# Calculation and analysis of basic ice melting current of steel core heating wires

MengyiKong[1] YongWang[2] RengjieLi SiteMo[3]

1 Engineering Cost Major of Jiaxing Nanyang Polytechnic Institute，Jiaxing Zhejiang，314000；

INTI international university，Malaysia，71800；

2 State Grid Jiaxing Power Supply Co., Ltd.，Jiaxing Zhejiang，314000；

Corresponding author: MengyiKong

ABSTRACT: The paper presents a novel ice-melting scheme based on the integration of existing thermal ice-melting techniques and the utilisation of steel-core heating wires. The addition of an insulating layer between the steel core and the aluminium strand enables online ice melting, effectively addressing the adverse effects of traditional thermal ice-melting methods caused by power outages. The paper initially examines the underlying principle and practical viability of ice melting in the context of steel-core heating conductors. The findings indicate that steel-core heating conductors possess significant engineering applications. Subsequently, the mechanism of thermal ice melting of transmission lines and the principles of heat transfer were employed to establish the heat balance equation and the heat conduction differential equation of the ice melting process. This resulted in the mathematical model of the critical ice melting current and the maximum ice melting current of steel-core heating conductors, thereby providing a theoretical basis for the selection of ice melting current of steel-core heating conductors. Subsequently, the precision of the proposed methodology for calculating the critical melting current was validated through simulations and experimentation conducted using the ANSYS software.

Keywords：steel core heating wire; online ice melting; heat transfer principles; critical ice melting current; ANSYS

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## 1.INTRODUCTION

In recent years, there have been notable changes in the global climate, with an increase in the frequency of severe weather events. In some regions of the world that are susceptible to ice-related disasters, the accumulation of ice has resulted in extensive damage to a multitude of infrastructure systems, including overhead transmission lines and communication networks. In some regions, a considerable quantity of ice accumulates on communication cables and overhead conductors, resulting in significant challenges and economic losses, as well as inconvenience to the general public [1].

The risks posed by ice accumulation on transmission lines are becoming increasingly significant. In the most benign scenario, they result in flashover and tripping. In the most extreme case, they cause damage to fittings, broken lines, and fallen towers, thereby threatening the safe operation of overhead transmission lines [2]. In particular, the widespread freezing weather in January 2008 caused extensive damage to China's power grid system, resulting in significant economic losses. Domestic power companies, research institutes, design institutes, equipment manufacturers and other units have long been engaged in research and exploration on grid anti-icing and anti-icing technologies. This has resulted in the gradual formation of a comprehensive set of ice disaster prevention and control technology systems, which provide technical support for the safe and stable operation of the power grid. It provides technical guarantee for safe and stable operation [3,4].

Current transmission line de-icing technology has evolved from the early mechanical de-icing method to the most widely used AC and DC short-circuit ice melting method. Ice melting technology has come a long way, but there are still some shortcomings. Firstly, AC and DC ice melting methods all need to be carried out after a power failure, which causes certain economic losses and seriously affects people's normal lives; secondly, there are many loads that need to be transferred before melting, and the operation mode of multiple power grids has a greater impact [5]; thirdly, on-site operation is complex and inefficient, requires a long preparation time before melting ice, and there are potential safety hazards; fourthly, for ice melting on long transmission lines, the required ice melting power supply capacity is very large, and the system is difficult to supply. It can be seen that the existing ice-melting methods have made excellent contributions to mitigating the icing disaster of the power grid, but they are still difficult to meet the construction needs of smart grids.

This paper proposes a real-time online ice-melting technology scheme based on steel-core heating wires, which can achieve real-time and automatic anti-icing and ice-melting operations on transmission lines [6,7]. The proposed ice-melting scheme does not require power outages or additional ice-melting power sources, and is an economical and effective intelligent anti-icing and ice-melting technology. The simulation and experimental results show that the proposed scheme is effective and feasible, and has certain reference significance for real-time online ice-melting.

## 2.This paper presents a comprehensive analysis of the principle and feasibility of steel-core heating wire for ice melting

It proposes a real-time online ice melting technology scheme based on steel-core heating wire, which is founded upon a thorough examination of the advantages and disadvantages of existing ice melting methods. The paper begins by delineating the structure and ice melting mechanism of steel-core heating wire. It then proceeds to illustrate the viability of steel-core heating wire in engineering applications through a detailed economic and technical comparison.

### 2.1.A detailed examination of the structural composition of steel-core heating conductors is presented in this study

In light of the attributes inherent to coaxial cable structures, this article puts forth a novel composite conductor configuration, founded upon the utilisation of conventional transmission conductors. The structure is illustrated in Figure 1. The key innovation is the addition of a layer of insulating material between the steel core and the aluminium strand, based on the existing transmission conductor. This maintains the insulation of the inner and outer conductors. The steel-core heating wire is composed of three distinct layers: a steel core, an insulating layer and an aluminium strand. The steel core and the aluminium strand are insulated at one end, while the other end is in a short-circuit state. This configuration ensures the uninterrupted transfer of power while simultaneously preventing the accumulation of ice on the transmission line.

