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Thermodynamic Stress Analysis and Fault Prevention Strategies for Transmission Lines Under Freezing Weather Conditions

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ABSTRACT

With the continuous growth of electricity demand, the safety and stability of transmission lines have become critical research topics in power systems. Freezing weather imposes extreme loads and temperature variations on transmission lines, significantly affecting their structural integrity and functionality, potentially leading to power supply interruptions or even major failures. Therefore, studying the thermodynamic stress and mechanical behavior of transmission lines under freezing conditions, along with effective fault prevention strategies, is essential for ensuring power system reliability. Existing research has primarily focused on the impact of individual factors such as ice accumulation and temperature fluctuations on transmission lines. However, comprehensive studies addressing the combined effects of these factors on the overall thermodynamic stress and mechanical behavior of transmission lines remain insufficient. While some scholars have developed stress analysis models based on thermal equilibrium equations to reveal the influence of environmental factors such as temperature and humidity on thermal stress, most studies lack systematic analyses integrating multiple influencing factors. In particular, there is still a research gap in developing refined mechanical models and fault prevention strategies. Therefore, it is imperative to integrate thermodynamic and mechanical analyses to establish precise multi-factor coupled models. This study aims to construct thermal equilibrium equations and mechanical models for transmission lines, systematically analyze their thermodynamic stress and mechanical behavior under freezing conditions, and propose improved fault prevention strategies to enhance the safety and stability of transmission lines. The findings will provide theoretical foundations and technical support for optimizing transmission line design, operation, maintenance, and emergency management.

1. INTRODUCTION

As the power system plays an increasingly crucial role in supporting modern society, the stability and reliability of transmission lines have become particularly important [1-4]. Under severe weather conditions, especially during freezing weather, transmission lines are susceptible to factors such as ice and snow accumulation and sudden temperature drops, which can reduce their load-bearing capacity and even lead to failures [5,6]. Freezing weather has a significant impact on the thermodynamic stress and mechanical behavior of transmission lines, thereby affecting the safety and stability of power transmission [7-9]. Therefore, studying the thermodynamic stress and fault prevention of transmission lines under freezing weather conditions has important theoretical significance and practical value.

In the design and operation of transmission lines, conducting systematic thermodynamic and mechanical analysis in response to the specific challenges posed by freezing weather can effectively prevent failures [10-13]. Studying the thermal equilibrium and mechanical models of transmission lines under freezing weather conditions to reveal their stress distribution and failure mechanisms will help optimize transmission line design, improve transmission line safety, and provide a theoretical basis for emergency management [14-17]. At the same time, the formulation of fault prevention strategies can help power companies strengthen monitoring and maintenance during freezing weather, reduce power outages caused by extreme weather events, and enhance power supply reliability and disaster resistance.

Although existing studies have covered some thermodynamic and mechanical analyses of transmission lines under freezing weather conditions, most research focuses on the impact of single factors and ignores the complexity of multi-factor coupling effects, especially the synergistic effects of thermodynamic stress and mechanical behavior [18-20]. Furthermore, most studies emphasize theoretical derivation and experimental verification but lack systematic model development and comprehensive analysis, and there is still a significant gap in the design of fault prevention strategies. Therefore, existing research methods remain insufficient in addressing the practical operational problems of transmission lines under freezing weather conditions, necessitating further in-depth research.

This study primarily approaches the problem from both thermodynamic and mechanical perspectives, systematically constructing thermal equilibrium equations and mechanical models of transmission lines under freezing weather conditions and conducting thermodynamic stress analysis and fault prevention strategy research. In terms of thermal equilibrium, this study analyzes the impact of different climatic conditions on the thermal stress of transmission lines by constructing accurate thermal equilibrium equations. In terms of mechanical modeling, it investigates the stress distribution and failure mechanisms of transmission lines under freezing weather conditions based on their mechanical behavior. Through in-depth research in these two aspects, this study aims to provide theoretical foundations and technical support for the design, operation, and fault prevention of transmission lines, thereby improving the safety and stability of power systems, with important academic significance and practical application value.

2. THERMAL EQUILIBRIUM EQUATION OF TRANSMISSION LINES UNDER FREEZING WEATHER

Under freezing weather conditions, there is a close coupling relationship between the electrical, thermal, and mechanical states of transmission lines. Specifically, the flow of current and changes in meteorological conditions directly affect the temperature of transmission lines through thermal effects, thereby altering the electrical parameters of the transmission lines. In addition, under freezing weather, conductors experience thermal expansion and contraction due to low temperatures and load effects, leading to mechanical deformations of transmission lines, including changes in conductor length and reductions in cross-sectional area. These mechanical effects indirectly affect electrical parameters by altering the geometric parameters of transmission lines, thereby impacting the electrical performance of the transmission lines and the power system's load flow. Therefore, to comprehensively understand the impact of freezing weather on transmission lines, it is necessary to conduct a detailed analysis within the framework of thermodynamic and mechanical coupling, particularly considering the interactions among temperature, stress, and electrical performance.

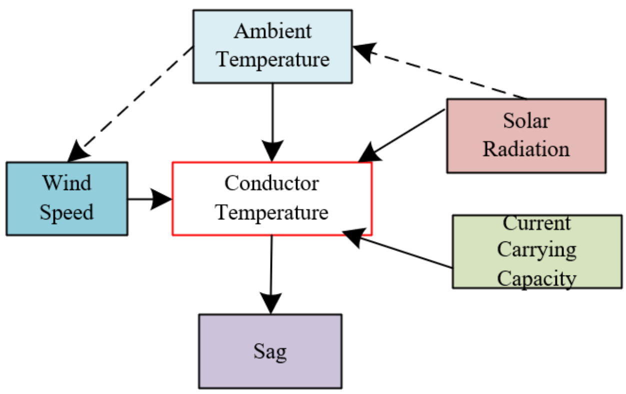

Figure 1. Factors affecting conductor temperature under freezing weather

Specifically, this study analyzes the state of transmission lines under freezing weather and propose fault prevention strategies from both thermodynamic and mechanical perspectives. Figure 1 presents the factors affecting conductor temperature under freezing weather. In terms of thermodynamic stress analysis, the first step is to establish the thermal equilibrium equation for transmission lines, considering meteorological factors such as temperature, humidity, and wind speed, which influence conductor temperature changes, and then analyze the direct impact of temperature changes on electrical parameters. Subsequently, based on thermal expansion and contraction and the stress-strain effect, this study examines how temperature changes indirectly affect the electrical performance of transmission lines through mechanical deformation, further influencing the load flow distribution of the power system. The research on fault prevention strategies focuses on how to monitor and regulate the temperature, stress, and deformation of transmission lines to identify potential fault risks in advance and propose corresponding maintenance and adjustment measures.

