Comparison of AC Flashover Performance of Snow-Accreted Insulators Under Natural and Artificial Simulation Environments

YUYAO HU, XINGLIANG JIANG, SIHUA GUO, AND ZHONGYI YANG

1 College of Electrical and Electronic Engineering, Shandong University of Technology, Zibo 255000, China
2 State Key Laboratory of Power Transmission Equipment and System Security and New Technology, Chongqing University, Chongqing 400044, China
3 State Grid Chongqing Electric Power Research Institute, Chongqing 401123, China

Corresponding author: Yuyao Hu (hyuyao@sdut.edu.cn)

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ABSTRACT The research on snow-accreted insulators has been performed in an artificial climate chamber. However, the differences in the distribution, density and compactness of snow accretion under natural and artificial simulation environments cause differences in the flashover performance of snow-covered insulators. In the present work, a series of flashover tests were conducted on snow-coated glass and silicone rubber insulators in the climate chamber and at Xuefeng Mountain Natural Icing Test Base. The discrepancies in the electrical characteristics and flashover process of snow-covered insulators under two test environments were compared and analyzed. Results show that the arc flashover gradient of snow accreted insulator at high altitude site is higher than that in the laboratory because of the differences of the environmental parameters. Affected by the adiabatic effect and capillary action of snow layer, within the range of the study the flashover gradient of insulators covered with snow increases with the increasing in the snow thickness. The calculation of various forces applied on arcs during its propagation demonstrates that when the arc current is less than 0.2 A, the local arcs develop along the snow surface of the insulators under the action of an electrostatic force. As the current increases beyond 0.2 A, the thermal buoyancy is predominant, thereby causing arcs to levitate from the insulator surface.

INDEX TERMS Snow-covered insulator, flashover gradient, arc propagation, electrostatic force, thermal buoyancy.

I. INTRODUCTION

Insulator is an important facility of transmission lines, so its electrical performance plays a decisive role in the satisfactory reliability of power systems. However, ice and snow accretion on outdoor insulators considerably degrades their electric strength in cold climate regions, which leads to numerous flashover accidents in China and abroad [1]–[4]. That prompts scholars to give a great concern about iced and snow-covered insulators.

A systematic investigation on iced and polluted insulators have been carried out and achieved significant advances in the formation mechanism of ice and pollutant accumulation [5]–[7], electrical properties [8]–[10] and discharge development [11], [12]. However, less attention has been paid to the effect of snow accretion on the external insulation of transmission lines. Hu et al. [13] researched the effect of snow accretion on the various type of the insulators in an artificial climate chamber, and arrived at the conclusion that the relationship between the snow flashover gradient of the insulators and equivalent salt deposit density is a power function with a negative exponent. Jiang et al. [14] found that the DC (direct current) flashover voltage of artificial snow-covered insulator is lower than that of the AC (alternating current). Moreover, for the insulators covered with an uneven snowpack distribution, the discharge developed along the leeward side [15]. The investigation on snow disasters showed that compared with cap and pin insulator, the long rod insulator is more likely to be bridged by snowpack, thereby resulting in leakage current increasing [16]. Zhang et al. [17] pointed out that the water melted from snow wets the pollution on post insulator surface to form a highly conductivity water film, which is a key factor.
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FIGURE 1. Multi-functional artificial climate chamber in the laboratory.

FIGURE 2. Xuefeng mountain natural icing test base.

FIGURE 3. Schematic diagram of flashover tests of snow-accreted insulators.

II. TEST EQUIPMENT, SAMPLES AND PROCEDURES

A. TEST EQUIPMENT

The artificial simulation tests were performed in a climate chamber with a diameter of 7.8 m and a height of 11.8 m (Figure 1). The temperature in the chamber can be as low as –45 °C by adjusting the refrigeration system. The IEC standard nozzles are installed to generate the supercooled water droplets with the diameter of 10–120 µm. The wind speed is adjustable in the range from 0 to 12 m/s.

The field examinations were carried out at Xuefeng Mountain Natural Icing Test Base (Figure 2) with typical microtopography and micrometeorological characteristics, which is the elevation of 1400 m. Icing lasts from October to March of the following year, and the annual precipitation exceeds 1800 mm. The icing duration is up to 50 days, the annual icing frequency is more than 15 times. Therefore, the test base is an ideal place to study ice and snow accretion on transmission lines.