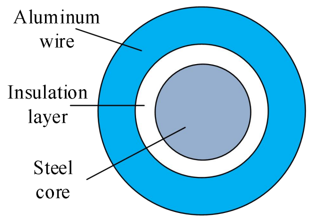



Figure 1 System structure block diagram

### 2.2.The mechanism of ice melting by steel-core heating wire

The real-time online ice-melting system for steel-core heating wire comprises three main components: the heating wire, the ice-melting switch control system and the ice-cover detection device. The steel-core heating wire constitutes the primary component of the system, assuming responsibility for both power transmission and ice-melting prevention. The ice-cover detection device is primarily utilized for the real-time measurement of ice accumulation on the wire, subsequently issuing melting signals. The switch control device is responsible for regulating the opening and closing of the ice-melting switch (S1) in accordance with the signals transmitted by the ice-cover detection device. In the absence of ice covering the conductor, switch S1 is in the closed position, allowing the steel core and aluminium strand to operate in a short circuit. This configuration results in the conductor exhibiting the same characteristics as a conventional power transmission conductor. In the event that the conductor is covered with ice, the critical melting current and maximum melting current are calculated in accordance with the actual working conditions and the requirements set forth in the current Chinese standard, which stipulates that the temperature of the conductor during melting should not exceed 70°C. Subsequently, the adjustable resistor is adjusted to permit the steel core to conduct an appropriate quantity of current, and switch S1 is disconnected concurrently to satisfy the requirement of rapidly melting ice without causing the conductor temperature to exceed the permissible limit.

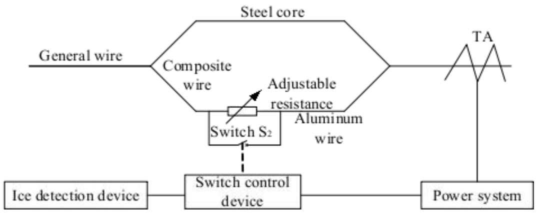



Figure 2 System structure block diagram

## 2.3.Feasibility analysis of ice melting of steel core heating conductor

1) Economic and technical comparison

The manufacturing materials and processes of steel-core heating conductors are essentially analogous to those employed in the fabrication of existing overhead transmission lines. The fabrication of composite conductors can be accomplished directly through the utilisation of existing overhead transmission conductor manufacturing apparatus. In comparison to conventional steel-core aluminium stranded conductors, the manufacturing cost of steel-core heating conductors is approximately 20% higher. In the case of lines that require de-icing, the only necessary replacement is of the steel-core heating wire, with no additional power equipment required. Furthermore, the steel-core aluminium stranded wire that is replaced can be recycled or employed in the erection of other lines that are not covered with ice, thus preventing the waste of resources.

Table 1 Technology comparison

| content | Steel core hot wire melt ice | Communication short circuit melting ice | DC short circuit melting ice |
|---|---|---|---|
| Ice melting power supply | No external power supply is required | Ice melting transformer | direct-current main |
| Ice melting current | Line current, controllable | AC short-circuit current,not controllable | DC short-circuit current, controllable |
| Whether the power | deny | yes | yes |
| Applicable line | Suitable for all overhead lines | Short distance lines below 500kV | Part of the line |
| Ice melting distance | Preset the segmentation, and automatically melt the ice | Fixed distance | Fixed distance |
| Ice melting efficiency | High, energy consumption is used for melting ice | High, there is a reactive power loss | High, energy consumption is used for melting ice |
| Impact on the system | Overload is required | Basically no impact | Basically no impact |

Table 1 presents a comparative analysis of the primary technical indicators associated with steel-core heating conductors, AC short-circuit ice melting, and DC short-circuit ice melting. As can be observed from the comparative analysis presented in the table, the ice melting method based on steel-core heating conductors exhibits certain advantages over the traditional AC and DC short-circuit ice melting methods. However, it is also evident that this approach has certain inherent limitations..(a): The replacement of existing overhead lines with modified ones that utilise different conductors necessitates a lengthy power outage, which has a considerable impact on the reliability of the power supply. Nevertheless, this consequence is not applicable to newly installed lines.(b): The insulation layer in steel-core heating conductors exhibits poor thermal conductivity. In the event that the system load is excessive or the ambient temperature is considerable, the dissipation of heat within the steel core is impeded. Nevertheless, this issue can be addressed by enhancing the thermal conductivity of the insulation layer and regulating the circuit loading [8]; (c): The overall cost of steel-core heating conductors is marginally higher than that of conventional transmission conductors; however, there are no additional operating and maintenance costs. Furthermore, the utilisation of steel-core heating conductors for ice melting does not necessitate power outages, thereby mitigating the potential economic losses associated with such processes. In contrast, the use of AC and DC short-circuit ice melting is contingent upon the occurrence of power outages, which inevitably results in significant economic losses and considerable inconvenience to the general public.

2)Feasibility analysis

Prior to the implementation of the ice melting method based on steel core heating wires, it is essential to ascertain that the line is capable of accommodating the requisite load current, which is defined as a value exceeding the critical ice melting current. The total load on the transmission line is subject to change on a continual basis, which presents a challenge for accurate calculation. However, it can be converted and verified in accordance with the economic current density of the line design. Table 2 below presents the economic current density of wires and cables as specified in China.

To illustrate, the 120/25 conductor, when its annual maximum load utilisation hours exceed 5000, has a calculated minimum load of 133A. The subsequent calculation and simulation demonstrate that the critical melting current is 84A at an ambient temperature of -10° C, a wind speed of 7m/s, and an ice thickness of 15mm. The minimum load current of the transmission line is greater than the critical melting current, thus demonstrating that the steel-core heating conductor is capable of meeting the requisite ice-melting conditions.

