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Multiphysics simulation and shed structure optimization of catenary icing insulator

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Abstract: It is not easy to make the insulators of the railway catenary for the dry and cold environment of the icy Qinghai-Tibet plateau, without causing serious ice-related flashover accidents. To study the operating status of catenary icing insulators, a two-dimensional icing model of catenary cantilever insulators was established based on the winter environmental characteristics of the Golmud station on the Qinghai-Tibet Railway. Compared different directions of ice growth, the spatial electric field distribution, and surface temperature distribution characteristics of icing insulators were analyzed by multi-physical field coupling simulation. The results show that as the thickness of the ice layer increases and the length of the icicle increases, the field intensity of the insulator gradually increases, and the surface temperature continues to rise. When the ice edge grows vertically downward, the electric field intensity of the insulator is the smallest, and the electric field intensity is the largest when the ice edge grows horizontally. Although the surface temperature of the insulator will rise with the increase of icing degree, it is lower than the freezing point and will not have a great impact on insulation performance. Secondly, when the cantilever insulator is arranged obliquely, the increase in the inclination angle will cause the electric field to increase and the temperature to rise slightly, so the inclination angle of the oblique cantilever should be reduced as much as possible during installation. Finally, the insulator with better insulation performance is obtained by optimizing the structure of the flat cantilever insulator.

Key words: cantilever icing insulator, electrostatic field, finite element simulation, multi-physical field coupling, temperature field

1. Introduction

The Qinghai-Tibet Railway has a total length of 1956 km and an average altitude of more than 4000 m [1]. The weather in the place it passes through is bad, and the insulators are easily iced in dry and cold winter, which reduces the insulation performance of the insulators and causes frequent flashover accidents [2]. Through the insulator icing test, C. Tavakoli and others found that the ice weight and salt density have a greater impact on the insulator's flashover voltage, and the arc extinction and arc extinguishing processes are obvious during the discharge process, and the arc is severely [3]; Zhao Jiayao found that different environmental parameters have a great influence on the shape, thickness, and length of icicles [4]. Zhang Zhijin and others took an XP-160 suspension insulator as the research object and obtained the influencing factors of flashover voltage of icing insulators through artificial icing and natural icing tests, respectively, and the comparison showed that the two icing methods had little influence on the results [5]; W. Ciesielka *et al*. made an in-depth study on the reliability of transmission lines in Poland under icing conditions, and put forward corresponding measures to improve the reliability of transmission lines [6].

To reduce the error caused by the test and save the cost as much as possible, N. Mhaguen established the finite element model of an ice-covered insulator, and obtained the critical flashover voltage of an ice-covered insulator through simulation, to realize the prediction of the flashover voltage of the ice-covered insulator [7]. Volat C. improved the one-arc and two-arc models in the flashover process of ice-covered insulators and used the finite element model to predict the critical flashover voltage of ice-covered insulators, making the results more accurate and the model more reliable and complete [8]. Lu Jiazheng established a finite element simulation of icing of a 220 kV insulator, and obtained the optimized insulator shed structure through calculation [9].

Based on the research background of Golmud city on the Qinghai-Tibet Railway, this paper established the composite cantilever insulator FQB-25/12 icing model and calculated through finite element analysis how to obtain ice thickness, the length of the icicle, and how the growth angle of the icicle on the cantilever insulator affects the electrostatic field and temperature field distribution of the insulator. Finally, the shed structure of the cantilever insulator was optimized according to the thermoelectric characteristics of the insulator, which provided a theoretical basis for the layout of the catenary cantilever. It also provides solutions for the selection of catenary insulators in areas with heavy icing.

2. Models of icing insulator

2.1. Insulator models

This paper takes the catenary cantilever insulator as the main research object, different icing forms as the research model, vertical icing insulators as the control group, flat cantilever icing, and inclined cantilever icing as the main research content. The structural parameters are shown in Table 1, where, H is the height of the structure, h is the dry arc distance, L is the creepage distance, and D is the diameter of the shed.

Table 1. Basic structural parameters of insulator

Model	H (mm)	h (mm)	L (mm)	D (mm)
FQB-25/12	760 ± 20	616	≥ 1600	192/140

2.2. Parameter setting

To study the icing characteristics of insulators under different structures and installation methods, the establishment of the electrostatic field, current field, and solid heat transfer field coupling multiple physical fields to simulate icing insulators is necessary. The various parameters used in the calculation are shown in Table 2 [9, 10].

