Research on Dynamic Response of Ice-shedding of Transmission Lines in XinJiang under Coupled Operating Conditions

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Abstract*—At present, the field of research examining the transmission lines' reactive behavior under dynamic conditions within intricate environmental settings remains fraught with numerous inadequacies.Notably, the transmission corridors situated in Xinjiang,predominantly nestled amidst mountainous terrain, pose unique challenges,particularly in the realm of ice-shedding phenomena.The intricacies of this environment necessitate a nuanced understanding of ice-shedding responses,as the established patterns observed in other regions cannot be directly applied to the mountainous regions of Xinjiang.In this research endeavor,we commence by delving into the derivation of a nonlinear finite element initial configuration tailored specifically for transmission lines in Xinjiang,leveraging the Newton-Raphson methodology.By incorporating actual transmission line parameters into iterative computations,we successfully establish a two-span three-phase 'conductor-insulator' finite element model,accompanied by a vector cloud depiction illustrating the intricate dynamics of ice-shedding jumps.Subsequently,we embark on an investigation into the multifaceted factors influencing conductor ice-shedding jumps,grounded in the fundamental dynamic equation.Through meticulous simulations,we discern the evolution of conductor points' positions and the peak longitudinal unbalanced tensions across varying ice-shedding magnitudes and altitude differentials.Our findings underscore the imperative to bolster the resilience of transmission towers against unbalanced tensions in terrain characterized by pronounced elevation disparities,thereby safeguarding the seamless operation of transmission lines.Lastly,we extend our analysis by constructing a comprehensive three-span three-phase 'conductor-insulator' finite element model that encapsulates the intricate tower-line coupling dynamics unique to Xinjiang.This endeavor culminates in simulations assessing the minimum phase-to-phase distance between conductors under six distinct ice-shedding scenarios amidst intense wind conditions.Our simulations,spanning various wind velocities and attack angles,reveal insights into the frequency of safety distance breaches,potential risk scenarios associated with these six ice-shedding conditions,and the optimal strategies for proactive de-icing in high-wind weather.

Keywords—transmission lines, ice-shedding, jumping, finite element simulation, coupled operating conditions

I. Introduction

The ice-shedding process of iced conductors is an extremely complicated physical phenomenon, which involves many factors and complex interactions. The complexity is further increased when accounting for the interactions within the tower-line system. At the same time, the strong nonlinearity and high flexibility of the wire itself also greatly increase the difficulty of the research on the ice-shedding problem. Consequently, examining the dynamic response of transmission lines to ice-shedding under coupled conditions is essential.

Utilizing ADINA, Roshan Fekr[1] constructed a two-span conductor plane model,, and studied the static and dynamic responses of the model under the combination of 21 working conditions with six parameters : ice thickness, span, suspension point height difference, number of spans, unequal span, and partial ice shedding. The influence of each parameter was discussed. Wang J[2] devised a model for an overhead transmission line featuring multiple spans and incorporating three degrees of freedom, which can simulate the galloping of iced conductors, perform static and dynamic analysis, and improve the design of multi-span multi-split lines. Mcclure[3] used ADINA to simulate the tower collapse caused by broken wires, studied the transient dynamic response of the counductor under the influence of impact load, summarized the modeling method of wire dynamic analysis macroscopically, and focused on the propagation law of impact load. The research results are also applicable to problems such as hardware damage or ice shedding. Kollar[4] conducted simulations to assess the dynamic behavior of sub-conductors within bundled conductors subsequent to the shedding of ice accumulations. Meanwhile. Kalman[5] delved into the dynamic response of conductors under diverse operational scenarios, incorporating stall spacing and varying external impact load combinations. This was achieved by constructing a nonlinear finite element model tailored specifically for isolated stalls, thereby laying a solid foundation for the exploration of icing-induced damage criteria. Barbieri[6], on the other hand, introduced a nonlinear mathematical framework to mimic the dynamic response of conductors. This numerical model was formulated utilizing the finite element method, and its predictions were subsequently validated against experimental data. The analysis revealed that the deformation exhibited by the conductor was intricately linked to the excitation frequency, the inherent qualities of the conductor material, as well as the specific excitation conditions.