Table 2. Economic current density value

| Line category | The wire material | Annual Maximum load utilization hours | | |
|---|---|---|---|---|
| | | Under 3000 | 3000-5000 | More than 5000 |
| overhead network | copper | 3.00 | 2.25 | 1.75 |
| | aluminium | 1.65 | 1.15 | 0.90 |
| cable line | copper | 2.5 | 2.25 | 2.0 |
| | aluminium | 1.92 | 1.73 | 1.54 |

## 3.Calculation of basic ice melting current of steel core heating wire

In order to guarantee the efficacy of the ice-melting process, it is essential to examine the ice-melting properties of the ice-covered conductors under diverse ambient temperatures, wind speeds, and ice thicknesses. The findings of the study can be employed as a foundation for the selection of the actual ice-melting current for ice-covered high-voltage transmission lines.

### 3.1.Calculation of critical current of steel core heating conductor based on the principle of thermal balance

The control ice-melting switch and adjustable resistance permit the steel core to pass a certain intensity of current, thereby initiating the heating process and enabling the transfer of heat to the ice layer through the insulation layer and the aluminium strand. Once the temperature of the outermost layer of the aluminium strand reaches 0 ° C, and the heat generated by the steel core is precisely equal to the heat transmitted to the environment through the ice layer, the current at this point is defined as the critical ice-melting current. This is the minimum current required to achieve the melting point of the ice layer, as the surface temperature of the aluminium strand reaches this temperature [9].

In the absence of heat generation by the aluminium strand, the steel core may be considered the sole heat source. The heat flux density of the steel core per unit length is given by the following equation:

$$q_g = I^2 r_g \tag{1}$$

I is the current flowing through the steel core, A; rg is the resistance of the steel core per unit length, Ω/m.

When in a critical state, the heat generated in the steel core is exactly equal to the heat transferred to the environment through the ice layer, i.e.:

$$I^2 r_g = \frac{\pi(T_l - T_i)}{R_q} \tag{2}$$

Where , Tl is the surface temperature of the aluminium strand, ℃; Ti is the surface temperature of the ice layer,℃; Rq is the radial thermal resistance of the ice layer. According to Fourier's law and the temperature distribution of a cylinder, the radial thermal resistance of the upper half of the ice cylinder is:

$$R_q = \frac{\ln[(R_c + d_i)/R_c]}{\pi\lambda_i} \qquad (3)$$

Where Rc is the radius of the wire, m; di is the thickness of the ice, m； di is the thermal conductivity of the ice, W/(m·C).

The heat from the air introduced through the upper part of the ice cylinder is completely exchanged with the air in the form of convective heat transfer, i.e.:

$$I^2 r_g = 2\pi h\left(R_c + d_i\right)\left(T_i - T_e\right) \qquad (4)$$

The average convective heat transfer coefficient h is defined as the sum of the natural convective heat transfer coefficient hn and the forced convective heat transfer coefficient hf on the surface of the conductor[10]. The latter is expressed in W/(m2·K), while the former is given by hn. The following formulas are used for calculation:

The natural convective heat transfer coefficient is defined as follows:

$$h_n = \frac{Nuk_a}{D} \qquad (5)$$

$$Nu = A \cdot \mathrm{Re}^B \qquad (6)$$

$$\mathrm{Re} = Gr\,\mathrm{Pr} \qquad (7)$$

$$Gr = \frac{g \cdot (T_i - T_e)(D)^3}{\upsilon^2\left[\frac{(T_i - T_e)}{2} + 273.15\right]} \qquad (8)$$

In this context, the Nusselt number Nu, the coefficient of thermal conductivity of air ka, the diameter of the cylindrical conductor D，m； the Reynolds number Re, the Grashof number Gr, the coefficient in the corresponding case B, the Prandtl number Pr, and the acceleration of gravity g are all variables ， m/s2. The kinematic viscosity of air $\upsilon$ is a constant, $\upsilon = 1.328 \times 10^{-5} m^2/s$

The forced convective heat transfer coefficient on the conductor surface is

$$h_f = \frac{Nu_f k_a}{D} \qquad (9)$$

$$Nu_f = A_f \,\mathrm{Re}^m \,\mathrm{Pr}^n \qquad (10)$$

$$\mathrm{Re} = \frac{D v_a \rho_a}{\mu} \qquad (11)$$

$$\mathrm{Pr} = \frac{\mu \bullet C_a}{k_a} \qquad (12)$$

In formula NufFor the number of forced convection Nusselt, m, n are constant, n generally take 1 / 3, m value depends on the size of Re; for the air density; v $\rho_a$ $\rho_a = 1.293 kg/m^3$ a $\mu$ Wind speed, m/s; dynamic viscosity coefficient of air,; A $\mu = 1.72 \times 10^{-5} kg/(m \cdot s)$ fFor the coefficient in the case of forced convection; CaFor the specific heat capacity of the air, $C_a = 1005 J/kg \cdot ℃$.