Under freezing weather conditions, constructing the thermal equilibrium equation of transmission lines is the foundation for studying conductor temperature, thermal stress, and fault prevention. The temperature variation of the conductor is not only affected by the magnitude of the current flowing through the transmission line but is also closely related to the surrounding meteorological conditions. Specifically, as current passes through the conductor, the conductor itself generates heat. Additionally, environmental factors such as temperature, wind speed, humidity, and ice and snow accumulation also influence the temperature of the conductor. Figure 2 illustrates the schematic model of a transmission line conductor under freezing weather. To accurately describe the comprehensive effects of these factors on conductor temperature, this study, based on IEEE standards, constructs the thermal equilibrium equation for the m-th segment, the j-th tension section, and the t-th span of the transmission line under freezing weather. This equation couples the heat generated by current passing through the conductor, the heat exchange between the conductor and the surrounding environment, and the thermal inertia of the conductor itself.

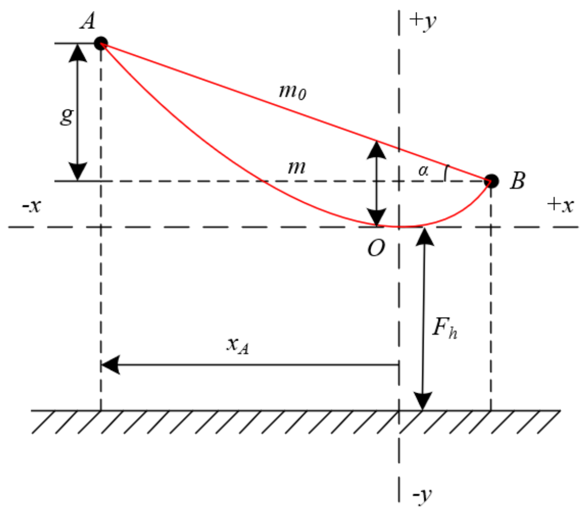

Figure 2. Schematic model of transmission line conductor under freezing weather

The basic form of the thermal equilibrium equation can be derived based on the principle of heat flow conservation. In short, the change in the heat of the conductor is equal to the difference between the heat it absorbs and the heat it dissipates. When current flows through the conductor, the resistance inside the conductor generates Joule heat, which varies with the magnitude of the current. At the same time, the heat exchange between the conductor and the external environment also affects its temperature. This heat exchange includes radiation, convection, and conduction heat transfer methods, with specific conditions varying depending on the environment. Under freezing weather conditions, the temperature is low and often accompanied by changes in wind speed and ice-snow coverage, which significantly alter the heat exchange efficiency between the conductor and the environment.

When constructing the thermal equilibrium equation, it is particularly necessary to consider the "thermal inertia" of the conductor. Due to the lag in the heat conduction process, the temperature change of the conductor does not respond instantaneously to changes in current, which means that there is a certain delay effect between the temperature change of the conductor and the change in current. This phenomenon reflects the thermal inertia of the conductor, that is, the time delay in heat transfer from inside the conductor to the outside. Thermal inertia causes the conductor's temperature response to be slower than current changes, and this asymmetry is especially prominent under freezing weather conditions. When the ambient temperature fluctuates drastically, the adjustment of the conductor's temperature may lag behind changes in the external climate, increasing the complexity of system prediction and control. The thermal equilibrium equation in this study accurately considers this delay effect in the model, making the equation more accurately reflect the actual temperature variations of the conductor.

Specifically, assuming that the product of the mass per unit length and specific heat capacity of transmission line m is represented by $l_m Z_m$, the conductor temperature of the t-th span in the j-th tension section of transmission line m at time s is denoted as $S_{m,j,t}(s)$. The Joule heat generation per unit length of the conductor in the t-th span of the j-th tension section of transmission line m at time s is represented by $w^{RE}{}_{m,j,t}(s)$. The solar heating per unit length of the conductor in the t-th span of the j-th tension section of transmission line m at time s is denoted as $w^{SO}{}_{m,j,t}(s)$. The convective heat dissipation per unit length of the conductor in the t-th span of the j-th tension section of transmission line m at time s is represented by $w^{CO}{}_{m,j,t}(s)$. The radiative heat dissipation per unit length of the conductor in the t-th span of the j-th tension section of transmission line m at time s is denoted as $w^{RA}{}_{m,j,t}(s)$. The current flowing through transmission line m is denoted as I_m. The resistance per unit length of the conductor in the t-th span of the j-th tension section of transmission line m at time s is represented by $R^{RE}{}_m$. The temperature coefficient of resistance of the conductor is denoted as β, and the reference conductor temperature is represented by S^{RE}. The system's base power is denoted as T^Y. The light absorption rate of the conductor of the transmission line is represented by α, and the solar radiation intensity at the t-th span of the j-th tension section of transmission line m at time s is denoted as $W^{tr}{}_{m,j,t}$. The conductor diameter of transmission line m is represented by F. The convective heat dissipation coefficient of the t-th span of the j-th tension section of transmission line m at time s is denoted as $X^{CO}{}_{m,j,t}(s)$, which is mainly determined by the wind speed $n_{m,j,t}$ around the overhead conductor and the angle $\sigma_{m,j,t}$ between the wind direction and the conductor axis. The ambient temperature at the t-th span of the j-th tension section of transmission line m at time s is denoted as $S^{AM}{}_{m,j,t}(s)$. The radiative heat dissipation coefficient per unit length of the conductor in the t-th span of the j-th tension section of transmission line m at time s is represented by $X^{AM}{}_{m,j,t}(s)$. The thermal equilibrium equation is constructed as follows:

$$l_m Z_m \frac{dS_{m,j,t}(s)}{ds} = w^{RE}_{m,j,t}(s) + w^{SO}_{m,j,t}(s) - w^{CO}_{m,j,t}(s) - w^{RA}_{m,j,t}(s) \tag{1}$$

$$w^{RE}_{m,j,t}(s) = I^2_m(s) R^{RE}_s \left[1+\beta\left(S_{m.j.t}(s) - S^{RE}\right)\right] \times \left(T^Y / 3\right) \tag{2}$$

$$w^{SO}_{m.j.t}(s) = \alpha W^{tr}_{m.j.t}(s) F_s \tag{3}$$

$$w^{CO}_{m,j,t}(s) = X^{CO}_{m,j,t}(s)\left(S_{m,j,t}(s) - S^{AM}_{m,j,t}(s)\right) \tag{4}$$

$$w^{RA}_{m,j,t}(s) = X^{RA}_m \left[\begin{array}{c} \left(273+S_{m,j,t}(s)\right) \\ {}^4-\left(273+S^{AM}_{m,j,t}(s)\right)^4 \end{array}\right] \tag{5}$$

By solving the heat balance equation, we can obtain the dynamic response of conductor temperature to changes in current and meteorological conditions, thereby revealing the variation patterns of parameters such as conductor temperature, stress, and sag under freezing weather conditions. Due to factors such as low temperatures, high wind speeds, and ice and snow accumulation in freezing weather, the conductor temperature undergoes significant fluctuations, which directly affect the conductor's resistance. Figure 3 illustrates the thermodynamic model of the transmission line conductor under wind deflection conditions. Changes in resistance lead to variations in current distribution, thereby affecting the power transmission efficiency of the transmission line and the distribution of system power flow. By analyzing the relationship between conductor temperature, current, and meteorological conditions, the thermal state of the transmission line can be predicted more accurately, allowing timely adjustments to current load to prevent overload risks due to excessively high temperatures or brittleness and deformation of conductor materials caused by excessively low temperatures. Meanwhile, the conductor undergoes thermal expansion or contraction under temperature changes. Especially under low-temperature conditions, temperature variations cause significant changes in conductor length, leading to mechanical stress and deformation, such as sag variation and changes in conductor tension. These thermodynamic stresses not only affect the structural stability of transmission lines but may also lead to faults such as conductor breakage, slackening, or excessive deformation under extreme weather conditions.

Through the analysis of these thermodynamic stresses, several key fault prevention conclusions can be drawn. First, when a transmission line operates in freezing weather, real-time monitoring of temperature and stress should be strengthened, particularly under conditions of drastic meteorological changes. By predicting temperature variation trends through the heat balance equation, current load adjustments or other emergency measures can be taken in time to prevent transmission line failures caused by overload or excessive cooling. Furthermore, for possible conductor deformation and stress concentration areas, transmission line design should be optimized by increasing anti-freezing capability and improving conductor materials and structures to reduce the risk of faults caused by thermal expansion and stress concentration. Additionally, based on the analysis of the heat balance equation, transmission line inspection and maintenance strategies can be optimized. For example, before freezing weather, potential fault areas can be predicted through simulations, and necessary inspections and reinforcements can be carried out in advance to reduce the probability of faults.

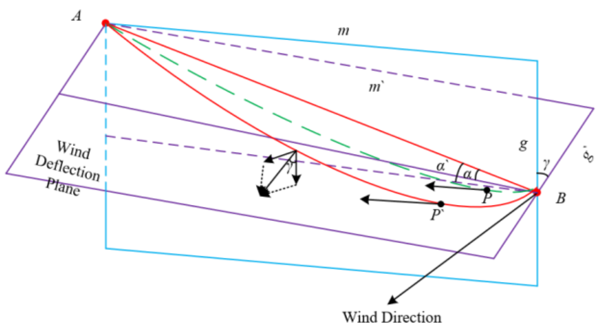

Figure 3. Thermodynamic model of the transmission line conductor under wind deflection conditions

3. THERMODYNAMIC MODEL OF TRANSMISSION LINES UNDER FREEZING WEATHER CONDITIONS

Under freezing weather conditions, the construction of the mechanical model of transmission lines is one of the core aspects of studying their thermodynamic stress, structural stability, and fault prevention. This model quantitatively analyzes the stress and strain of transmission line conductors and their interrelationships to reveal the mechanical behavior of conductors in freezing weather. The construction of the mechanical model must consider the influence of environmental factors and current variations on conductor status, particularly the potential threats to transmission line stability and safe operation under extreme climate conditions.

The impact of freezing weather on transmission lines is not limited to temperature reduction; it also includes ice and snow adhesion and wind forces. Ice and snow accumulation increases the external load on the conductor, causing deformation under the combined effects of current and external pressure. In the model, the stress coefficient $A_{m,j,t}$ quantifies this external influence. The calculation method of the stress coefficient considers the influence of conductor temperature changes and environmental meteorological conditions (such as ice and snow accumulation and wind speed) on conductor stress. Specifically, when calculating the stress coefficient, it is necessary to comprehensively consider the effect of conductor temperature variations and wind and ice accumulation on the mechanical properties of the conductor. As temperature changes, the physical properties of the conductor (such as thermal expansion coefficient and elastic modulus) also change, which affects the transmission and accumulation of stress. Furthermore, environmental conditions, particularly ice adhesion, significantly increase the external load on the conductor, further exacerbating stress levels. Figure 4 gives the accurate calculation process of the thermodynamic state of transmission lines under freezing weather conditions.

