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Analysis of Ice-shedding of Overhead Line Based on Elastic Deformation Principle

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SUMMARY

The ice-shedding of overhead line causes dramatic movement of conductor, which may decrease the air clearance between phase conductor and may cause flashover in severe case. Moreover, if the effect of ice-shedding of overhead line is not taken fully consideration, large dynamic tension caused by ice-shedding jump of conductor may damage the devices used to fasten conductor. Conductor icing is not uncommon for transmission lines, so it is necessary to study ice-shedding jump of conductor. Based on the view that ice-shedding jump is a form of movement in which the conductor tension is suddenly released and the conductor bends elastically, the paper discusses the process of ice-shedding jump and proposes a new calculation method for the variation of sag and tension, which is different from the conventional numerical methods. The study suggests that the adverse effects of ice-shedding jump of conductor should be considered when span is small, and proposes the preliminary condition for determining whether transmission lines are harmed by ice-shedding jump of conductor.

KEYWORDS

Overhead transmission line; elastic expansion; ice-shedding jump; calculation formula; prevention and treatment of ice disasters

0 Introduction

In the process of ice-shedding jump of conductor, the air clearence between phase conductor decreases. If the clearence cannot meet the corresponding insulation requirement, it may lead to phase flash-over or trip accidents. In order to reduce or avoid these accidents, there should be sufficient vertical distance and horizontal offset between phase conductor or between conductor and ground conductor to meet the electrical clearance in different periods of ice-shedding[1,2]. Moreover, if the effect of ice-shedding of overhead line is not taken fully consideration, the dynamic tension caused by ice-shedding of conductor is huge, which may damage the conductor, insulator string, tower and so on. In the design of transmission lines in heavy icing area, the influence of ice-shedding jump should be considered in the lay-out of conductor and the selection of towers[3].

Theoretically, when the conductor is covered with ice, the elastic potential energy of conductor increases with the growth of ice. When the ice is partially or completely dislodged due to artificial melting, temperature rise or wind vibration impact, the potential energy stored of conductor is quickly converted to kinetic energy, causing the conductor to bounce in a half-wave. With the continuous energy exchange, the conductor fluctuates up and down in the form of standing wave. Due to the constraints of air resistance, conductor strand friction and oscillating inertia force of insulator string, the jump amplitude decreases rapidly and reaches a stable state under the new condition.[2]

There are two main methods to study the ice-shedding jump of conductor, the experimental and numerical method. With the rapid development of computer technology, ABAQUS, ADINA, ANSYS and other software are used to study the ice-shedding jump by numerical analysis[4-9].

In some references, it is believed that there is a linear relation between ice-shedding jump height(H) and the sag difference before and after ice-shedding(Δf); that is, $H = k_a \cdot \Delta f$, where k_a is the ice-shedding jump height coefficient; k_a=1.85[10] or k_a=1.66[11], k_a may also be other value. The value of k_a is not unique, which indicates that the coefficient is influenced by many other factors and cannot be directly applied to calculation in many cases.

It is found that a slight variation of conductor length often leads to a significant variation of conductor sag by transmission line designers and construction technicians in their work. Based on the view that the ice-shedding jump of conductor is a a form of movement in which the conductor tension is suddenly released and the conductor bends elastically, directly reflecting the nature of ice-shedding, this paper discusses the process of ice-shedding jump, proposes two calculation methods, namely the general calculation method and simplified calculation method, which are suitable for engineers and technicians.

1 Formation mechanism and calculation formula of ice-shedding jump of conductor

1.1 Formation mechanism of ice-shedding jump of conductor

In order to explain the formation mechanism of the ice-shedding, it is assumed that the research object is an isolated span without tension insulator string, and both ends of the conductor are directly connected with the rigid tower.

In general, when the ice sheds and the conductor jumps, the conductor should be within the elastic limit, which belongs to the linear elastic deformation, and the linear elastic deformation obeys Hooke's law. Young's modulus is one of the physical quantities describing the stress-strain relationship of conductor in elastic deformation state. The suspended conductor is equivalent to a thin spring, as shown in Figure 1.

