

Received March 9, 2020, accepted March 29, 2020, date of publication April 6, 2020, date of current version October 7, 2020.

Digital Object Identifier 10.1109/ACCESS.2020.2986167

Influence of Crystallization Effect During Icing Water Phase Transition on the Flashover Characteristics of Ice-Covered Insulators

YUYAO HU¹, XINGLIANG JIANG², ZHONGYI YANG², AND XINGBO HAN²

¹College of Electrical and Electronic Engineering, Shandong University of Technology, Zibo 255000, China

²State Key Laboratory of Power Transmission Equipment and System Security and New Technology, Chongqing University, Chongqing 400044, China

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

This work was supported by the National Natural Science Foundation of China under Grant 51907109.

ABSTRACT The crystallization effect during the phase transition of icing water has a significant impact on the electrical performance of an ice-covered insulator. However, the spatial distribution of conductive ions in the ice layer remains poorly understood. In this study, the crystallization effect was confirmed through a condensation test of the potassium permanganate solution. The influence of freezing water conductivity, ice thickness and equivalent salt deposit density on the spatial distribution of conductive ions was determined by a triangular ice sample, wherein the effect on the flashover characteristics of ice-covered insulator was investigated. Results show that MnO_4^- migrates to the unfrozen area during freezing, thus accumulating on the droplet top. The conductivity of melted water on the exterior surface of an ice sample is considerably higher than that of icing water. The former can reach a maximum of 5.7 times the latter when the freezing water conductivity method is adopted. This value is 9.7 for a polluted ice sample. A highly conductive water film forms on the insulator surface because of the crystallization effect in the melting period, thereby improving the leakage current and reducing the residual ice resistance, which results in the decrease of flashover voltage.

INDEX TERMS Crystallization effect, icing water, ice-covered insulator, leakage current, flashover voltage.

I. INTRODUCTION

Ice flashover is one of the major events that threatens the safe and stable operation of power systems. Many reports on power outages caused by icing in overseas have emerged [1]–[3]. China is a country that is prone to severe icing. Since the first ice accident was recorded in the power grid in 1954, thousands of failures on transmission lines due to ice have occurred. On January 24, 2018, an ice-snow storm similar to what happened in 2008 swept most of the power grids in southern China. Failures such as tower collapse, disconnection, and flashover shutdown occurred in many provinces [4]–[6].

Ice accidents occur with uncontrollability and extreme difficulty of emergency treatment, which has prompted scholars to explore various solutions to these issues. Significant breakthroughs have been achieved in the icing growth model [7]–[9], icing monitoring and formation

mechanism [10]–[11], and flashover characteristics of the insulators [12]–[14]. Natural icing observation stations and test sites have been established [15]–[16], which helps in investigating power system icing.

A highly conductive water film can be found on the surface of the ice-covered insulator during melting, which is the prerequisite for a flashover. The water film with high conductivity originates from the crystallization effect, that is, the conductive ions that dissolve in icing water are excluded to the outer surface of the ice layer in the freezing process. Extensive research on these issues have been conducted at home and abroad. Porkar and Farzaneh [17] established a multi-physical model that includes heat transfer, hydrodynamics and Joule heat to obtain a numerical solution of water film conductivity on the ice surface of the insulator. Deng *et al.* [18] proved that the salt distribution in the ice layer is changed by the salt migration in the crystallization process, which caused the increasing leakage current in the melting process. Studies by Jiang *et al.* [19] showed that ion migration is related closely to applied voltage, and that the

The associate editor coordinating the review of this manuscript and approving it for publication was Boxue Du.

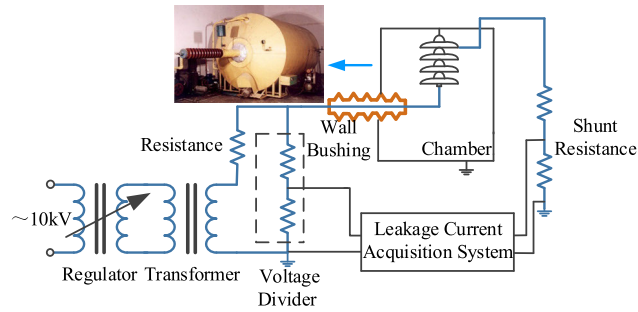


FIGURE 1. Schematic diagram of the flashover test.

extent of ion migration decreases with the increasing electric field strength. Farzaneh *et al.* [20]–[21] developed a linear relationship between water film conductivity and icing water conductivity by using an ice sample. The AC (alternating current) and DC (direct current) flashover models of iced insulators were also established.

Although the preceding studies show that the conductivity of the water film on the insulator surface is higher than that of applied water, the spatial distribution of the conductive ions in a solid ice layer and the migration of ions dissolved in the cooling water during the phase transition still needs to be further studied. Hence, the condensation test of the potassium permanganate solution was carried out to visualize the migration of conductive ions during the phase transition. To avoid the difficulties caused by various ice appearances and uneven ice distribution on the insulator surface, a triangular ice sample was adopted to analyze the effects of freezing water conductivity (σ_{20}), equivalent salt deposit density (ESDD) and ice thickness (d) on the crystallization effect of icing water. Flashover tests were conducted to investigate the influence of the crystallization effect on the electrical performance of an ice-covered insulator. An in-depth study of the source, the distribution and the changing trend of ions in the ice layer during de-icing will deepen the understanding of the flashover mechanism of the iced insulator.

II. TEST EQUIPMENT, SPECIMENS AND PROCEDURES

A. TEST EQUIPMENT

All icing and flashover tests were performed in an artificial climate chamber with a diameter of 2.0 m and a length of 4.0 m. The temperature in the chamber can be as low as -36 ± 1 °C. The diameter of the water droplet ranges from 10 to 120 μm . The wind speed ranges from 0 to 12 m/s, which fulfills the requirements of the icing test [22]. The schematic diagram of the flashover test is shown in Fig. 1. The power supply with a rated voltage of 150 kV and a rated current of 6 A comprises the YDJ-900/150 test transformer and TDJY-1000/10 voltage regulator.

