Electrical Performance of Composite Insulators under Icing Conditions

Fanghui Yin[1, 2], **Xingliang Jiang**[1]
[1]State Key Laboratory of Power Transmission Equipment & System Security and New Technology,
College of Electrical Engineering, Chongqing University,
Chongqing 400044, China

and **Masoud Farzaneh**[2]
[2]NSERC / Hydro-Quebec / UQAC Industrial Chair on Atmospheric Icing of Power Network Equipment (CIGELE) and Canada Research Chair on Engineering of Power Network Atmospheric Icing (INGIVRE) www.cigele.ca
Université du Québec à Chicoutimi, Chicoutimi, QC, Canada

ABSTRACT

Due to the substantial advantage compared to porcelain and glass insulators, Composite insulators have been widely accepted in electric power utilities worldwide. Compared with porcelain and glass insulators, the flashover performance of composite insulators is superior under the contaminated condition, whereas their icing flashover performance should be investigated further. As shown in previous studies, many factors influence the flashover performance of composite insulators under icing conditions. In order to figure out the factors that influence the flashover performance of insulators, experiments were carried out on ice-covered energized and de-energized composite insulators under icing condition. The results show that the flashover performances of composite insulators are superior under energized condition compared with de-energized condition. Under energized condition, when icing is light, the flashover performance of different shed configurations is decided by creepage distance. When icing is moderate, the flashover performance of insulator is influenced by water freezing conductivity, shed configuration, creepage factor, and so on. When icing is heavy, most of the sheds are bridged and the configuration of the last few sheds near the high voltage end have important effect on the flashover performance.

Index Terms - **Composite insulator, Shed configuration, Icing flashover, energized icing.**

1 INTRODUCTION

THE consumption and generation of electric power is seldom in the same region, so that electric power is transmitted through transmission lines from the generation sites to the distribution level at high voltages [1]. Two types of insulators, ceramic and composite insulators, are used to provide electrical and mechanical support for transmission lines. The use of composite insulators in recent years has increased to the extent that most utilities are using these insulators on major transmission lines. The primary motivation of their wide acceptance by the electric power utilities is their substantial advantage compared to porcelain and glass insulators. Firstly, due to their low surface energy, composite insulators maintain good hydrophobic surface properties in the presence of wet conditions such as fog, dew and rain. Secondly, composite insulators are lightweight which results in a more economical design of the towers and in reduced installation and maintenance costs such as insulator washing which is often required for porcelain and glass insulators in heavily contaminated environment. Thirdly, compared with porcelain and glass insulators, composite insulators have excellent pollution performance due to the hydrophobicity of the housing material and are thus suitable for use in highly polluted areas. In recent years, especially after the 2008 Chinese Winter Storm which was a series of winter storms that affected large portions of Southern and Central China from January 25 to February 6, 2008, many Chinese researchers made a lot of studies on the influence of ice on insulator flashover performance, icing test methods and so on. According to some studies [2-12], the flashover voltage of ice-covered composite insulators is lower than that of ice-covered porcelain and glass insulator strings on the same operation voltage level under the same icing condition. The main reason for this shortcoming is the effect of the insulator shape configuration. Compared with the shapes of porcelain and glass insulator strings, the shed spacing of composite insulators is shorter which makes the air gaps between adjacent sheds of a composite insulator easy to be bridged [13-15]. As the air gaps are bridged, the total leakage distance decreases, leading to a lower flashover voltage. Many studies show that *CF* (creepage factor) is also an important factor influencing the electrical performance of composite insulators. A

Manuscript received on 21 January 2014, in final form 9 June 2014, accepted 22 June 2014.

DOI 10.1109/TDEI.2014.004571

optimal *CF* should be chosen when composite insulators are used in the icing districts. The Chinese Electric Power Industry Standard suggests that *CF* should not be higher than 3.2 for grade I (light) and grade II (medium) polluted regions and 3.5 for grade III (heavy) and grade IV (very heavy) polluted regions. Some research shows that the optimal *CF* ranges from 3.2 to 3.4 based on experimental studies on composite insulators with different salt deposits[14]. In Hu's study [16], many experiments were carried out with *CF*s of composite insulators ranging from 2.87 to 3.94. The results showed that when the icing is light, the flashover performance of composite insulators increases and then decreases with the increase of *CF*. When the icing is moderate or heavy, there is no obvious relationship between flashover performance and *CF*. However, most of these studies are based on de-energized conditions. There are few studies on flashover performance of insulators energized at service. Therefore, it is meaningful to study the flashover performance and icing characteristic of energized composite insulators with AC service voltage under the icing condition [5][18]. To find out relationships between flashover performance of composite insulators under AC and parameters such as *CF*, in icing conditions, some experiments have been carried out in the large climate chamber of Chongqing University.

2 TEST FACILITIES, SPECIMENS AND PROCEDURES

2.1 TEST FACILITIES

The experimental investigations were carried out in the large multi-function artificial climate chamber with a diameter of 7.8 m and a height of 11.6 m at Chongqing University. The climate chamber consists of a power system, cooling system, water spraying system and wind controlling system. The minimum temperature in the chamber can be regulated down to -45 ±1 ℃ and the air pressure in the chamber can be as low as 30 kPa, which can simulate atmospheric conditions at an altitude of 9000 m.

For the tests, power was supplied by a 2000 kVA/500 kV test transformer and was channeled in through a 330 kV wall bushing. A relatively uniform wind was obtained by using a system of ten fans set in a tapering box with a diffusing honeycomb panel. The wind speed can be controlled between 0-12 m/s and the water droplets produced from nozzles had a diameter size from 20 to 120 μm. Details of the test circuit of the ice-covered flashover experiment are presented in [16].

2.2 SPECIMENS

This paper presents two groups of composite insulators used in the icing districts. Three types are applied to the 35 kV nominal AC system (type A to type C) and four types are used for the 110 kV nominal AC system (type D to type G). The *CF*s of the insulators range from 2.17 to 3.42. The profiles and configurations of the test specimens are presented in Figure 1 and Table 1.

2.3 TEST PROCEDURES

According to previous studies [19-21], flashovers often happen in wet-grown conditions. This type of ice involves the formation of icicles around the insulator skirts and bulks of glaze deposits on the surface of insulators. Therefore, wet-grown ice was focused on in this paper. As the insulators in service may be contaminated before icing, two methods are used to simulate the icing process in laboratory. The first one is the solid layer method in which the insulator is contaminated and dried before icing. The second one is the freezing water conductivity method in which the insulator is cleaned before icing and then sprayed with water of equivalent conductivity as compared with the first method. The equivalence relationship between the solid layer method and the freezing water conductivity method in terms of

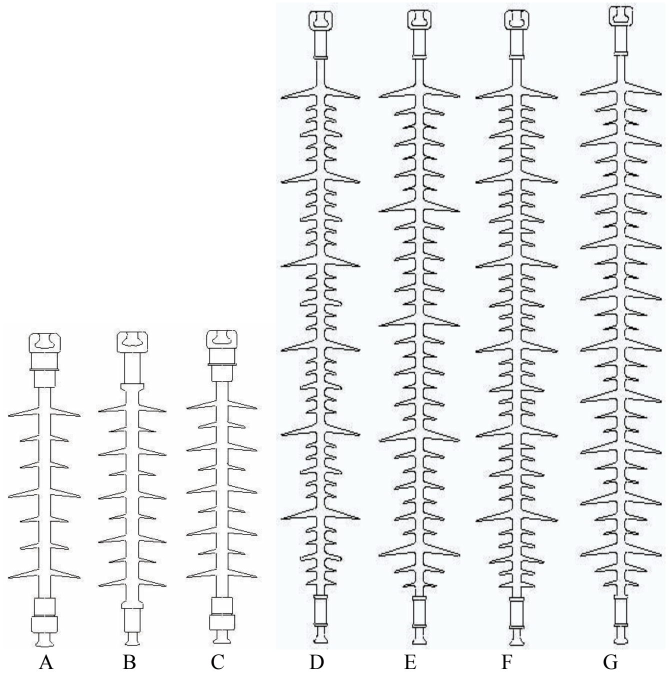


Figure 1. Profiles of tested specimens.