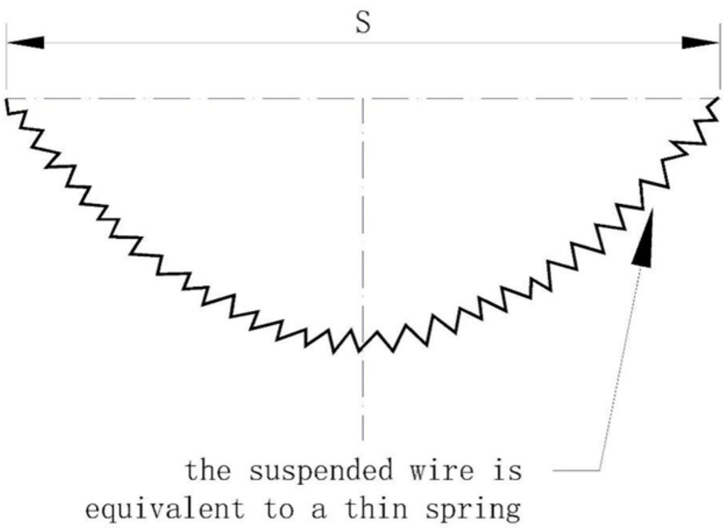

Fig.1 Equivalent diagram of conductor and thin spring

When the conductor is coated with ice, the load and tension increase, the conductor is stretched and the sag increases; once the ice is off the conductor, the load and tension decrease, the conductor is shortened and the sag decreases, and then the conductor jumps up; an elastically deformed conductor will stop at an equilibrium after several leap cycles, as shown in Figure 2.

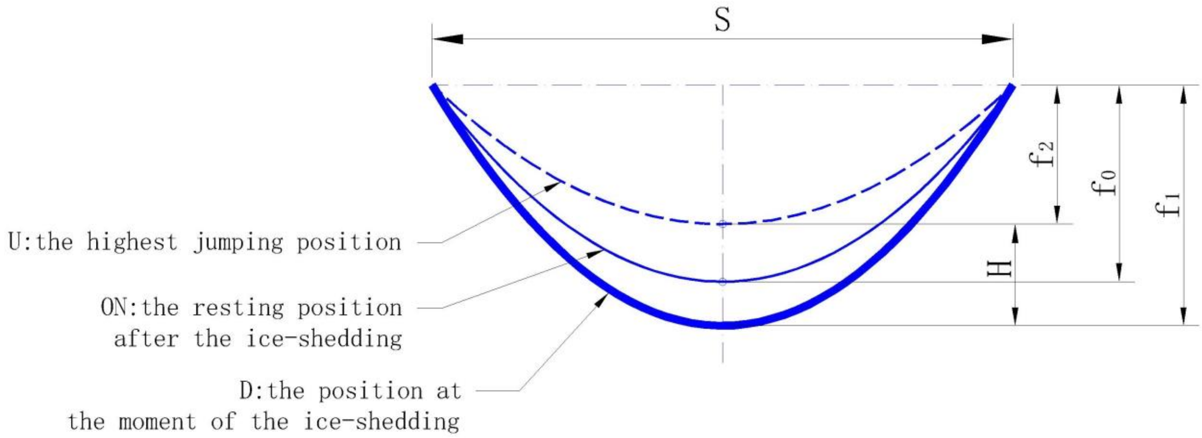

Fig.2 Schematic diagram of conductor ice-shedding

In Figure 2, the ice on the conductor begins to shed at position D, and the conductor jumps upward to the highest point U and finally stays at the position ON.

The conductor length at the moment of the ice-shedding is equal to the length L_1 of the ice-coated conductor; the conductor length when jump finally stops is exactly equal to the conductor length L_0 after the ice-shedding; and both L_1 and L_0 can be obtained according to transmission line mechanics calculation method, $\Delta L_1 = L_1 - L_0$. ΔL_2 is the reduction of the conductor length L_2 at the highest position U from the conductor length L_0 at the position ON, that is, $\Delta L_2 = L_0 - L_2$. Combined with the analysis in Figure 1, ΔL_1 and ΔL_2 are equivalent to the deformation quantity of a thin spring. The relation can be considered as a mechanical vibration with ON being the equilibrium position.