B. SPECIMENS

Determining the distribution of the conductive ions using ice-covered insulators because of various appearances and distributions of ice in the climate chamber and the field is difficult, as shown in Fig. 2. Therefore, an ice sample formed by a

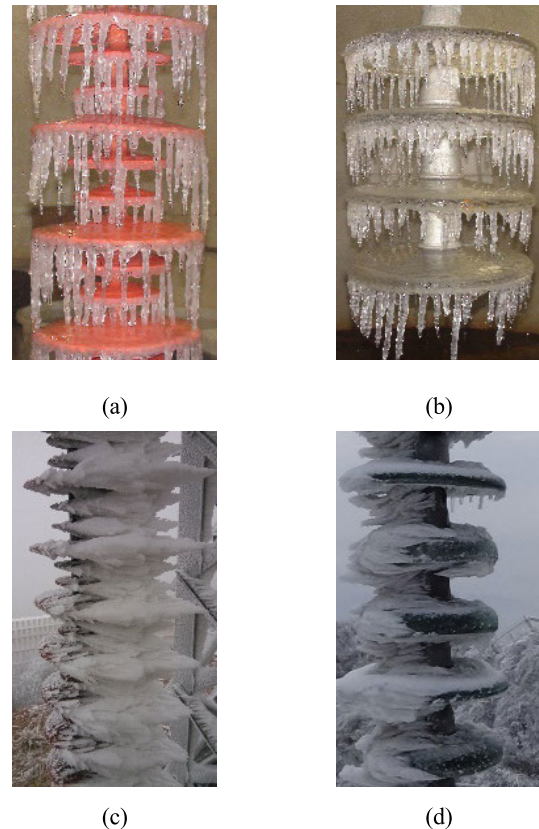


FIGURE 2. Appearances of ice-covered insulators: (a) Composite insulator in the chamber; (b) Glass insulator in the chamber; (c) Composite insulator in the field; (d) Glass insulator in the field.

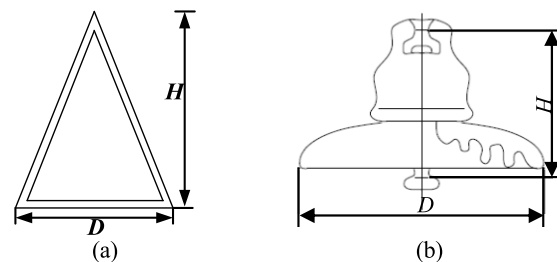


FIGURE 3. Structure diagram of specimens: (a) Triangular glass mold; (b) Porcelain insulator.

triangular glass model was proposed by the NSERC/Hydro-Quebec Industrial Chair on the Atmospheric Icing of Power Network Equipment (CIGLE) (Fig. 3(a)), whose height (H) and base (D) is 280 mm and 200 mm, respectively, with a uniform ice distribution to investigate the spatial distribution of the conductivity.

Three pieces of porcelain insulators per string were selected as specimens (Fig. 3(b)). The structural parameters are as follows. The diameter (D) of the shed is 280 mm. The height (H) is 170 mm. The creepage distance is 405 mm.

C. TEST PROCEDURES

1) TWO METHODS FOR ICING

The triangular ice samples were prepared by two methods (freezing water conductivity and solid-layer methods)

to investigate the effect of σ_{20} and ESDD on the spatial distribution of conductive ions in the ice layer [23]–[24]. The first method is that ice on the insulator was formed by three conductivities of 100, 300 and 500 $\mu\text{S}/\text{cm}$ obtained by adding NaCl to deionized water. All conductivity values in this paper were corrected to 20 °C. The second method is that the insulator surface was covered with a thin layer of pollutant before icing. The conductive and non-conductive materials in the contamination layer were simulated with NaCl and Kaolin, respectively, to obtain three different pollution levels of 0.05/0.30, 0.08/0.48 and 0.15/0.90 mg/cm^2 .

2) SPECIMENS ICING

The test procedures for insulator icing are described in [24]–[25]. Experimental studies show that ice is formed layer by layer in the crystallization process of freezing water. Therefore, controlling the water flow reasonably is necessary to generate qualified triangular ice samples. If the flow of water is excessively, the ice layer will not match the actual situation. On the contrary, it could not guarantee that the conductive ions in the water have sufficient time to migrate before freezing. Because of this, the water flow rate was controlled at 3 min/mm by a valve.

3) ICE-MELTING EXPERIMENT

To analyze the spatial distribution of ions in the ice layer, the triangular ice samples were melted and the conductivity of melted water (γ_{20}) was measured. The test procedures are as follows. (a) The ice sample was taken out of the climate chamber and placed in a constant temperature environment. Assuming that the heat flux on the surface of the sample was uniform, the melting rate of ice was consistent. (b) After heating for 10 min, the sample melted from the outside to the inside. The melted water droplets were collected by a funnel, and then dropped into a 100 mL graduated cylinder. Subsequently, the graduated cylinder was taken out to measure the conductivity and the temperature of melted water and replaced it with a new one every 4 min. (c) The melting test was incomplete until the sample melted completely.

4) FLASHOVER TESTS

In the ice-melting period, the flashover voltage and leakage current of the ice-covered insulator were obtained by using the uniform boost method [24]. A container was placed under the iced insulator to collect the melted water during flashover, and their conductivity and temperature were measured.

III. DROPLET FREEZING AND CONDUCTIVE IONS MIGRATION

To visually demonstrate conductive ions movement during the droplet freezing, potassium permanganate solution was used instead of deionized water to observe the permanganate ion (MnO_4^-) migration in the present study. The schematic is shown in Fig. 4.

The test steps are as follows. First, the temperature of the climate chamber was cooled to approximately $-5\text{ }^\circ\text{C}$. Then,

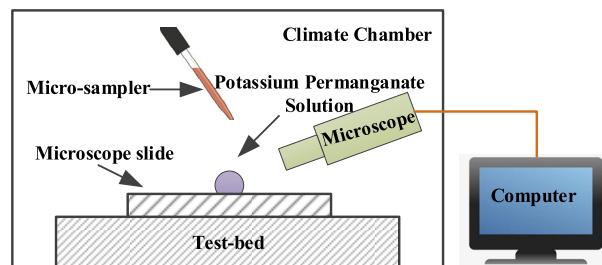


FIGURE 4. Diagrammatic sketch of test setup.