Specifically, assuming that the initial horizontal stress of the j-th tension section under the initial conductor temperature $S^{IN}_{m,j,t}$ is denoted as $G^{IN}_{m,j}$, for the t-th span of the j-th tension section of transmission line m, the horizontal stress $G_{m,j,t}$ can be expressed as the product of the initial horizontal stress $G^{IN}_{m,j}$ and the stress coefficient $A_{m,j,t}$ of the t-th span. The elastic modulus of transmission line m is denoted as R_m, the cross-sectional area of the transmission conductor as P_m, and the span length of the t-th span of the j-th tension section of transmission line m as $x_{m,j,t}$. The inclined span length of the t-th span of the j-th tension section of transmission line m is denoted as $M^{INC}_{m,j,t}=\sqrt{(x^2_{m,j,f}+g^2_{m,j,f})}$, wherein $g_{m,j,t}$ represents the height difference between the suspension points at both ends of the t-th span of the j-th tension section of transmission line m, and the number of spans in the j-th tension section of transmission line m is denoted as $v^{m,j,SP}$. Then, $A_{m,j,t}$ can be obtained by solving the following equation:

$$
\begin{aligned}
&A^4_{m,j,t}\left(A_{m,j,t}K_{t,1}K_{t,2}-D_t\right) \\
&+\left(A_{m,j,t}J_{t,1}J_{t,2}-D_t\right)\left(A^2_{m,j,t}J_{t,3}+J_{t,4}\right) \\
&\frac{x^2_{m,j,t}}{\left(M^{INC}_{m,j,t}\right)^2}=0, t=1,\dots,v^{m.j.SP}
\end{aligned}
\tag{6}
$$

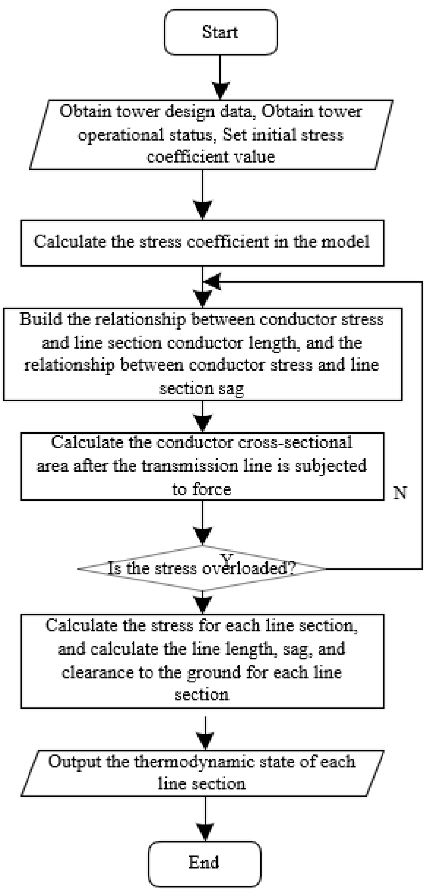

Figure 4. Accurate calculation process of the thermodynamic state of transmission line under freezing weather conditions

The impact of freezing weather on the mechanical behavior of transmission lines is not only reflected in stress changes but also includes variations in conductor length, sag, and cross-sectional area. Changes in conductor stress directly induce conductor deformation, which in turn leads to changes in the geometric parameters of the transmission line. According to the mechanical model, conductor stress causes changes in conductor length, which is closely related to temperature variation. When the temperature decreases, the conductor contracts, while when the temperature rises, the conductor expands. In addition, changes in conductor stress also affect the sag of the transmission line. Sag refers to the vertical distance that the conductor droops under force, and its variation directly reflects the stress state of the conductor. When the conductor is subjected to excessive stress, the sag may exceed the design value, thereby affecting the operational safety of the transmission line. Therefore, when calculating conductor stress, the mechanical model must simultaneously compute sag variations to ensure the structural stability and safety of the transmission line. Assuming the thermal expansion coefficient of transmission line m is represented by γ_m, the values of $J_{t,1}...J_{t,4}$ in the above equation can be obtained through the following equations:

$$J_{t,1}=\left(1+\widehat{M}_{m,j,t}^{INC}\right)\frac{M_{m,j,t}^{INC}}{x_{m,j,t}} \tag{7}$$

$$\begin{aligned}J_{t,2}=&-\left(1+\bar{M}_{m,j,t}^{INC}\right)^2\frac{M_{m,j,t}^{INC}}{x_{m,j,t}}+\frac{R_mP_m}{G_{m,j}^{INI}}\bar{M}_{m,j,t}^{INC}\\&+\frac{R_mP_m\gamma_m}{G_{m,j}^{INI}}\left(1+\bar{M}_{m,j,t}^{INC}\right)\left(S_{m,j,t}-\bar{S}_{m,j,t}^{INI}\right)\end{aligned} \tag{8}$$

$$J_{t,3}=\frac{x_{m,j,t}^2}{24\left(G_{m,j}^{INI}/l_m\right)^4} \tag{9}$$

$$\begin{aligned}J_{t,4}=&\frac{x_{m,j,t}^4}{720\left(\dfrac{G_{m,j}^{INI}}{l_m}\right)^8}\\&-\left[\frac{x_{m,j,t}^2}{\left(\bar{M}_{m,j,t}^{INC}\right)^2}\cdot\frac{x_{m,j,t}^4}{1152\left(\dfrac{G_{m,j}^{INI}}{l_m}\right)^8}\right]\end{aligned} \tag{10}$$

$\bar{M}_{m,j,t}^{INC}$ can be obtained through the following equation:

$$\begin{aligned}&\bar{M}_{m,j,t}^{INC}-\frac{x_{m,j,t}^2}{\left(M_{m,j,t}^{INC}\right)^2}\left[\frac{x_{m,j,t}^2}{24\left(\dfrac{G_{m,j}^{INI}}{l_m}\right)^4}+\frac{x_{m,j,t}^4}{720\left(\dfrac{G_{m,j}^{INI}}{l_m}\right)^8}\right]\\&+\left[\frac{x_{m,j,t}^4}{\left(M_{m,j,t}^{INC}\right)^4}\cdot\frac{x_{m,j,t}^4}{1152\left(\dfrac{G_{m,j}^{INI}}{l_m}\right)^8}\right]=0\end{aligned} \tag{11}$$

In this paper, the mechanical model of the transmission line achieves a comprehensive simulation of conductor temperature and stress variations by coupling the thermal balance equation with the mechanical equations. The thermal balance equation provides the variation law of conductor temperature, while the mechanical model further computes the geometric parameter changes of the conductor based on the relationship between conductor temperature and stress. The key to the mechanical model lies in the coupling relationship between stress and temperature, especially under freezing weather conditions, where the decrease in conductor temperature may lead to greater thermal stress accumulation, and ice and snow accumulation increase the external load on the conductor, thereby jointly contributing to complex structural deformation of the transmission line. By simulating and analyzing these factors, the variation trends of conductor temperature, stress, sag, and other parameters can be obtained, thereby providing data support and decision-making references for fault prevention.