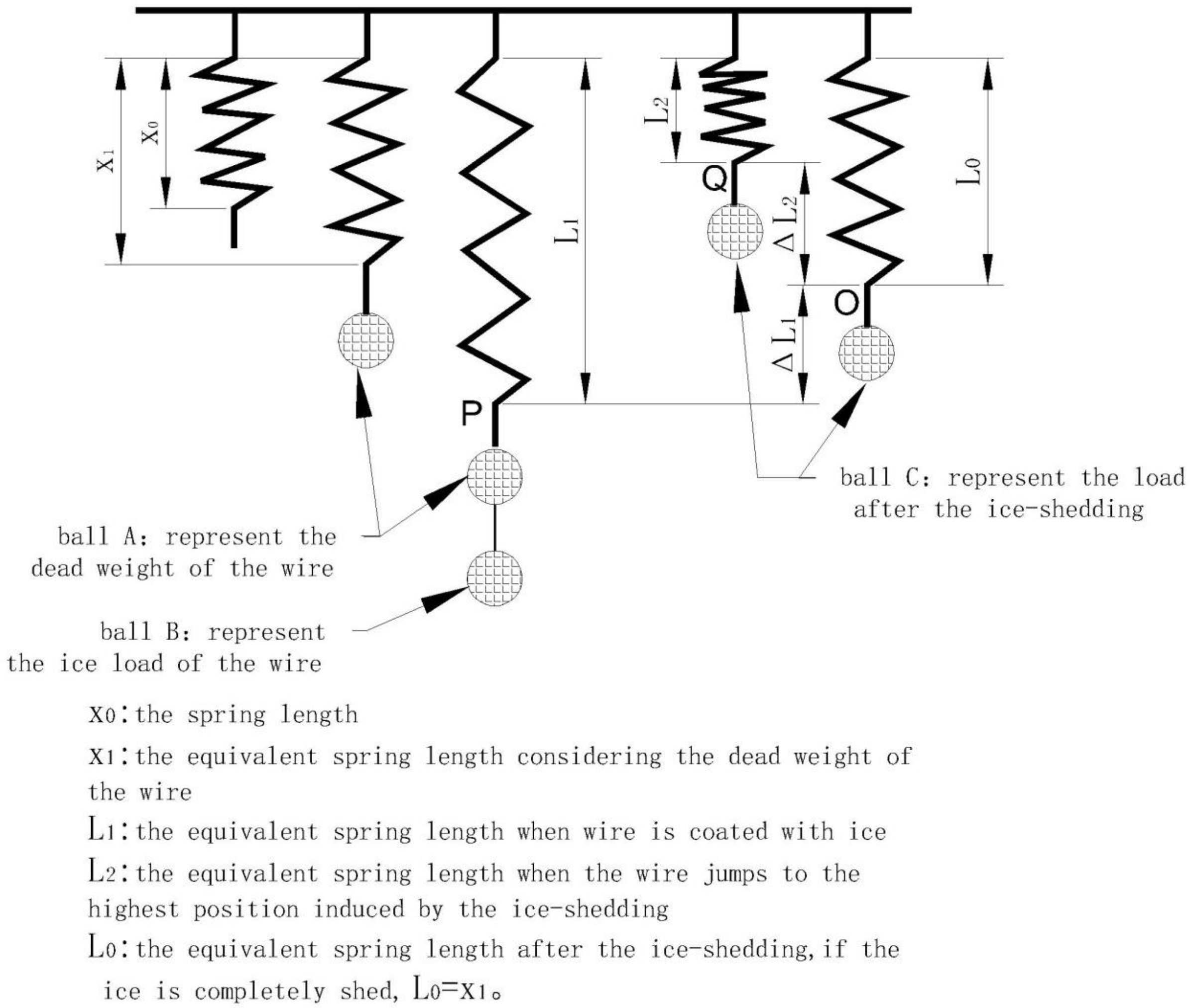

Fig.3 Schematic diagram of vertical suspension spring vibrator vibration

In Figure 3, a vertically suspended spring vibrator is used to simulate the conductor ice-shedding process. Assuming that the spring has no mass, the mass of the conductor is equivalent to ball A, and the spring elongation by bearing the gravity of ball A is X_1. The ice-coated conductor is equivalent to ball B. When conductor is coated with ice, the conductor length is equivalent to the spring length and the elongation is L_1. The ice-shedding process is equivalent to cutting off the thin line between ball A and ball B. After the ice-shedding, the variable quantity of conductor length is equivalent to that of spring length. The conductor is shortened by an amount that equals to the variable of the spring length to L_2, the sag is minimal, and the conductor jumps to the highest position. In practice, the conductor or spring vibrator will stop at the equilibrium position O, and the length of the conductor or spring is L_0, due to the influence of air resistance, the energy loss of the metal atom movement and so on.
Hypothesis proposition: The variable quantity of the conductor length caused by ice-shedding is equivalent to that of the spring length caused by mechanical vibration, that is, the variable quantity of the conductor length before and after the ice-shedding is the same as the law of the spring length.
If this proposition is true, by combining the analysis in Figure 2 and Figure 3,

$$\Delta L_2 = k_\mu \cdot \Delta L_1 \quad (1)$$

k_μ is the damping coefficient of the variable quantity of conductor length, less than 1.0; if the influence of air resistance and spring gravity is ignored, then k_μ=1.0, which is equivalent to simple harmonic vibration.
The conductor length when the conductor jumps upwards to the highest position is calculated as follows.

$$L_2 = L_0 - \Delta L_2 \quad (2)$$