Correspondence between the values of Table 3 A and B and the Gr number

| flow regime | Gr | A | B |
|---|---|---|---|
| laminar flow | 1.43*104~5.76*108 | 0.48 | 0.25 |
| transition | 5.76*108~4.65*109 | 0.0165 | 0.42 |
| swift current | >4.65*109 | 0.11 | 0.333 |

Table 4 The correspondence between the values of and m and the Re number

| Re | Af | m |
|---|---|---|
| 4~40 | 0.911 | 0.385 |
| 40~4000 | 0.683 | 0.466 |
| 4000~40,000 | 0.193 | 0.618 |
| 40,000~40,0000 | 0.0266 | 0.805 |

Simultaneously with the above formulas (9)~ (12), the critical melting current of the steel core heating wire is obtained as

$$I_c = \sqrt{\frac{-2\pi\lambda_i\left(R_c + d_i\right)hT_e}{r_g(R_c + d_i)h\ln\left[\left(R_c + d_i\right)/R_c\right] + r_g\lambda_i}} \quad (13)$$

From equations (4) and (13), it can be seen that under conditions of critical melting, the critical melting current is affected by the thickness of the ice cover, the ambient temperature, the ice surface temperature and the wind speed. Chapter 4 of the article will present the findings of a simulation analysis.

## 3.2.Calculation of the maximum melting current of steel-core heating wires

The use of steel-core heating wires for the purpose of melting ice entails the risk of severe overheating of the steel core if the current flowing through it is excessive. If the steel core is operated at a high temperature for an extended period, it will accelerate the ageing process and significantly impair the mechanical properties of the steel core. It is essential to ascertain the maximum melting current of the steel-core heating wire in order to prevent overheating and damage to the circuit.

Once the steel core heating wire has generated heat as a result of the current, this heat will then be transferred radially to the outer layer.(In engineering, when the length of a cylindrical object is greater than 10 times the radius, it can be considered a one-dimensional heat conduction problem in the radial direction.) When the external environment remains constant, the following differential equation of heat conduction is satisfied during the ice melting process..

$$\frac{1}{r}\times\frac{\partial}{\partial r}(k_\theta r\frac{\partial T_\theta}{\partial r}) + q_\theta = \rho_\theta c_{p_\theta}\frac{\partial T_\theta}{\partial t} \quad (14)$$

In this context, $\theta$ represents the area divided according to the material composition, specifically the steel core, insulation, aluminium strand and ice layer. In this context, the variable "r" radius for different regions Similarly,m； $k_\theta$ denotes the thermal conductivity of the different areas, W/(m • ℃); while $T_\theta$ denotes the temperature of the different areas, which we may express as ℃. Finally, $q_\theta$ denotes the heat generated per unit volume, J/m3; $\rho_\theta$ is the density of the material in the different regions, kg/m3; $c_{p\theta}$ is the specific heat capacity of the material in the different zones, J/(kg • ° C); except for the steel core, there is no internal heat source in the other zones, so $q_\theta$ =0 in the other zones.

According to the heat transfer and ice melting physics, the boundary condition of temperature continuity is satisfied at the interface between the steel core, the insulation layer, the aluminium strand and the ice layer, i.e.:

$$-k_g\frac{\partial T_g}{\partial r}|_{r=r_g} = -k_j\frac{\partial T_j}{\partial r}|_{r=r_g} \quad (15)$$

$$-k_j\frac{\partial T_j}{\partial r}|_{r=r_j} = -k_l\frac{\partial T_l}{\partial r}|_{r=r_l} \quad (16)$$

$$-k_l\frac{\partial T_l}{\partial r}|_{r=r_l} = -k_i\frac{\partial T_i}{\partial r}|_{r=r_i} \quad (17)$$

At the same time, the temperature at the interface between the aluminium strand and the ice layer is always maintained at 0° C, satisfying the first type of boundary condition:

$$T_l(r,T)|_{r=r_l} = 0 \quad (18)$$

When there is a temperature difference between the surface temperature of the ice and the ambient temperature, heat is exchanged between the ice and the environment. The heat diffusion equation at this interface satisfies the third type of boundary condition:

$$-k_i \frac{\partial T_i}{\partial r}|_{r=r_i} = h\left(T_i - T_e\right) \qquad (19)$$

Where h is the heat exchange coefficient between the ice layer and the environment, W/(m2.℃); Ti is the surface temperature of the ice layer, ℃; Te is the ambient temperature, ℃.

The current standard in China stipulates that the maximum temperature of a steel-core aluminium conductor when operating under load must not exceed 70° C, and in special circumstances the maximum temperature limit can be set at 90° C. The maximum allowable current for a steel-core heating wire is the maximum current that can pass through the steel core to ensure that the temperature of the steel core does not exceed 70° C.

The final solution for the temperature distribution of the steel core is as follows:

$$T_g\left(r_g\right) = \frac{qr_g^{\ 2}}{2k_j}\ln\frac{r_j}{r_g} + \frac{qr_g^{\ 2}}{2k_l}\ln\frac{r_l}{r_j} + \frac{qr_g^{\ 2}}{2k_i}\ln\frac{r_i}{r_l} + \frac{qr_g^{\ 2}}{2r_i h} + T_e \qquad (20)$$

Where $q = I^2 r_g / A_g$ ,Ag is the cross-sectional area of the steel core, m2; when Tg=Tmax=70, the current obtained is the maximum ice-melting current.

$$I_{\max} = \sqrt{\frac{T_{\max} - T_e}{r_g\left(\frac{\ln r_2/r_1}{2\pi k_j} + \frac{\ln r_3/r_2}{2\pi k_l} + \frac{\ln r_4/r_3}{2\pi k_i} + \frac{1}{2\pi r_4 h}\right)}} \qquad (21)$$

## 4.Simulation analysis of the critical melting current of steel-core heating wires and the surface temperature of ice

Based on the analysis of the structure of the steel-core heating wire and the principle of ice melting, this paper will use ANSYS 19.0 finite element analysis software to perform a finite element analysis of the critical melting current of the steel-core heating wire. The simulation method used is a combined electromagnetic and thermal coupling simulation. In ANSYS, the calculation results of the electromagnetic simulation are used as the heat source applied to the steel core, and then the boundary conditions are set according to the actual physical process of ice melting to perform the analysis and calculation. The critical melting current of the steel core heating wire under different conditions is finally obtained.