Table 1. The profile parameters of the tested insulators.

Type	Dry arc distance h (mm)	Leakage distance L (mm)	Shed diameters D1/D2/D3 (mm)	Shed numbers N1/N2/N3	Rod diameter D (mm)	Shed spacing d1/d2/d3 (mm)	CF=L/h
A FXBW-35/70 (I)	478	1035	150/90	3/4	24	60/60	2.17
B FXBW-35/70 (II)	495	1145	129/89	5/4	25	45/45	2.31
C FXBW-35/70 (III)	511	1295	150/100	5/4	24	45/45	2.53
D FXBW-110/100 (I)	1209	3587	170/100/80	6/6/24	20	45/50/85	2.97
E FXBW-110/100 (II)	1217	3778	170/100/60	5/13/13	20	35/50/85	3.10
F FXBW-110/100 (III)	1210	4014	170/130/80	6/6/24	20	40/70/85	3.32
G FXBW-110/100 (IV)	1206	4125	170/100/60	10/10/10	20	35/50/85	3.42

impact on the flashover voltage of ice-covered composite insulators is investigated in [27]. Previous studies showed that it is difficult to get uniform pre-contamination on the surface of the insulators before icing using the solid layer method. The test results based on the solid layer approach are more scattered than those based on freezing water conductivity. In Qin Hu's study [16], the solid layer method was selected. The insulators were pre-contaminated before icing with salt deposit density of 0.05 mg/cm^2 and non-soluble deposit density of 0.3 mg/cm^2. During the experiments, a freezing water conductivity of 120 µS/cm was used in the spray system. According to [27], it is equivalent to a freezing water conductivity of about 500 to 600 µS/cm using the freezing water conductivity method. Unlike Hu's study, the freezing water conductivity polluting method was used in this paper, with γ_{20} (freezing water conductivity at 20 ℃) values set at 300, 640, 1120 and 1825 µS/cm. The test procedures were depicted as following.

2.3.1 PRE-CONTAMINATION

Before the tests, all the specimens were cautiously cleaned so that all traces of dirt and grease were removed. Then the specimens were dried naturally.

2.3.2 PARAMETER DEFINING ICING DEGREE

As icing degree is a very important factor influencing flashover performance, two methods were used in the experiments to define icing degree. The first method consists in measuring the ice thickness d (in mm) of the ice accretion on monitor cylinders. Two monitor cylinders with length of 600 mm and diameter of 28 mm are set at the top and bottom positions near the specimen respectively during the experiment. The monitor cylinders rotated at one r.p.m. The average ice thickness on both cylinders was used as the measure of icing degree. The second method consists in measuring the average weight of ice accreted on the insulator. After the ice is accreted on the insulator, the ice weight is measured.

2.3.3 FLASHOVER TEST METHOD

In the real world, the insulators are at service voltage during the icing process. In presence of an electrical field, ice weight, ice density and ice shape will be different as compared to the de-energized condition. Therefore, it is more realistic to do the experiments under energized rather than the de-energized conditions.

There are suggested methods for testing ice-covered composite insulators [21-23]. Chongqing University has carried out studies of the flashover performance of iced insulators since 1980s [16] and has obtained many results. Based on these results, some methods to prevent ice flashovers on transmission lines have been proposed. As flashover of ice-covered insulators is more likely to occur during ice melting periods, Chongqing University put forward a U-shaped curve method to investigate the flashover performance of iced insulators during ice melting periods. The U-shaped curve method was recommended as one of the test methods used for evaluating the electric strength of ice-covered insulator in the work statement of CIGRE 33.04.09 [25-26]. To obtain the U_{fmin}, the U-shape curve method was chosen in this paper. Voltage was applied during the ice accretion process. The voltages applied for the 35 and 110 kV composite insulators were 22 and 67 kV respectively in the tests. During the ice accretion period, the ambient temperature was kept at -7 ℃ to -5 ℃. When ice accretion on the monitor reached the expected degree, the spraying system was turned off. Then, the iced composite insulator was frozen for 15 minutes. The detailed procedure can be found in [16].

The flashover tests were followed with the gradually rising voltage method. The voltage was increased to 75% of the expected flashover voltage V_e at a rate of 15 kV/s and then increased at a lower rate of 2%× V_e/s until flashover. The flashover procedure was repeated at an interval of 2 to 3 min until most of the ice accreted on the composite insulator melted. The test procedure is depicted in Figure 2.

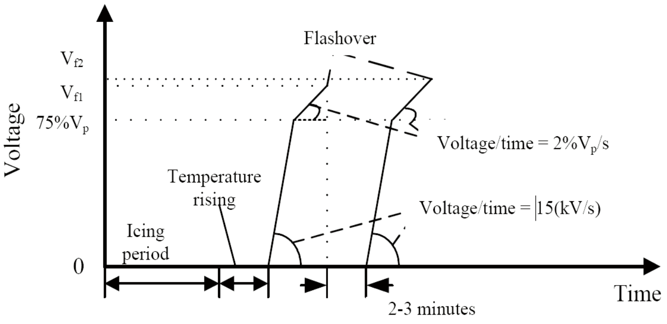


Figure 2. Test procedure of the experiments.

After the tests, the U-shape curve of the flashover voltage of the iced composite insulator was drawn up. If a series of flashover voltages obtained by the U-shape curve method are noted as U_{f1}, U_{f2},.., U_{fn}, then the minimum flashover voltage can be obtained as

$$U_{f\min} = Minimum(U_{f1}, U_{f2}, U_{f3}, ..., U_{fn}) \quad (1)$$

From Figure 3, it can be observed that flashover performance of the insulators first decreases to a minimum and then increases gradually. The curve of flashover performance over time looks like a U-shape curve.

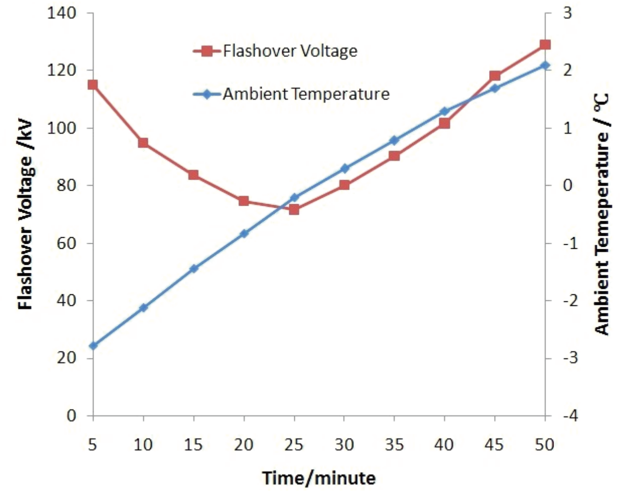


Figure 3. Flashover voltages and ambient temperature during the test of insulator E with the conductivity of 1825 µS/cm.