In engineering application and research, the maximum and minimum values of sag and tension during the ice-shedding jump are involved. In Figure 2, the sag reaches its maximum value at the lowest point of the conductor, where the tension before ice-shedding is known, so the minimum tension at the moment of ice-shedding can be calculated. The sag reaches a minimum value at the highest point of the conductor, and the maximum tension of the conductor after ice-shedding is an unknown quantity that needs to be calculated. The following two calculation methods are proposed.

1.2 General calculation method of tension and sag of ice-shedding jump

This method obtains the conductor length by formula (2), and then the tension and sag of conductor can be calculated.

Given the span (*S*), the angle of elevation difference (*β*), the conductor load (*p)* and the conductor length (*L*). In this paper, the oblique parabola formula is applied to calculate the tension (*T*) and sag (*f)*.

$$T = pS\cos\beta\sqrt{\frac{S}{24(L\cos\beta - S)}} \qquad (3)$$

$$f = \frac{p}{8T\cos\beta}S^2 \qquad (4)$$

1.3 Simplified calculation method of tension and sag of ice-shedding jump

Assuming that $\Delta L_2 = \Delta L_1$, sag is calculated by conductor length, and a simplified calculation formula is derived for sag at the highest position,and then the tension of conductor can be calculated.

In this method, we choose the following simplified formula to calculate the sag (*f*).

$$f = \sqrt{\frac{3}{8}S(L - S)} \qquad (5)$$

where,

S is line span, m

L is the conductor length in the span, m

If $\Delta L_2 = \Delta L_1 = \Delta L$, the sag at these three positions in Figure 2 can be expressed by the following equations:

$$\begin{cases} f_0 = \sqrt{\frac{3}{8}S(L_0 - S)} & (6) \\ f_1 = \sqrt{\frac{3}{8}S(L_0 + \Delta L - S)} & (7) \\ f_2 = \sqrt{\frac{3}{8}S(L_0 - \Delta L - S)} & (8) \end{cases}$$

By Equation (6) and (7), ΔL can be calculated:

$$\Delta L = \frac{f_1^2 - f_0^2}{f_0^2}(L_0 - S) \qquad (9)$$

Substitute Equation (9) into Equation (8), note that Equation (6) is substituted into f_0:

$$2f_0^2 = f_1^2 + f_2^2 \qquad (10)$$

Its physical meaning is: 2 times the square value of sag after ice-shedding is equal to the quadratic sum of the sag before ice-shedding and the sag at the highest position, where f_1 and f_0 are known quantities as they can be calculated according to transmission line mechanics.