### 4.1.Parameter determination and modeling

There are many types of ice on transmission lines, but the most influential is hoarfrost. Therefore, this paper selects cylindrical uniform hoarfrost as the ice on the transmission line for analysis and modelling. A three-dimensional electromagnetic-thermal coupling finite element model of the transmission line is established, and the temperature field is analysed by applying a direct current to the steel-core heating wire, using the LGJ120/25 model wire as an example. The relevant parameters of the steel-core heating wire are shown in Table 5 and Table 6.

Table 5 Steel core heating wire parameter table

| The wire model | Aluminum specifications | Steel specifications | insulating course | Outer diameter (mm2) |
|---|---|---|---|---|
| LGJ120/25 | 7/4.72 | 7/2.10 | 1/1 | 16.74 |

Table 6 Electrothermal parameters of icing model

| material | Density (kg/m3) | Thermal conductivity (W/ m • K) | Specific heat capacity (J/kg • ℃) | resistivity (Ω • m) |
|---|---|---|---|---|
| steel core | 7850 | 45 | 460 | 1.7*10-7 |
| Aluminium stranded conductor | 2670 | 237 | 880 | 2.83*10-8 |
| insulating course | 930 | 0.4 | 2300 | 1*1018 |

| | | | | |
|---|---|---|---|---|
| ice | 900 | 2.26 | 2100 | 1*1011 |
| air | 1.1614 | 0.026 | 1007 | 1*1019 |

## 4.2.Analysis of the critical melting current of steel-core heating wires and the factors affecting the surface temperature of ice

The heat exchange between the ice and the environment has a great influence on the critical melting process, so it is necessary to analyse the surface temperature of the ice. The following formula can be derived from equations (2), (3) and (4):

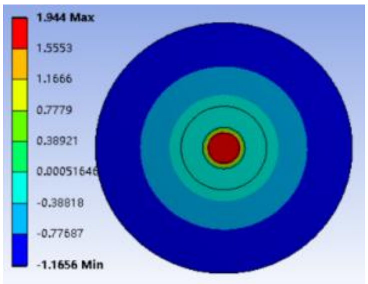
$$T_i=\frac{(R_c+d_i)h\ln\left[(R_c+d_i)/R_c\right]T_e}{(R_c+d_i)h\ln\left[(R_c+d_i)/R_c\right]+\lambda_i} \qquad (22)$$

From Equation (22), it can be seen that the surface temperature of the ice layer depends on the ice thickness, the convective heat transfer coefficient of the ice surface, the ambient temperature, and the thermal conductivity of the ice layer.

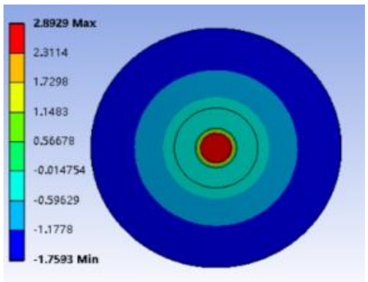
The critical melting current of the steel-core heating wire is affected by multiple factors. As shown in Equation (13) in Chapter 2, the critical melting current is a function of the ambient temperature, wind speed, ice thickness, and steel core radius.

This study examines the impact of ambient temperature on the critical melting current

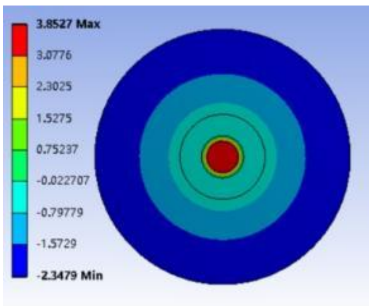
The simulation conditions are set as follows: combined electric-thermal simulation, thermal module selection of steady-state heat conduction analysis, ice-covered conductor model of LGJ120/25, wind speed of 2.5m/s, ice thickness of 15mm; the effects of the ambient temperature of -10℃, -8℃, -6℃ and -4℃ on the critical ice-melting current and the temperature distribution of the ice-covered conductor are simulated respectively.



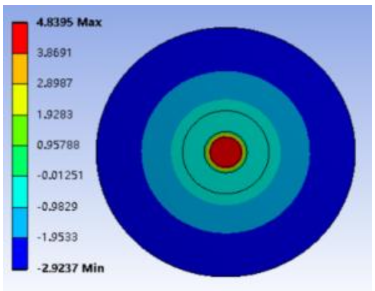

(a) -4℃




(b) -6℃




(c) -8℃




(d) -10℃

Figure 3 Influence of ambient temperature on critical ice melting current

Equation (13) calculates that the critical ice melting currents under different temperature conditions are 42.99 A, 51.495 A, 60.795 A and 67.97 A, respectively.The critical ice melting currents simulated in ANSYS are 42.1A, 51.495A, 59.5A, and 66.57A, respectively.The discrepancy between the calculated and simulated results is 2.1%, which is within an acceptable range and provides evidence of the accuracy of the proposed critical ice-melting current calculation formula.