Table 2. Simulation parameters

Material	ρ (g/cm^3)	ε_r	σ (S/m)	C_p (J/(kg·K))	λ (W/(m·K))
Fittings	$7.3 \cdot 10^3$	10^7	10^6	460	49.9
Silicone rubber	$0.97 \cdot 10^3$	3.5	10^{-12}	1460	0.16
Mandrel	$2.5 \cdot 10^3$	3.0	10^{-12}	794.2	1.09
Ice	$0.92 \cdot 10^3$	75	10^{-6}	2100	2.22
Air	1.342	1	0	1.004	0.024

In the table, ρ is the density; ε_r is the relative permittivity; σ is the conductivity; C_p is the heat capacity at constant pressure; λ is the thermal conductivity. The dynamic viscosity of the air is 1.67.

3. Simulation calculation

This paper takes the Qinghai-Tibet Railway line as the research background. Through the literature [11] and on-site investigations, it is found that the average winter temperature in Golmud city is about minus 3°, and the wind speed in winter is 3 m/s. According to the literature [12], the wind speed is set to 3 m/s, Table 3 shows the ice thickness and icicle length on the surface of the insulators under different freezing times at a temperature of minus 3°C.

Table 3. Different types of insulator icing

Insulator type	Ice thickness (mm)	Icicle length (mm)
FQB-25/12	0	0
	3	13
	6	26

The cantilever insulators are divided into flat cantilevers and oblique cantilever insulators. The installation layout of the cantilever insulator is shown in Figure 1. The flat cantilever insulator refers to the horizontal installation. A certain angle $\angle\,\alpha$ is included between the oblique cantilever and the ground, and its size is adjustable. The ice coating mode of the control group insulator is the same as that of the line insulator, and the insulator is arranged vertically, and the ice edge grows vertically and downward.

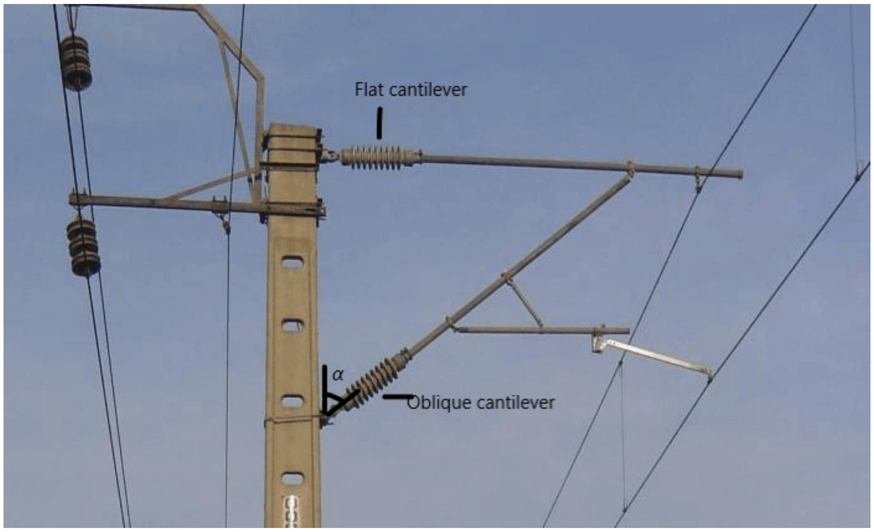


Fig. 1. Installation layout of cantilever insulator

3.1. Electrostatic field model

A simplified two-dimensional model of the electrostatic field of different insulators was established, and the finite element method was used for calculation using COMSOL Multiphysics simulation software. The differential equation and boundary conditions satisfied by the electrostatic field are shown in Equation (1).

