap between icicles and the next shed, therefore, the U_{50} is relatively high. When the ice deposit reaches to a certain degree, the sheds are fully bridged by icicles. The discharge path is almost unchanged, so the U_{50} decreases slightly.

E. *DC Flashover performance of Tested Insulators*

Tab. IV and V show the test results gained by different pollution methods, in which the U_{50} is the 50% flashover voltage; σ is the standard deviation; E_{50} is the flashover stress; *ISP* (μS·g·cm^{-2}) is the icing stress product defined as the product of ice weight per centimeter of dry arc distance and the electrical conductivity of melted water.

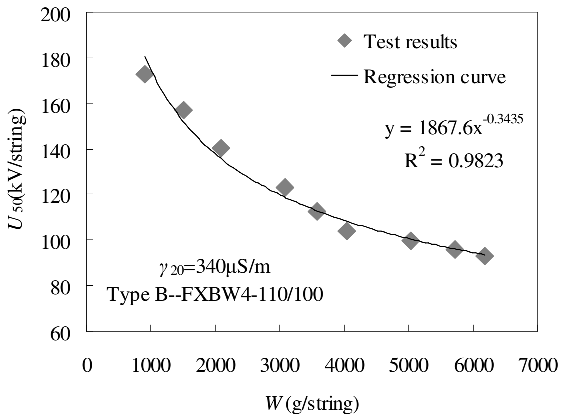


Fig.2 The relation between the $U_{50\%}$ and ice amount

In Tab. IV and Tab. V, the standard deviations (σ) of dc 50% icing flashover voltage, which obtained by SLPM and IWCM, respectively are 3.9%~8.1% and 2.1%~5.9%. The standard deviations of U_{50} obtained by SLPM are lager than that obtained by IWCM because the degree of the non-uniformity of contamination and the degrees of the destruction to hydrophobicity of composite insulators are different.

TABLE IV
TEST RESULTS OF 50% FLASHOVER VOLTAGE OF ICED INSULATORS WITH SOLID LAYER METHOD

SDD_g/(mg/cm^2)		0.03	0.05	0.08	0.12	0.15
Type A	U_{50} /kV	143.2	126.7	113.9	103.7	97.9
	σ%	4.4%	5.8%	6.4%	7.4%	8.1%
	E_{50}/(kV/m)	118.3	104.7	94.1	85.7	80.9
Type B	U_{50} /kV	130.9	115.4	107.4	93.4	88.9
	σ%	3.9%	5.6%	6.5%	7.3%	7.6%
	E_{50}/(kV/m)	124.7	109.9	102.3	89.0	84.7

TABLE V
TEST RESULTS OF 50% FLASHOVER VOLTAGE OF ICED INSULATORS WITH ICING-WATER-CONDUCTIVITY METHOD

γ_{20}(μS/cm)		80	200	340	640	1000
Type A	ISP	2314.0	5785.1	9834.7	18512.4	28925.6
	U_{50} (kV)	187.3	157.0	130.7	113.0	98.0
	σ%	4.9%	5.9%	5.4%	4.3%	2.1%
	E_{50}(kV/m)	154.8	129.8	108.0	93.4	81.0
Type B	ISP	1752.4	4381.0	7447.6	14019.0	21904.8
	U_{50}(kV)	172.3	146.2	121.8	104.9	87.9
	σ%	3.3%	4.5%	5.7%	4.2%	3.8%
	E_{50}(kV/m)	164.1	139.2	116.0	99.9	83.7

According to the Tab. V and VI, the relationships between E_{50} and SDD_g, ISP are shown in Fig.3 and 4 respectively. Fig.3 and Fig.4 show that the E_{50} decreases with the increase of SDD and ISP according to a power function. The curves in Fig.3 and 4 are expressed as eqns (3) and (4), in which eqn (4) is a unified empirical expression for the two types of insulators The correlation coefficients of regression equations (3) and (4) are greater than 0.9.

