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REVIEW ARTICLE

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Progress in research on ice accretions on overhead transmission lines and its influence on mechanical and insulating performance

Abstract Atmospheric ice accretion on transmission lines is of great danger to the security of service of electrical power system. This paper reviews the progress in research dealing with the formation of ice accretions on transmission lines and the effects of ice on the mechanical and electrical performance of transmission lines. The results show that ice accretions on transmission lines can be categorized into five types: glaze, hard rime, soft rime, hoar frost, and snow and sleet. In all types of ice accretions, glaze grown in a wet regime is of the greatest danger to the transmission lines. Meteorological conditions, terrain and geographic conditions, and some other factors significantly influence the ice accumulation speed and the ice amount. Drastic decrease of mechanical property and electric property as a result of severe icing is the main reason for ice accidents. The amount of ice, the asymmetrical ice accretion, and the asynchronous ice shedding can considerably change the conductor strain, conductor sag, variation amount of the span, displacement of the insulator string, and the tension difference. The amount and type of ice, the uniformity of ice accumulation, and the conductivity of freezing water have significant influence on the flashover voltage of ice-covered insulators.

Keywords transmission lines, icing, mechanical performance, electrical performance

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1 Introduction

Accumulation of ice and snow is a beautiful natural phenomenon. However, it may be a natural disaster for overhead transmission lines. In many cold climate regions of the world, overhead transmission and distribution lines as well as their substation equipment are subjected to ice accretions. The mechanical and electrical performances of transmission lines are adversely affected by the severe ice accretions. Under certain conditions, a drastic decrease in the mechanical and electrical performance can lead to collapse of poles and towers, flashovers of insulator strings, galloping of conductors, and consequent power outages, which will greatly threaten the security of service of the electrical power system [1–4].

According to incomplete statistics, ice accidents of transmission lines have occurred more than 1000 times in China since the 1950s [3–13]. In February 2005, Middle China electric network, especially Hunan and Hubei electric network, encountered a historically rare ice disaster with the longest span of time, the most extensive coverage, and the most serious failure. Some transmission lines were covered with ice accretions with a thickness of 80–100 mm, which greatly exceeded the designed standard of 10–20 mm. Severe icing led to the frequent tripping of 500 kV transmission lines of Middle China electric network. In Hunan, Hubei, Chongqing, and some other provinces, a number of high-voltage transmission towers collapsed, and the framework of the electric networks was damaged. In Hunan Province, three 500 kV transmission lines were out of service. Most severely, ten 500 kV transmission lines in Middle China electric network were out of service simultaneously. However, with the forthcoming construction of 1000 kV alternating current (AC) and ±800 kV direct current (DC) transmission lines in China, there will be more and more ultra-high-voltage (UHV) AC and DC transmission lines crossing micro-terrain and micro-climate regions, and icing phenomena of transmission lines will be unavoidable.

The accidents caused by ice accretions on transmission lines have also been reported from a large number of other cold climate countries, including Canada [14–16], America [17–19], Finland [20], Japan [21], Norway [22], etc. The most remarkable incidents with Ontario Hydro and Hydro-Quebec occurred on March 9–10, 1986, April 18, 1988, and December 26, 2005, respectively. The origin of the events on the Ontario Hydro network was the accumulation of ice and short icicles on the insulators caused by freezing rain and fog. This resulted in outages of most of the 500 kV transmission lines in Southern Ontario. Incidents that took place at the Arnaud substation on the Hydro-Quebec system were caused by wet snow [23,24].

The socioeconomic consequences, as well as academic interests, have led some researchers to do comprehensive and in-depth researches on the ice accretions on transmission lines. Especially, in severe icing countries, such as Canada, America, China, Japan, and Russia, the influences of several major ice parameters on the flashover performance of diverse insulator types under icing conditions have been investigated [3,9,25–30]. Lots of great achievements have been gained in the research into the transmission lines' anti-icing and de-icing measures, the mechanism of icing on transmission lines, and the flashover performance of ice-covered transmission lines.

Unfortunately, in spite of the scope of the efforts made on the investigations into the ice accretions on transmission lines, the various researchers are not in agreement over certain points and some investigations are not in-depth. As to the characteristics of the ice accretions on transmission lines, Kuroiwa categorized them into three types: glaze, hard rime, and soft rime [31]. Jiang et al. categorized them into seven types: soft rime, hard rime, glaze, crystal rime, ice formed by freezing snow, ice formed by thawing snow, and mixed rime [9]. Up to now, research work about the factors influencing the ice accretions on transmission lines is not in-depth. As to the electrical performance of ice-covered insulators, Kawai reported that the flashover voltage of the cleaned and iced insulators was approximately equal to that of a salt deposit of 0.1 $mg \cdot cm^{-2}$ [18], while Cherney noted that there was no flashover under service voltage with the iced insulators [32]. The flashover only occurred when the insulators were contaminated to a level of 0.4 $mg \cdot cm^{-2}$ before being subjected to icing. Besides, the influence of ice accretions on the mechanical performance of transmission lines also deserves comprehensive researches.