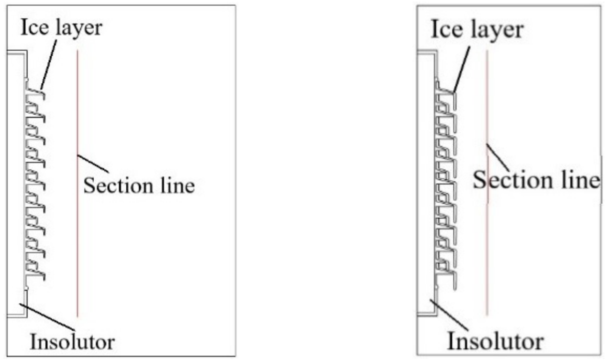
$$\begin{cases} \nabla \cdot \boldsymbol{D} = 0, & D_{1n} = D_{2n} \\ \nabla \cdot \boldsymbol{E} = 0, & E_{1t} = E_{2t} \end{cases}, \tag{1}$$

where $\boldsymbol{D}$ is the electric displacement vector and $\boldsymbol{E}$ is the electric field strength vector. n stands for the normal component, t stands for the tangential component; 1 and 2 are the mediators.

To facilitate the collection of the same feature quantity, a cut line is set in the air domain of the two-dimensional model, and the icing characteristics of the insulator are obtained by comparing the data on the cut line. The two-dimensional simplified model of the vertical icing of the cantilever insulator is shown in Figure 2.

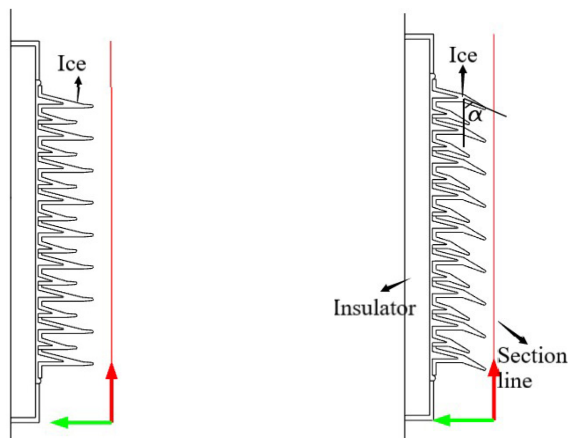
In the figure, the ice layer covers the surface of the insulator, and the icicle grows downward. Figure 1 tapers the tip of the icicle according to the literature [12], that is, the top is thicker and the bottom is thin. According to the rated operating line voltage of the insulator, which is 25 kV, the maximum allowable voltage is 29 kV, and the peak voltage is 41 kV. Set the voltage at the steel cap to 41 kV and the voltage at the steel foot to 0 kV.

As the actual research object, the real cantilever insulator layout is divided into the parallel layout and inclined layout. According to different arrangements, the ice growth direction on the insulator surface is different. As shown in Figure 3, where (a) is the flat cantilever icing, the icicle grows perpendicular to the diameter of the insulator rod, and the ice layer covers the whole surface of the insulator; (b) is the inclined cantilever icing, and the insulator has a certain angle $\angle \alpha$ with the ground, which can be adjusted according to the actual installation situation. Therefore, there



(a) Ice layer thickness equals 3 mm, icicle length equals 13 mm (b) Ice layer thickness equals 6 mm, icicle length equals 26 mm

Fig. 2. Two-dimensional model of vertical icing insulator



(a) Flat cantilever icing (b) Inclined cantilever icing

Fig. 3. Two-dimensional cantilever icing insulators

is a certain angle α between the growth direction of the icicle on the surface of the inclined cantilever insulator and the diameter of the insulator rod.

The model of a cantilever insulator with three different arrangement modes is used to simulate the insulator under different icing conditions in the electrostatic field. The distribution of the spatial electric field intensity of the three kinds of ice insulators is shown in Figure 4.

It can be seen from Figure 3 that the spatial electric field distribution of insulators after icing under three different installation modes is different. The results show that the spatial electric field intensity of the vertical insulator is smaller than that of the horizontal insulator and the inclined insulator, and the curve is smooth, which indicates that the mutation of a spatial electric field