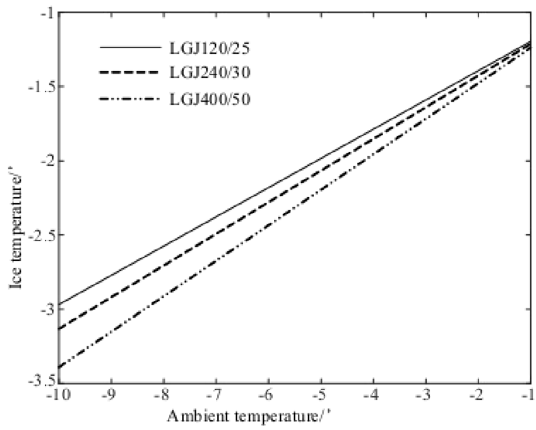
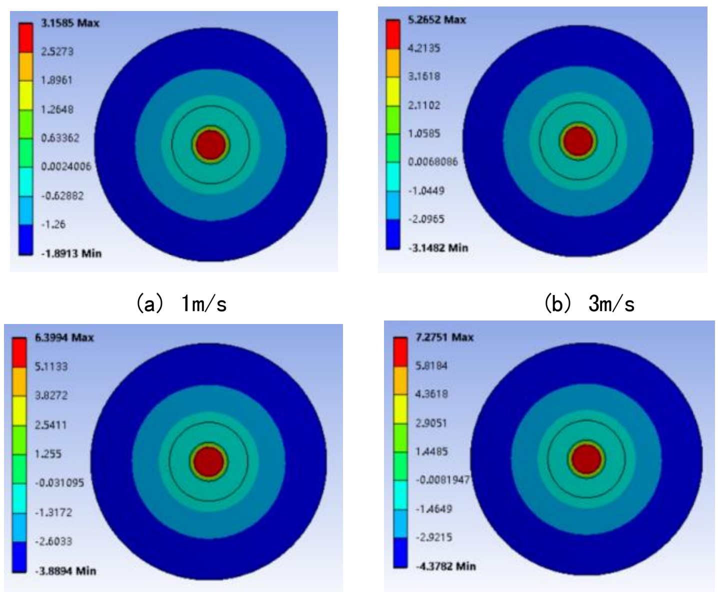



Figure 4 Influence of ambient temperature on ice surface temperature

At lower ambient temperatures, the initial temperature of the ice is also lower, and the energy required to heat the inner surface of the ice to 0° C is also greater. As can be seen from the results in Figures 3 and 4, at the critical state, there is a linear relationship between the surface temperature of the ice and the ambient temperature, and at the same time, as the ambient temperature decreases, the critical melting current increases significantly.

(b)Effect of wind speed on critical ice melting current

The simulation conditions are set as follows: the ice-covered conductor model is LGJ120/25, the ambient temperature is -10° C, and the ice thickness is 15mm. The effects of the critical melting current and the temperature distribution of the ice-covered conductor are simulated at wind speeds of 1m/s, 3m/s, 5m/s, and 7m/s, respectively.




(a) 1m/s (b) 3m/s

(c) 5m/s (d) 7m/s

Figure 5 Influence of wind speed on critical ice melting current

The critical melting currents calculated at wind speeds of 1 m/s, 3 m/s, 5 m/s and 7 m/s are 54.742 A, 70.818 A, 78.887 A, 84.18A; the simulated critical melting currents were 53.865A, 69.25A, 77.37A, and 82.1A, respectively, and the simulation results were very close to the calculated results.

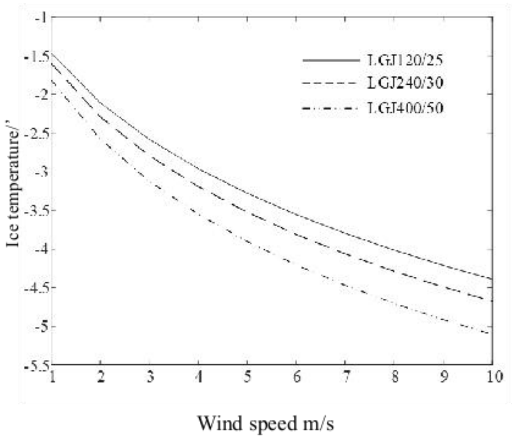
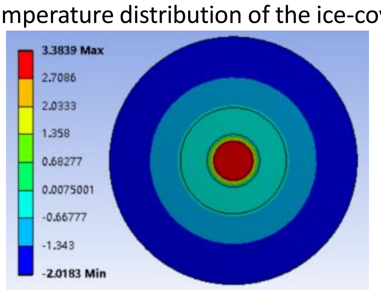



Figure 6: Effect of wind speed on ice surface temperature

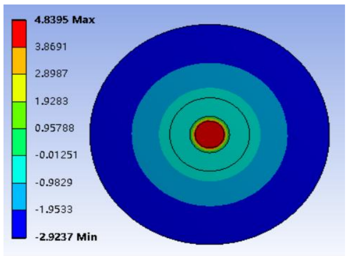
As evidenced by Formula (22), the surface temperature of the ice layer is contingent upon a number of factors, including the thickness of the ice layer, the convective heat transfer coefficient of the ice layer surface, the ambient temperature, and the thermal conductivity of the ice layer. As wind speed rises, the convective heat transfer of the ice layer surface increases markedly, resulting in a reduction in the surface temperature of the ice layer and an increase in the critical melting current. However, both the ice surface temperature and the critical melting current exhibit a certain degree of saturation. Once wind speeds reach 11 m/s or above, the impact of wind speed on the critical melting current and ice surface temperature begins to diminish.