To obtain a better idea of the formation of ice accretions on transmission lines and the effects of ice on the mechanical and electrical performance of transmission lines, this paper will try to review the progress in research dealing with this subject, especially the research results gained by the researchers in Chongqing University, China.

2 Ice accretions on transmission lines

2.1 Types of ice accretions

Ice accumulation on transmission lines has been the subject of various laboratory studies and field observation [9,24,33,34]. Based on the long-term field observations and laboratory studies on ice accretions on transmission lines, the conditions favoring the formation of various types of ice in nature are summarized in Table 1 [3].

Ice accretions on transmission lines are formed essentially from the impinging of super-cooled droplets on their surface. Depending on the atmospheric and environmental conditions, five types of ice can be produced: glaze, hard rime, soft rime, hoar frost, and snow and sleet. Glaze is transparent and has a density in the range of 0.9 to 0.92 $g \cdot cm^{-3}$. Hard rime is opaque and has a density in the range of 0.6 to 0.9 $g \cdot cm^{-3}$. Soft rime is white, opaque and has a density in the range of 0.3 to 0.6 $g \cdot cm^{-3}$. Hoar frost is white, fragile and has a density in the range of 0.05 to 0.3 $g \cdot cm^{-3}$. Snow and sleet are of low density and weak adhesive capacity. Hard rime, soft rime, hoar frost, and snow and sleet are grown in a dry regime, i.e., all the water droplets impinging on the impact surface are completely frozen. Because there is no runoff water, no icicles are formed; the deposit temperature, which is a consequence of a balance between the rate of heat liberation by the freezing of the droplets and the rate of heat transfer by forced convection to the environment, is below 0°C. Glaze is grown on a wet regime at a deposit temperature of 0°C. The icing processes in such a regime involve the loss of

Table 1 Conditions favoring the formation of various types of ice

type of ice	density/($g \cdot cm^{-3}$)	atmospheric conditions	
		surrounding air temperature/°C	wind velocity/($m \cdot s^{-1}$)
glaze	0.9 – 0.92	−3 – 0	1 – 20
hard rime	0.6 – 0.9	−8 – −2	5 – 20
soft rime	0.3 – 0.6	−13 – −8	5 – 20
hoar frost	0.05 – 0.3	< −10	—
snow and sleet	< 0.05	0	< 3

water and the formation of icicles. For different size and concentration of air bubbles, the opacity and whiteness of formed ice deposits are also different.

2.2 Factors influencing ice accumulation on transmission lines

The types of ice accretions are mainly affected by air temperature, wind velocity, water droplet size, and liquid water content. In addition to the meteorological conditions, terrain and geographic conditions, altitude, configuration, and parameters of conductors all tend to influence the general characteristics of ice.

2.2.1 Meteorological conditions

Meteorological factors influencing the icing on transmission lines mainly include atmospheric temperature, atmospheric humidity, wind velocity, wind direction, etc. In general, in order to make the ice accumulate easily, at least three conditions must be satisfied. 1) The atmospheric humidity should be high enough to make the dry snow not coagulate on conductors. Generally, the relative humidity should reach 90%–95%. 2) The appropriate atmospheric temperature should be below 0°C. 3) The wind velocity is large enough to make the water droplets move. It is commonly larger than 1 $\mathrm{m \cdot s^{-1}}$. If the relative humidity is too low or the wind velocity is too small, even the atmospheric temperature is below 0°C, no ice accretions will deposit on conductors [3,35].

Based on the observations of ice accretion on transmission lines in Hubei Province, China, the relationship between the times of ice accretions and temperature can be plotted in Fig. 1, the relationship between the ice accumulation speed and temperature can be plotted in Fig. 2, and the relationship between the ice accumulation speed and wind velocity can be plotted in Fig. 3 [3].

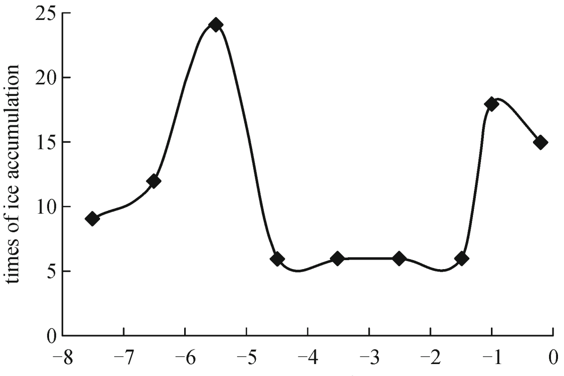

Fig. 1 Relationship between the times of ice accretions and temperature (adapted from Ref. [3])