Wang[7] studied the jump of conductor under random non-uniform de-icing bounce by establishing the three degrees of freedom multi-span conductor model, and studied the influence of de-icing bounce position, ice-shedding rate and ice-shedding times on the jumping law. It is proved that non-uniform ice-shedding has more serious ice jump amplitude than uniform ice-shedding. Chen[8] simulated icing by hanging concentrated load, carried out ice-shedding jump tests under different span combinations and ice-shedding methods, and simulated the test conditions by computer. By comparison, the numerical simulation and the simulation experiment results have the same regularity and similar values. Hou[9] analyzed the nonlinear dynamic process of conductor ice-shedding, established the three degrees of freedom multi-span conductor model, and calculated the time-history response of conductor ice-shedding jump by using the explicit integral of central difference as the calculation method. Meng Xiaobo[10] constructed a multi-span conductor model incorporating three degrees of freedom, examining the multifaceted impact of various parameters on the dynamic behavior of conductors during ice shedding. These parameters included ice thickness, the amount of ice shed, span length, the quantity of intermediate spans within the tension zone, variations in suspension point heights, and the phenomenon of uneven ice shedding. Based on the analysis, a recommendation was put forward suggesting that a conversion factor of 1.8 could be applied to approximate the transition from static to dynamic unbalanced tension, with a certain safety margin incorporated to ensure robustness.Chen Kequan[11] used ABAQUS to establish a 7-span 4-bundled transmission line model, calculated and analyzed the dynamic response of the conductor under various working conditions with different structural parameters of the tension section, and obtained the law of the ice jump height and tension of the conductor changing with time.

II. Finite element model of transmission line based on nonlinear finite element method

A. Form-finding of Transmission Line

The foundational step in developing a finite element model for the tower-line system is the accurate form-finding of the transmission line itself, as this precision underpins the reliability of subsequent analytical endeavors. With a keen eye on engineering applications, this study adopts the nonlinear finite element methodology rooted in the Newton-Raphson iterative framework to construct a transmission line model that captures intricate behaviors with enhanced fidelity. This method is based on the initial shape, and gradually iterates on the basis of it, and finally obtains the initial configuration of the transmission line conductor.The calculation of the initial configuration of the wire is generally divided into two categories[12] : one is to construct a mathematical model based on the catenary or parabolic theory and establish the corresponding equation. In the framework of this model, the horizontal tension at the lowest point is used as the convergence criterion, and then the iterative calculation is carried out on the basis of the approximate curve. Through repeated iteration until the convergence condition is satisfied, the accurate description of the wire configuration is realized. The second is to adopt the method of establishing a plane linear model between two suspension points, set the corresponding convergence conditions, and directly perform iterative calculations. After each calculation, the model parameters are updated in time to gradually approach the real wire configuration. Through this iterative calculation and model updating method, the initial configuration of the wire can be finally obtained, which provides accurate initial conditions for subsequent research.

For the characteristics of the conductor is only subjected to tension but not pressure, this paper adopts Link10 rod unit in simulation software to simulate the conductor, sets the value of horizontal tension at the lowest point as the convergence condition, updates the finite element model, carries out iterative calculations, and finally obtains the initial configuration of the conductor.

B. Finite Element Modelling of Conductor-insulator

Conductivity, mechanical strength, quality and economy should be comprehensively considered when selecting overhead transmission line conductors. Therefore, JL/G1A-400/35 steel core aluminum stranded wire is selected, which has the advantages of good electrical conductivity, high mechanical strength, simple structure and large transmission capacity. The conductor is a flexible cable structure, which is only tensioned but not compressed, and its shape is catenary. The rod element Link10 is used to simulate the wire, which is a 3D rod element and can only withstand axial tension or compression. The unit schematic diagram is shown in Figure 1.

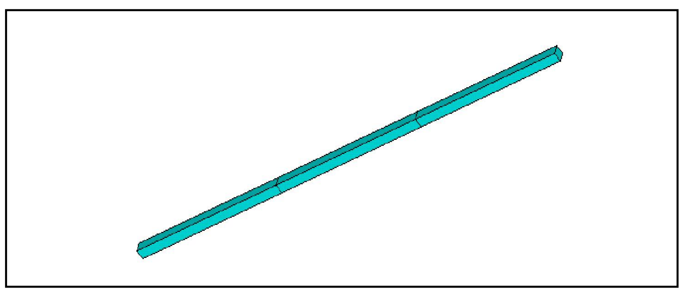


Fig. 1. Link10 unit schematic diagram

The insulator string in the coupled finite element model of the tower-line system adopts composite insulators. Considering that the stress part of the insulator string is mainly the core rod, other components are treated as the additional mass of the core rod, and the rod element Link8 is used for simulation. The rod element has the characteristics of large deformation and stress stiffening. If the insulator is iced, the icing on its surface is equivalent to a vertical load, which is applied to the insulator.

Taking a 220 kV transmission line with a conductor model of 2×JL/G1A-400/35 in Xinjiang as an example.The parameters of the example conductor are as follows: conductor type 2×JL/G1A-400/35, gear distance is 400 m, cross sectional area of the conductor is 426 mm^2, diameter of the conductor is 26.82 mm, modulus of elasticity is 65 GPa, tensile breaking force is 103,900 N, and the horizontal tension under the average annual temperature is 30,000 N. The mechanical attributes of the wire are detailed in Table I, while the numerically determined arc sags at each nodal point along the conductor are presented in Table II.