Table 2. E_h and ice weight when the ice thickness d=15 mm.

Type / γ_{20} (μS/cm)		D		E		F		G	
		Ice weight (kg/m)	E_h (kV/m)	Ice weight (kg/m)	E_h (kV/m)	Ice weight (kg/m)	E_h (kV/m)	Ice weight (kg/m)	E_h (kV/m)
U_{app} = 0 kV	300	4.19	148.5	3.66	154.6	4.02	138.0	5.06	120.8
	640	3.97	110.2	3.64	114.8	4.32	90.5	5.22	88.3
	1120	4.3	78.7	3.78	84.2	4.13	79.3	5.39	77.8
	1825	4.01	54.4	3.7	58.8	3.95	58.2	5.22	51.7
U_{app} = 67 kV	300	3.76	154.9	3.7	162.9	3.78	144.3	4.85	129.3
	640	3.8	116.8	3.49	121.2	3.57	106.1	4.64	94.0
	1120	3.36	88.3	3.29	90.1	3.55	86.7	4.66	81.9
	1825	3.23	66.1	3.16	68.3	3.47	60.6	4.39	58.7

Table 3. E_h and ice weight when the ice thickness d=15 mm.

Type / γ_{20} (μS/cm)		A		B		C	
		Ice weight (kg/m)	E_h (kV/m)	Ice weight (kg/m)	E_h (kV/m)	Ice weight (kg/m)	E_h (kV/m)
U_{app} = 0 kV	300	4.77	98.3	5.19	101.0	5.48	99.8
	640	4.81	67.0	5.05	74.6	5.28	76.3
	1120	4.67	62.8	5.25	67.5	5.38	67.5
	1825	4.92	46.0	5.09	48.5	5.54	52.8
U_{app} = 22 kV	300	4.14	104.6	4.79	107.1	4.95	105.7
	640	3.79	72.6	4.24	78.2	4.62	82.2
	1120	3.64	67.0	3.9	70.1	4.29	70.1
	1825	3.45	52.3	3.78	52.5	4.17	58.7

Table 4. E_h (kV/cm) when d=15 mm and Type = C.

	300 (μS/cm)	640 (μS/cm)	1120 (μS/cm)	1825 (μS/cm)
U_{app} =14 kV	99.8	80.2	70.5	56.8
U_{app} =30 kV	109.6	94.0	82.2	68.5

Table 5. E_h when γ_{20} = 640 μS/cm and U_{app} = 67 kV.

	D	E	F	G
	E_h(kV/m)	E_h(kV/m)	E_h(kV/m)	E_h(kV/m)
d=5 mm	171.3	183.6	182.2	189.3
d=30 mm	71.2	80.4	69.3	75.7

3 TEST RESULTS AND ANALYSIS

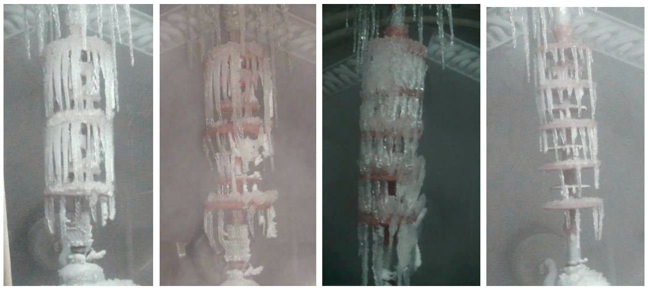
3.1 TEST RESULTS

The flashover performance of Type A to Type G insulators were carried out in the climate chamber using the test method described in Section 2. The test results are shown in Table 2-5. Figure 4 shows pictures of the insulators after icing. The minimum flashover voltages U_{fmin} were obtained by the U-shape curve method. The flashover voltage gradient E_h is used in this paper.

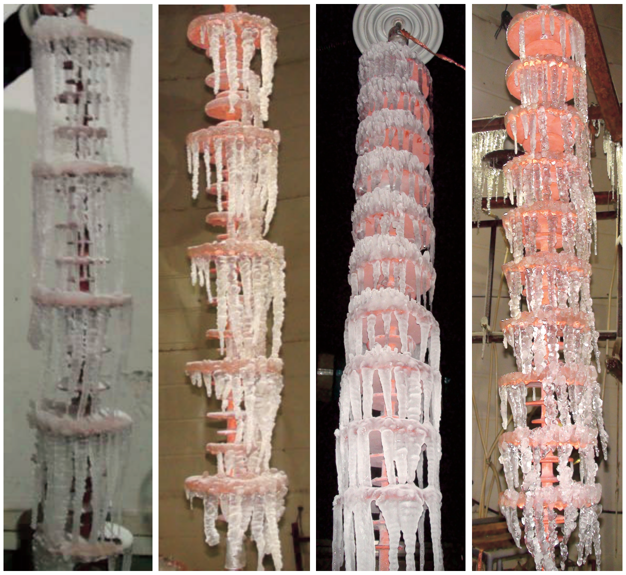
$$E_h = U_{f\,\min} / h \tag{2}$$

where h is the dry arc distance.

Pictures of iced insulators are shown in Figure 4. From these, it can be seen that the icicles of insulators are different under energized and de-energized conditions. Without voltage, water droplets at icicle tips are only subjected to gravity and wind force causing the icicles to grow almost vertically downward. In presence of voltage, the water droplets in the tips are also subject to electric field force. Under the resultant forces, the icicles grow vertically first and then toward the rod of the insulator. It can also been seen that when there is no voltage, adjacent sheds are more easily bridged by the icicles. When icing degree is moderate, even the big sheds are bridged. However, when voltage is applied, the big sheds can hardly be bridged even the icing degree is heavy. This can be explained by the fact that as icicles grow, leakage distance decreases and electric field at the air gap increases. When the electric field is increased up to a certain level, discharge happens which stops icicle growth because of Joule heat.



(a) Type A De-energized (b) Type A Energized (c) Type B De-energized (d) Type B Energized



Type E De-energized Type E Energized Type G De-energized Type G Energized

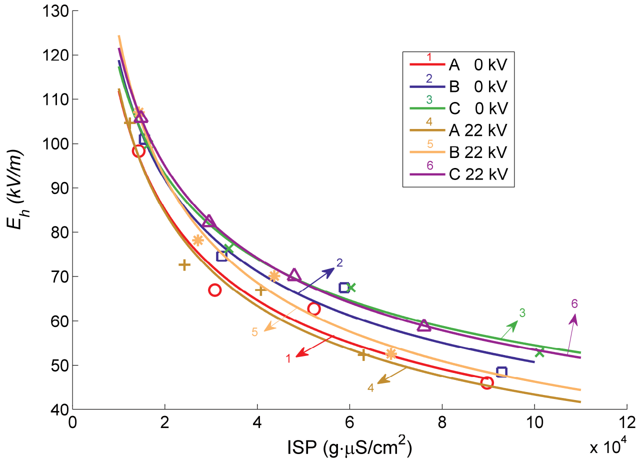
Figure 4. Pictures of ice-covered insulator types compared as energized and de-energized.