In the construction of the mechanical model, the key thermodynamic parameters considered include conductor temperature, stress coefficient, conductor length variation, sag variation, etc. These parameters not only need to be accurately calculated through mathematical models but also require validation and comparison with actual meteorological data and power system operation data to improve the prediction accuracy of the model. The parameter D_t in Eq. (6) depends on the conductor stress in three consecutive spans $t-1$, t, and $t+1$, as well as the wind speed and wind direction around span t. Assuming that the length of the insulator string in the t-th span of the j-th tension section of transmission line m is represented by $M^{INS}_{m,j,t}$, and the equivalent vertical force acting on the insulator string is represented by $C_{m,j,t}$, the specific calculation formula of D_t is:

$$\begin{aligned}D_t=&\frac{R_mP_mx_{m,j,t}}{G_{m,j}^{INI}\left(M_{m,j,t}^{INC}\right)^2}\\&\left\{\left[\frac{\left(A_{m,j,t+1}-A_{m,j,t}\right)M_{m,j,t+1}^{INS}}{\sqrt{\left(C_{m,j,t+1}/G_{m,j}^{INI}\right)^2+\left(A_{m,j,t+1}-A_{m,j}^{INI}\right)^2}}\right]\right.\\&\left.-\left[\frac{\left(A_{m,j,t}-A_{m,j,t-1}\right)M_{m,j,t+1}^{INS}}{\sqrt{\left(C_{m,j,t-1}/G_{m,j}^{INI}\right)^2+\left(A_{m,j,t}-A_{m,j,t-1}\right)^2}}\right]\right\}\\&+\frac{R_mP_mx_{m,j,t}}{G_{m,j}^{INI}\left(M_{m,j,t}^{INC}\right)^2}\left\{M_{m,j,t+1}^{INS}\left[1-\frac{\left(A_{m,j,t+1}-A_{m,j,t}\right)M_{m,j,t+1}^{INS}}{\sqrt{\left(C_{m,j,t+1}/G_{m,j}^{INI}\right)^2+\left(A_{m,j,t+1}-A_{m,j,t}^{INI}\right)^2}}\right]\right.\\&\left.-M_{m,j,t}^{INS}\left[1-\frac{C_{m,j,t}/G_m^{INI}}{\sqrt{\left(C_{m,j,t+1}/G_{m,j}^{INI}\right)^2+\left(A_{m,j,t}-A_{m,j,t-1}\right)^2}}\right]\right\},\\&t=1,\dots,v^{m,j,SP}\end{aligned} \tag{12}$$

Assume that the self-weight of the insulator string in the t-th span of the j-th tension section of transmission line m is represented by $B_{m,j,t}$, and the coordinates of span t are represented by $z_{m,j,t}$. The specific calculation formula for $C_{m,j,t}$ is:

$$\begin{aligned} C_{m,j,t} &= \frac{B_{m,j,t}}{2} + A_{m,j,t-1} G_{m,j}^{INI} SINg \\ &\left[l_m \left(x_{m,j,t-1} + z_{m,j,t-1} \right) / A_{m,j,t-1} G_{m,j}^{INI} \right] \\ &- A_{m,j,t} G_{m,j}^{INI} SINg \left[l_m z_{m,j,t} / A_{m,j,t} G_{m,j}^{INI} \right] \end{aligned} \tag{13}$$

Assume that the horizontal tension in the t-th span of the j-th tension section of transmission line m is represented by $G^{d}_{m,j,t}= A_{m,j,t}G^{INI}_{m,j}P_m$, and the specific load of the t-th span of the j-th tension section of transmission line m is represented by $\varepsilon_{m,j,t}$. The value of $z_{m,j,t}$ can be obtained by the following equation:

$$z_{m,j,t} = \frac{G_{m,j,t}^{d}}{\varepsilon_{m,j,t}} LN \left[\begin{array}{c} \dfrac{G_{m,j,t}^{d}}{\varepsilon_{m,j,t} \left(M_{m,j,t}^{INC} - g_{m,j,t} \right)} \\ \cdot \left(1 - \exp\left(-\varepsilon_{m,j,t} \cdot \dfrac{x_{m,j,t}}{G_{m,j,t}^{d}} \right) \right) \end{array} \right] \tag{14}$$

The relationships between conductor stress $G_{m,j,t}$ and span conductor length $M_{m,j,t}$, as well as between conductor stress $G_{m,j,t}$ and span sag $G^{SA}_{m,j,t}$, can be expressed by the following equations:

$$\begin{aligned} &M_{m,j,t} - \sqrt{x_{m,j,t}^2 + g_{m,j,t}^2} \\ &- \frac{\varepsilon_{m,j,t}^2 x_{m,j,t}^4}{24 A_{m,j,t}^2 \left(G_{m,j}^{INI}, t \right)^2 \sqrt{x_{m,j,t}^2 + g_{m,j,t}^2}} = 0 \end{aligned} \tag{15}$$

$$\begin{aligned} &M_{m,j,t}^{SA} - \frac{G_{m,j,t}^{d}}{\varepsilon_{m,j,t}} \left[\begin{array}{l} \sqrt{1 + \left(\begin{array}{c} \dfrac{\varepsilon_{m,j,t} g_{m,j,t}}{2 G_{m,j,t}^{d} SINg} \\ \left(\varepsilon_{m,j,t} x_{m,j,t} / 2 G_{m,j,t}^{d} \right) \end{array} \right)^2} \\ COSg \left(\dfrac{\varepsilon_{m,j,t} x_{m,j,t}}{2 G_{m,j,t}^{d}} \right) \end{array} \right. \\ &\left. - \frac{g_{m,j,t}}{x_{m,j,t}} ASg \left(\begin{array}{c} \dfrac{\varepsilon_{m,j,t} g_{m,j,t}}{2 g_{m,j,t}^{D} \sinh} \\ \left(\varepsilon_{m,j,t} x_{m,j,t} / 2 G_{m,j,t}^{d} \right) \end{array} \right) - 1 \right] = 0 \end{aligned} \tag{16}$$