Except that there is no climate chamber and wall bushing for the field test, the schematic diagram of flashover tests of snow-covered insulators under natural and artificial simulation environments is the same, as shown in Figure 3. The power in the chamber is supplied by an AC corona free test transformer with a rated voltage of 500 kV and a rated current of 4 A. The power is the AC source for pollution test in the field. Its rated voltage and current are 300 kV and 2 A, respectively. The rated input voltage is 10 kV and the short-circuit impedance is 7.6%.
FIGURE 4. Profiles of the samples: (a) type A; (b) type B; (c) type C; (d) type d.

TABLE 1. Structural parameters of the samples.

| Type | Materials | H  | D  | L   |
|------|-----------|----|----|-----|
| A    | glass     | 147| 261| 320 |
| B    | glass     | 127| 380| 365 |
| C    | SIR C     | 615| 110/80| 1375| |
| D    | SIR D     | 320| 125/90| 540 |

B. TEST SAMPLES

The samples were four types of the insulators with two different surface materials, which were denominated by glass A, glass B, SIR C and SIR D, respectively. The structural parameters and profiles of the samples are shown in Figure 4 and Table 1, in which H is the structural height, D is the diameter of shed, and L is the creepage distance.

C. TEST PROCEDURES

1) PRETREATMENT OF SAMPLES

In the laboratory, the dirt and grease on the surface of the insulators was cleaned with deionized water, whose conductivity is less than 10 μS/cm.

Limited by conditions on site, deionized water is not available, so the pollutants on the insulators were removed with the groundwater, whose conductivity is less than 20 μS/cm.

For silicone rubber insulators, de-hydrophobic pretreatment was necessary to facilitate their polluting.

2) SAMPLES CONTAMINATION

The solid-layer method was utilized to pollute the insulator surfaces before snow accumulating in the chamber. Conductive and non-conductive materials were simulated with NaCl and Kaolin, respectively. Three different ESDDs were simulated, namely 0.05, 0.10 and 0.15 mg/cm. The ratio of ESDD to non-soluble deposit density was 1:4. The quality of two materials was determined by an electronic analytical balance. Then they were dissolved into deionized water and stirred evenly. The contaminated liquid was coated on the insulator surface with a brush manually.

To facilitate the tests, the dipping method in the field was adopted for contaminating the insulators to obtain the same polluting level as that in the chamber.

3) METHOD FOR SNOW ACCRETION ON THE INSULATORS

The relevant test standards for snow accumulation on the insulators are lack. The improved method that developed from the method proposed by Yaji et al. [22] was adopted. In [22], the artificial snow was generated, and then coated on the surface of the insulators by spraying manually. However, snowmaking and its accretion were conducted simultaneously in this study. The detailed test procedures are as follows [23], [24]. First, the insulators were suspended at a predetermined position in the chamber and water conductivity was adjusted to approximate 80 μS/cm. Second, the cooling system was turned on to stabilize the temperature at −9℃ to −13℃. Then the sprinkling and speed regulation systems were turned on. The wind speed was controlled at about 3 m/s. The diameter of sprayed water droplets was in the range of 10 to 20 μm and then coated on the insulators in the form of snowflakes. Third, when snow accretion on the insulator met the requirements, the cooling, sprinkling and speed regulation systems were turned off.

In the field, before the snowfall was approaching, the pre-treated insulators were hung on the test stand, and natural snowfall accreted on the insulator surface. If natural snowfall accumulation did not reach the required thickness, a manual coating was used to meet the test requirements.

4) FLASHOVER TESTS OF SNOW ACCRETED INSULATORS

After snow accretion on the insulators was completed, AC voltage was applied to obtain the minimum flashover voltage of snow-covered insulators by using the U-type method [25].

III. COMPARISON OF ELECTRICAL PERFORMANCE OF SNOW-ACCRETED INSULATORS IN THE CHAMBER AND IN THE FIELD

A. VISUAL OBSERVATION OF SNOW ACCRETION ON THE INSULATORS IN THE CHAMBER AND ON SITE

Figure 5 shows the appearances of snow-covered insulators in an artificial climate chamber and on site.