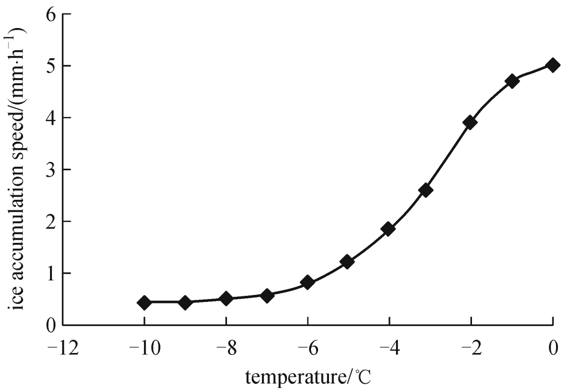

Fig. 2 Relationship between ice accumulation speed and temperature (adapted from Ref. [3])

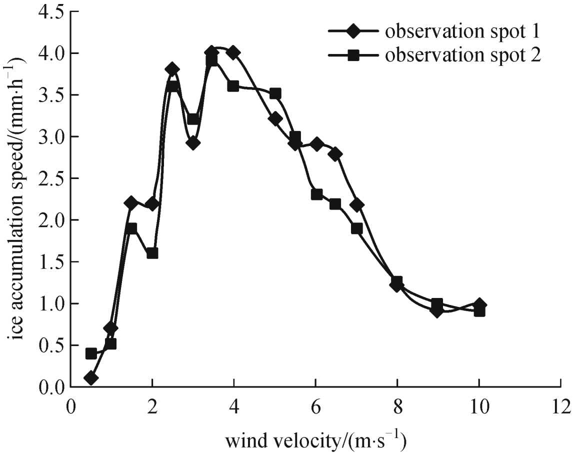

Fig. 3 Relationship between ice accumulation speed and wind velocity (adapted from Ref. [3])

It can be concluded from Fig. 1 that the ice accretions mostly occurred at the temperature of −5.5°C and −1°C. That is to say, the glaze often formed at −1°C, and the rime often formed at −5.5°C. It can be concluded from Fig. 2 that the ice accumulation speed is the largest when the ambient temperature is about 0°C.

Some researchers deem that the larger the wind velocity is, the larger the ice accumulation speed is [36]. However, based on the observations of ice accretions on transmission lines in Hubei Province, China, the statistical materials show that the most favorable wind for the ice accumulation speed is in the range of 3 to 6 $\mathrm{m \cdot s^{-1}}$. When the wind speed is below 3 $\mathrm{m \cdot s^{-1}}$, the ice accumulation speed increases with the increase of wind velocity. Upon the wind speed exceeds 6 $\mathrm{m \cdot s^{-1}}$, the ice accumulation speed decreases with the increase of the wind velocity, as shown in Fig. 3.

2.2.2 Terrain and geographic conditions

In micro-terrain zones such as narrow mountain pass, mountaintops, mountain slopes rounded with cloud and mist, and rivers and lakes, the severe icing phenomenon is likely to occur [37,38].

For example, there is a 35 kV transmission line with an east-west direction in Three Gorges district crossing a mountain with an altitude of 1500–1800 m in Luoping, Wushan. It passes through the wind valley between mountains with a south-north direction and there is no barrier around. Since it was put into service, ice depositions with a thickness more than 35 mm have occurred nearly every year.

2.2.3 Configuration and parameters of conductors

Configuration and parameters of conductors mainly include cross-sectional area of conductor, torsional stiffness, type of conductor (bundled conductor or single conductor), etc. The influence of cross-sectional area of conductor on icing is mainly embodied by the collecting coefficient (the effectiveness of conductors capturing the overcooled water droplets in the atmosphere) and the impact of cross-sectional area on the torsional stiffness [37].

Based on the observation data of the ice accretions on Chinese transmission lines, the relationship between the ice accumulation speed and the diameter of the conductor can be plotted in Fig. 4 [3,35]. It can be concluded that the ice accumulation speed decreases with the increase of the diameter of the conductor.

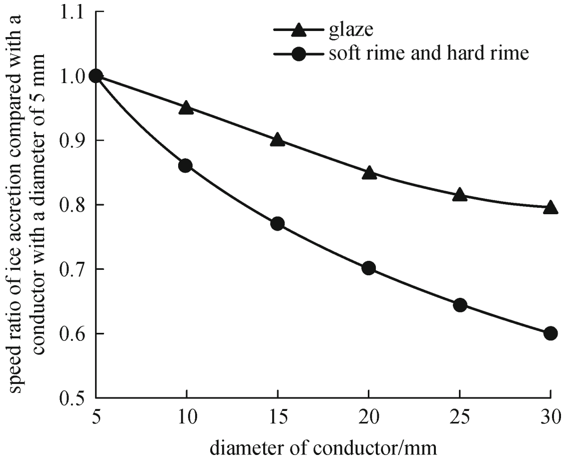

Fig. 4 Relationship between the ice accumulation speed and the diameter of the conductor (adapted from Refs. [3,35])

The torsional stiffness of conductors determines the capability of torsion and has a great influence on the cross-sectional shape of conductors covered with ice deposits. The thin and long conductor has a small torsional stiffness and is prone to twist, which can lead to cylinder ice deposits with a larger amount.