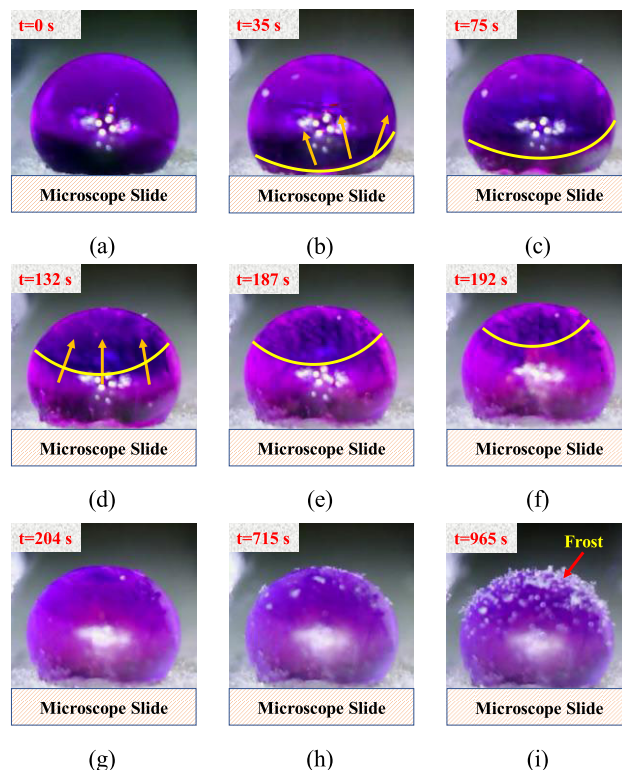


FIGURE 5. Droplet freezing and conductive ions migration.

the potassium permanganate solution with a concentration of 1:5000 was siphoned by a 10 μL micro-sampler to form the droplet on a microscope slide. Finally, a microscope with a pre-adjusted position was utilized to record the freezing process. Fig. 5 shows the time sequence of the acquired images of a freezing droplet after it impinged onto a frozen microscope slide.

The following conclusions can be drawn from Fig. 5:

1) When the droplet contacted the microscope slide, whose temperature was lower than 0 °C, the droplet did not freeze immediately but remained supercooled. At this time, the droplet was still transparent. As the heat exchange rate between the droplet and the slide is faster than that with the environment, the droplet freezing started from the solid-liquid interface on its bottom edge at 35 s (Fig. 5(b)). The golden arrow represented the freezing direction.

2) As shown by the yellow line in Fig. 5, a clear concave interface could be observed in the freezing process.

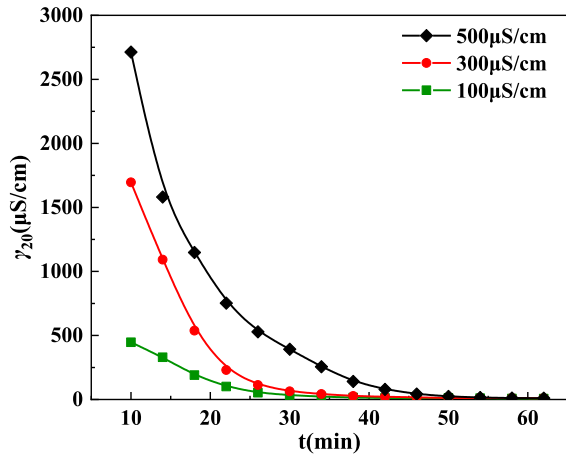


FIGURE 6. Relationship γ_{20} between and t under different σ_{20} .

The portion of the droplet near the slide was solid, the other portion is liquid, and the inside of the droplet was a mixed state. While time went by, MnO_4^- in the droplet migrated (Fig. 5(c)–(f)). That is, as the concave interface advanced toward the top of the droplet, ions gradually gathered, which proves that the crystallization effect does exist during the freezing process of the droplet.

3) Once the droplet was frozen completely to form an ice bead, its temperature dropped to the same temperature as the slide, and then remained the same. The ice bead became muddy (Fig. 5(g)). The apparent frost generated by humid air condensation adhered to the surface of the ice bead after 965 s (Fig. 5(h)–(i)). Therefore, when studying the distribution of ions, taking out the triangular ice samples from the chamber in time is necessary to avoid the frost from affecting the results.

IV. SPATIAL DISTRIBUTION OF CONDUCTIVE IONS IN A TRIANGULAR ICE SAMPLE

A. INFLUENCE OF FREEZING WATER CONDUCTIVITY ON THE DISTRIBUTION OF IONS

Fig. 6 shows the time change in melting water conductivity (γ_{20}), where the ice thickness (d) is 10 mm, and applied water conductivity (σ_{20}) is 100, 300 and 500 $\mu S/cm$, respectively.

In Fig. 6, the melting water conductivity decreases with the increasing melting time for three freezing water conductivities. The relationship between them is nonlinear, which is consistent with the results obtained by Zhang *et al.* [26]. A higher σ_{20} corresponds to a higher γ_{20} . When σ_{20} is 100, 300 and 500 $\mu S/cm$, the maximum values of γ_{20} are 4.5, 5.7 and 5.4 times the conductivity of icing water, respectively. The melting water conductivity presents a significant decline as time passes. The γ_{20} values are 101, 231 and 752 $\mu S/cm$ after melting for 22 min. Compared with the initial values, they decrease by 77.4%, 86.4% and 72.3%, respectively. Subsequently, the conductivity drops slowly to a low level. Apparently, the ion migration occurs during the phase transition of icing water from the liquid phase to the solid phase, resulting in a considerable number of

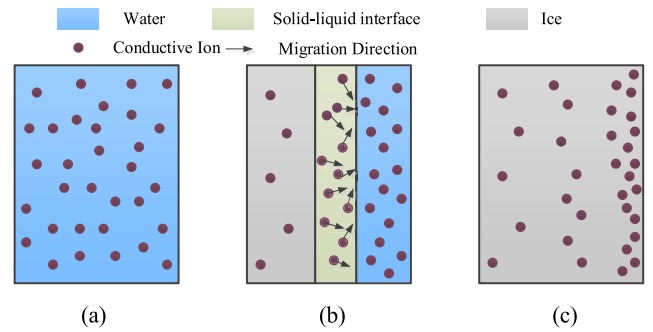


FIGURE 7. Migration of conductive ions during the crystallization of icing water: (a) Liquid phase; (b) Solid-liquid mixed phase; (c) Solid phase.

conductive ions accumulating on the outer surface of an ice sample.