In Figure 5, the amount of the snowpack on the windward side of the insulators is greater than that on the leeward
side under two different environments. The reasons can be explained by the following. Natural icing test base is a mountain pass type with a fixed wind direction in the winter. And the wind direction in the chamber is also fixed. Once the viscous fluid encounters obstacle like the insulator, its velocity is attenuated rapidly because of the blocking effect, and a boundary layer forms on the insulator surface. While the airflow blows towards the windward side of the insulator, its velocity is stratified. And the velocity within the boundary layer is much smaller than the inflow speed (Figure 6(a)). Therefore, in an environment convenient for snow accretion, when the snow particles move to the vicinity of the insulator with the airflow, their velocity decreases significantly because of the viscous effect of the airflow. The particles separated from the airflow collide with the windward side of the insulator and accumulate to form snowing. Meanwhile, the airflow through the leeward side flows backwards and a reflux vortex is observed because of the influence of backpressure gradient and fluid viscosity stagnation (Figure 6(a)). Affected by the backflow vortex, the particles accrete on the leeward side. From the particle trajectories shown in Figure 6(b), it is concluded that almost all the particles terminate in the rod and the shed facing the direction of the inflow. However, on the two sides that deviate from the direction of the incoming flow, the particles easily bypass the insulator with the air flow, which is not conductive to snow accreting. Therefore, the snow accumulation on the insulators is non-uniform.

B. INFLUENCE OF THE ESDD ON THE ELECTRICAL PERFORMANCE OF SNOW-COVERED INSULATORS

Snow accretion on the insulator can be considered as a special type of icing. Hence, the flashover voltage of snow-covered insulators as a function of the ESDD can be depicted by the following equation [13]:

$$U_f = A \times \text{ESDD}^{-n}$$  \hspace{1cm} (1)

where $U_f$ is the minimum flashover voltage of snow-covered insulator. $A$ is a constant coefficient related to the material and structure of the insulator. $n$ is an exponent describing the influent degree of the ESDD on $U_f$.

The results obtained in the chamber and on site cannot be compared directly because of the difference in altitude. The flashover voltage obtained in the field are corrected to that corresponding to an altitude of the chamber [26]:

$$\frac{P_N}{P_A} = \left( \frac{1 - H_N/45.1}{1 - H_A/45.1} \right)^{5.36}$$  \hspace{1cm} (2)

$$U_C = \frac{U_f}{(P_N/P_A)^{n_0}}$$  \hspace{1cm} (3)

where $P_N$ and $P_A$ are the pressure of the test base with an altitude of $H_N$ and the pressure of the chamber with an altitude of $H_A$, respectively. $U_C$ is corrected voltage. $n_0$ is the influence coefficient of air pressure on $U_f$. The preceding studies indicate that the values of $n_0$ for glass and silicone rubber insulators are approximate 0.5 [25]. Therefore, $n_0$ is taken as 0.5 in this paper.

To compare the flashover characteristics of the insulators with different structural configurations and leakage distances, an average arc flashover gradient is introduced to describe the electrical performance of snow-accreted insulators:

$$E_L = U_C / L = a \times \text{ESDD}^{-n}$$  \hspace{1cm} (4)
where $E_L$ is the average arc flashover gradient. $L$ is the leakage distance of the insulator.

$$a = \frac{A}{(P_N/P_A)^{n/\delta}}/L \quad (5)$$

The flashover tests of snow-covered insulators were investigated to analyze the differences of the flashover characteristics in different environmental conditions. The results were fitted according to equation (4), as shown in Figure 7, where the thickness is 10 mm and ESDD is 0.05, 0.10 and 0.15 mg/cm$^2$. The fitted values of $a$, $n$ and $R^2$ are listed in Table 2, in which $R^2$ is the determining coefficient indicating the correlation between the data and the formula.

The following conclusions can be drawn from Figure 7 and Table 2.

(1) The data has a high degree of fitting, and the error bar is within 8%. Therefore, the relationship between the AC arc flashover gradient and the equivalent salt deposit density is a power function with a negative exponent under two test environments.