TABLE I. WIRE PARAMETERS

Parameter	Data
cross sectional area (mm^2)	426
outside diameter(mm)	26.82
breaking force (kN)	103.9
unit mass (kg / m)	1.349
elastic modulus (N / mm^2)	65000
linear expansion coefficient (10^{-6} / °C)	20.5

TABLE II. CALCULATION RESULTS of CONDUCTOR NODE SAG

Node	Arc Sag
50	5.722
100	9.825
150	12.295
200	13.117
250	12.294
300	9.825
350	5.722

Utilizing the aforementioned data, a finite element representation of the two-span, three-phase 'conductor-insulator' assembly within the transmission line system has been constructed, as depicted in Figure 2. Furthermore, a visualization of the displacement patterns resulting from ice shedding, in the form of a vector cloud map, is presented in Figure 3.

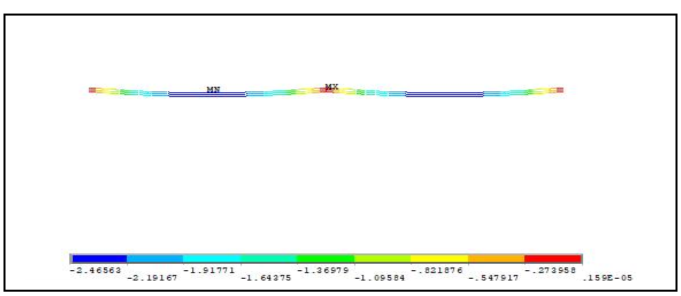


Fig. 2. Two-span three-wire finite element model

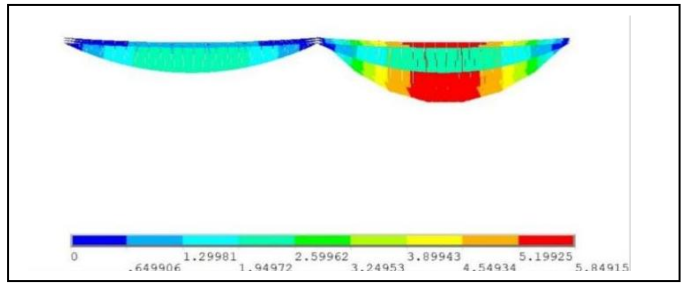


Fig. 3. Vector cloud map

III. STUDY ON THE INFLUENCING FACTORS OF ICE-SHEDDING JUMP

A. *Ice-shedding Mechanism*

Upon the accumulation of ice on the conductor, there is a corresponding augmentation in its potential and elastic energies. When subjected to favorable temperature conditions or external stimuli, the ice suddenly detaches from the surface, triggering a transformation of the stored elastic energy into kinetic energy and a reconfiguration of potential energy. This energetic transformation propels the conductor into oscillatory motions. However, the vibratory behavior is gradually dampened by various factors, including energy dissipation mechanisms such as air resistance, inherent damping within the conductor, the inertial forces imparted by the insulator string, and others. Ultimately, the conductor achieves a new state of equilibrium. The fundamental dynamic equation that governs this ice-shedding-induced jump phenomenon in conductors is:

$$M\ddot{u}+C\dot{u}+Ku=F(t) \tag{1}$$

The formula encompasses key matrices designated as M,C, and K representing mass, damping, and stiffness, respectively. These matrices, along with the vectors for acceleration, velocity, and displacement, and the external force vector *F(t)* ,are essential components in analyzing the complex nonlinear dynamics of ice-shedding on transmission line conductors.

Addressing this intricate issue, the present study employs the nonlinear transient dynamic finite element approach to model and solve the ice-shedding jump phenomenon in conductors. This method enables us to delve into the temporal behavior of the structure's dynamic response under various loading conditions, thereby facilitating the computation of stress, strain, and displacement evolution within the mechanical model of the ice-shedding jump over time, across diverse combinations of static, transient, and harmonic loads.

B. *Changes of Position and Unbalanced Dynamic Tension of Ice-shedding Conductor after Ice-shedding*

After the actual transmission line ice-shedding, the ice-shedding jump heights at different positions are different. The displacement changes of each position of ice-shedding are obtained through simulation research, as shown in Fig.4. It is 1/2 of the ice-shedding gear, 1/4 of the ice-shedding gear, the hinge point of the lower end of the insulator, 1/4 of the non-ice-shedding gear, and 1/2 of the non-ice-shedding gear. Affected by environmental factors, after a period of time, the wire tends to be stable. Considering the influence of wind speed on conductor ice-shedding, ice wind load is provided to the conductor before 100s, and only wind load is provided after 100s. Figure 5 illustrates the imbalanced variations in dynamic tension experienced by the conductor span during the ice-shedding process. Notably, the peak longitudinal dynamic tension precedes the shedding event, whereas the maximum tension along the conductor's axis emerges subsequent to the ice's detachment.