As to the single conductors, because of the small torsional stiffness, the conductors are easy to twist under the action of the asymmetrical icing and the cross-sectional shape is an approximate cylinder. On the other hand, for the bundled conductors, because of the relative larger torsional stiffness of each sub-conductor as a result of the existence of spacers, the conductors are difficult to twist under the action of the asymmetrical icing. The asymmetry of icing on conductors is unavoidable and the cross-section of the icing is aliform. Therefore, as to the bundled conductors, the lift and torsional torque caused by the wind excitation are larger than those of single conductors, and the galloping is much more likely to occur [39]. The comparative results of the ice accumulation speed of bundled conductors with different bundle number are shown in Fig. 5.

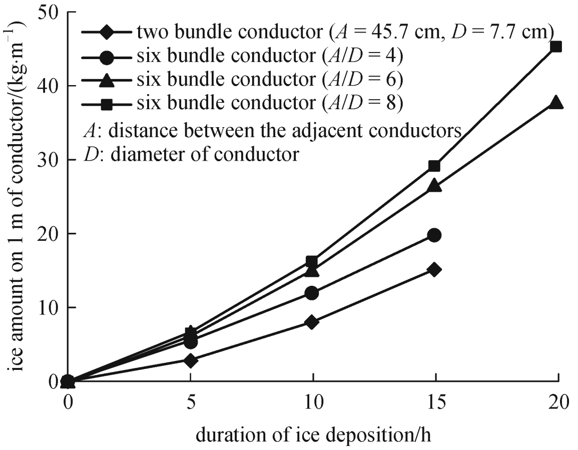

Fig. 5 Ice accumulation speed of bundled conductors with different configurations

2.2.4 Altitude and suspension height of conductors

In general, the higher the altitude is, the easier the icing occurs. At a high altitude, the type of ice accretions is rime mostly. At a low altitude, the ice accretion is much thin and the type is usually glaze or mixed rime [3]. For example, in hilly areas in Hunan, Hubei, Henan, the north of Guangdong, the south of Jiangxi, and the south of Anhui, the ice accretions are mostly glaze, while in alpine areas in Yun-Gui Plateau and some other areas with an altitude of more than 1000 m, the ice depositions are mostly rime.

In the terrestrial atmospheric layer, with the increase of altitude, the wind velocity and density of fog droplets will also increase. Therefore, the higher the suspension point is, the heavier the ice accretion is. The relationship between the ice thickness and the suspension height of the conductor is shown in Fig. 6. It can be concluded that the higher the conductor is, the thicker the ice is.

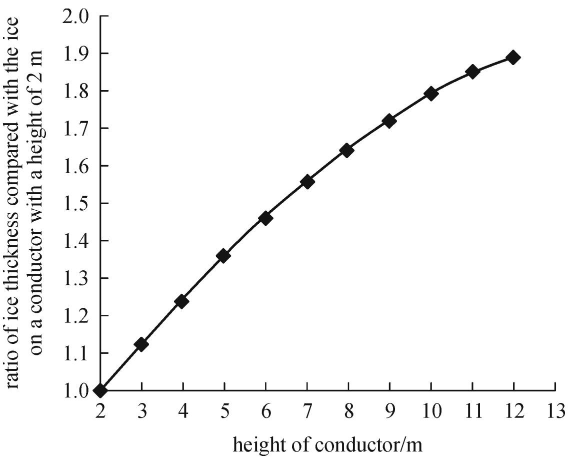

Fig. 6 Relationship between the ice thickness and the suspension height of the conductor

3 Influence of ice accretions on mechanical performance of transmission lines

3.1 Influence of ice accretions on static load, horizontal stress, and conductor sag

If the conductors are covered with ice accretions, the specific loading of the conductors will change. The total specific loading of ice-covered conductor can be calculated as follows [40]:

$$\gamma_3 = \gamma_1 + \gamma_2 = \frac{q_0}{A} + 0.027728\left[\frac{b(b+D)}{A}\right], \tag{1}$$

where γ_1 is the self-weight specific loading, $\mathrm{N \cdot m^{-1} \cdot mm^{-2}}$; γ_2 is the icing-weight specific loading, $\mathrm{N \cdot m^{-1} \cdot mm^{-2}}$; γ_3 is the total specific loading, $\mathrm{N \cdot m^{-1} \cdot mm^{-2}}$; q_0 is the sole weight of conductor, $\mathrm{N \cdot m^{-1}}$; A is the cross-sectional area of conductor, $\mathrm{mm^2}$; b is the thickness of ice accretions, mm; and D is the diameter of conductor, mm.

As to the overhead transmission lines with contour suspension points, the state equation describing the variation of stress is as follows:

$$\sigma_{0n} - \frac{E\gamma_n^2 l^3}{24\sigma_{0n}^2} = \sigma_{0m} - \frac{E\gamma_m^2 l^3}{24\sigma_{0m}^2} - \alpha E(t_n - t_m), \tag{2}$$

where σ_{0n}, t_n, and γ_n are parameters under one atmospheric condition; σ_{0m}, t_m, and γ_m are parameters under another atmospheric condition; σ_{0n} and σ_{0m} are the horizontal stress, $\mathrm{N \cdot mm^{-2}}$; t_n and t_m are the atmospheric temperature, °C; γ_n and γ_m are the total specific loading, $\mathrm{N \cdot m^{-1} \cdot mm^{-2}}$; l is the line span, m; α is the temperature linear expansion factor, $\mathrm{°C^{-1}}$; and E is the Young's modulus, $\mathrm{N \cdot mm^{-2}}$.