3.2 RELATIONSHIP BETWEEN THE FLASHOVER AND THE ICING STRESS PRODUCT

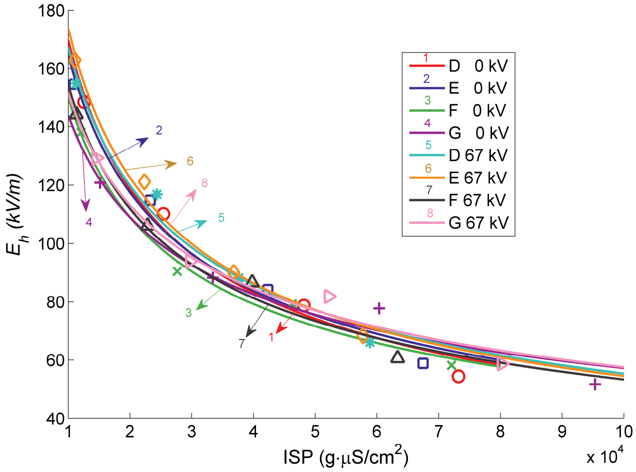
Previous studies show that the flashover voltage of an ice-covered insulator decreases as ice weight and freezing icing

Table 6. The values of A, p and R^2 for different types of composite insulators under energized and de-energized condition.

		U_{app}=0 kV for all types of insulators				U_{app}=22 kV for A,B,C U_{app}=67 kV for D,E,F,G			
FXBW-35/70	A, p, R^2	A	B	C		A	B	C	
	A	4063	4030	2605		4542	6763	3262	
	p	0.39	0.38	0.33		0.4	0.43	0.35	
	R^2	0.962	0.949	0.983		0.962	0.977	0.999	
FXBW-110/110	A, p, R^2	D	E	F	G	D	E	F	G
	A	29151	20840	10612	7689	19706	22897	13702	8444
	p	0.55	0.52	0.46	0.42	0.51	0.52	0.48	0.43
	R^2	0.975	0.978	0.98	0.935	0.977	0.991	0.975	0.963



(a)



(b)

Figure 5. Relationship between AC flashover and ISP.

water conductivity increase [7-9, 28-30]. Decrease in electric strength is a result of both factors. The combined effect of icing water conductivity and ice weight can be described by the icing stress product (*ISP*). *ISP* is defined as the product of ice accretion per centimeter of dry arc distance and water conductivity corrected to 20 ℃:

$$E_h = A \cdot (ISP)^{-p} \tag{3}$$

where A is the coefficient whose value is related to the profile of insulators; p is the characteristic exponent characterizing the influence of *ISP*.

Based on the results of Tables 2 and 3, relation between E_h and *ISP* can be plotted as shown in Figure 5. The values of A, p and the correlation coefficient R^2 are also shown in Table 6. From Table 6 and Figure 5, it can be seen that the exponent p is different, being related to the profile of the insulator. Thus the profile of the insulator can affect the flashover performance of composite insulators. Furthermore, the values of p are different under energized conditions from de-energized ones even for the same composite insulator. In general, for the same composite insulator, the value of p is larger under energized conditions which means that the *ISP* has a more negative effect on the flashover performance of insulators. This can be explained by the fact that insulator surfaces, acting as a condensation nucleus, accelerate the freezing velocity of cooling water. During the transition of freezing water to ice, the regular arrangement of water molecules lead to the expulsion of conductive impurities (mainly NaCl for these experiments) to the surface of the ice which makes the salinity at the ice surface higher than that of the ice [31-32]. Consequently, the conductivity of melting water is higher than that of freezing water for polluted insulators. When icing is effected under energized conditions, it induces the salt expulsion process, due to the heat effect. Thus, melting water conductivity collected during the flashover test under the energized condition is higher than under the de-energized conditions, which is consistent with the experimental observations.

The following relationship was observed between flashover stress E_{50}, in kV per meter of dry arc distance, and *ISP* in (g/cm)×µS/cm for the selection of station insulators with respect to ice and snow under the most severe meteorological conditions leading to slow melting [22].

$$E_{50} = 396 \cdot (ISP)^{-0.19} \tag{4}$$

From Figure 6, it can be seen that when freezing conductivity is large and icing is moderate, in which conditions the insulators are not bridged, the test flashover voltages are higher than the calculated values based on Equation (4). Compared with the de-energized conditions, the difference between the test values and the calculated ones are larger under the energized conditions. From Figure 7, this difference can be obtained when icing is heavy and conductivity is modest, but the test flashovers are still higher than the calculated values. There are some reasons that can account for this. Firstly, Equation (4) only applies when the insulator is fully bridged. A composite line insulator with alternative diameter sheds is not easy to be bridged unlike a station insulator. In particular, when tests are carried out under energized conditions, the insulators can hardly be fully bridged because of heat effect even when icing is heavy. Secondly, because droplet diameter is small, ice accretion is actually a mixture of hard rime and glaze. Thirdly, the temperature rise during the test procedure is about 6 ℃/h, which is higher than 2-3 ℃/h recommended by IEEE Standard 1783 [20]. Fast temperature rise makes the ice melt a little faster.

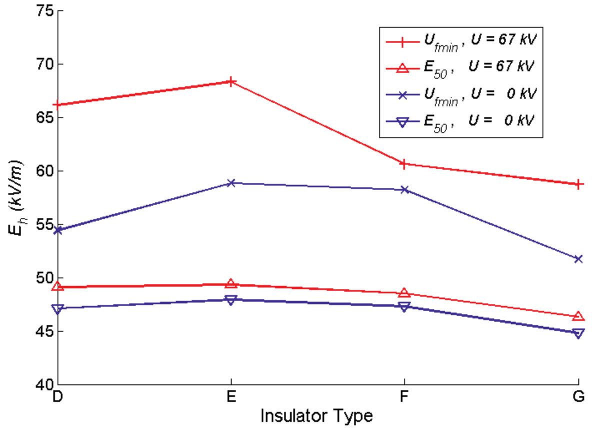


Figure 6. U_{fmin} and calculated E_{50} under the energized and de-energized condition when the conductivity is 1825 µS/cm and ice thickness is 15 mm.

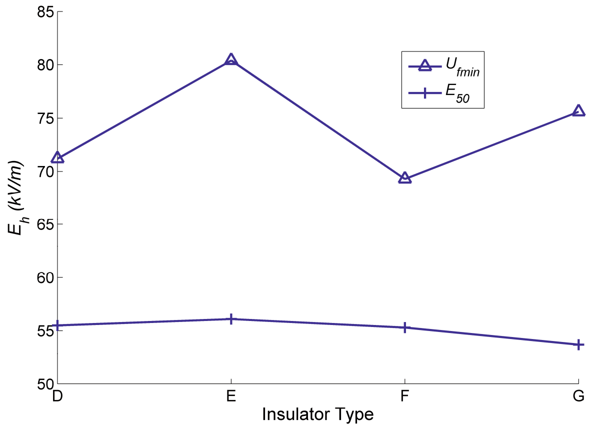


Figure 7. U_{fmin} and calculated E_{50} under the energized condition (U_{app} = 67 kV) when the conductivity is 640 µS/cm and ice thickness is 30 mm.