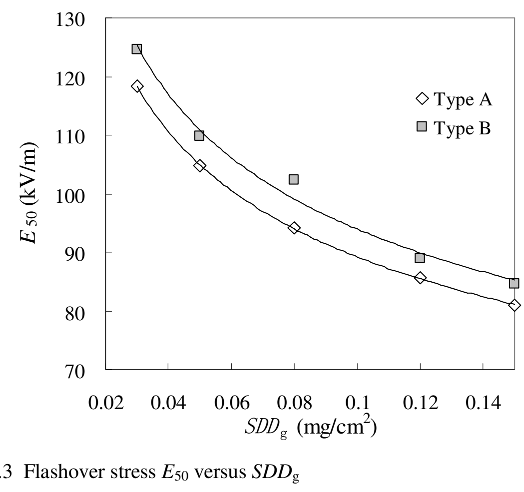


Fig.3 Flashover stress E_{50} versus SDD_g

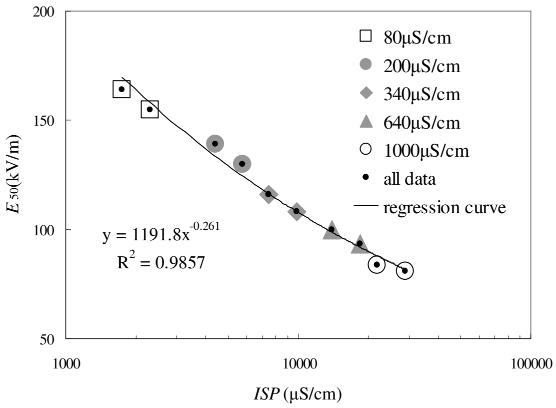


Fig.4 Flashover stress E_{50} versus ISP

$$E_{50}(s) = A\left(SDD_g\right)^{-a} = \begin{cases} 52.00\left(SDD_g\right)^{-0.2344} & (\text{Type A}) \\ 54.18\left(SDD_g\right)^{-0.2390} & (\text{Type B}) \end{cases} \tag{3}$$

where $E_{50}(s)$ is the flashover stress of iced insulator polluted with SLPM (the conductivity of the applied water, γ_s, is 80 μS/cm); SDD_g (mg/cm^2) is the salt deposit density used in SLPM; A is a coefficient related with the configuration and material of the insulators, and the ice amount etc., a is the characteristic exponent characterizing the influence of SDD_g on E_{50}.

$$E_{50}(w) = B(ISP)^{-b} = 1191.8(ISP)^{-0.261} \tag{4}$$

where $E_{50}(w)$ is the flashover stress of iced insulator polluted with IWCM; B is a coefficient related with the configuration and material of the insulators, and the ice amount etc.; b is the characteristic exponent indicating the influence of ISP on E_{50}.

F. Hydrophobicity of Composite Insulator and Its Influence on Icing Flashover Voltage

The observation in the tests shows that the super-cooling impinging droplets on the composite insulator surface are discontinuous because of hydrophobicity, and then they are frozen to discontinuous ice particles (shown as Fig.5). With the continuation of icing, the surface of insulator is gradually covered by ice layer, and the icing occurs on the surface of ice layer. At this time, the icing has nothing to do with the hydrophobicity of the insulator. Because of the formation of discontinuous ice particles, a large number of small gas cavities exist at the interface of insulator and ice layer. Under the applied voltage, the voltages across these cavities are high enough to establish partial arcs. Those arcs can melt ice. Moreover, they can burn the insulator surface which will result in the destruction of hydrophobicity. Partial arcs in those small cavities usually can be extinguished by the ice-melting water, and this can change the electric field distribution on the insulator surface. This change can lead to re-ignition of arcs. The hydrophobicity of the insulator is destroyed seriously by these remittent arcs, and this is the main reason for lowering icing flashover voltage.

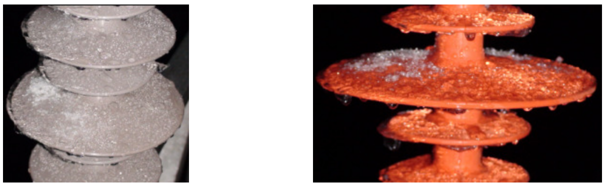
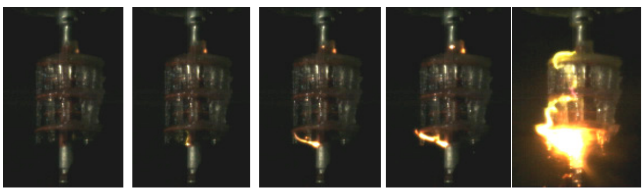