The conductor sag at the highest position is:

$$f_2 = \sqrt{2 \cdot f_0^2 - f_1^2} \qquad (11)$$

In the derivation of Equations (4), (10), (11), the following three factors are ignored: 1) The variation of the elastic coefficient while jumping; 2) jumping amplitude attenuation caused by air resistance; 3) the effect caused by the conductor being equivalent to a spring vibrator. Due to the damping effect of these three factors on the ice-shedding jump, the calculation results in a larger jump amplitude and the tension of conductor at the highest position, which is the most severe case. A certain safety margin is calculated for the ice-shedding jump height according to this simplified formula.

In this paper, the flat parabola formula is chosen to calculate the tension at the lowest point of the conductor sag when the conductor jumps to the highest position (T_2):

$$T_2 = \frac{P_0}{8f_2}S^2 \quad (12)$$

Where, P_0 is the load per unit length of conductor after ice-shedding, N/m

1.4 One of the judgment conditions that transmission lines may be damaged

The simplified calculation formulas (10) and (11) reflect the relation of the sag at the moment of the ice-shedding, the sag when the conductor rests after ice-shedding, and the sag when the conductor jumps to the highest position. In Formula (11), if $2 \cdot f_0^2 - f_1^2 < 0$, then the sag f_2 at the highest position has no real value, so does the tension T_2; in formula (12), if f_2 is equal to 0, then $T_2 \to \infty$. Its physical meaning is: In the process of bouncing up, the conductor length is shortened; if the conductor length is equal span, it would produce significant stress, which may damage the tower and insulator string, pull the conductor broken or cause other accidents. Since Formula (11) has a certain safety margin, we can make Formula (13) a preliminary judgment on the damage of transmission lines caused by ice-shedding.

$$2 \cdot f_0^2 \le f_1^2 \quad (13)$$

2 Comparative Analysis

In reference [5], simulation test and numerical methods are respectively used to study the ice-shedding jump characteristics of icing conductor. Assuming the same original parameters, the calculation results in reference [5] are compared with the results calculated in this paper as shown in the following table.

Table 1 Calculation results and comparison

The original parameters:

No.	Item	Content	Unit
1	Conductor type	LGJ-300/40	
2	Cross-sectional area	338.9	mm^2
3	Diameter	23.9	mm
4	The calculated breaking force	87742	N
5	Unit mass	1.131	kg/m
6	Modulus of elasticity	73000	Mpa
7	Linear expansion coefficient	0.0000196	1/℃
8	Safety factor of conductor	2.5	
9	Span	235	m
10	Temperature during icing	-5	℃
11	Wind speed during icing	10	m/s
12	The thickness of ice	15	mm
13	The ratio of ice-shedding	100%	
14	Temperature during ice-shedding	0	℃

The conductor tension at the highest position after ice-shedding, calculation results and comparison:

1	Experimental results in reference [5]	35490	N
2	Numerical results in reference [5]	37654	N
3	The general calculation result in this paper	35728	T
4	The simplified calculation result in this paper	35955	N

According to the method of calculating conductor tension at the highest position recommended in this paper, the simplified calculation value is slightly larger than the general calculation result, both of them are among the experimental results and simulation results in reference [5]. However, the example listed in this paper is an individual case, and more evidence is needed for verification.

3 Examples

Taking the Alloy Conductor Steel Reinforced conductor JLHA1/G1A-400/50 as an example, the design ice thickness is 30mm, 10% of the ice mass has melted before ice-shedding. Specific calculation parameters are shown in the following table.