3.3 INFLUENCE OF FREEZING WATER CONDUCTIVITY AND *CF* ON ICE WEIGHT

From Table 2, it can be seen that ice weights are different under the different icing conditions. When there is no voltage applied, the ice weight of a fixed specimen is almost constant under different γ_{20} values. With the voltage applied, the ice weight decreases as water conductivity increases. This is because some icicles are burned down during icing when the voltage is applied and the increase of γ_{20} has a positive effect in heat production. It can also be seen from Table 2 that under the energized conditions ice weight is less than with the de-energized conditions within a range of 7.8 to 29.8% with an average of 19.1% for the 35 kV composite insulators and within a range of 1.1 to 21.9% with an average of 11.3% for the 110 kV composite insulators. Tables 7 and 8 show the ice weights and their relative standard deviations when icing is moderate and conductivity is 640 µS/cm. From these tables, it can be seen that test-to-test repeatability of ice weights is good when no voltage is applied during the icing process and the relative standard deviations are between 4.8 and 8.5%. When icing occurs with applied voltage, the test-to-test repeatability degrades and the relative standard deviations are between 9.2 to 13.2%. These results are reasonable as the icing process is more complex with voltage applied. Except for gravity, buoyancy force and drag force, the trajectory of water droplets is also influenced by the electric field when approaching the insulator. As ice weight increases during the icing process, there is some discharge at the high electric field location which makes the growth of ice more random. The *CF* coefficient also influences ice weight. As shown in Figure 8, when ice thickness is 15 mm, the weight of ice accretion is proportional to the *CF* coefficient for FXBW-35/70 and FXBW-110/100. With the same arcing distance, a larger *CF* means a longer leakage distance which can be achieved by decreasing the shed spacing. As the shed spacing is shortened, the sheds are more easily bridged. From the experiment results, it can also be seen that ice density has no relationship with water conductivity when there is no voltage applied during the ice accretion. With voltage applied, ice density first decreases and then increases as water conductivity increases.

Table 7. Ice weight and relative standard deviation when d=15 mm and conductivity = 640 µS/cm.

	A		B		C	
	Ice Weight (kg/m)	σ%	Ice Weight (kg/m)	σ%	Ice Weight (kg/m)	σ%
U_{app} = 0kV	4.81	8.5	5.05	6.6	5.28	7.3
U_{app} = 22kV	3.79	10.9	4.24	11.7	4.62	9.4

Table 8. Ice weight and relative standard deviation when d=15 mm and conductivity = 640 µS/cm.

	D		E		F		G	
	Ice Weight (kg/m)	σ%	Ice Weight (kg/m)	σ%	Ice Weight (kg/m)	σ%	Ice Weight (kg/m)	σ%
U_{app} = 0 kV	3.97	7.8	3.64	8.1	4.32	8.3	5.22	4.8
U_{app} = 67 kV	3.8	12.7	3.49	13.2	3.57	10.4	4.64	9.2

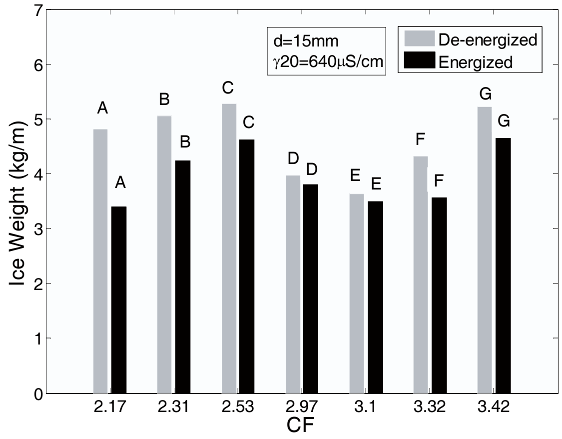


Figure 8. Ice weight comparison with different *CF*s. The applied voltage is 22 kV for A, B, C and 67 kV for D, E, F, G under the energized condition.

3.4 INFLUENCE OF FREEZING WATER CONDUCTIVITY AND *CF* ON FLASHOVER VOLTAGE

From the experiment results, it was observed that the flashover performance of insulators is better with voltage applied than without. The ratios of U_{fmin} under energized and de-energized condition are shown in Tables 9 and 10. The flashover voltages are 3.8 to 13.6% higher for 35 kV composite insulators and 4.3 to 21.4% higher for 110 kV composite insulators under energized conditions compared with the de-energized conditions. Compared with de-energized conditions, the adjacent sheds are not as easily bridged because of the presence of electric field under energized conditions. When ice melts, there is a thin water film on the surface of the ice. Since an increase in freezing water conductivity can lead to an increase in water film conductivity, freezing water conductivity has a negative influence on the flashover performance of composite insulators. Flashover performance is also influenced by the *CF* coefficient. For example, when ice thickness is 15 mm and conductivity is 640 µS/cm, the difference of flashover voltage gradient can be as large as 22 kV/m under the same energized or de-energized conditions, which is consistent with [16]. When conductivity is higher than 640 µS/cm, the influence of *CF* diminishes.

Table 9. Ratio of U_{fmin} under energized and de-energized condition when the ice thickness d = 15 mm.

Type / γ_{20} (µS/cm)	A	B	C
300	106.4	106.0	105.9
640	108.4	104.9	107.7
1120	106.7	103.9	103.8
1825	113.6	108.3	111.1

Table 10. Ratio of U_{fmin} under energized and de-energized condition when the ice thickness d = 15 mm.

Type / γ_{20} (µS/cm)	D	E	F	G
300	104.3	105.3	104.6	107.0
640	106.0	105.6	117.3	106.4
1120	112.1	106.9	109.3	105.3
1825	121.4	116.1	104.1	113.6

3.5 INFLUENCE OF ICE THICKNESS ON FLASHOVER VOLTAGE

The results of previous studies show that icing flashover voltage under energized or de-energized conditions decreases with an increase in ice thickness *d* or ice weight. A recently rough relation has been established at the CIGELE laboratory (UQAC) that the ice thickness on the reference cylinder and the weight of accreted ice per meter of 300 mm uniform shed profile station post insulator can be related as follows [22]:

$$\text{Ice Weight}_{\text{g/cm dry arc}} = 4 \times \text{Thickness}_{\text{mm}} \quad (5)$$

In this experiment, the relation between ice thickness and ice weight are plotted and compared with composite insulator S [24], which has a *CF* of 3.19, in Figure 9. The ratio of ice weight (g/cm dry arc) and ice thickness (mm) is between 2.3 and 3.1 when *d* is no higher than 15 mm. When *d* increases further, the ratio decreases due to the fierce discharge activity. Because the post insulator [22] is easier to be bridged and has a larger diameter, it is reasonable that the ratio for the station post insulator is higher than that of line insulators.

The relationship between E_h and *d* can be expressed as the following power function

$$E_h = A \cdot d^{-c} \quad (6)$$

where A is a constant related to the pollution level, material and profile of the insulator; *d* is the ice thickness accreted on the monitoring cylinder, in mm; *c* is the exponent characterizing the influence of ice thickness on the icing flashover voltage.

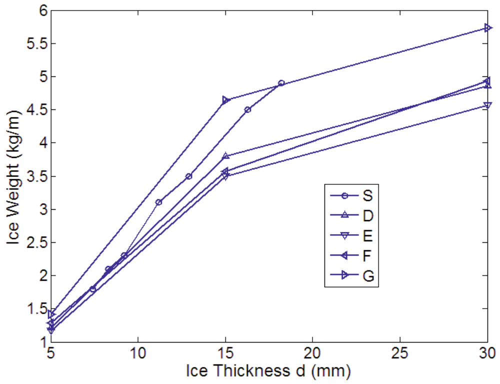


Figure 9. Relationship between AC flashover and ice thickness *d* when conductivity is 640 µS/cm and U_{app} = 67 kV.