With horizontal stress σ_0, total specific loading γ, and line span l, the maximum sag f_M at the median point of the conductor can be calculated as follows:

$$f_M = f_{l/2} = \frac{\gamma l^2}{8\sigma_0}. \tag{3}$$

A 35 kV overhead transmission line with contour suspension points is taken as an example. The conductor model is LGJ-95, and the line span l is 120 m. The other conductor parameters are as follows: Young's modulus $E = 7.84 \times 10^7\ \mathrm{N \cdot mm^{-2}}$; temperature linear expansion factor $\alpha = 19 \times 10^6\ \mathrm{°C^{-1}}$; cross-sectional area $A = 113\ \mathrm{mm^2}$, diameter $D = 13.7$ mm, self-weight specific loading $\gamma_0 = 0.03503\ \mathrm{N \cdot m^{-1} \cdot mm^{-2}}$; and horizontal stress (under the condition: temperature $t = 20$°C, without ice accretions and wind) $\sigma_0 = 64.211\ \mathrm{N \cdot mm^{-2}}$.

If the conductors are covered with ice accretions at the temperature of −5°C, and the ice thickness varies in the range of 0 to 12.5 mm, the corresponding total specific loading γ, the horizontal stress σ_0, and the maximum sag f_M can be calculated. The results are shown in Table 2.

It can be concluded that, with the increase of ice thickness, the total specific loading, the horizontal stress, and the maximum sag will increase. With regard to the example mentioned above, compared with the case without ice accretions, when the conductor is covered with ice accretions with a thickness of 20 mm, the total specific loading will increase by 229.4%, the horizontal stress will increase by 34.65%, and the maximum sag will increase by 139.9%.

3.2 Influence of asymmetrical ice accretion or asynchronous ice shedding on the tensile force of conductors

For some cases, the ice may accrete asymmetrically or shed asynchronously, which will bring about the difference in tensile force.

Figure 7 shows a section of an overhead line with asymmetrical ice accretion. The first span has relatively

Table 2 Total specific loading, horizontal stress, and maximum sag of ice-covered conductor

b/mm	$\sigma_0/(\mathrm{N \cdot mm^{-2}})$	f_M/m	$\gamma/(\mathrm{N \cdot m^{-1} \cdot mm^{-2}})$
0.0	93.986	0.671	3.503×10^{-2}
2.5	97.464	0.830	4.497×10^{-2}
5.0	102.499	1.018	5.797×10^{-2}
7.5	109.113	1.221	7.405×10^{-2}
10.0	117.192	1.431	9.319×10^{-2}
12.5	126.557	1.641	11.539×10^{-2}

heavy specific loading γ_m, and the other spans have relatively light specific loading γ_n ($\gamma_\mathrm{n} < \gamma_\mathrm{m}$). Figure 8 shows a section of an overhead line with asynchronous ice shedding. The centering span has light specific loading γ_n and the other spans have relatively heavy specific loading γ_m ($\gamma_\mathrm{m} > \gamma_\mathrm{n}$).

As to the span with heavy accumulation of ice, the relationship between the tension of the conductor and the shortened amount of the span can be shown as follows [41]:

$$T = A\sqrt{\frac{(l_0 - \Delta l)^3 \gamma_\mathrm{m}^2}{24\Delta l + \dfrac{l_0^3 \gamma_\mathrm{m}}{\sigma_\mathrm{m}^2}}}, \tag{4}$$

where T is the tension of the conductor, N; A is the cross-sectional area of conductor, mm^2; l_0 is the primary length of the span, m; Δl is the shortened amount of the span, m; γ_m is the total specific loading of the span with heavy accumulation of ice, N$\cdot$m$^{-1}\cdot$mm^{-2}; and σ_m is the primary horizontal stress, N$\cdot$mm^{-2}.

As to the span with light accumulation of ice, the relationship between the tension of the conductor and the increased amount of the span can be shown as follows:

$$T = A\sqrt{\frac{(l_0 + \Delta l)^3 \gamma_\mathrm{n}^2}{\dfrac{l_0^3 \gamma_\mathrm{n}}{\sigma_\mathrm{n}^2} - 24\Delta l}}, \tag{5}$$

where Δl is the increased amount of the span, m; γ_n is the total specific loading of the span with light accumulation of ice, N$\cdot$m$^{-1}\cdot$mm^{-2}; and σ_n is the primary horizontal stress, N$\cdot$mm^{-2}. The meanings of other symbols are as before.