Table 2 List of conductor and calculation parameters

No.	Item	Content	Unit
1	Conductor type	JLHA1/G1A-400/50	
2	Cross-sectional area	451.54	mm^2
3	Diameter	27.6	mm
4	The calculated breaking force	177564	N
5	Unit mass	1.5093	kg/m
6	Modulus of elasticity	64500	Mpa
7	Linear expansion coefficient	0.0000208	1/℃
8	Safety factor of conductor	3	
9	Temperature during icing	-5	℃
10	Wind speed during icing	15	m/s
11	The thickness of ice	30	mm
12	Percent ice that has been melted	10%	
13	Percent ice-shedding of residual ice	100%	
14	Temperature at ice-shedding	0	℃

The ice-shedding jump height and its coefficient k_a at different spans are shown in Figure 4 and Figure 5 respectively. $k_a = H/\Delta f$, $H = f_1 - f_2$, $\Delta f = f_1 - f_0$, as shown in Figure 2. For span among 25m~75m, which is considered as the isolated span connecting substation gantry with terminal tower, the conductor was paid out to reduce wire tension significantly. For span among 100m~200m, the conductor length is shortened while jumping; the shortened conductor length is too small, so the conductor needs to be properly relaxed. For a span greater than 225m, the conductor safety factor is 3.0 and the maximum design tension is 59188N; the general calculation method is applied here. The relation between maximum dynamic tension of conductor during ice-shedding and span is shown in Figure 6.