(2) For the tested insulators, the $E_L$ obtained in the field is higher than that determined from the chamber under the same pollution level. Taking silicone rubber insulator for instance, when the ESDD is 0.10 mg/cm$^2$, the arc gradients are 69.2 kV/cm and 66.6 kV/cm under the two test environments, respectively. The former is 3.90% higher than the latter. And the gap reaches 4.51% for a glass insulator.

C. INFLUENCE OF SNOW THICKNESS ON THE ELECTRICAL PERFORMANCE OF SNOW-COVERED INSULATORS

Figure 8 shows the arc flashover gradient of snow-accreted insulators in an artificial climate chamber and on site, where snow thicknesses are 10, 20 and 30 mm, respectively, and the ESDD is 0.02 mg/cm$^2$. The water conductivity applied for snowing is 80 µS/cm in the chamber and this is less than 20 µS/cm in the field.

(1) In the range of our study, the arc flashover gradient increases with the increase of snow thickness whether under natural conditions or under the laboratory environment.

(2) There are two reasons for this. On one hand, the pollution on the insulator surface is dissolved into the water melted from snow to form a conductive water film, thereby reducing the residual resistance. However, the snow layer has a thermal insulation effect. Therefore, the thicker the snow layer on the insulator is, the harder it will melt. On the other hand, the snow layer is a porous medium with a capillary effect. The melted water may be partially absorbed by the snow layer. A thicker snow layer corresponds to absorbing more melted water. In this way, the power supply is required to provide more energy to make the melted water pass through the snow layer, thereby dissolving the pollution on the surface of the insulator. Therefore, the flashover voltage of snow accreted insulators is high for a thicker snowpack.

(3) However, the variation of flashover gradient with snow thickness is inconsistent with the results of silicone rubber insulators in [13], which is explained as follows. The distance between the adjacent sheds of silicon rubber insulator is much smaller than that of glass insulator. Snow accretion significantly changes its structure, resulting in the leakage distance not being effectively utilized, thereby reducing the flashover voltage.

(4) For the two types of tested insulators, the arc flashover gradient of artificial snow accretion is lower than that of natural snowfall at the same thickness. Taking glass B insulator for instance, when the thickness is 20 mm, the $E_L$ of
IV. ARC PROPAGATION ALONG THE SNOW-COVERED INSULATORS

A. FLASHOVER PROCESS OF AN INSULATOR COVERED WITH THE ARTIFICIAL SNOW IN THE CHAMBER

The discharge along the surface of the snow-covered insulator is a complex thermodynamic process related to snow melting, gas ionization, and generation and development of the local arc. To study the discharge mechanism in depth, the flashover process of snow-covered glass A insulator was recorded by a high speed camera in an artificial climate chamber, as shown in Figure 9, where the ESDD is 0.05 mg/cm\(^2\) and snow thickness is 10 mm.

From Figure 9, the following conclusions can be concluded.

1. As the applied voltage increased, the discharges first occurred at high-voltage end due to a relatively high current density (Figure 9(a)). Subsequently, the obvious discharges appeared on the lower surface of each insulator (Figure 9(b)). Moreover, their position was random.

2. The discharges on the lower surface of the sheds mainly propagated along the leakage distance of the insulator with the increasing applied voltage, and gradually transformed into a white arc with a small diameter bridging the gap between adjacent sheds (Figure 9(c)). Furthermore, as the density of arc current increased, the diameter of the white arc became larger and its brightness was brighter (Figure 9(d)).

3. At the moment of the flashover, the arc temperature was as high as 5000–6000 °C [27]. Thus, the air gap inside snow layer expanded sharply, causing snowpack to fall off the insulator in an explosive manner, as shown in Figure 9(e)–(f).

B. FLASHOVER PROCESS OF THE INSULATORS COVERED WITH NATURAL SNOWFALL IN THE FIELD

For comparison, the flashover tests were performed on the silicon rubber and glass insulators covered with natural snowfall at Xuefeng Mountain Natural Icing Test Base and the flashover processes are shown in Figure 10 and Figure 11, where the thickness is 10 mm and the ESDD is 0.05 mg/cm\(^2\).