If both sides of the insulator string are spans with light accumulation of ice, the relationship between the displacement of the insulator string and the tension difference can be shown as follows:

$$\delta_\mathrm{n} = \frac{\lambda \Delta T}{\sqrt{\left(\gamma_\mathrm{n} A l_0 + \dfrac{G_\mathrm{J}}{2}\right)^2 + \Delta T^2}}, \tag{6}$$

where δ_n is the displacement of the insulator string, m; γ_n is the total specific loading, N$\cdot$m$^{-1}\cdot$mm^{-2}; ΔT is the tension difference, N; λ is the length of the insulator string, m; and G_J is the weight of the insulator string, N. The meanings of other symbols are as before.

If the two sides of the insulator string are spans with

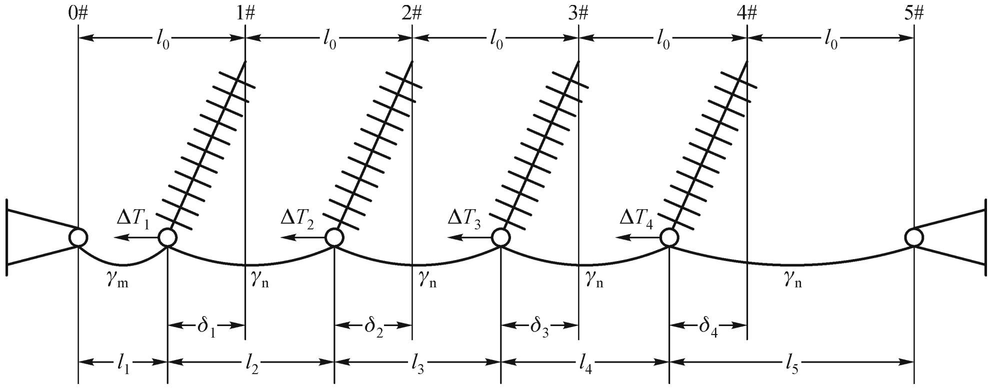

Fig. 7 Sketch map of a segment of an overhead line with asymmetrical ice accretion

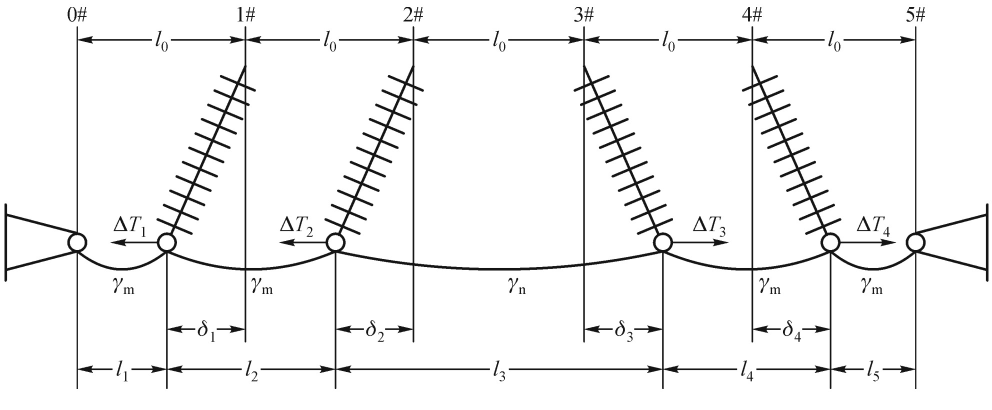

Fig. 8 Sketch map of a segment of an overhead line with asynchronous ice shedding

different amount of ice accretions, the relationship between the displacement of the insulator string and the tension difference can be shown as follows:

$$\delta = \frac{\lambda \Delta T}{\sqrt{\left[\frac{1}{2}(\gamma_{\mathrm{m}} + \gamma_{\mathrm{n}})Al_0 + \frac{G_{\mathrm{J}}}{2}\right]^2 + \Delta T^2}}, \tag{7}$$

where δ is the displacement of the insulator string, m. The meanings of other symbols are as before.

An 110 kV overhead transmission line with contour suspension points is taken as an example. The conductor model is LGJ-185, and the line span l is 210 m. There are five spans in the strain segment, as shown in Fig. 7. The designed anti-icing thickness is 20 mm, the designed stress of the ice-covered conductor is 98 $\mathrm{N \cdot mm^{-2}}$, and the wind velocity in the course of icing is 15 $\mathrm{m \cdot s^{-1}}$. The other conductor parameters are as follows: cross-sectional area $A = 216.76\ \mathrm{mm^2}$, diameter $D = 19.02$ mm, Young's modulus $E = 7.84 \times 10^7\ \mathrm{N \cdot mm^{-2}}$, and self-weight specific loading $\gamma_0 = 0.035\ \mathrm{N \cdot m^{-1}}$.

Case 1 Suppose that the ice accretes asymmetrically. Only one span connecting with the strain pole is covered with ice accretions with a thickness of 20 mm, and other spans are covered with ice accretions with a thickness of 7.4 mm.

The calculated values of conductor strain, conductor sag, and variation amount of the span are shown in Table 3. The calculated values of displacement of the insulator string and the tension difference are shown in Table 4.