To investigate the influence of the ice thickness on icing flashover under energized conditions, four types of FXBW-110/100 insulators, namely D, E, F and G were used in the artificial climate chamber under the different icing levels of the present study. The values of E_h under the typical ice thicknesses resulting from light, moderate and heavy icing conditions, are shown in Tables 2 and 5. The relationship between E_h and *d* is plotted in Figure 10. The values of *A*, *c* and R^2 are shown in Table 11.

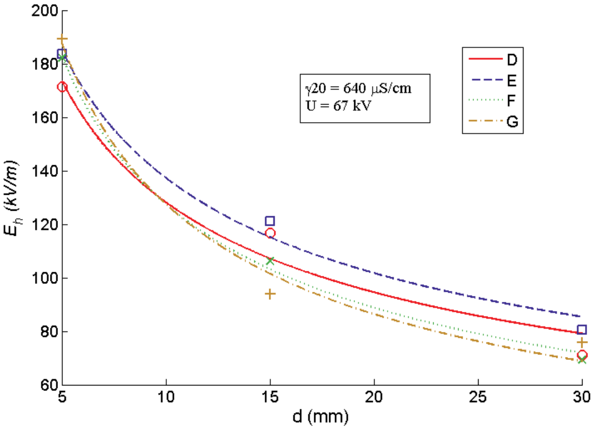


Figure 10. Relationship between AC flashover and ice thickness *d*.

Table 11. The values of A, c and R^2 for different types of insulators

	D	E	F	G
A	383.9	389.5	436.6	424
c	0.47	0.45	0.53	0.52
R^2	0.956	0.984	0.996	0.972

According to the results presented in Tables 2, 5 and 11 and the experimental observations during the tests, the following conclusions can be drawn.

(1) For all types of composite insulators with different shed configurations, the flashover voltage gradient E_h will first decrease with an increase in ice thickness, and then change very slowly.

(2) When icing is very light ($d < 10$ mm), all four types of composite insulators behave satisfactorily. It was found that shed configuration has little influence on the flashover performance. This can be explained by the fact that when icing is light, all the sheds remain unabridged. In this situation, insulators with a higher leakage distance have a better flashover performance. For example, insulator G whose leakage distance is 4125 mm has the highest E_h of 189.3 kV/m. Insulator D whose leakage distance is 3587 mm, lower than other three types, has the lowest E_h of 171.3 kV/m.

(3) When icing is moderate (10 mm $\leqslant d \leqslant$ 20 mm) , insulators with good design show better flashover performance than others. For example, from Tables 2 and 5, it can be seen that insulator E behaves better than insulators D, F and G, with G being the worst. The reason for this is that when ice thickness is larger than 10 mm, most of the small sheds are bridged by icicles except those with large diameter. As the spacing of the largest diameter of insulator G is 105 mm, it can easily be bridged when ice thickness is increased further, as seen in Figure 4. When the big sheds are bridged, the flashover performance dramatically decreases. However, as the spacings of the adjacent big diameter of insulators D, E and F are respectively about 180, 180 and 245 mm. it difficult for them to be bridged under moderate icing conditions.

(4) When icing is heavy ($d > 20$ mm), insulator E shows the best behavior among the four types. Surprisingly, insulator G behaves even better than insulators D and F. This is totally different as compared to the de-energized condition where the flashover performance of all types of insulators are almost the same.

(5) The characteristic exponent c accounting for the influence of ice thickness on flashover voltage is related to the shed configuration. Compared with c values of the other insulator types, that of insulator E is the smallest one at 0.45. As the smaller c is, the more stable flashover performance will be under icing condition.

3.6 SHED CONFIGURATION DISCUSSION FOR ICE-COVERED COMPOSITE INSULATORS

Compared with glass and porcelain insulators, the inferior flashover performance of composite insulators under icing condition is mainly due to the shed configuration. As the shed spacings are relatively large and as there are metal electrodes between the high voltage and ground ends, the potential distribution along glass and porcelain strings is more uniform than that of composite insulators. Based on a previous study, one of the most important factor affecting the flashover performance of composite insulators is the presence of air gaps, as seen the discharge paths in Figure 11. The breakdown voltage of air gap V_b can be determined as a function of air gap length [33-34]:

$$V_b = 4.1x + 3.8 \tag{7}$$

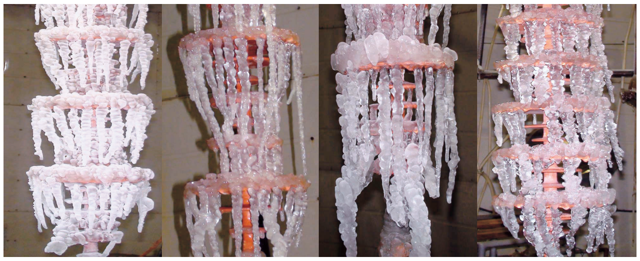
where x is the air gap length in cm. From this equation, it can be seen that the principle of shed configuration optimization is to increase air gap length as much as possible.

Here follows suggestions towards this optimization that can be drawn from the experiments under energized condition:

(1) Increase the diameter and spacing of sheds to create long air gaps. The major reason of the poor flashover performance of composite insulator under icing condition lies in the compact insulator sheds which can be easily bridged by icicles if the diameter and spacing of sheds are too small.

(2) Use alternative diameters to create the air gaps at different positions. For composite insulators which are used for nominal voltages higher than 110 kV, 3 or 4 different diameters can be chosen to create more air gaps.

Figure 11. Flashover path of composite insulators



Type D Type E Type F Type G

Figure 12. Photograph of the high voltage end.

(3) The spacing of the big sheds should not be too long. If that spacing is too long, the small sheds between adjacent big sheds will all be bridged by icicles which will decrease the total air gap length. The big shed can also shield the small diameter shed below it from icing. With the length of the composite insulator constant, if the spacing of big sheds is too large, the number of largest sheds will decrease, leading to the decrease of the total shield effect.

(4) The distance between the last big shed and the high voltage end should not be too long, as can be seen in Figure 12.

For insulators D and F, the last big shed is far away from the high voltage end. When the voltage is applied during the icing process, the last middle diameter sheds near the high voltage end is bridged to the last shed. With the conductive water film, the sheds from the last middle shed to the last shed have nearly a same potential. When the icicles from the last big shed is long enough, changes in the electric field will cause the icicles of the last sheds which are bridged together to grow horizontally, leading to a great decrease of the air gap length and a lower flashover voltage. For insulators E and G, as the distance of the last big shed to the high voltage end is short, there is no icicle on the small diameter sheds due to both the shield and heat effects. This is the reason why under energized condition, the flashover voltages of insulators E and G are higher than those of insulators D and F when the icing is heavy.

4 CONCLUSIONS

Based on the icing flashover tests on three types of 35 kV composite insulators and four types of 110 kV composite insulators under energized and de-energized conditions, the following conclusions can be drawn:

(1) The insulators are icing differently if they are under energized or de-energized conditions. In the case of de-energized condition, the icicles are growing downward vertically and even the big sheds of the insulators can be bridged by icicles when the icing is heavy. While in the case of energized condition, the icicles are growing downwards and toward the axis of the insulator. Due to the heat effect, the big sheds are hard to be bridged.