Fig.5 photos of water droplets and ice particles on the surface of composite insulators

G. Influence of Pollution Methods on the Icing Flashover Path

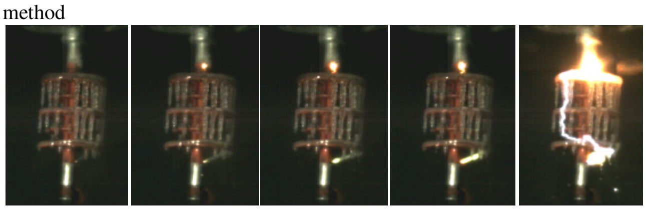
Due to the different methods used to simulate the contamination on ice-covered insulators, the process and path of icing flashover are different. Fig.6 and Fig.7 show the dc icing flashover process of ice-covered composite insulators (Type C) contaminated by SLM and IWCM respectively.

SLPM*:* The hydrophobicity of composite insulator can transfer to the surface of pollution layer when the insulator is covered by pollution layer [23], so the ice closing to the interface of polluted insulator and ice layer is the form of discontinuous particles. The local electric field strengths in gas cavities which exist between the discontinuous ice-particles are very strong, and these strong electric fields can cause partial discharge which can melt inner ice layer. The electric materials contained in pollution layer are dissolved in the inner ice-melting water, so this ice-melting water with high conductivity provides the channel for flashover. Although the outer ice layer is melted firstly under the effect of ambient temperature and joule heat of partial arcs formed on icicle tips, the ice-melting water on the outer surface of ice layer does not provide the channel for flashover because its conductivity is much lower than that of inner ice-melting water. Therefore, the icing flashover path of iced insulator polluted by the SLM propagates along the interface of insulator and ice layer, so there are severe burning traces on the surface of insulators after icing flashover.



(1) (2) (3) (4) (5)

Fig.6 Flashover process of iced composite insulator polluted with solid layer method



(1) (2) (3) (4) (5)

Fig.7 Flashover process of iced composite insulator polluted with icing-water –conductivity method

IWCM: Because of the "crystallization effect" of the ice, the contaminants in the freezing water are precipitated to the surface of ice, so the contaminants are distributed evenly on both the inner and the outer surface of ice. With the effect of ambient temperature and joule heat of partial arcs formed on icicle tips, the outer surface of ice layer is melted at first. The conductive materials which are precipitated to the outer surface of ice layer are dissolved in the ice-melting water. This outer ice-melting water with relatively high conductivity provides the channel for flashover. Thus the flashover path usually propagates along the outer surface of ice layer, so the burning degree of insulator sheds is relatively slighter and the dispersion of flashover voltage is relatively small.

Ⅳ. Equivalence of Influence of The Two Pollution Methods on icing Flashover Stress

H. Equivalence Model

The electrical conductivity of freezing water can be characterized by equivalent salt content. According to the relationship between the conductivity of the used rinse liquid of polluted insulator and the salt content recommended by reference[22], the equivalent sodium chloride content in one gram of ice, frozen from one gram of freezing water with conductivity of γ(μS/cm), can be calculated by eqn (5)

$$\beta = 4.553\times10^{-4}\times\gamma^{1.0301} \tag{5}$$

where β is the equivalent sodium chloride content in one gram of ice (g), the scope of application of eqn (5) is 75 μS/cm≤ γ≤2600μS/cm.

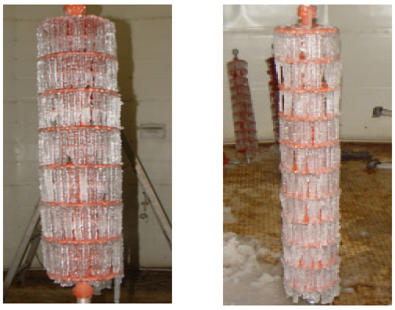
Owing to crystallization effect, when the ice amount on the clean insulator is W (g/string), the equivalent sodium chloride content, M, on the inner and outer surface of ice layer is as follows:

$$\begin{aligned} M &= \beta W/2 = 2.2765\times10^{-4}W\times\gamma^{1.0301} \\ &= \frac{2.2765\times10^{-4}\times h}{W_0^{0.0301}}\times(ISP)^{1.0301} \end{aligned} \tag{6}$$

where h is the dry arc distance, W_0 is the ice weight per centimeter of dry arc distance.