The migration of conductive ions during the phase transition can be illustrated in Fig. 7. The formation of the ice layer goes through three stages, namely, liquid, solid-liquid mixed, and solid phase. The flow in the liquid phase is weak at a low crystal growth rate and the migration is considered diffusion-controlled mass transfer process. Consequently, when the temperature of the icing water is lower than the phase change temperature, ice crystals start to set in at the solid-liquid interface based on the preceding study in Section III. The aqueous solution tends to freeze in the form of pure water, thereby causing conductive ions in icing water repelling to the unfrozen water in the front of the solid-liquid interface. As the interface advances, ions continue to diffuse into the liquid phase under the action of temperature gradient and concentration gradient. Once the speed of the ions diffusion is lower than that of the interface advancing, a part of the ions is frozen in the solid phase, as shown in Fig. 7(b). As the interface moves forward, the ion concentration in the liquid phase increases until the ions released at the interface are equivalent to that carried away by the diffusion. As time passes, ions are gradually accumulated in a small volume of the liquid water and are forced to gather there because they cannot diffuse. The freezing water is frozen completely at this time. Therefore, the highest ion concentration occurs on the surface of the ice layer, as shown in Fig. 7(c).

B. INFLUENCE OF ICE THICKNESS ON THE DISTRIBUTION OF IONS

The relationship between melting water conductivity and time is shown in Fig. 8, where σ_{20} is 500 $\mu S/cm$ and d is 5, 10 and 20 mm, respectively.

The results in Fig. 8 indicated that the following:

1) The melting water conductivity decreases over time at the same freezing water conductivity but with different ice thickness. The ion concentration on the outer surface of the ice sample is high but is low on the inner surface.

2) Ice thickness affects ion migration. When d is 5, 10 and 20 mm, the number of measured points in Fig. 8, whose values are higher than icing water conductivity of 500 $\mu S/cm$, are 2, 5 and 10, respectively, accounting for 22.2%, 35.7%

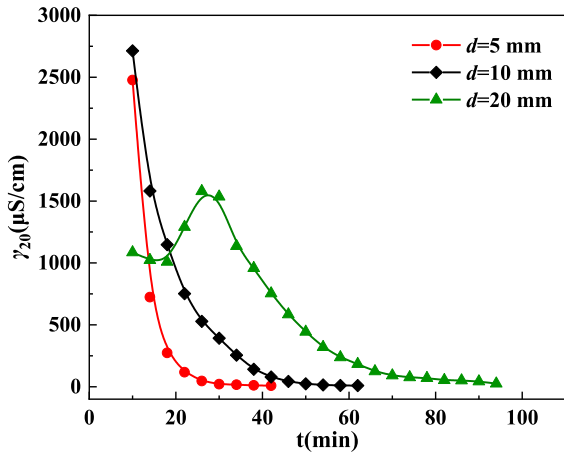


FIGURE 8. Relationship γ_{20} between and t under different d .

and 45.5% of the total number of measurements. Therefore, the thinner the ice thickness, the more ions are likely to migrate to the outer surface of the ice. Conversely, a part of the ions is frozen in the solid phase at a thicker ice thickness because they migrated slower than the solid-liquid interface advancing forward. Thus, the ion distribution is relatively uniform.

C. INFLUENCE OF ESDD ON THE DISTRIBUTION OF IONS

The time change of the melting water conductivity is shown in Fig. 9, where the σ_{20} is $120 \mu\text{S}/\text{cm}$, d is 12 mm, and ESDD is 0.05, 0.08 and $0.15 \text{ mg}/\text{cm}^2$, respectively.

In Fig. 9, the conclusions can be summarized as follows:

- 1) When the mold surface is polluted by contamination, the melting water conductivity on the outer surface of the ice layer is far greater than that on the inner surface. The maximum conductivity is 9.7 times that of freezing water.
- 2) Conductivity decreases gradually as melting time increases. However, it increases slightly at the interface between the mold surface and the ice layer in which the surface pollutant of the mold and ions in the ice layer is dissolved in melted water, causing an increase in the conductivity.

V. INFLUENCE OF CRYSTALLIZATION EFFECT ON FLASHOVER PERFORMANCE OF ICE-COVERED INSULATOR

A. INFLUENCE OF CRYSTALLIZATION EFFECT ON THE LEAKAGE CURRENT

Fig. 10 shows the time change of a typical leakage current waveform during the flashover of the ice-covered insulator under an icing water conductivity of $300 \mu\text{S}/\text{cm}$, where the ice thickness is 10 mm. Fig. 11 shows the variation of leakage current over time with a period of 1.8 s–2.3 s in the flashover process to analyze the influence of the crystallization effect under three conductivities.

In Fig. 10, the leakage current during the flashover of the iced insulator increases gradually with the increasing applied voltage. Moreover, the leakage current flowing through the