(2) The flashover performances of all types of composite insulators first decrease with an increase in ice thickness, and then change very slowly. The flashover performance of composite insulators under energized conditions is better than that under de-energized conditions in a range between 3.8% and 21.4%.

(3) Freezing water conductivity and *CF* coefficient have an influence on ice weight under energized condition. When freezing water conductivity increases, ice weight decreases due to the heat effect. As *CF* describes the compactness of the shed configuration. A larger *CF* leads to a smaller shed spacing which is more prone to be bridged. With the sheds bridged by the icicles, the ice weight increases.

(4) When icing is light, shed configuration has little influence on the icing flashover performance of composite insulators. However, leakage distance plays an important role, a longer leakage distance leading to a better flashover performance.

(5) When icing is moderate, the shed configuration of composite insulators is the main factors influencing icing flashover performance. To improve the flashover performance, alternative diameters can be used to create air gaps at different positions. Big sheds can also play positive role in the shed configuration. However, the distance of big sheds should be appropriate. If the distance between the big sheds is too short, the whole insulator will be bridged easily, leading to a low flashover voltage. If the distance is too long, the shield effect of big sheds will be reduced.

(6) When icing is heavy, the flashover performance of the composite insulators is mainly decided by the last few sheds under the energized condition. From the experiments, it can be seen that the distance between the last big shed and the high voltage end should not be too long.

(7) The conductivity of melting water is higher than that of freezing water used for spray. When icing is carried out under energized conditions, the salt expulsion process is accelerated due to the heat effect. Thus, melting water conductivity collected during the flashover test under the energized condition is higher than under the de-energized conditions.

ACKNOWLEDGMENT

This work was supported by the National Basic Research Program of China (973 Program: 2009CB724501/502/503), the Funds for Innovative Research Groups of China (grant no. 51021005) and also in collaboration with NSERC/Hydro-Quebec/UQAC Industrial Chair on Atmospheric Icing of Power Network Equipment (CIGELE) and the Canada Research Chair on Engineering of Power Network Atmospheric Icing (INGIVRE) at the Université du Québec à Chicoutimi.

REFERENCES

[1] T. Doshi and R. S. Gorur, "Electric Field Computation of Composite Line Insulators up to 1200 kV AC", IEEE Trans. Dielectr. Electr. Insul, Vol. 18, No. 3, pp. 861-867, 2011.

[2] J. Hu, C. Sun, X. Jiang, Z. Zhang and L. Shu, "Flashover Performance of Pre-contaminated and Ice-covered Composite Insulators to be Used in 1000 kV UHV AC Transmission Lines", IEEE Trans. Dielectr. Electr. Insul, Vol. 14, No. 6, pp. 1347-1356, 2007.

[3] F. Su and S. Hu, "Icing on Overhead Transmission Lines in Cold Mountainous District of southwest China and Its Protection", Proceedings of 4th International Workshop on Atmospheric Icing of Structures, Paris, France, pp. 354-357, 1988.

[4] E. A. Cherney, "Flashover performance of artificially contaminated and iced long-rod transmission line insulators", IEEE Trans. Power App. Syst., Vol. 99, pp. 46–54, 1980

[5] M. Farzaneh, J. Kiernicki and J.-F Drapeau, "Ice accretion on energized line insulators", Int'l. J. Offshore and Polar Engineering, Vol. 2, No. 3, pp. 228-233, 1992

[6] W.A. Chisholm, "Insulator Leakage Distance Dimensioning in Areas of Winter Contamination Using Cold-fog Test Results", IEEE Trans. Dielectr. Electr. Insul, Vol. 14, pp. 1455-1461, 2007.

[7] M. Farzaneh and W. A. Chisholm, *Insulators for icing and polluted environments,* Wiley-IEEE Press, 2010.

[8] X. Jiang, S. Wang, Z. Zhang, S. Xie and Y. Wang, "Study on AC Flashover Performance and Discharge Process of Polluted and Iced IEC Standard Suspension Insulator String", IEEE Trans. Power Del, Vol. 22, pp. 472-480, 2007.

[9] N. Sugawara and M. Farzaneh, "On the Role of Water Film in the Mechanism of Flashover of Iced Insulator", IEEE Int'l. Sympos. Electr. Insul., Washington, DC, pp. 281-286, 1986.

[10] N. Sugawara, K. Hokari, K. Yoshida, H. Ando, M. Hirota and Y. Tatokoro, "Insulation Properties of Atmospheric Iced Insulators Installed in High Mountains", 6th Int'l. Workshop on the Atmospheric Icing of Structures, Budapest, Hungary, pp. 237-242, 1993.

[11] X. Jiang, C. Sun, L. Shu and W. Sima, "AC flashover performance and voltage of long polluted and iced XP-70 suspension insulator string", IEEE 7th Int'l. Conf. Properties and Applications of Dielectr. Materials, Vol. 1, pp. 158-161, 2003.

[12] L. Shu, C. Sun, J. Zhang and L. Gu, "AC flashover performance on iced and polluted insulators for high altitude regions", 7th Int'l. Sympos. High Voltage Eng., Dresden, Germany, Vol. 4, pp. 303-306, Paper 43.13, 1991.

[13] J. F. Drapeau, M. Farzaneh, M. Roy, R. M. Chaarand and J. Zhang, "An experimental study of flashover performance of various post insulators under icing conditions", IEEE Conf. Electr. Insul. Dielectr. Phenomena (CEIDP), Vol. 1, pp. 359-364, 2000.

[14] L. Shu and F. Mao, “Comparison of the DC Pollution Flashover Performances among Composite Insulators and Porcelain and Glass Insulators”, Proc. Chinese Soc. Electr. Eng., Vol. 27, No. 36, pp. 26-29, 2007 (in Chinese).

[15] A. Meier and W. M. Niggli, “The Influence of Snow and Ice Deposits on Supertension Transmission Line Insulator Strings with Special Reference to High Altitude Operation”, IEE Conf. Publ. 44, London, England, pp. 386-395, 1968.

[16] Q. Hu, L. Shu and X. Jiang, “Effects of Shed Configuration on AC Flashover Performance of Ice-covered Composite Long-rod Insulators,” IEEE Trans. Dielectr. Electr. Insul., Vol. 19, No. 1. pp. 200-208, 2012.

[17] M. Farzaneh, J. Zhang and C. Volat, “Effect of insulator diameter on AC flashover voltage of an ice-covered insulator string”, IEEE Trans. Dielectr. Electr. Insul., Vol. 13, pp. 264-271, 2006.

[18] X. Jiang, Z. Zhang and L. Shu, “Study on Icing of Energized Insulators with AC Service Voltage and Electrical Performance,” IEEE Int’l. Sympos. Electr. Insul., Indianapolis, USA, pp. 335-338, 2004.

[19] M. Farzaneh and J.-F. Drapeau, “AC Flashover Performance of Insulators Covered with Artificial Ice”, IEEE Trans. Power Delivery, Vol. 10, No. 2, pp. 1038-1051, 1995.

[20] IEEE Standard 1783, “Guide for Test Methods and Procedures to Evaluate the Electrical Performance of Insulators in Freezing Conditions”. IEEE Press, New York, USA, 2009.