When the sheds are completely bridged by icicles, the ice-covered insulator shaped like a cylinder (shown in Fig.8). The diameter and the height of the cylinder depend on the structure and profile of the insulator. It is assumed that the icicles are evenly and continuously distributed on the edge of sheds, then, the lateral area of cylindrical ice-covered insulator is $\pi D_c h$ (cm^2), h is the dry arc distance of insulator, D_c is the average diameter of all different sheds of multi-sheds composite insulator. When the ice amount on clean insulator reaches to W (g) (using IWCM, and the conductivity of freezing water is γ), the equivalent salt deposit density SDD_w (mg/cm^2) can be obtained as follows:

$$SDD_w = \frac{M}{\pi D_c h} \approx 0.725\times10^{-4}\frac{1}{W_0^{0.0301}D_c}(ISP)^{1.0301} \tag{7}$$



Type A Type B

Fig.8 photos of ice-covered tested insulators

Based on eqn (7), for the pre-polluted insulator iced with applied water with conductivity of γ_s (γ_s =80 μS/cm in this paper), the additional equivalent salt deposit density SDD_s (mg/cm^2), which is caused by the ice with weight of W, can be calculated as the following:

$$SDD_s \approx 0.725\times10^{-4}\frac{1}{W_0^{0.0301}D_c}(ISP_s)^{1.0301} \qquad (8)$$

where ISP_s is the product of W_0 and γ_s.

If the salt deposit density of pre-contamination used in SLPM is SDD_g, then the total equivalent salt deposit density (SDD_d) , the combined effect of pre-contamination and the ice amount , can be calculated as:

$$SDD_d = SDD_s + SDD_g = 0.725\times10^{-4}\frac{1}{W_0^{0.0301}D_c}(ISP_s)^{1.0301} + SDD_g \qquad (9)$$

It is supposed that the SLPM and IWCM have an equivalent influence on flashover stress, this meant that the equivalent salt deposit density (SDD_w) equals to the total equivalent salt deposit density (SDD_d). Based on eqns (7) to (9), the equivalent relationship between SLPM and IWCM method can be expressed as follows:

$$\begin{aligned} ISP &= \left(\frac{W_0^{0.0301}D_c}{0.725}SDD_g\times10^4 + (ISP_s)^{1.0301}\right)^{1/1.0301} \\ &\approx \eta\times SDD_g + ISP_s \end{aligned} \qquad (10)$$

In China, most flashover of ice-covered insulator strings of transmission lines results from pollution on insulators before icing, and the conductivity of rain or super-cooling droplet in most of the mountainous regions generally varies from 80μS/cm to 120μS/cm. It is known from eqn (10) that if the IWCM is employed to equivalently simulate the contamination, the icing water conductivity should be determined by the insulator structure (i.e. shed diameter and dry arc distance) and the ice amount.

H. Validation of Equivalence model

For the four types of insulators (Type A to D) tested in the paper, the relationship between SDD_g and ISP are expressed as the following:

$$ISP = \begin{cases} 187402SDD_g + 2314.0 & \text{Type A} \\ 135211SDD_g + 1752.4 & \text{Type B} \end{cases} \qquad (11)$$

According to eqn (11), the relationship curves between ISP and SDD_g are shown in Fig.9.

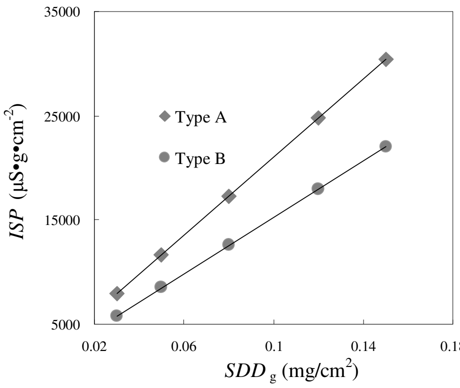


Fig9 The relation curve between SDD_g and ISP

Based on eqns(3), (4), (10), (11) as well as Tab. IV and Tab. V, the equivalent conversion results of solid-layer method and icing-water-conductivity method are shown in Tab.VI and Tab.VII, in which the maximum error of 50% icing flashover stress between equivalent results and the test results is only -4.05%. Therefore, the equivalent relationship between the salt deposit density (SDD_g) and the icing stress product (ISP) represented by eqn (10) or (11) is acceptable and the assumptions in equivalence model in previous section prove to be reasonable.