(c)The effect of ice thickness on the critical melting current

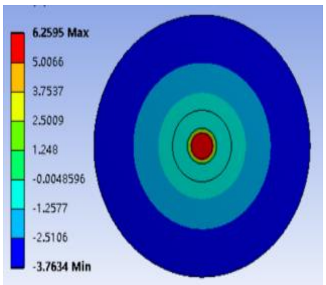
The simulation conditions are set as follows: the ice-covered conductor type is LGJ120/25, the ambient temperature is -10°C, and the wind speed is 2.5m/s; the effects of ice thickness of 10mm, 15mm, 20mm and 25mm on the critical melting current and the temperature distribution of the ice-covered conductor are simulated respectively.



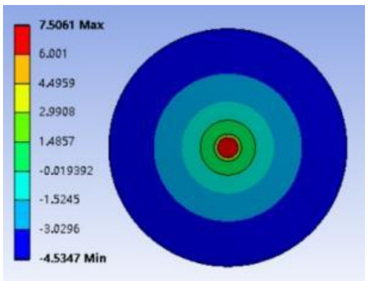

(a) 10mm




(b) 15mm




(c) 20mm




(d) 25mm

Fig. 7 Effect of ice thickness on critical ice melting current

The calculated critical melting currents for ice thicknesses of 10 mm, 15 mm, 20 mm and 25 mm are 59.375 A, 67.97 A, 74.05 A and 78.1 89A; the simulated critical melting currents were 57.65A, 66.57A, 73.46A, and 78.72A, respectively. As the ice thickness increased, the error between the simulation results and the calculated results became smaller and smaller.

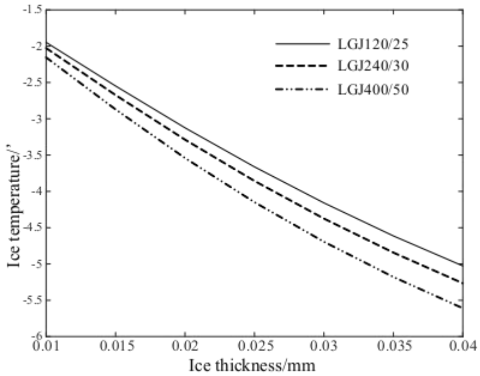


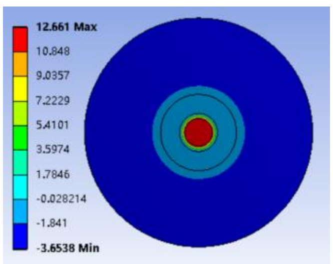

Fig. 8 Effect of ice thickness on ice surface temperature

An increase in ice thickness results in a corresponding increase in the convective heat transfer surface area of the ice, which in turn gives rise to an increase in the convective heat transfer loss on the ice surface. Furthermore, the thermal resistance resulting from heat conduction increases in proportion to the ice thickness, ultimately establishing a relationship between the ice surface temperature and ice thickness as illustrated in Figure 8.

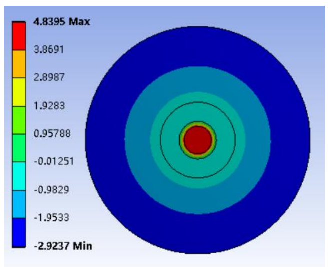
As the ice thickness increases and the outer surface temperature decreases, the critical melting current also decreases. According to Fourier's law, the rate of convective heat transfer is proportional to the temperature difference. Upon reaching a thickness of 40 mm, the critical melting current exhibits a plateau, indicating that the ice coating has reached a saturation point with regard to its impact on the critical melting current.

(d) The influence of the thermal conductivity of the insulation on the critical melting current

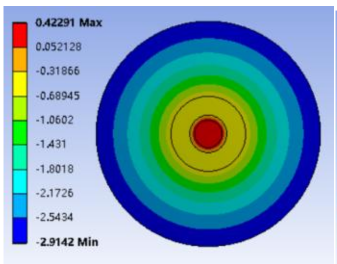
The simulation conditions are set as follows: the conductor is LGJ120/25, the ambient temperature is -10° C, the wind speed is 2.5m/s, and the ice thickness is 15mm; the effects of the insulation layer thermal conductivity of 0.1W/m • K, 0.3W/m •K, 2W/m •K and 10W/m •K on the critical melting current and ice-covered conductor temperature distribution are simulated respectively..



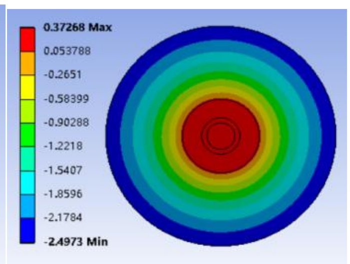

(a) 0.1W/m • K




(b) 0.3W/m • K




(c) 2W/m • K




(d) 10W/m • K

Fig. 9 Effect of ice thickness on critical ice melting current

The simulation results indicate that the thermal conductivity of the insulation layer has a negligible impact on the surface temperature of the ice layer and the critical current. The thermal conductivity of the insulation layer exerts a considerable influence on the temperature distribution of the ice-covered conductor. A reduction in thermal conductivity will result in a notable increase in temperature of the steel core. At thermal conductivities of approximately 3.5 W/m • K, there is essentially no temperature differential between the steel core, the insulation layer and the aluminium strand.