From Figure 10 and Figure 11, the conclusions can be summarized as follows.

1. Compared with the discharges in Figure 9, the arc diameter during the flashover of snow-covered insulators in the field is larger with the following explanation. The decrease in air pressure reduces air density at high altitude, resulting in poor thermal conductivity of the air. When the accumulated heat is sufficient to induce thermal ionization, then the air around the arc changes from an insulated state to a conductive state, thereby increasing the cross-sectional area of the arc.

2. According to the observation of the discharge phenomena during the flashover on site, the development of the local arcs does not propagate along the insulator surface, but deviate from the surface to form a arc levitation phenomenon. Taking glass A as an example, the distinct yellow arcs occurred on each insulator with the increasing applied voltage and they were tightly attached to the insulator (Figure 10(b)). These arcs consisted of two parts. One was on the upper surface of the insulator and the other was on the lower surface. As extending, all arcs on the upper surface float away from the insulator, while others on the lower surface still cling to the insulator (Figure 10(c)). Once the arc floating formed, the obvious discharge traces were observed at the arc channel. When the arcs on the second and third insulators developed to contact each other, the arc on the lower surface of the second insulator disappeared instantly, thereby forming a single arc discharge channel (Figure 10(d)–(e)). As the applied voltage continued to rise, the newly formed arc and the arc on the first insulator elongated, and then the two arcs were connected to form a complete arc (Figure 10(f)). Except that the arc on the lower surface of the third insulator was close to the surface, the rest floated in the air. An arc levitation was also observed in the flashover process of the silicon rubber insulator. However, there is no arc floating during the discharge of snow-covered insulators in the chamber.

3. The arc levitation phenomenon can be explained as follows. The arcs on the insulator surface are mainly affected by electrostatic force, electromagnetic force and thermal
buoyancy during the development of discharges [28]:

\[
\begin{align*}
F_e &= \varepsilon_0 E^2 r_a^2 / 2 \\
F_m &= \mu_0 r_a^2 [I/(2\pi r_a)]^2 / 2 \\
F_t &= \rho g (\pi r_a^2) r_a
\end{align*}
\]  

(6)

where \(F_e\), \(F_m\) and \(F_t\) represent electrostatic force, electromagnetic force and thermal buoyancy, respectively. \(\varepsilon_0\) is the permittivity of vacuum. \(E\) is the electric field strength of the arc root. \(r_a\) is the arc radius. \(\mu_0\) is the permeability of vacuum. \(I\) is the arc current. \(\rho\) is the air density. \(g\) is the gravitational acceleration.

The results showed that for a snow-covered insulator, the relationship between the arc current and its radius can be expressed as [20]:

\[
r_0 = \sqrt{\frac{I}{2.439\pi}}
\]

(7)

where \(r_0\) is the arc radius.

The arc radius increases with the decreasing air pressure, which can be expressed as follows [29]:

\[
r_a = \sqrt{\frac{I}{2.439\pi}} \left(\frac{P}{P_0}\right)^{-0.465}
\]

(8)

where \(P\) is the pressure at high altitude and \(P_0\) is the standard atmospheric pressure.

Considering the influence of the pressure on the electric field, the relationship between the arc gradient and the current can be approximated by the following equation [21], [25]:

\[
E = 100.25 \times \left(\frac{P}{P_0}\right)^{0.5} \times I^{-0.66}
\]

(9)

The pressure as a function of the altitude can be depicted by the following [25]:

\[
\frac{P}{P_0} = \left(1 - \frac{H}{45.1}\right)^{5.36}
\]

(10)

Substituting equations (7)–(10) into equation (6) yields the following formulas:

\[
\begin{align*}
F_e &= 5.807 \times \left(\frac{P}{P_0}\right)^{0.07} \times I^{-0.32} \times 10^{-9} \\
F_m &= 1.592 \times I^2 \times 10^{-8} \\
F_t &= 1.880 \times \frac{293}{273 + t} \times \left(\frac{P}{P_0}\right)^{-0.395} \times I^{1.5} \times 10^{-6}
\end{align*}
\]

(11)

The temperature of the partial arc during the discharge development is generally 5000–6000 °C, resulting in a
FIGURE 12. The relationship between the forces applied to the arc and arc current.