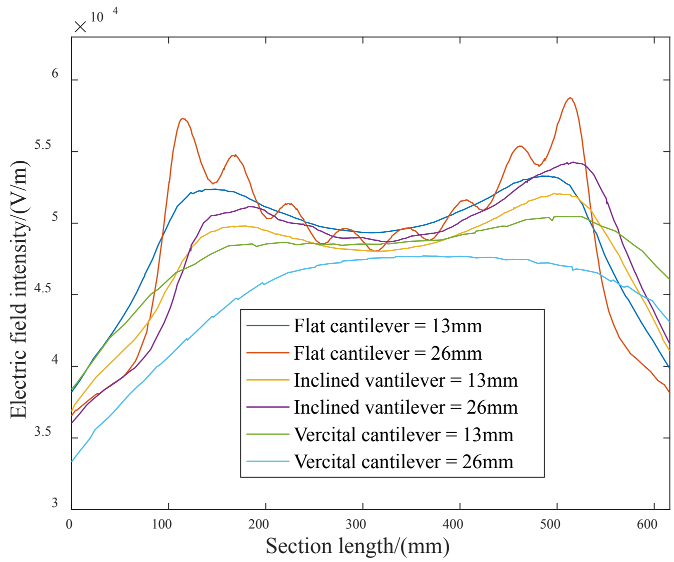


Fig. 4. Electric field distribution of insulators in different layout

is small, and the vertical ice growth has little effect on the spatial electric field distribution of insulators. For the horizontal insulator, the mutation rate of the space electric field increases after icing, and the curve is broken. The overall space electric field intensity is greater than that of the vertical insulator. However, the electric field distribution curve of inclined iced insulators is wavy and fluctuates greatly, which indicates that the mutation rate of the spatial electric field of inclined cantilever insulators after icing is the largest, resulting in the overall electric field strength higher than that of the other two kinds of insulators, that is, the influence of insulator inclination on the electric field distribution of insulators after icing is the largest. On the other hand, with the extension of icing time, when the length of the icicle increases from 13 mm to 26 mm, the electric field intensity of insulators with three arrangements decreases in varying degrees, and the change is most obvious when the insulator is arranged vertically. This shows that the increase of icing degree may reduce the space electric field intensity of insulators, and the existence of an ice layer will strengthen the insulation performance of insulators.

According to some literature [13, 14], the arrangement angle of the catenary cantilever can be adjusted within a certain range, and the spatial electric field distribution of the insulator at different angles can be obtained by changing the installation angle of the inclined cantilever as shown in Figure 5.

In the figure, the cantilever mounting angles $\angle\alpha$ are 60° and 65°, respectively, and the icicle length is 13 mm and 26 mm, respectively. It can be seen from the figure that when the mounting angle of the cantilever is increased, the electric field intensity in the space of the insulator also increases and the length of the icicle increases, and the space field intensity also increases.

$$\angle\alpha = 65°,$$

$$L_{\text{icicle}} = 26\ \text{mm} > \angle\alpha = 60°,$$

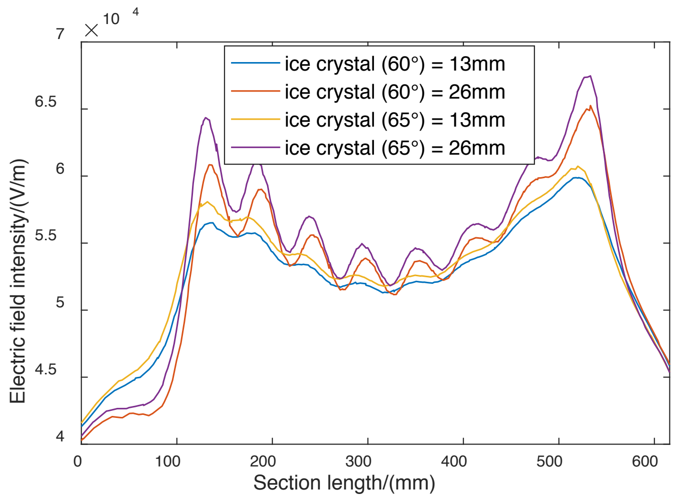


Fig. 5. Spatial electric field distribution of insulators with different arrangement angles of inclined cantilever

$$L_{\text{icicle}} = 26\text{ mm} > \angle\alpha = 65°,$$

$$L_{\text{icicle}} = 13\text{ mm} \ \angle\alpha = 60°,$$

$$L_{\text{icicle}} = 13\text{ mm}.$$

Therefore, the inclination angle of the cantilever should be as small as possible when installing the cantilever in the area with heavy ice, so as to reduce the probability of the insulator icing flashover and ensure the reliable operation of the insulator.

3.2. Thermoelectric coupled field model

Joule heat is generated when current passes through the ice-coated insulator [15] and the heat is dissipated to melt the ice. Liao Jiajun used ANSYS software to simulate and analyze the influence of the insulator's melting water film on the electric field distribution [16]; M. Ravisha *et al*. studied the electrothermal effect in an Alternating Current electric field and other physical fields [17]. Therefore, studying the temperature field distribution of ice-coated insulators in the thermoelectric coupling state can determine the location of the insulator's melting ice early and prevent the insulator from icing flashover.