Case 2 Suppose that the ice sheds asynchronously. Only the middle span is covered with ice accretions with a thickness of 7.4 mm, and other spans are covered with ice accretions with a thickness of 20 mm.

The calculated values of conductor strain, conductor sag, and variation amount of the span are shown in Table 5. The calculated values of displacement of the insulator string and the tension difference are shown in Table 6.

From Tables 3–6, the following conclusions can be reached.

With regard to asymmetrical ice accretion or asynchronous ice shedding, for the span with the heaviest ice accumulation, there is largest tensile force and largest sag. For the span with the lightest ice accumulation, there is smallest tensile force and smallest sag.

For the straight-line poles with different ice loads on two sides, there is a largest tension difference.

4 Influence of ice accretions on insulating performance of transmission lines

Several ice parameters, including type and density, amount, and distribution, as well as electrical conductivity

Table 3 Conductor strain, conductor sag, and variation amount of the span of the segment with asymmetrical ice accretion

span No.	tension of each span T_i/N	variation amount of the span Δl_i/m	maximum sag f_{M}/m
1	15773	−0.6463	10.760
2	13302	+0.2410	5.863
3	12365	+0.1727	6.307
4	11843	+0.1274	6.585
5	11609	+0.1052	6.718

Table 4 Displacement of the insulator string and the tension difference of the segment with asymmetrical ice accretion

pole No.	displacement of the insulator string δ_i/m	tension difference $\Delta T_{i(i+1)}$/N
1	0.6463	2471
2	0.4053	937
3	0.2326	522
4	0.1052	234

Table 5 Conductor strain, conductor sag, and variation amount of the span of the segment with asynchronous ice shedding

span No.	tension of each span T_i/N	variation amount of the span Δl_i/m	maximum sag f_{M}/m
1	20087	0.0948	8.449
2	19648	0.1352	8.638
3	18850	0.4601	4.137
4	19648	0.1352	8.638
5	20087	0.0948	8.449

Table 6 Displacement of the insulator string and the tension difference of the segment with asynchronous ice shedding

pole No.	displacement of the insulator string δ_i/m	tension difference $\Delta T_{i(i+1)}$/N
1	0.0948	440
2	0.2301	797
3	−0.2301	797
4	−0.0948	440

of water used for ice formation (applied water) have a significant influence on the withstand voltage of ice-covered insulators.

4.1 Influence of the type of ice

Phan and Matsuo examined the minimum flashover voltage of a short string of one or two cap-and-pin insulator units covered with soft rime, hard rime, or glaze. The test results showed that ice grown in a wet regime with a density of $0.87\,\mathrm{g\cdot cm^{-3}}$ formed at −12°C was the most severe type of ice build-up because of the high probability of flashover occurrence [42].

Khalifa and Morris studied the flashover performance of line insulators under rime ice of various densities. The research results showed that, when the rime ice density increased from 0.32 to $0.8\,\mathrm{g\cdot cm^{-3}}$, the leakage current amplitudes were almost doubled [43].

Fujimura et al. examined the performance of insulators covered with snow taken from a mountain or with the artificial ice produced in a cold room. It was concluded that the AC withstand voltage of an insulator string covered with ice is about 40% lower than that of an insulator string covered with snow if the water melted from such snow or ice had a conductivity within the range of 500 to $3000\,\mu\mathrm{S\cdot cm^{-1}}$ [44].

Farzaneh and Kiernicki have studied the effect of dry and wet-grown ice on the maximum withstand voltage gradient of different insulator types [14]. The results showed that wet-grown ice deposits were more dangerous than ice grown in a dry regime. For example, as to the IEEE standard insulator covered with wet-grown ice, the maximum withstand voltage was $70\,\mathrm{kV\cdot m^{-1}}$; if it is covered with dry-grown ice, the maximum withstand voltage was more than $148\,\mathrm{kV\cdot m^{-1}}$.

4.2 Influence of the amount of ice accretions

The amount of ice accumulated (i.e., the thickness of ice layer, the number of icicles, and the thickness of ice layer) has a considerable effect on the withstand voltage and the minimum flashover voltage of ice-covered insulator string.

Farzaneh and Kiernicki measured the maximum withstand voltage gradient of a post insulator covered with wet-grown ice. These results showed that the maximum withstand voltage gradient of the post insulator tested decreased with an increase of ice thickness up to 3 cm and then remained constant [14].

Fujimura et al. reported that the more an insulator was covered with snow, the lower the withstand voltage became. The withstand voltage becomes saturated with a quantity of snow of 875 g per insulator length (146 mm) [44]. The test results showed that, under artificial icing conditions, the withstand voltage of the insulator decreased with an increase of the length of icicles. If the insulator sheds were completely bridged by long icicles, the withstand voltage would decrease to 60% of that without no icicles.

The experimental investigations carried out in Chongqing University show that the minimum flashover voltage decreased with the increase of ice amount. However, it seemed that the minimum flashover voltage leveled off after complete icicle bridging, as shown in Fig. 9 [3].