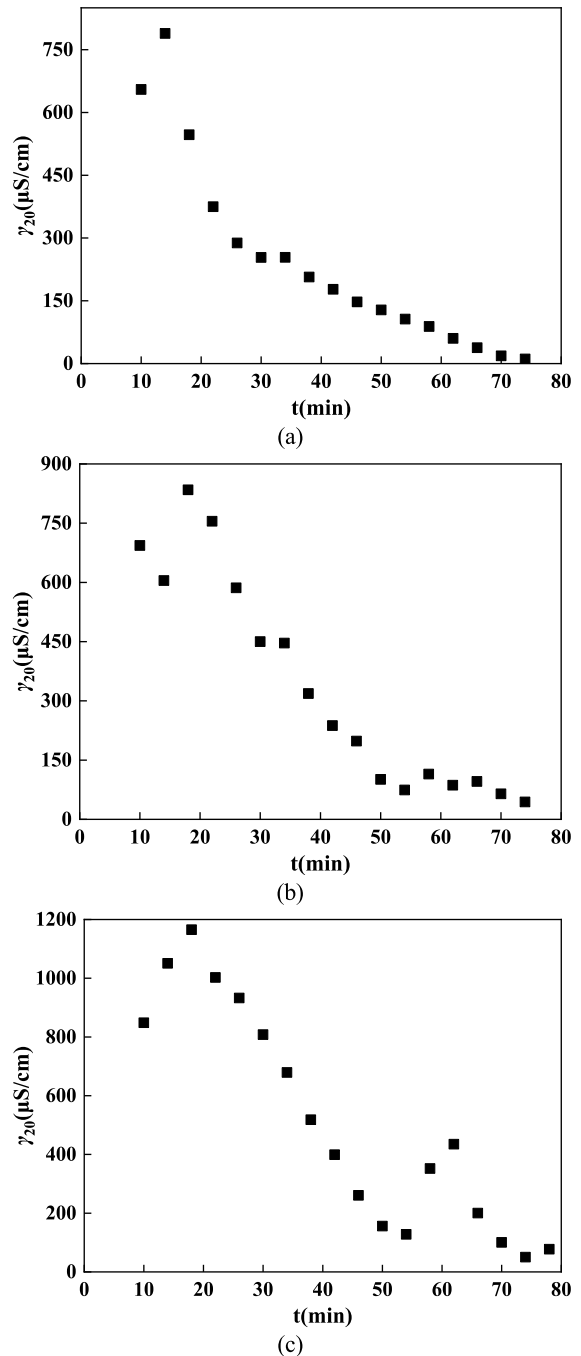


FIGURE 9. Relationship γ_{20} between and t under different ESDD: (a) ESDD= $0.05 \text{ mg}/\text{cm}^2$; (b) ESDD= $0.08 \text{ mg}/\text{cm}^2$; (c) ESDD= $0.15 \text{ mg}/\text{cm}^2$.

water film increases rapidly at the critical flashover moment. The flashover occurs immediately after it reaches the critical value. The higher the conductivity of icing water, the higher the critical flashover current (I_{CR}). When the applied water conductivity is 100, 300 and $500 \mu\text{S}/\text{cm}$, I_{CR} is 0.321, 0.570 and 0.807 A , respectively.

In Fig. 11, the magnitude of the leakage current increases from 18 mA–23 mA to 42 mA–50 mA as the freezing water conductivity increases from $100 \mu\text{S}/\text{cm}$ to $500 \mu\text{S}/\text{cm}$. According to the spatial distribution of ions in the ice layer

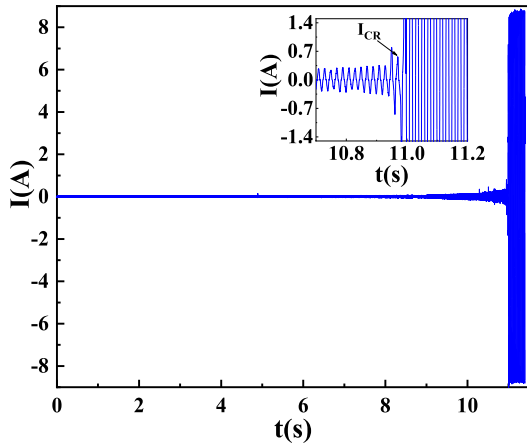


FIGURE 10. Time change of typical leakage current during flashing.

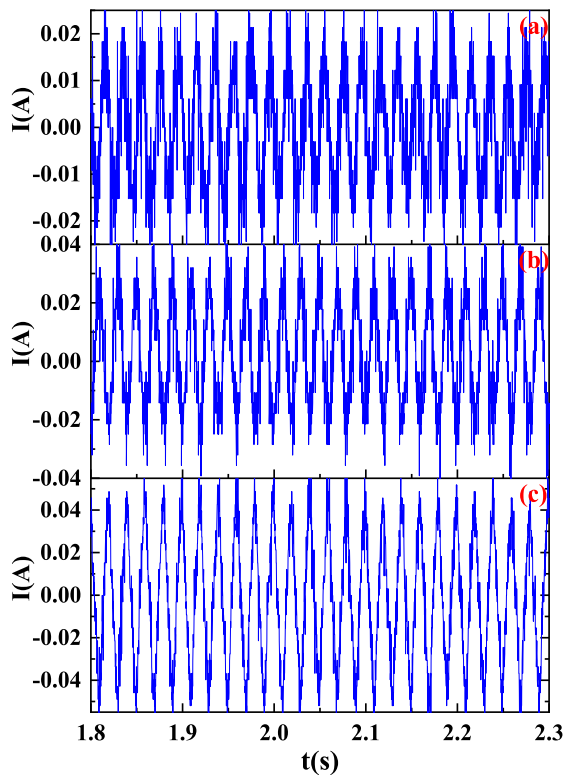


FIGURE 11. Time variation of leakage current in the period 1.8 s–2.3 s during the flashover of ice-covered insulators. (a) $\sigma_{20} = 100 \mu\text{S/cm}$, (b) $\sigma_{20} = 300 \mu\text{S/cm}$, (c) $\sigma_{20} = 500 \mu\text{S/cm}$.

in Section IV, a higher icing water conductivity corresponds to more conductive ions accumulating on the outer surface of the ice layer. Consequently, the water film conductivity on the ice surface is higher during the melting period, resulting in declining ice resistance. Hence, the leakage current is larger at the same voltage level.

B. INFLUENCE OF CRYSTALLIZATION EFFECT ON FLASHOVER VOLTAGE

Fig. 12 shows the typical discharge images photographed by a high-speed camera to present the flashover process of

TABLE 1. Flashover voltage of ice-covered insulators.

σ_{20} ($\mu\text{S/cm}$)	100	300	500
U_f (kV)	74.1	62.3	50.2
ESDD (mg/cm^2)	0.05	0.08	0.15
U_f (kV)	55.6	44.8	32.7

the ice-covered insulator. Its leakage current is shown in Fig. 13, where ESDD is 0.05 mg/cm^2 , d is 10 mm, and σ_{20} is $80 \mu\text{S/cm}$.

Following the completion of the icing test, the ice surface on the insulator melted, forming a water film due to the rising ambient temperature. As the voltage was applied to the insulator, the leakage current flowed through the film and generated Joule heat, which had a dual influence on the conductivity of the water film. On the one hand, according to Section III and IV, the conductive ions dissolved in freezing water gathered gradually on the ice surface during freezing. The ice layer melted from the outside to the inside to form a water film causing by an increase of ambient temperature and Joule heat effect of leakage current during the melting period. Therefore, the water film contained a large number of the conductive ions because of the crystallization effect of icing water, which improved the conductivity of the water film. On the other hand, the melted water was also evaporated by the Joule heat, causing the conductivity to decrease. A corona discharge occurred because of the high leakage current density at the steel foot (Fig. 12(a)). The leakage current at this stage was approximately 18 mA (Fig. 13(a)).