The thermoelectric coupling field consists of an alternating current field and a solid heat transfer field. The boundary conditions of the alternating current field are shown in Equation (2).

$$\begin{cases} \nabla\cdot\boldsymbol{J} = 0, & J_{1n} = J_{2n} \\ \nabla\cdot\boldsymbol{E} = 0, & E_{1t} = E_{2t} \end{cases}, \tag{2}$$

where $\boldsymbol{J}$ is the current density vector and $\boldsymbol{E}$ is the electric field intensity vector. n stands for the normal component, t stands for the tangential component; 1 and 2 are mediators.

The heat transfer equation of the solid heat transfer field is shown by Equation (3).

$$\rho C_P \frac{\partial T}{\partial t} + \rho C_P \boldsymbol{u} \cdot \nabla T + \nabla \cdot (-k \nabla T) = Q, \tag{3}$$

where: ρ is the density, C_P is the constant pressure heat capacity, T is the temperature, t is the time, k is the thermal conductivity, $\boldsymbol{u}$ is the velocity field and Q is the heat source.

According to Newton's cooling law, the boundary conditions are set as shown in Equation (4).

$$-\boldsymbol{n} \cdot (-k \nabla T) = h(T_{\text{ext}} - T). \tag{4}$$

The left side of the equation is the initial boundary condition, and the right side is the convective heat flux, where h is the heat transfer coefficient and T_{ext} is the external temperature.

The temperature field of three ice-covered configurations of FQB-25/12 insulators is simulated and analyzed. The results are shown in the Appendix.

In the Appendix, Figures (a)–(d) show the temperature distribution on the surface of the cantilever insulator when there is no ice on the surface and the ice cover thickness is 3 mm, 6 mm, and 9 mm. It can be seen from the figure that when there is no ice on the insulator surface, the temperature will not change, which is consistent with the ambient temperature. With the increase of ice thickness, the temperature on the insulator surface begins to change, and the minimum temperature begins to rise gradually, from 2.87°C to 2.72°C. The maximum temperature also rises from 2.71°C to 2.53°C, which indicates that with the increase of ice thickness, the temperature on the insulator surface will rise, but it is lower than 0°C of the freezing point, and there will be no ice melting. From the point of view of temperature distribution, the place where the temperature changes greatly are generally the middle part of the insulator, showing the distribution characteristics of high temperature in the middle and low temperature at both ends, and the temperature change of ice layers is not obvious.

Figures (e)–(f) show the temperature distribution of the cantilever insulator when it is covered with ice vertically. With the increase of ice thickness and icicle length, the surface temperature of the insulator begins to rise. The overall temperature is larger in the upper part and smaller in the lower part, and the highest temperature occurs in the ice layer rather than the insulator, which indicates that the icicle growth direction has a great influence on the temperature field distribution of the insulator.

Figures (g)–(h) show that the flat cantilever is covered with ice, the ice edge grows horizontally, and the temperature rises slightly with the increase of the icing degree. The surface temperature of the fittings at both ends is the lowest, the temperature at both ends of the shed is higher, and the temperature in the middle is lower.

Figures (i)–(j) show the inclined cantilever icing with an inclination of 60° and Figures (k)–(l) show the inclined cantilever icing with an inclination of 65°. With the increase of ice thickness and icicle length, the temperature begins to rise, and the temperature distribution presents the characteristics of high at both ends of the shed and low in the middle of the shed. The temperature at the metal fittings at both ends is the lowest, and the lower ice temperature is toward the ice tip. When the inclination angle of the insulator increases, the temperature change is not obvious. Generally speaking, when the surface of the insulator is covered with ice, the temperature will rise in varying degrees with the increase of icing degree, but the maximum temperature is less than 0°C. There will be no molten water, which will not have a great impact on the insulation performance of insulator.