Assume that the conductor cross-sectional area before loading in the t-th span of the j-th tension section of transmission line m is represented by $\delta^{0}_{m,j,t}$, and the conductor cross-sectional area after loading is represented by $\delta^{1}_{m,j,t}$. The cross-sectional area of the conductor after loading can be calculated using:

$$\delta_{m,j,t}^{m} = \frac{\delta_{m,j,t}^{0} x_{m,j,t}}{M_{m,j,t}} \tag{17}$$

Based on the mechanical model of the transmission line under freezing weather conditions, a series of thermodynamic stress analysis results can be obtained. From the perspective of the mechanical model, conductor temperature is a key factor affecting the transmission line state. Under freezing weather conditions, as the temperature decreases, the conductor temperature also decreases, which directly leads to changes in thermal stress. The decrease in conductor temperature causes it to contract, while the increase in ice and snow load significantly increases the external pressure on the conductor. These changes result in significant variations in conductor stress, which in turn affect the geometric parameters of the conductor, such as sag, span length, and tension. The combined effect of thermal stress at low temperatures and external ice and snow load may lead to conductor deformation, relaxation, or even breakage, seriously affecting the safety of the transmission line. As conductor stress changes, the geometric parameters of the line also change accordingly. An increase in sag reduces the clearance between the conductor and the ground or other equipment, increasing the risk of contact and collision, which may cause short circuits or damage to power equipment. Changes in span length affect the distribution of tension along the line, thereby impacting the stability of the entire transmission network. Especially under freezing weather conditions, changes in stress and sag may alter the load distribution of the line, thus affecting power flow distribution in the system.

This series of thermodynamic stress analysis results reveals the complexity of transmission line operation under freezing weather conditions and potential fault risks. Based on these analyses, the following fault prevention conclusions are proposed:

(1) Real-time Monitoring and Stress Detection: Since changes in conductor temperature and external meteorological conditions directly affect stress distribution, it is necessary to monitor parameters such as transmission line temperature, stress, and sag in real time. Under extreme weather conditions (e.g., freezing weather, cold waves), the line status should be regularly inspected, especially during peak loads or sudden temperature drops. Increased monitoring of conductor temperature and stress variations can help detect potential issues in time and prevent failures caused by excessive stress.

(2) Dynamic Load Adjustment and Regulation: Under freezing weather conditions, changes in thermal stress and external load may reduce the transmission capacity of the line. To prevent overload-induced failures, the current load should be dynamically adjusted based on real-time meteorological data, line conditions, and load status. Avoiding excessive current when conductor temperature is too low can prevent stress overload. Additionally, rational power flow distribution and avoiding excessive concentration on a single line are crucial for maintaining system stability.

(3) Optimization of Line Design and Structural Reinforcement: To mitigate the impact of freezing weather on transmission lines, optimization can be made in line design and structure. For example, selecting conductor materials with higher frost resistance, enhancing the conductor's ability to

withstand ice and snow loads, or incorporating structures adapted to freezing weather conditions during design, such as strengthening the tension sections and increasing the conductor suspension distance. For high-risk areas, lines can be reinforced in advance to prevent deformation or breakage under freezing weather conditions.

(4) Fault Prevention Strategies under Freezing Weather Conditions: Based on stress analysis, a series of fault prevention measures can be proposed for faults that may occur under freezing weather conditions. For example, before an impending freezing event, preemptively inspect and maintain the line, reinforce susceptible tension sections, remove ice accumulation from the line, and regularly inspect and replace conductors that may experience fatigue damage. Intelligent inspection systems can utilize weather forecasts and real-time data to identify high-risk lines in advance, reducing the likelihood of faults.

(5) Fault Diagnosis and Emergency Plans: Even with sufficient preventive measures, lines may still experience failures under excessive stress or other extreme conditions in freezing weather. Therefore, a comprehensive fault diagnosis and emergency response mechanism should be established. If conductor temperature becomes too low or stress becomes excessive, temporary load shedding or current cut-off measures should be taken immediately. At the same time, emergency plans should be activated, and maintenance personnel should be dispatched to repair the faulty section, preventing fault propagation and minimizing losses.

4. EXPERIMENTAL RESULTS AND ANALYSIS

According to the calculation results of conductor temperature of transmission line under freezing weather shown in Figure 5, it can be seen that there are certain differences in the calculated values of different methods in different time periods. Within each period (5-30 minutes), the calculation results of Method 1 (Finite Element Method) and Method 2 (Thermal Circuit Method) are almost completely consistent, with temperature values fluctuating between 74°C and 130°C, indicating that these two methods have similar calculation accuracy under this condition. Method 3 (State-Space Method) has lower temperature calculation values in shorter periods (5 minutes to 20 minutes), with a maximum temperature value of 116°C and relatively small fluctuation range. However, at 25 minutes and 30 minutes, the temperature values slightly increase to 116°C and 118°C, respectively. The relatively conservative temperature estimation may be due to the simplification of the nonlinear variations of the thermodynamic process in the State-Space Method. The calculation results of Method 4 (the proposed method) show that, in each period, its temperature variation trend is consistent with that of Method 1 and Method 2, but there are slight numerical differences. In most periods (such as 25 minutes and 30 minutes), the calculation results are slightly lower than those of Method 1 and Method 2, being 116°C and 118°C, respectively, indicating that the proposed method provides a relatively conservative and stable prediction of temperature changes.