The first aspect of the Joule heat gradually played a leading role with increasing in the applied voltage. Therefore, the ice layer melted further, and the film conductivity increased. As a result, the air gaps between the icicle tip and the ice layer undertook most of the voltage applied to ice-covered insulator. By exceeding the critical breakdown voltage, the intermittent blue-purple filamentary discharges appeared in the gaps with a slight squeak sound (Fig. 12(b)). The current increased to 30 mA (Fig. 13(b)). The energy provided by the power supply was low, most of which was used to melt the ice, resulting in the discharge disappearing (Fig. 12(c)). The blue-purple discharges appeared in more gaps and became intense as the voltage rose (Fig. 12(d)–(e)).

Meanwhile, as the leakage current increased, the violet discharge turned into a flaxen partial arc, shortening the gap at the tip of the icicle (Fig. 12(f)). With the further increase in applied voltage, the energy supplied by the power increased, causing the arc temperature to rise, which is beneficial to the development of ionization and the facilitation of the partial arc propagation. The flaxen arc transformed into a white arc at the moment (Fig. 12(g)) and the current was approximately 100 mA (Fig. 13(c)). As the voltage continued to increase, the power energy was sufficient not only to melt the ice layer,

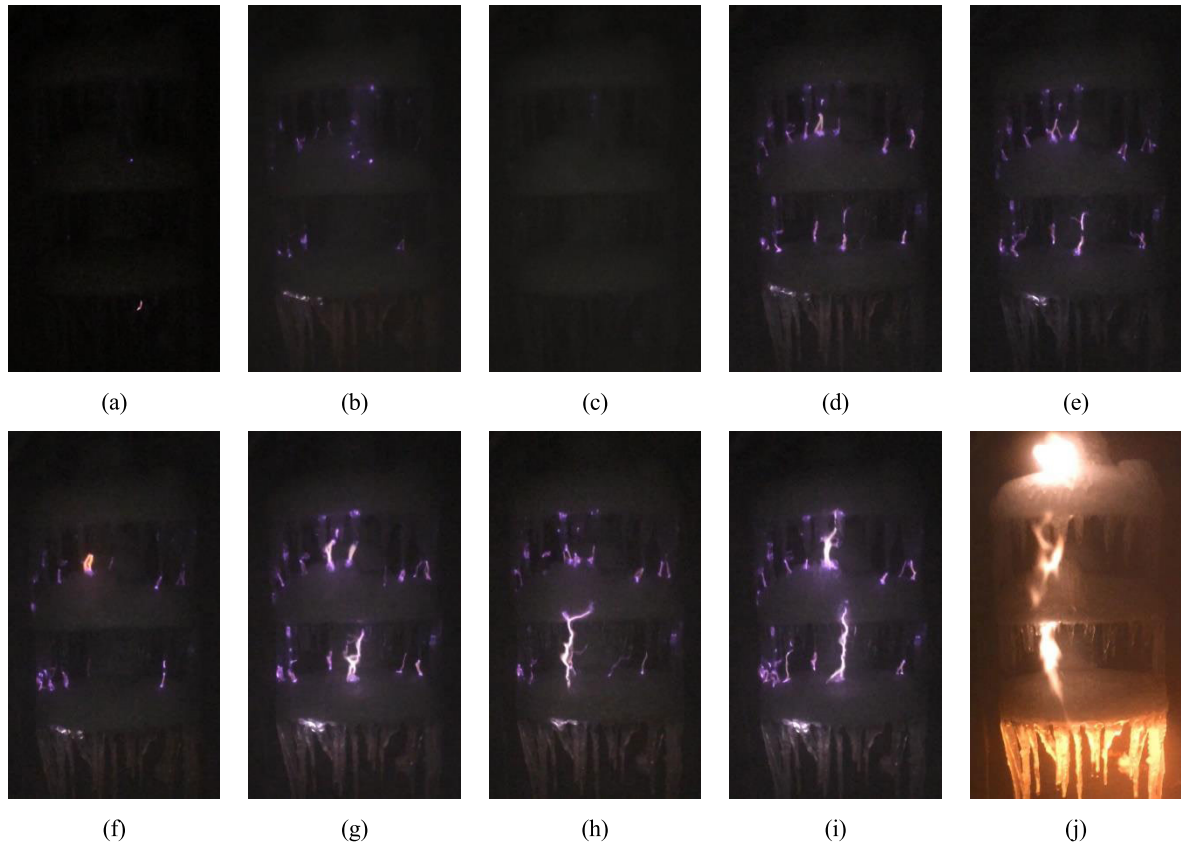


FIGURE 12. The flashover process of ice-covered insulator.

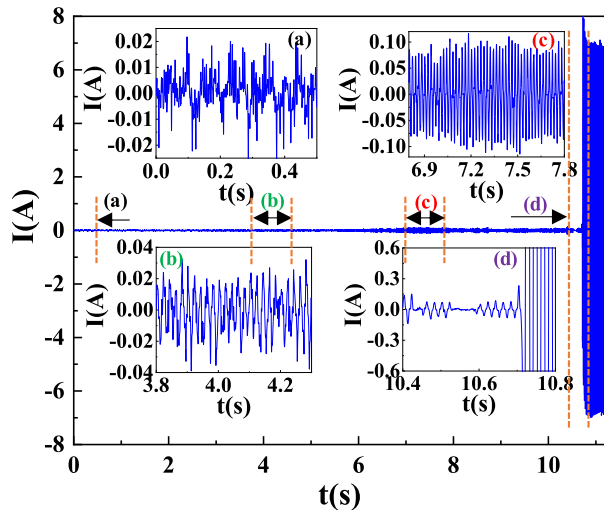


FIGURE 13. Leakage current waveform during flashover.

but also promote the development of the arc (Fig. 12(h)–(i)). The leakage current increased rapidly because of the arc with small resistance and the decreasing residual ice resistance. When the leakage current increases to the critical value (Fig. 13(d)), the partial arcs were connected rapidly and a flashover occurred (Fig. 12(j)).

To analyse the influence of the crystallization effect on the electrical performance of iced insulator, a series of flashover tests were conducted. The flashover voltage of ice-covered insulators and their melting water conductivities in the flashover process when the freezing water conductivity and solid-layer methods are adopted are shown in Table 1 and Fig. 14, respectively.