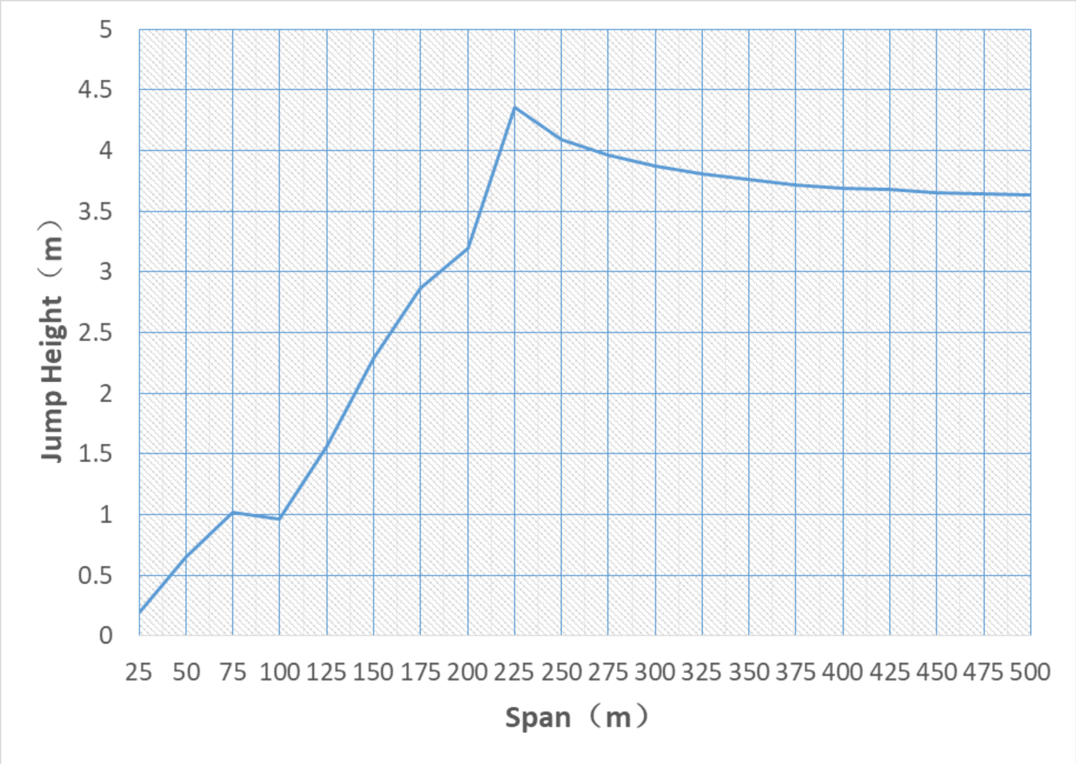

Fig.4 Relation between ice-shedding jump height and span for JLHA1/G1A-400/50

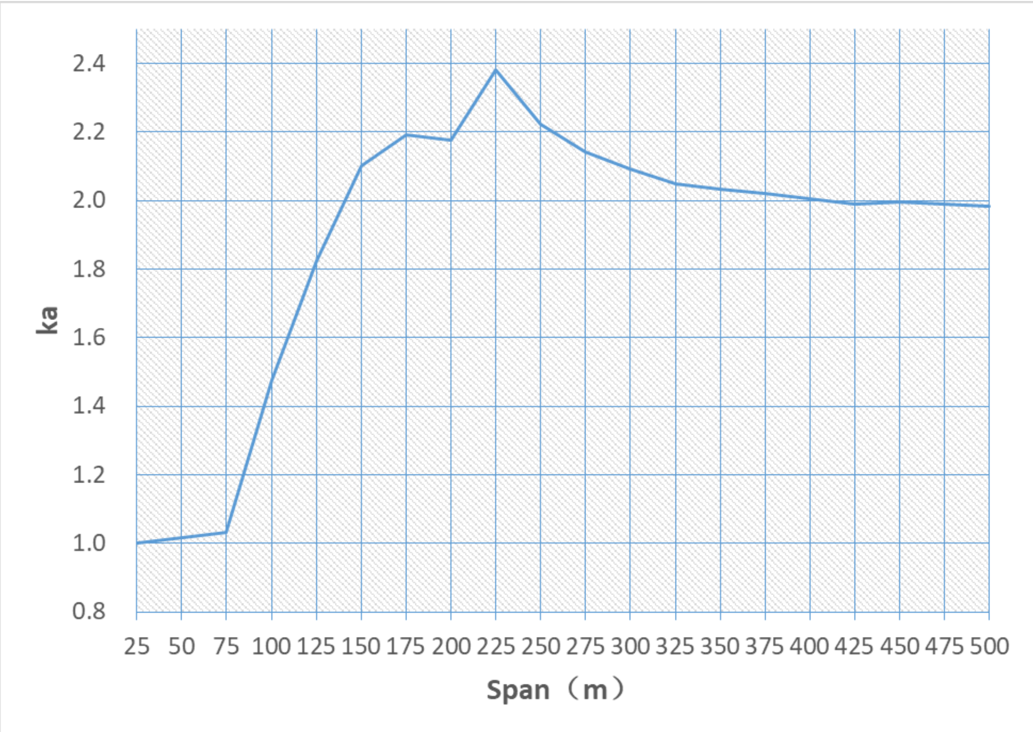

Fig.5 Relation between k_a and span for JLHA1/G1A-400/50

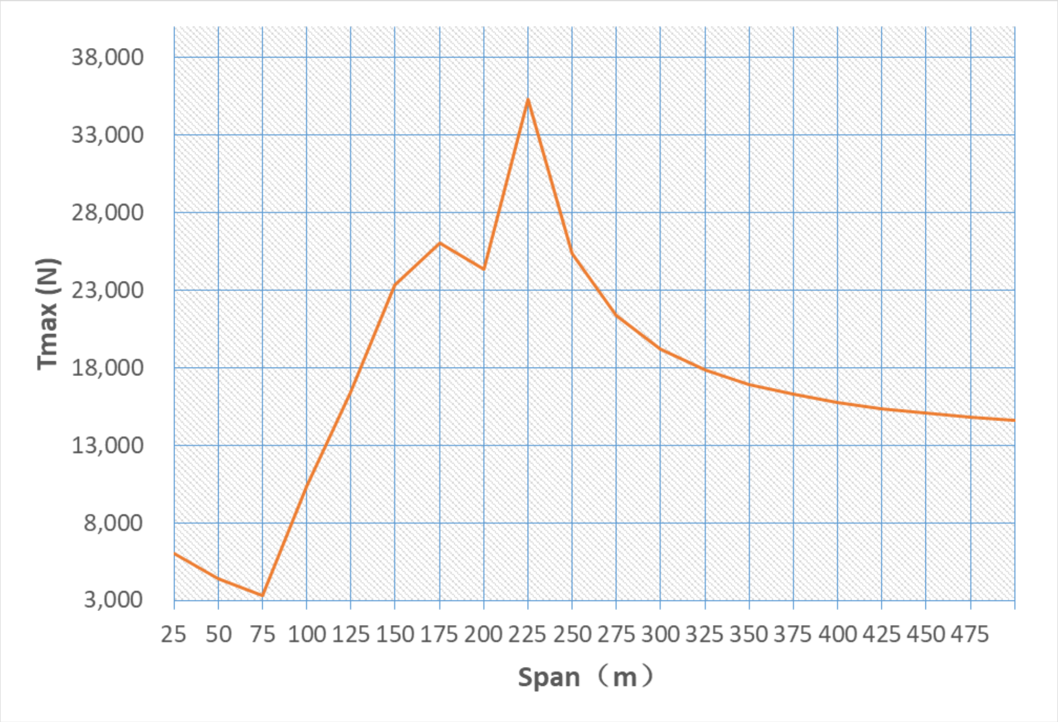

Fig.6 Relation between maximum dynamic tension of conductor and span for JLHA1/G1A-400/50

It can be seen from the above curves related to the isolated span that the amplitude and tension of conductor ice-shedding jump tends to decrease as the span increases. If the maximum design tension of conductor is the same at different spans, the maximum dynamic tension of conductor increases as the span decrease.

4 Conclusion

At present, many simplified calculation formulas in references generally apply the calculation results of finite element method and numerical analysis method, and the formulas are obtained by fitting. Due to manual intervention in formula fitting, a linear relation is commonly used, such as $\mathrm{H} = k_a \cdot \Delta\mathrm{f}$, with k_a being the uncertain coefficient:

$$f_1 - f_2 = k_a(f_1 - f_0) \qquad (14)$$

In this paper, the simplified calculation formula is derived by deductive method without uncertain coefficients:

$$2f_0^2 = f_1^2 + f_2^2 \qquad \text{equivalent to } (10)$$

We hope to open up new research horizons for peers with resources and conditions.

The proposed algorithm is simple, practical, and strongly independent without finite element analysis or software. It is well integrated with the existing calculation methods of overhead transmission lines, and can be easily embedded into them.

To this day, people often pay attention to the ice overload caused by large span or large elevation difference in the ice disaster of the transmission lines. Through formula derivation and calculation analysis, this paper proposes the possibility of accidents during ice-shedding jump of conductor. In other words, the ice growth of conductor may pose a threat to the large span, while the ice-shedding of conductor may pose a threat to the small span.