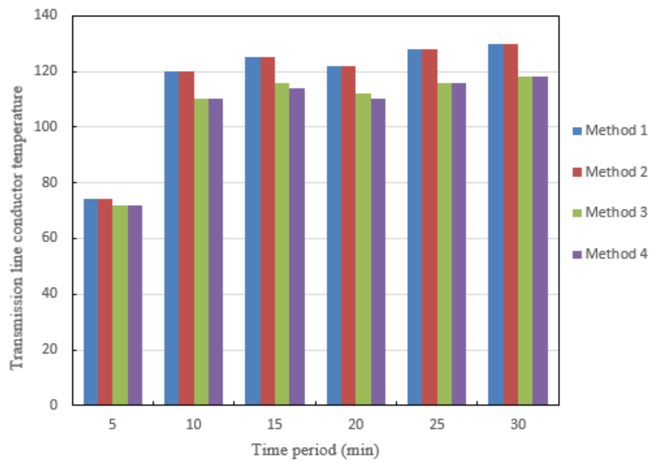

Figure 5. Conductor temperature calculation results of transmission line under freezing weather

Table 1. Calculation results of thermal stress of transmission line conductors at different temperatures

Conductor Temperature (°C)	Traditional Method Stress (*MPa*)	Thermodynamic State Stress of Each Span of the Proposed Method (*MPa*)						
		1	2	3	4	5	6	7
41	55.125	55.236	55.236	54.236	53.201	53.201	52.365	52.365
44	53.268	54.258	53.245	52.315	52.458	51.236	52.145	42.158
51	52.145	53.201	52.012	51.253	52.369	51.025	51.236	51.203
54	51.258	52.326	51.265	52.154	51.245	47.236	47.236	47.568
61	52.312	51.254	52.033	51.236	48.235	46.235	46.236	45.325
64	48.562	52.301	51.254	49.235	46.215	45.236	44.201	44.236
71	47.526	51.248	48.269	46.235	45.236	44.125	43.236	43.215

According to the calculation results of thermal stress of transmission line conductors at different temperatures provided in Table 1, the data shows the variation trend of the stress calculated by the traditional method and the proposed thermodynamic state stress of each span under different temperature conditions. For example, at a temperature of 74°C, the stress calculated by the traditional method is 55.125 MPa, while the stress values calculated by the proposed method in each span (1 to 6) are slightly different, ranging from 53.201 MPa to 55.236 MPa, indicating that under different thermodynamic states, the stress variations of the transmission line show certain differences. In the case of gradually decreasing temperature, such as at a temperature of 44°C, the stress calculated by the traditional method is 51.258 MPa, while the stress values of the proposed method fluctuate, with the lowest being 43.215 MPa. This reflects that in a low-temperature environment, the stress variations in different spans are more significant. Particularly, for different thermodynamic states of each span, the proposed method provides more refined stress prediction results.

According to the thermal stress data of each span of transmission line conductors at different temperatures shown in Figure 6, it can be observed that with temperature variation, the stress values of each span exhibit different trends. As the conductor temperature increases from 40℃ to 70℃, the stress values gradually decrease. For example, in Span 1, the stress decreases from 56.2 MPa at 40℃ to 51 MPa at 70℃, while in Span 7, the stress decreases from 56 MPa to 44 MPa, showing a relatively consistent downward trend. This change reflects that at higher temperatures, the thermal stress of the conductor material gradually decreases, which may be due to the thermal expansion effect of the conductor material and the temperature correlation in the thermodynamic model. Furthermore, the stress differences among different spans indicate that the stress distribution varies under different states. For instance, the stress values in Span 1 are generally higher, while those in Span 7 are lower, demonstrating that under thermodynamic states, different spans exhibit different responses to thermal stress.

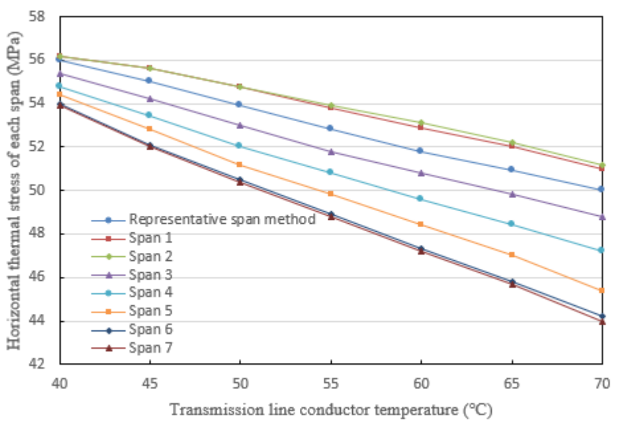

Figure 6. Thermal stress of each span of transmission line conductors at different temperatures

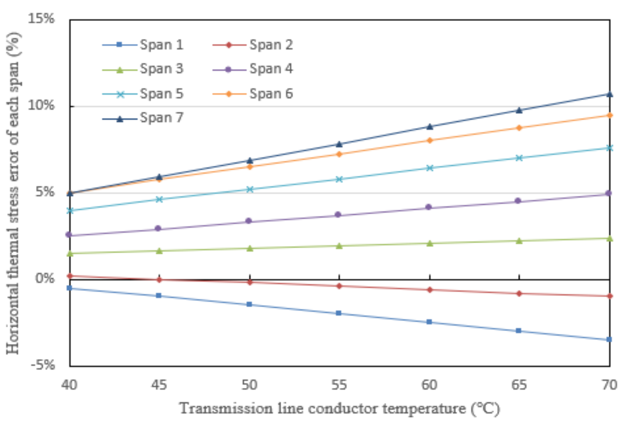

Figure 7. Thermal stress error of each span of the transmission line conductor

According to the thermal stress error data of each span of the transmission line conductor at different temperatures shown in Figure 7, it can be observed that as the temperature increases, the thermal stress error of each span exhibits different variation trends. Specifically, the thermal stress error of Span 1 gradually increases with the temperature rise, from -0.50% at 40℃ to -3.50% at 70℃; whereas the error of Span 2 remains relatively small at most temperatures, especially at 45℃ and 50℃, where the error is almost zero (close to 0%). In Spans 3 to 7, as the temperature increases, the thermal stress error significantly increases, particularly in Spans 5, 6, and 7, where the error reaches 7.60%, 10%, and 10.70%, respectively, at 70℃. These error data reflect the accuracy and stability of thermal stress prediction in different spans. As the temperature increases, the error becomes larger, especially in Spans 5 to 7, where the influence of temperature variation on thermal stress error is significantly pronounced, indicating that the accumulation effect of thermal stress calculation errors is more evident at high temperatures.