In Table 1, the flashover voltage of ice-covered insulators decreased as the σ_{20} and ESDD increased due to the following reasons. According to the preceding study, more conductive ions accumulated on the outer surface of the ice layer because of the crystallization effect with the increasing σ_{20} and ESDD, thereby causing the water film conductivity rising and reducing the residual resistance in the melting period, eventually resulting in the flashover voltage decreasing.

Fig. 14 shows that along with the flashover time, the conductivity of the melted water increases slightly and then decreased gradually, which is basically consistent with the preceding results. The reasons for the increase in melting water conductivity are as follows. In the flashover process, partial discharges and stable arcs occur on the surface of the ice-covered insulators, thereby generating various ions and impurities, dissolving in melted water together with ions in the ice layer because of the crystallization effect, which improves the melting water conductivity.

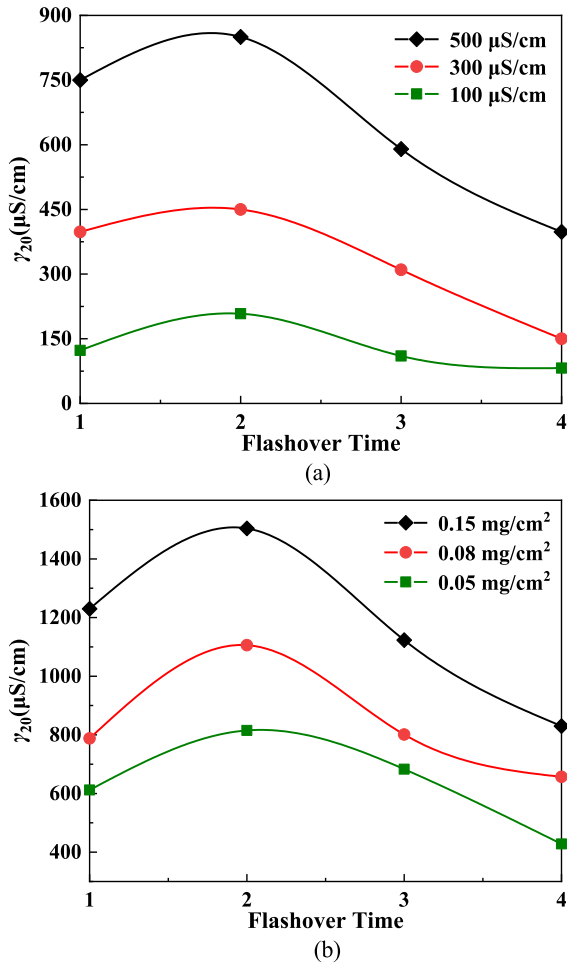


FIGURE 14. Relationship between the melting water conductivity and flashover time: (a) Freezing water conductivity method; (b) Solid-layer method.

VI. CONCLUSION

1. The results of the condensation test of the potassium permanganate solution shows that MnO_4^- migrates gradually to the liquid phase in the freezing process and accumulates on the top of the droplet, thereby proving that the crystallization effect exists during the phase transition of freezing water.

2. When the freezing water conductivity method is adopted to form a triangular ice sample, the maximum value of melting water conductivity should be 4.5–5.7 times that of icing water conductivity. A thick ice layer corresponds to a uniform ion distribution. For a polluted ice sample, the conductivity of melted water on the exterior surface is higher than that on the internal surface because of the crystallization effect.

3. The conductive ions accumulate gradually on the surface of the insulator during the phase transition, forming a highly conductive water film in the de-icing period, which improves the leakage current during a flashover. When applied water conductivity is 100, 300 and 500 $\mu\text{S/cm}$, the critical flashover current is 0.321, 0.570 and 0.807 A, respectively.

4. The crystallization effect is significant with the increasing freezing water conductivity and equivalent salt deposit density. Therefore, the residual ice resistance, which does

not bridge by arc, declines and subsequently reduces ice flashover voltage. Regardless of the ions and impurities generated by the discharge and arc in the flashover process of ice-covered insulators dissolving in melted water, the melting water conductivity decreases with the increasing flashover test time.