4. Optimization of cantilever insulator sheds

4.1. Shed structure optimization

To reduce the damage to the catenary power supply caused by the icing of the cantilever insulator, the structure of the existing shed needs to be optimized. It can be seen from Figure 3 that the electric field intensity of the flat cantilever insulator after icing is significantly higher than that of the inclined cantilever insulator, so it is necessary to optimize the flat cantilever insulator, and only the horizontal growth of icicles is considered in the optimization process. At this stage, the cantilever insulators are mostly the "one large and one small" sheds. In the optimization, an insulator model with the uniform sheds and the "one large and two small" sheds is established. The simulation calculation of the space electric field of the ice-coated insulators of different shed structures is carried out, and the results are shown in Figure 6.

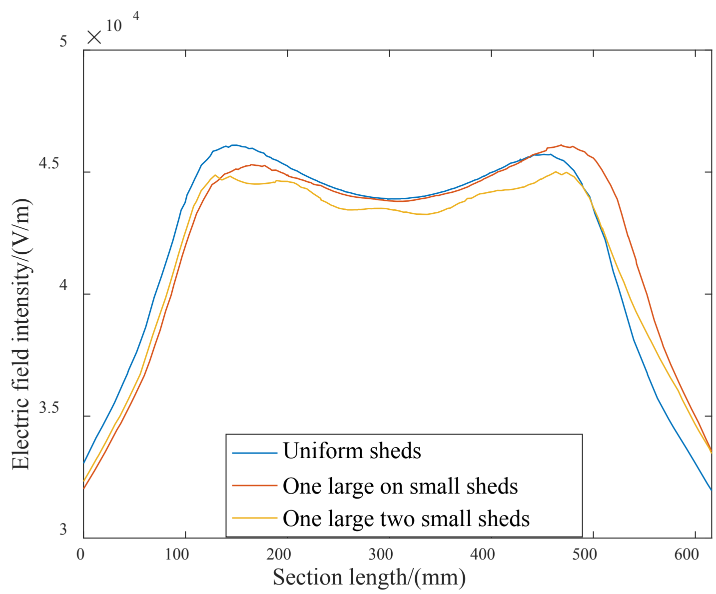


Fig. 6. Electric field distribution of icing insulators with different shed structures

The figure shows the electric field distribution diagram with an ice thickness of 6 mm and an icicle length of 26 mm when the insulators with three different shed structures are arranged in parallel. It can be seen from Figure 5 that among the three types of insulators, the cantilever insulator with "uniform sheds" has the largest electric field intensity after icing, while the insulator with "one large and two small" structures has the smallest electric field intensity after icing and the insulator with "one large and one small" sheds is in the middle. This shows that the insulator with "one large and two small" sheds has the smallest decline in insulation performance after icing, and it can play a better role to select the "one large and two small" shed structure to optimize the insulator. However, according to the literature [18, 19], partial discharges may occur in the insulating sheath only when the field intensity on the spot reaches the order of 10^6 V/m.

Compared with the simulation results, the insulation performance of the insulators of the three shed structures can be guaranteed under heavy ice conditions. The normal operation of the insulator will not affect the normal power supply of the catenary.

4.2. Shed spacing optimization

For the insulators with optimized shed structures, different shed spacing is selected for optimization. The shed spacing is the distance between the large shed and the small shed. The simulation model is built by selecting the sheds with a spacing of 9 mm, 18 mm, and 27 mm, respectively. The electric field distribution of different shed spacing structures is obtained by calculation, as shown in Figure 7.

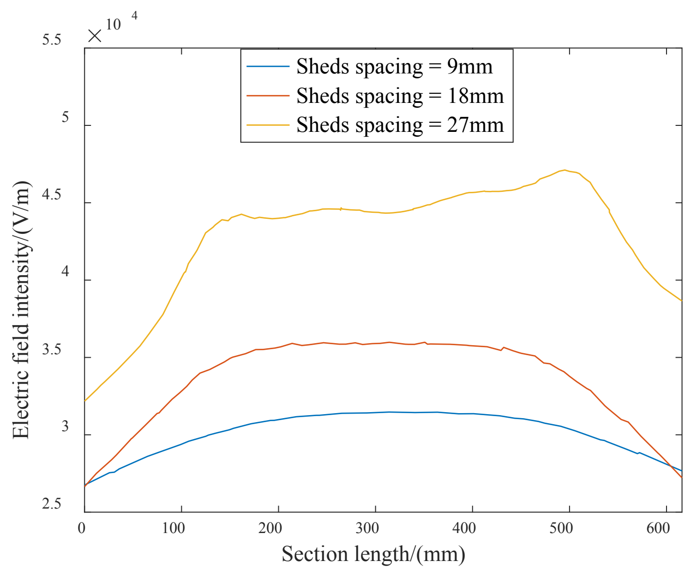


Fig. 7. Electric field distribution of icing insulators with different shed spacing