[21] M. Farzaneh, T. Baker, A. Bernstorf, K. Brown, W.A. Chisholm, C. de Tourreil, J.F. Drapeau, S. Fikke, J.M. George, E. Gnandt, T. Grisham, I. Gutman, R. Hartings, R. Kremer, G. Powell, L.Rolfseng, T.Rozek, D.L. Ruff, D. Shaffner, V. Sklenicka, R. Sundararajan and J. Yu, “Insulator Icing Test Methods and Procedure”, A position paper prepared by the IEEE Task Force on Insulator Icing Test Methods, IEEE Trans. Power Del., Vol. 18, pp. 1503-1515, 2003.

[22] M. Farzaneh, T. Baker, A. Bernstorf, J. T. Burnham, T. Carreira, E. Cherney, W. A. Chisholm, R. Christman, R. Cole, J. Cortinas, C. de Tourreil, J. F. Drapeau, J. Farzaneh-Dehkordi, S. Fikke, R. Gorur, T. Grisham, I. Gutman, J. Kuffel, A. Phillips, G. Powell, L. Rolfseng, M. Roy, T. Rozek, D. L. Ruff, A. Schwalm, V. Sklenicka, G. Stewart, R. Sundararajan, M. Szeto, R. Tay, and J. Zhang, “Selection of Station Insulators With Respect to. Ice and Snow—Part I Technical Context and Environmental Exposure”, IEEE Trans. Power Delivery, Vol. 20, pp. 264-270, 2005.

[23] M. Farzaneh, T. Baker, A. Bernstorf, J. T. Burnham, T. Carreira, E. Cherney, W. A. Chisholm, R. Christman, R. Cole, J. Cortinas, C. de Tourreil, J. F. Drapeau, J. Farzaneh-Dehkordi, S. Fikke, R. Gorur, T. Grisham, I. Gutman, J. Kuffel, A. Phillips, G. Powell, L. Rolfseng, M. Roy, T. Rozek, D. L. Ruff, A. Schwalm, V. Sklenicka, G. Stewart, R. Sundararajan, M. Szeto, R. Tay and J. Zhang, “Selection of station insulators with respect to ice and snow-part II: methods of selection and options for mitigation”, IEEE Trans. Power Delivery, Vol. 20, pp. 271-277, 2005.

[24] Z. Zhang, X. Jiang, J. Hu and C. Sun, “Influence of Icing Degree on Dc Icing Flashover Performance of Composite Insulator”, High Voltage Eng., Vol. 35, No. 10, pp. 2545-2550, 2009 (in Chinese).

[25] CIGRE Task Force 33.04.09, “Influence of Ice and Snow on the Flashover Performance of outdoor insulators Part I: Effects of Ice”, Électra, No. 187, pp. 90-111, 1999.

[26] CIGRE Task Force 33.04.09, “Influence of Ice and Snow on the Flashover Performance of outdoor insulators Part II: Effects of Snow”, Électra, No. 188, pp. 55-69, 2000.

[27] X. Jiang, Z. Zhang and J. Hu, “Equivalence of Pollution Simulation Methods for AC Flashover Performance of Iced Composite Insulator”, Proc. Chinese Soc. Electr. Eng. (CSEE), Vol. 30 No.13, pp. 115-120, 2010 (in Chinese).

[28] M. D. Charneski, G. L. Gaibrois, and B. F. Whitney, “Flashover tests on artificially iced insulators,” IEEE Trans. Power App. Syst., Vol. 101, No. 8, pp. 2429-2433, 1982.

[29] X. Jiang and H. Yi, Ice Accretion on Transmission Lines and Protection. Beijing, China: China Power, 2002 (in Chinese).

[30] C. Sun, W. Sima, and L. Shu, Atmospheric Environment and External Electrical Insulation. Beijing, China, China Power Press, 2002 (in Chinese).

[31] X. Jiang, L. Chen and Z. Zhang, “Equivalence of Influence of Pollution Simulating Methods on DC Flashover Stress of Ice-Covered Insulators”, IEEE Trans. Power Delivery, Vol. 25, pp. 2113-2120, 2010

[32] Y. Deng, Z. Jia and X. Wei, “Mechanism of salt migration in icicles during phase transition and its impact on ice flashover”, IEEE Trans. Dielectr. Electr. Insul, Vol. 19, pp. 1700-1707, 2012.

[33] S.Taheri, M. Farzaneh and I. Fofana, "Influence of air gaps on the DC withstand voltage of ice-covered UHV insulators", IEEE Conf. Electr. Insul. Dielectr. Phenomena, pp. 745-748, 2012

[34] M. Farzaneh, C. Volat and J. Zhang, “Role of air gaps on AC withstand voltage of an ice-covered insulator string”, IEEE Trans. Dielectr. Electr. Insul, Vol. 13, pp. 1350-1357, 2006.

Fanghui Yin was born in Jiangxi Province, China, in May 1983. He received the B.Sc. and M.Sc. degrees from Chongqing University, Chongqing, China, in 2004 and 2008, respectively. He is currently pursuing the Ph.D. degree from the College of Electrical Engineering, Chongqing University. He is presently a Ph.D. degree student at Université du Québec à Chicoutimi (UQAC), Canada, in collaboration with Chongqing University, Chongqing, China. His main research interests include high voltage technology, external insulation and transmission line’s icing.

Xingliang Jiang was born in Hunan Province, China, on 31 July 1961. He received the M.Sc. and Ph.D. degrees from Chongqing University, Chongqing, China, in 1988 and 1997, respectively. His employment experiences include the Shaoyang Glass Plant, Shaoyang, Hunan Province; Wuhan High Voltage Research Institute, Wuhan, Hubei Province; and the College of Electrical Engineering, Chongqing University. His research interests include high-voltage external insulation and transmission line icing and protection. He is the member of working groups of CIGRE B2.29 and IWAIS. Dr. Jiang has published two books and over 180 papers about his professional work. And He received the Second-Class Rewards for Science and Technology Advancement from China in 2005 and 2009; Beijing Government in 1998; Ministry of Education in 1991 and 2001, respectively; the first-class Reward for Science and Technology Advancement from the Ministry of Power in 2004 and 2005; the Second-Class Reward for Science and Technology Advancement from the Ministry of Technology in 2005; the First-Class Reward for Science and Technology Advancement from the Ministry of Education in 2006; and the First-Class Reward for Science and Technology Advancement from Chongqing City in 2006 and 2008, Hunan Province in 2011.

Masoud Farzaneh (M'83-SM'91-F’07) is Director-founder of the International Research Center CENGIVRE, Chairholder of the NSERC/Hydro-Quebec/UQAC Industrial Research Chair CIGELE, and Chairholder of the Canada Research Chair INGIVRE related to power transmission engineering in cold climate regions, at University of Québec at Chicoutimi (UQAC). His field of research encompasses high voltage and power engineering, including the impact of cold climate on overhead transmission lines. He has authored or co-authored about 600 technical papers, and 17 books or book chapters. To date Professor Farzaneh has trained about 130 postgraduate students and postdoctoral fellows. Actively involved with IEEE and CIGRÉ, he was President of IEEE DEIS for 2013, and is member of the Editorial Board of IEEE Transactions on Dielectrics and Electrical Insulation, Convenor of CIGRE WG B2.44 on coatings for protection of overhead lines during winter conditions, as well as member of the Executive Committee of CIGRE Canada. He is Fellow of IEEE, Fellow of The Institution of Engineering and Technology (IET) and Fellow of the Engineering Institute of Canada (EIC). His contributions and achievements in research and teaching have been recognized by several prestigious prizes and awards at national and international levels.