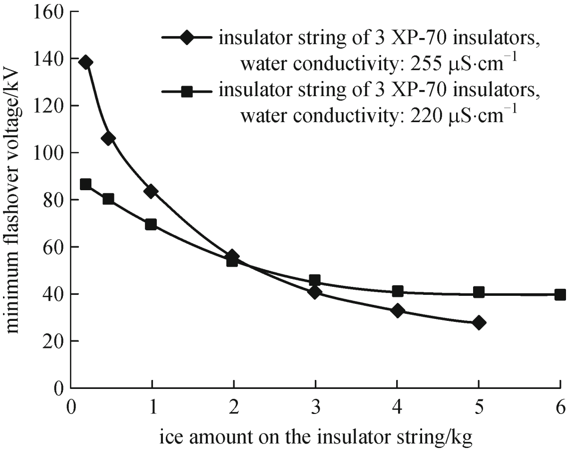

Fig. 9 Relationship between the minimum flashover voltage of the insulator string of three XP-70 units and ice amount (adapted from Ref. [3])

4.3 Influence of the conductivity of applied water

The conductivity of applied water, which is one of the most important parameters, significantly influences the flashover voltage of ice-covered insulators.

Fikke et al. reported that flashover events in mountain areas in Norway occur mainly under icing conditions combined with high ion contents of salt or from the combustion of fossil fuels in air [22].

Kannus and Verkkonen tested a series of insulators under artificial ice conditions. The resistivity of the freezing water varied from 0.7 to 90 $\Omega\cdot$m. It was found that when the resistivity of the freezing water decreased from 90 to 9 $\Omega\cdot$m, the leakage current pulse began to appear at an initial icing stage and the amplitude increased rapidly. The research results showed that the flashover voltage of two-unit suspension insulator string was linearly proportional to the square root of the resistivity of freezing water [45].

In Chongqing University, the effects of applied water conductivity on the minimum flashover voltage of different types of insulators have also been studied. Figure 10 shows the effect of applied water conductivity on the minimum flashover voltage of three types of insulator strings covered with 2800 g of wet-grown ice [3]. The results reveal that, in general, an increase in conductivity will lead to a lower flashover voltage, and the relationship between the minimum flashover voltage and the applied water conductivity can be approximately described by a power function.

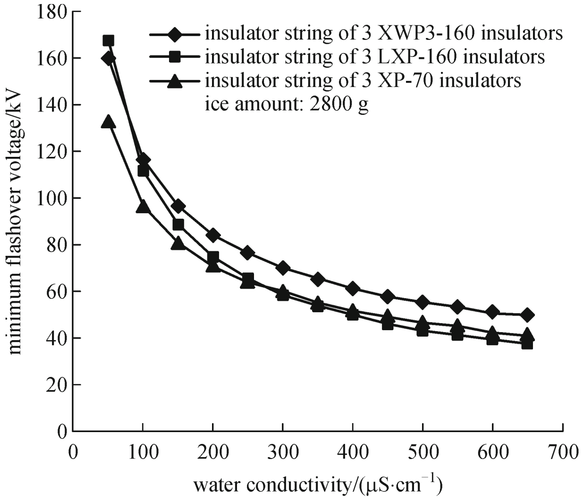

Fig. 10 Relationship between the minimum flashover voltage of three types of insulator strings and the applied water conductivity (adapted from Ref. [3])

5 Conclusions

A review of the research work on the formation of ice accretions on transmission lines and the effects of ice on the mechanical and electrical performance of transmission lines carried out by various researchers from different countries, and especially the research results obtained by the researchers in Chongqing University, China, confirm that the formation and types of ice accretions on transmission lines are affected by many factors, and the drastic decreases of mechanical property and electric property as a result of severe icing are the main reasons for ice accidents.

Ice accretions on transmission lines can be categorized into five different types: glaze, hard rime, soft rime, hoar frost, and snow and sleet. Meteorological conditions, terrain, and geographic conditions have great influence on the ice accumulation on transmission lines.

The glaze often formed at -1°C, and the rime often formed at -5.5°C. The ice accumulation speed is the largest when the ambient temperature is about 0°C. The ice accumulation speed is not in direct proportion to the wind velocity. The ice accumulation speed decreases with the increase of the diameter of the conductor. Under the same icing condition, the lift and torsional torque of the bundled conductors caused by the wind excitation are larger than those of single conductors, and the galloping is much more likely to occur. The higher the conductor is, the thicker the ice is.

Research on the mechanical performance of ice-covered transmission lines showed that, with the increase of the ice thickness, the total specific loading, the horizontal stress, and the maximum sag increase. With regard to asymmetrical ice accretion or asynchronous ice shedding, for the span with the heaviest ice accumulation, there is largest tensile force and largest sag. For the span with the lightest ice accumulation, there is smallest tensile force and smallest sag. For the straight-line poles with different ice loads on two sides, there is a largest tension difference.

Research on the insulating performance of ice-covered transmission lines showed that, as a general rule, the amount and type of ice, the uniformity of ice accumulation, and the conductivity of freezing water have a significant influence on the flashover voltage of ice-covered insulators.

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