It can be seen from Figure 6 that when the flat cantilever insulator is iced, the spatial electric field intensity of insulators with different umbrella spacing is different. When the shed spacing is 27 mm, the number of sheds decreases and the spatial electric field intensity is larger. The highest point of the curve reaches 4.711×10^4 V/m and the lowest point is 3.22×10^4 V/m. When the shed spacing is 9 mm, the maximum electric field intensity of the iced insulator is 3.136×10^4 V/m, and the minimum is 2.671×10^4 V/m. Comparatively speaking, the insulator with 9 mm shed spacing can ensure the insulation performance of the insulator.

4.3. Optimization of shed extension

In addition to considering the structure and spacing of the shed, the extension difference between the large shed and the small shed is also part of the consideration. The stick-out difference of the shed is the diameter difference between the large shed and the small shed. The stick-out value of the small shed is fixed as 26 mm, and the stick-out value of the large shed is adjusted as 59 mm, 48 mm and 37 mm, respectively. The ice-covering models of insulators with different stick-out values are built, and the electric field distribution of insulators is obtained through simulation calculation, as shown in Figure 8.

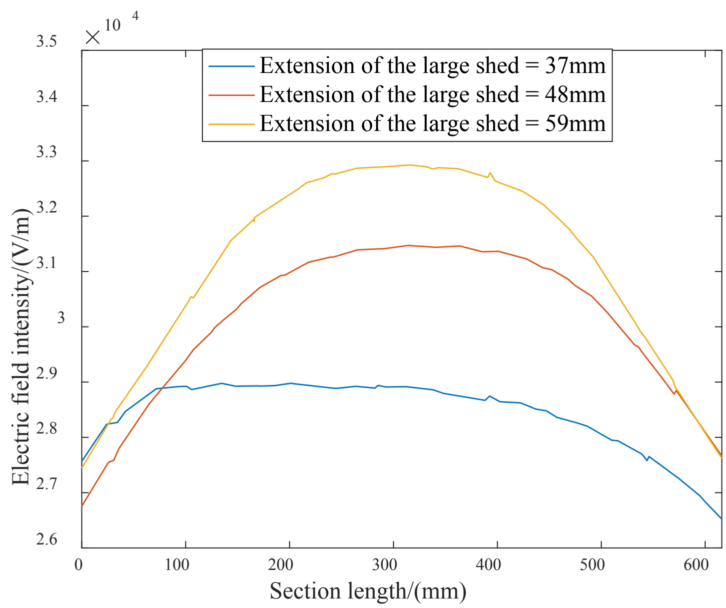


Fig. 8. Electric field distribution of icing insulators with different extension differences of the shed

It can be seen from Figure 7 that the electric field intensity on the insulator surface is the minimum when the extension value of the large insulator shed is 37 mm, and the extension difference of the large and small sheds is 11 mm. When the extension value of the large shed increases, the field intensity of the ice-covered insulator also increases. When the extension value of the large shed is 59 mm, the electric field strength of the insulator reaches the maximum value, that is, the difference between the large shed and the small shed is 33 mm. It can be seen from the figure that the extension value of the fixed small shed is 26 mm, and the insulator with a difference of 11 mm and the large shed with an extension value of 37 mm can be selected to minimize the surface field intensity of the insulator and ensure the safe operation of the ice-covered insulator.

4.4. Optimized insulator structure diagram

According to the previous optimization results, insulators with one large and two small shed structures were selected. The distance between the sheds was 9 mm, and the extension value of the large shed was 37 mm. The insulator model was constructed, as shown in Figure 9.