FIGURE 13. The relationship between the magnitude and direction of the comprehensive forces applied to the arc and arc current.

sharply increase in the temperature of the surrounding air. From equation (11), the thermal buoyancy decreases as the temperature increases. Assuming that the air temperature around the arc is basically the same as that of the arc, the arc is considered to be 5000 °C [27], and the forces are calculated by equation (11), as shown in Figure 12.

In Figure 12, when the arc current is less than 0.2 A, the electrostatic force dominates. Otherwise, the thermal buoyancy is predominant. Compared with electrostatic force and thermal buoyancy, the electromagnetic force applied to the arc is relatively small, hence, it can be ignored. Therefore, the combined force of electrostatic force ($F_e$) and thermal buoyancy ($F_t$) is defined as comprehensive ($F_c$) and the angle between $F_e$ and $F_c$ is defined as $\theta$.

The magnitude and direction of $F_c$ during the development of the partial arc varies with the current, as shown in Figure 13.

When the obvious local arcs just form, the electrostatic force plays a leading role. Since its direction is approximately paralleled to the surface of the insulator, the partial arc extends and develops along the insulator. As the applied voltage increases, the arc current increases. The thermal buoyancy dominates, and its direction is approximately perpendicular to the insulator, which causes the local arcs on the lower surface to cling to the insulator, however, the arcs on the upper surface float away from the insulator, forming an obvious arc floating phenomenon.

V. DISCUSSION AND ANALYSIS

In this paper, the insulator covered with natural snowfall was performed at Xuefeng Mountain Natural Icing Test Base with an altitude of 1400 m. The altitude of artificial climate chamber is 232 m. Because of the low air pressure and low air density at high altitudes, the local arc dissipates less heat due to air convection. In addition, from Section IV the arc levitation is observed during the flashover of snow-accreted insulators in the field, thereby causing the creepage distance not being effectively utilized. As a result, the flashover voltage of snow-covered insulator at high altitudes should be lower than that in the chamber. However, the results are reversed for the following explanation.

A. DIFFERENCES IN ENVIRONMENTAL PARAMETERS DURING THE SNOW ACCRETION TESTS

Environmental parameters, including temperature, humidity and wind speed, et al., are controllable constants in the artificial climate chamber. However, they are uncontrollable in
the natural environment and fluctuate within a small range in a short period of time, resulting in differences in the distribution, density and compactness of the snowpack between natural test and artificial simulation, as shown in Figure 14.

B. DIFFERENCES IN ENVIRONMENTAL PARAMETERS DURING THE FLASHOVER TESTS

The ambient temperature is constant and the wind speed is 0 in the flashover process of the insulators covered with the artificial snow. However, the temperature fluctuates and the wind speed varies in the field, as shown in Figure 15. The electrons generated by the discharges accelerate to diffuse under the action of wind, which affects the extension and development of the arcs on the surface of the insulators.

VI. CONCLUSION

1. When viscous fluid encounters obstacles, a boundary layer forms. Its internal velocity is very low, which is conductive to snow accumulation on the insulators. Due to the fixed wind direction, the amount of snow accretion on the windward side is greater than that on the leeward side under natural and artificial simulation environments.

2. For the tested insulators, the arc flashover gradient of snow-covered insulators in the chamber is lower than that on the leeward side under natural and artificial simulation environments.

3. The arc current is less than 0.2 A, the electrostatic force in the direction parallel to the insulator dominates, causing the arc attaching to the insulator surface tightly. With the increase of the current, the thermal buoyancy in the direction perpendicular to the insulator plays a major role, and then the arc floating forms. Compared with the above two forces, the electromagnetic force is so small that it can be ignored in the study of the discharge development of snow-covered insulators.

4. Due to the difference of environmental parameters between the climate chamber and the site, the distribution, interlaminar alternation and compactness of artificial snow accumulation on the insulator are not equivalent to those of natural snowfall accretion, which results in the difference of the electrical performance of snow-covered insulators under the two test environments. Therefore, more attention should be paid to studying their equivalence to provide the best design reference for the external insulation of transmission lines in snowy regions.

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