The critical melting current and ice surface temperature are significantly affected by wind speed, ice thickness and ambient temperature. Furthermore, the effects of wind speed and ice thickness on the critical melting current and ice surface temperature are subject to a certain degree of saturation.

The thermal conductivity of the insulation layer has a negligible effect on the critical melting current; conversely, it has a significant effect on the temperature distribution of the ice-covered conductor. However, when the thermal conductivity of the insulation layer is insufficient, it behaves similarly to an insulating material and exerts a notable influence on the critical melting current.

## 5.Experimental verification

In order to ascertain the veracity of the proposed methodology for calculating the critical melting current, an experiment was conducted in which the critical melting current of the steel core heating wire was evaluated in a low-temperature freezer. Initially, the current value of the steel core was calibrated in accordance with the calculated results, resulting in a slight reduction in the current value relative to the calculated value. Subsequently, the surface temperature of the aluminium strand is monitored at 5-minute intervals following the application of the current to the steel core. The temperature rise experiment of the bare wire indicated that the temperature of the steel core and the aluminium strand reached a stable state after approximately 20 minutes of current application without melting the ice. Therefore, the current adjustment interval was selected as 30 minutes. In the event that the surface temperature of the aluminium strand does not reach 0° C within the allotted 30 minutes, the current flowing through the steel core is increased by 2A until such time as the surface temperature of the aluminium strand reaches 0° C and remains stable.

The article presents the findings of an experimental investigation into the critical ice-melting current of steel core heating wires under varying wind speeds, ice thicknesses and ambient temperatures. The final results are compared with those obtained from simulations and calculations. The results of the comparison are presented in Table 7.

Table 7 Results of critical ice melting current under different conditions

| The wire model | Ice-covering thickness / mm | wind speed /m/s | ambient temperature /℃ | experiment /A | count /A | simulation /A |
|---|---|---|---|---|---|---|
| LGJ120/25 | 15 | - | -5 | 23 | 20.56 | 20.37 |
| | 10 | - | -10 | 34 | 29.89 | 25.76 |
| | 15 | 2.5 | -10 | 73 | 67.97 | 67.15 |
| | 15 | 4 | -11 | 85 | 79.03 | 78.55 |

As can be observed in Table 7, the experimental, calculated and simulation results for the critical current of steel-core heating wires under different conditions are largely consistent with one another. The maximum discrepancy between the calculated and experimental results is 10.8%, with the minimum discrepancy being 8.5%. When the critical melting current is low, the discrepancy between the calculated and experimental results is more pronounced. This is due to the fact that when the melting current is minimal, even a minor alteration in the external conditions will have a more pronounced effect on the outcomes. It should be noted that the experiments described in this paper were conducted in a low-temperature freezer, which may have resulted in fluctuations in the ambient temperature and wind speed. In light of the aforementioned considerations, the margin of error is deemed to be within an acceptable range, thereby substantiating the precision of the proposed calculation methodology.

## 6.Conclusion

1) In comparison with the conventional AC/DC short-circuit ice-melting technique, the ice-melting method reliant on

steel-core heating wires exhibits the benefits of a reduced ice-melting current and the absence of a necessity for a power outage. The viability of steel-core heating wires for ice melting has been demonstrated through an economic and technical analysis of steel-core heating wires.

2) The accuracy of the critical melting current calculation model proposed in the article was validated through experimental and ANSYS simulation-based verification. The impact of diverse environmental variables on the critical melting current was examined. The findings indicated that wind speed, ice thickness and ambient temperature all exerted a considerable influence on the critical melting current and ice surface temperature. However, the impact of wind speed and ice thickness on the critical melting current and ice surface temperature reached a point of saturation.

3) Once the thermal conductivity of the insulation layer between the steel core and the aluminium strand reaches a certain value, its impact on the critical melting current can be considered negligible. The experiment and simulation employed an insulation layer with a low thermal conductivity (thermal conductivity of the insulation layer is 0.3 W/m • K), which impacted the heat transfer of the steel core and resulted in a notable increase in steel core temperature. It is therefore the intention of the research team to focus the next phase of their study on insulation materials with enhanced thermal conductivity.

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MENGYI KONG was born in Wuzhen, Tongxiang City, Zhejiang Province, China in 1994. She received a bachelor's degree in civil engineering from Jiangxi University of Science and Technology, a master's degree from Belarusian State Technical University in 2022, and a doctorate in engineering management from INTI International University & Colleges in 2024.
From 2017 to 2019, she worked as a business standard officer in the business department of Jujiang Construction Group Co., Ltd. Since 2019, she has been a lecturer in the engineering cost major at Jiaxing Nanyang Vocational and Technical College. She has written one book, published three articles, and has one invention and three topics. His research interests include high-voltage electricity, civil engineering, and engineering management.
Dr. KONG received the Project Manager - Senior Technician in 2023 and the second prize of the 2023 Zhejiang Vocational College Skills Competition Construction Engineering Digital Measurement and Pricing Competition (Category 1) in 2024, and the third prize of the 2024 National Digital Construction Million Talent Vocational Skills Challenge - Construction Engineering Measurement - National.
THIRD C. AUTHOR, JR. (M' 87) received the B.S. degree in mechanical engineering from National Chung Cheng University, Chiayi, Taiwan region, in 2004 and the M.S. degree in mechanical engineering from Tsing Hua University, Hsinchu, Taiwan region, in 2006. He is currently pursuing the Ph.D. degree in mechanical engineering at Texas A&M University, College Station, TX, USA.