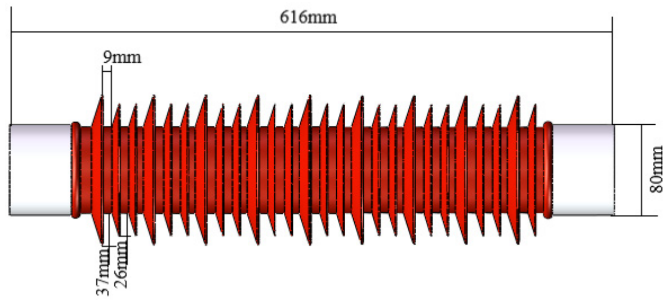


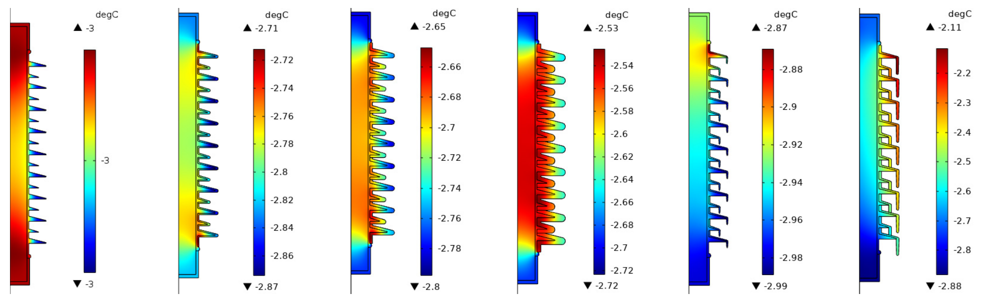
Fig. 9. Structure diagram of optimized insulator

5. Conclusion

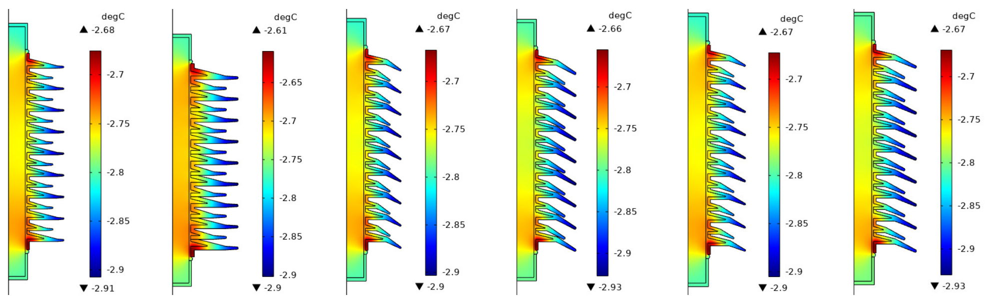
Aiming at the environmental characteristics of the Golmud station on the Qinghai-Tibet Railway, an icing model of the electrostatic field and thermoelectric coupling field of the catenary cantilever insulator is established. The simulation results are as follows:

1. After the insulator is iced, as the thickness of the ice layer increases, the length of the icicle grows, and the electric field intensity gradually increases. For the three types of iced insulators with vertical, inclined, and horizontal icicles, the electric field intensity of the insulator with vertical icicle growth is the smallest, followed by that with inclined icicle growth, and the electric field intensity is the largest when the icicle growth direction is perpendicular to the diameter direction of the insulator rod, which indicates that the icicle growth direction will also affect the spatial electric field intensity distribution of the insulator.
2. Calculate the temperature field of the icing insulator and find that the temperature of the insulator increases with the degree of icing. For the vertical growth of the ice layer, the temperature distribution of the insulator is high on the high voltage side and gradually decreases towards the low voltage side. For the horizontal growth of the ice layer and the growth of angles up to 60° and 65°, the surface temperature of the insulator is high on the high voltage side and low voltage side, and the temperature in the middle of the insulator is low, which indicates that the growth direction of icicles also affects the surface temperature distribution of the iced insulator. Secondly, the variation range of the surface temperature of the iced insulator is small, which will not be higher than 0°C, and there will be no ice melting. That is to say, the thermal effect of the current will not have a great impact on the ice layer and reduce the occurrence of flashover and other accidents.
3. According to the simulation results of the electrostatic field and temperature field, the cantilever insulator is optimized. Through the simulation calculation, it is found that the insulator with one big and two small umbrellas, when the distance between the umbrellas is 9 mm, the extension value of the large umbrellas is 37 mm, and the extension value of the small umbrellas is 26 mm, can effectively reduce the electric field distortion rate and the occurrence of Overhead Catenary System accidents when the icing is serious.

Appendix



(a) (b) (c) (d) (e) (f)



(g) (h) (i) (j) (k) (l)

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