The simplified formula $2 \cdot f_0^2 \leq f_1^2$ can be used as a preliminary basis for judging the possible damage to transmission lines caused by ice-shedding jump.

In the design and construction of transmission lines, the ground conductor is usually tighter than conductor, so the probability of damage to the ground conductor and its connecting devices is higher than that of conductor during ice-shedding.

The hypothesis proposition is expressed in formula (1), its physical meaning is: Taking the position when conductor rests after ice-shedding as the equilibrium position of vibration, and the difference between the length of the icing conductor and the length of conductor at this position as the initial elongation, when the conductor loses the tension that causes the initial elongation, the conductor vibrates elastically, the variation of conductor length leads to that of conductor sag and tension. We tried to prove the hypothesis by applying the existing research results and mathematical models of ice-shedding with rigorous mathematical reasoning, but unfortunately, we did not achieve satisfactory results. The hypotheses proposed in this paper still needs to be verified by rigorous mathematical derivation and experiments.

Although factors such as jump attenuation, influence of insulator string and dispersion of ice-shedding are ignored, and only isolated span is considered, the simplified calculation formula is simple and clear, and represents the worst-case scenario during the ice-shedding of conductor. It helps to make judgments easily in the design, operation and accident analysis of transmission line. It will play a positive role in the investigation, accident prevention, analysis and treatment of transmission lines in heavy icing area.

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