TABLE VI
VALIDATION RESULTS OF THE CONVERTING OF METHODS FROM SLPM TO IWCM

Insulator	SDD_g	$E_{50}(s)$	ISP(c)	γ(c)	E_{50}(c)	Δ%
Type A	0.03	118.3	8163.5	282.2	113.6	-4.05%
	0.05	104.7	11981.5	414.2	102.7	-1.89%
	0.08	94.1	17642.3	609.9	92.9	-1.35%
	0.12	85.7	25107.0	868.0	84.7	-1.18%
	0.15	80.9	30660.3	1060.0	80.4	-0.64%
Type B	0.03	124.7	5970.6	272.6	123.2	-1.16%
	0.05	109.9	8724.8	398.3	111.6	1.54%
	0.08	102.3	12808.9	584.8	101.0	-1.30%
	0.12	89.0	18194.9	830.6	92.1	3.56%
	0.15	84.7	22201.9	1013.6	87.5	3.30%

Note: Δ%=100%*[E_{50}(c)-E_{50}(s)]/E_{50} (s), E_{50}(s) is the test result with the SLPM (γ_s=80μS/cm at 20°C), SDD_g is the salt deposit density with SLPM; ISP(c) is the equivalent icing stress product which is converted SDD_g; γ(c) is the equivalent icing water conductivity; E_{50}(c) is the value which is calculated by eqn (4) with ISP(c)

TABLE VII
VALIDATION RESULTS OF THE CONVERTING OF METHODS FROM IWCM TO SLPM

Insulator	γ	ISP	E_{50} (w)	SDD(c)	E_{50}(c)	Δ%
Type A	80	2314.0	154.8	0	/	/

	200	5785.1	129.8	0.0185	132.5	2.08%
	340	9834.7	108.0	0.0401	110.5	2.30%
	640	18512.4	93.4	0.0864	92.3	-1.16%
	1000	28925.6	81.0	0.1420	82.2	1.45%
Type B	80	1752.4	164.1	0	/	/
	200	4381.0	139.2	0.0194	138.9	-0.21%
	340	7447.6	116.0	0.0421	115.5	-0.43%
	640	14019.0	99.9	0.0907	96.1	-3.76%
	1000	21904.8	83.7	0.1490	85.4	2.00%

Note: $\Delta\%=100\%*[E_{50}(c)-E_{50}(w)]/E_{50}(w)$, $E_{50}(w)$ is the test result with the IWCM, γ is the icing water conductivity (μS/cm) used in IWCM, *ISP* is the icing stress product, *SDD*(c) is the equivalent salt deposit density(mg/cm^2) which is converted from *ISP*, E_{50}(c) is the value which is calculated by eqn (3) with *SDD*(c)

Ⅴ. CONCLUSIONS

(1) The influence of pollution characterized by SLM and IWCM on 50% dc flashover stress of iced insulators is equivalent. And the equivalence is determined by the configuration of insulator and the icing degree.

(2) The pollution methods affect the icing flashover path. The path propagates along the outer surface of ice layer when the insulator is polluted by IWCM, while the path propagates along the interface of insulator and ice layer when the insulator is polluted by SLM.

(3) The standard error of test results of 50% dc icing flashover voltage of insulators polluted by SLM is greater than that of insulators polluted by IWCM. The IWCM is recommended to simulate the pollution because it is simple and the scatter of its test results is relatively small.

(4) The relationship between the 50% icing flashover voltage and the ice weight can be expressed as a power function, and there exists a saturated ice amount, namely, when ice amount on insulator exceed this value, the flashover voltage decreases very little with further increase of ice amount.

(5) There are a large number of small gas cavities in the ice layer closing to the interface of insulator and ice layer because of composite insulator's hydrophobicity. The icing flashover voltage would be reduced if the hydrophobicity of insulators is destroyed by intermittent partial arcs.

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