From the experimental results, the thermal stress error of different spans exhibits certain regularity during temperature variation. At low temperatures (such as 40℃ and 45℃), the errors of Spans 1 to 7 are generally small, indicating that temperature variations have a relatively minor impact on thermal stress, and the calculation error remains stable. However, at high temperatures (such as 65℃ and 70℃), the error gradually increases, especially in higher spans (such as Spans 5 to 7), where the growth of thermal stress error is more significant.

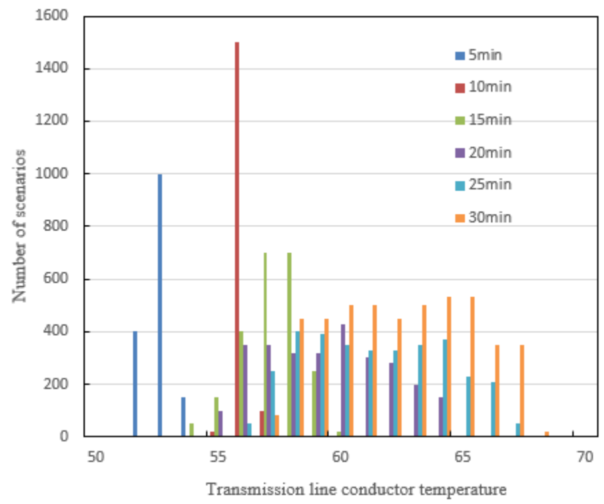

Figure 8. Temperature distribution of transmission line conductors at different time periods

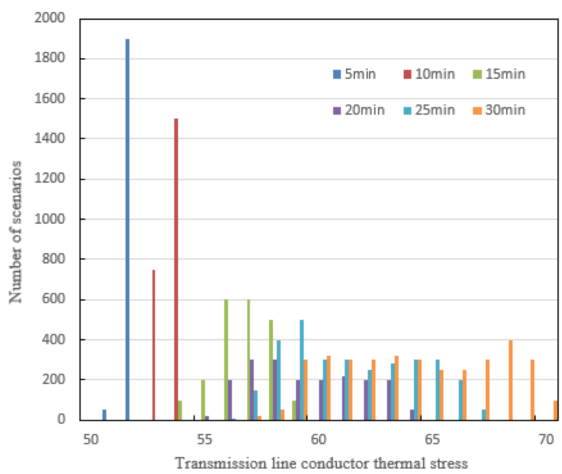

Figure 9. Thermal stress distribution of transmission line conductors at different time periods

From Figure 8, it can be seen that the conductor temperature exhibits a certain variation trend at different time points. In the 50℃ to 55℃ range, the temperature data at 5 minutes show a significantly high value, and as time progresses, the temperature distribution varies greatly at different time points. In the 55℃ to 65℃ range, the data distribution is relatively dense, with values distributed at different temperature levels.

In the 65°C to 70°C range, the temperature data values are generally lower. From Figure 9, it can be observed that at 50°C, the thermal stress value at 5 minutes is relatively high. Subsequently, as the temperature increases, the thermal stress values fluctuate significantly at different time points. In the 55°C to 65°C range, the thermal stress values vary considerably, exhibiting a complex distribution. In the 65°C to 70°C range, the thermal stress values are relatively low and show minor variations.

By integrating the data from both figures, it can be concluded that over time, the temperature and thermal stress of the transmission line conductors exhibit complex variations, indicating that different climatic conditions in freezing weather have a significant impact on the thermal stress of the transmission line. In the temperature range of 50°C to 55°C, higher thermal stress is likely to occur, which may be due to the combined effect of environmental factors in the initial state. In the range of 65°C to 70°C, the thermal stress is relatively low and varies slightly, suggesting that the transmission line remains relatively stable within this temperature range. Based on this, fault prevention strategies can consider strengthening the monitoring of transmission lines when the temperature is in the 50°C to 55°C range, closely observing thermal stress changes in real-time, and taking cooling or transmission current adjustment measures promptly to prevent excessive thermal stress from causing line failures. For temperature and thermal stress variations at different time points, a dynamic monitoring model can be established to predict potential problems in advance, allowing for timely maintenance and inspection of transmission lines to ensure their safe and stable operation under freezing weather conditions.

5. CONCLUSION

This paper constructed a thermal equilibrium equation and a mechanical model of transmission lines in freezing weather from both thermodynamic and mechanical perspectives, systematically analyzing the thermal stress of transmission lines under different climatic conditions and exploring the stress distribution and failure mechanisms under extreme weather conditions. Through precise thermal equilibrium equations, this paper analyzed the impact of different temperature variations on the thermal stress of transmission lines and, in combination with mechanical modeling, deeply investigated the mechanical behavior of conductors in freezing weather. The research results indicate that the proposed method can effectively simulate and predict the thermal stress variations of transmission lines under extreme climatic conditions. Especially in cases of significant temperature fluctuations, the thermal stress analysis of different spans provides accurate data support for fault prevention and line safety.

However, there are certain limitations in this study. First, the research is primarily based on assumptions of the thermal equilibrium equation and mechanical model. While these assumptions can accurately reflect most real-world scenarios, there may still be deviations when dealing with complex environmental variations, such as the combined effects of wind speed and ice thickness. Secondly, the study mainly focuses on the calculation and analysis of thermal stress, without a deeper exploration of factors such as material fatigue behavior and aging effects during long-term operation of transmission lines. Future research directions may focus on the following aspects: (1) further optimizing thermodynamic and mechanical models by incorporating more real-world climate data to enhance model adaptability and accuracy; (2) studying the long-term impact of climate change on transmission line operation and exploring stress prediction methods under the combined influence of multiple factors; (3) incorporating material performance variations over long-term use of transmission lines to further improve the model's predictive capability regarding line aging and fatigue damage. Overall, this paper provides valuable theoretical support for the analysis of thermal stress and fault prevention of transmission lines in freezing weather, offering a reliable technical reference for practical applications.

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