REFERENCES

- [1] M. Jabbari, C. Volat, and I. Fofana, "Numerical modelling of ice-covered insulator flashover: The influence of arc velocity and arc propagation criteria," *Energies*, vol. 11, no. 10, p. 2807, 2018.
- [2] M. Farzaneh, "Insulator flashover under icing conditions," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 21, no. 5, pp. 1997–2011, Oct. 2014.
- [3] Y. Liu, L. Shu, X. Jiang, Q. Hu, H. Yang, Z. Yu, and M. Zhu, "Study on conductive ions distribution in icicles of ice-covered insulators," *Int. J. Electr. Power Energy Syst.*, vol. 116, Mar. 2020, Art. no. 105567.
- [4] Y. Hu, S. Guo, R. Xian, X. Han, Z. Yang, and Y. Wu, "Flashover performance and process of suspension insulator strings artificially covered with snow," *Energies*, vol. 11, no. 11, p. 2916, 2018.
- [5] X. Jiang, Z. Zhang, Q. Hu, J. Hu, and L. Shu, "Thinkings on the restrike of ice and snow disaster to the power grid," *High Volt. Eng.*, vol. 44, no. 2, pp. 463–469, Feb. 2018.
- [6] X. Jiang, M. Bi, H. Wang, Z. Yang, and X. Han, "Influence of t-type arrangement on icing process and ac flashover performance of insulator strings," *Trans. China Electr. Soc.*, vol. 34, no. 17, pp. 3713–3720, Sep. 2019.
- [7] X. Han and X. Jiang, "Effect of DC electric field on water droplets' movement and icing process on insulator," *Cold Regions Sci. Technol.*, vol. 164, Aug. 2019, Art. no. 102780.
- [8] X. Han, X. Jiang, Z. Yang, and C. Bi, "A predictive model for dry-growth icing on composite insulators under natural conditions," *Energies*, vol. 11, no. 6, p. 1339, 2018.
- [9] J. Xingliang, W. Quanlin, Z. Zhijin, S. Lichun, H. Jianlin, H. Qin, P. Yang, and C. Yi, "Estimation of rime icing weight on composite insulator and analysis of shed configuration," *IET Gener., Transmiss. Distrib.*, vol. 12, no. 3, pp. 650–660, Feb. 2018.
- [10] Y. Zhu, C. Liu, X. Huang, X. Zhang, Y. Zhang, and Y. Tian, "Research on image recognition method of icicle length and bridging state on power insulators," *IEEE Access*, vol. 7, pp. 183524–183531, 2019.
- [11] L. Yang, X. Jiang, Y. Hao, L. Li, H. Li, R. Li, and B. Luo, "Recognition of natural ice types on in-service glass insulators based on texture feature descriptor," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 24, no. 1, pp. 535–542, Feb. 2017.
- [12] Y. Hu, X. Jiang, L. Xie, Z. Zhang, Q. Wang, and Y. Pan, "Influence of electric field strength on crystallisation effect during phase transition," *High Volt. Eng.*, vol. 44, no. 6, pp. 2074–2080, Jun. 2018.
- [13] Y. Liu, M. Farzaneh, and B. Du, "Investigation on shed icicle characteristics and induced surface discharges along a suspension insulator string during ice accretion," *IET Gener., Transmiss. Distrib.*, vol. 11, no. 5, pp. 1265–1269, Mar. 2017.
- [14] Y. Liu, M. Farzaneh, and B. X. Du, "Using chaotic features of leakage current for monitoring dynamic behavior of surface discharges on an ice-covered insulator," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 24, no. 4, pp. 2607–2615, Sep. 2017.
- [15] Z. Zhang, Y. Cheng, J. Zhao, X. Jiang, and C. Fan, "AC flashover performance of artificial icing and nature icing for XP-160 insulator string," *High Volt. Eng.*, vol. 44, no. 9, pp. 2777–2784, Sep. 2018.
- [16] X. Han, X. Jiang, C. Bi, Z. Yang, and Y. Huang, "Prediction of icing environment parameters based on decentralized rotating conductors," *Trans. China Electr. Soc.*, vol. 34, no. 5, pp. 1096–1105, Mar. 2019.
- [17] B. Porkar and M. Farzaneh, "A model for calculating thickness and surface conductivity of water film on an inclined insulator string," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 23, no. 1, pp. 149–157, Feb. 2016.
- [18] Y. Deng, Z. Jia, X. Wei, H. Su, Z. Guan, T. Wang, and K. Wang, "Mechanism of salt migration in icicles during phase transition and its impact on ice flashover," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 19, no. 5, pp. 1700–1707, Oct. 2012.
- [19] X. Jiang, Q. Wang, Z. Zhang, J. Hu, Q. Hu, and C. Zhu, "Ion migration in the process of water freezing under alternating electric field and its impact on insulator flashover," *Energies*, vol. 10, no. 1, p. 61, 2017.

[20] M. Farzaneh, J. Zhang, and X. Chen, "Modeling of the AC arc discharge on ice surfaces," *IEEE Trans. Power Del.*, vol. 12, no. 1, pp. 325–338, Jan. 1997.

[21] M. Farzaneh and J. Zhang, "Modelling of DC arc discharge on ice surfaces," *IEE Proc. Gener., Transmiss. Distrib.*, vol. 147, no. 2, pp. 81–86, Mar. 2000.

[22] *Guide for Test Methods and Procedures to Evaluate the Electrical Performance of Insulators in Freezing Conditions*, IEEE Standard 1783/2009TM, 2009.

[23] M. Farzaneh *et al.*, "Insulator icing test methods and procedures a position paper prepared by the IEEE task force on insulator icing test methods," *IEEE Trans. Power Del.*, vol. 18, no. 4, pp. 1503–1515, Oct. 2003.

[24] X. Jiang, L. Shu, and C. Sun, "Test method for iced insulators," in *Insulation of Electric Power System Under Pollution and Icing Condition*. Beijing, China: China Electric Power Press, 2009, pp. 147–159.

[25] Y. Hu, X. Jiang, L. Shu, Z. Zhang, Q. Hu, and J. Hu, "DC flashover performance of ice-covered insulators under complex ambient conditions," *IET Gener., Transmiss. Distrib.*, vol. 10, no. 10, pp. 2504–2511, Jul. 2016.

[26] J. Zhang, M. Farzaneh, and X. Chen, "Variation of ice surface conductivity during flashover," in *Proc. Conf. Electr. Insul. Dielectric Phenomena*, Virginia Beach, VA, USA, Oct. 1995, pp. 479–483.



XINGLIANG JIANG was born in Hunan, China, in 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, the Wuhan High-Voltage Research Institute, Wuhan, Hubei, and the College of Electrical Engineering, Chongqing University. He has published his first monograph-Transmission Line's Icing and Protection, in 2001. He has published more than 120 articles about his professional work. His special fields of interests include high-voltage external insulation, and transmission line's icing and protection. He received the Second-Class Reward for Science and Technology Advancement from Ministry of Power, in 1995, Beijing Government, in 1998, the Ministry of Education, in 1991 and 2001, respectively, the First-Class Reward for Science and Technology Advancement from Ministry of Power, in 2004, the Third-Class Reward for Science and Technology Advancement from Ministry of Power, in 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 2007, the First-Class Reward for Science and Technology Advancement from Chongqing City, in 2007, and the First-Class Reward of national technology improvements, in 2013.



ZHONGYI YANG was born in Chongqing, China, in 1990. He received the B.S. degree in electrical engineering from Chongqing University, Chongqing, in 2013, where he is currently pursuing the Ph.D. degree with the School of Electrical Engineering. His current research interest is the study of anti-pollution measures for insulators.



XINGBO HAN was born in Luzhou, Sichuan, China, in 1992. He received the B.S. degree in electrical engineering from Chongqing University, Chongqing, in 2015, where he is currently pursuing the Ph.D. degree with the School of Electrical Engineering. His current research interest is the electrical characteristics of ice-covered insulator strings in icing regions.

...



YUYAO HU was born in Heze, Shandong, China, in 1989. He received the B.S. degree in electrical engineering from the Inner Mongolia University of Science and Technology, Inner Mongolia, in 2012, and the Ph.D. degree in electrical engineering from Chongqing University, Chongqing, in 2017. He is currently a Lecturer with the College of Electrical and Electronic Engineering, Shandong University of Technology. His current research interest is the selection of external insulation for transmission lines.