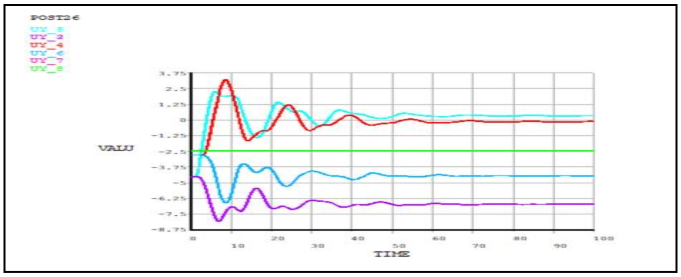


Fig. 4. Time history curve of each position after conductor ice-shedding

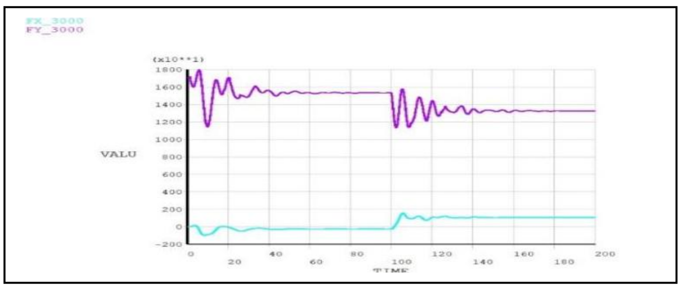


Fig. 5. Unbalanced tension change of ice-shedding gear

C. *The Influence of Ice-shedding Amount*

The investigation delves into the variations in longitudinal unbalanced tension associated with conductor ice-shedding, taking into account the varying amounts of ice shed and the specific spans affected by the shedding process. The model parameters are as follows : the amount of ice removal is 25%, 50%, 75% and 100% respectively, the middle span is used for ice removal, and the span of ice removal is 200m ~ 800m. Through simulation research, the variation curve of the maximum longitudinal unbalanced tension of the conductor under different ice-shedding amounts is obtained, as shown in Figure 6.

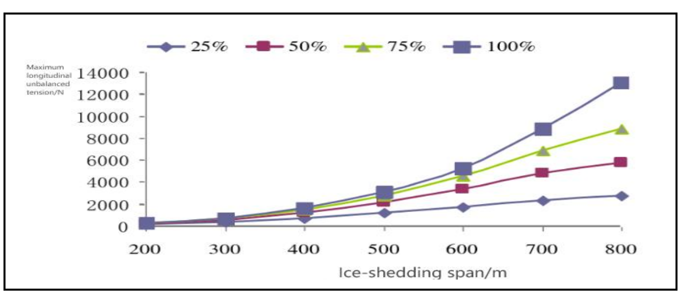


Fig. 6. The variation of the maximum unbalanced tension under different ice-shedding amounts

It can be seen from Fig.6 that with the increase of ice-shedding amount,the maximum longitudinal unbalanced tension of conductor ice-shedding shows an increasing trend. This is because the conductor is ice-shedding, the mass of the iced conductor is reduced, and the violent movement of the conductor produces a large tension difference. The larger the amount of ice-shedding, the smaller the mass of the conductor, the more severe the vibration, and the greater the longitudinal unbalanced tension of the conductor.

D. *The Influence of Height Difference*

In this section, the middle ice-shedding is adopted, and the height difference is at the left end of the ice-shedding section, and the height difference is 0,10% and 20% respectively. The simulation analysis reveals the variation profile of peak longitudinal unbalanced tension in the ice-shedding conductor, considering diverse elevation differentials, as illustrated in Figure 7.

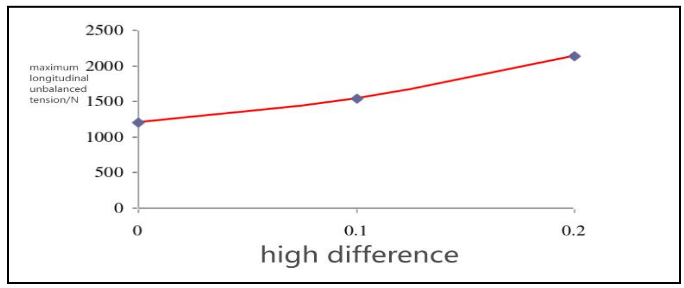


Fig. 7. The change of the maximum unbalanced tension under different elevation difference

Figure 7 illustrates a discernible trend: for scenarios with pronounced height disparities, an escalation in the height difference correlates with a gradual augmentation in the longitudinal unbalanced tension experienced by the conductor during ice-shedding. Therefore, the ability of the transmission tower to withstand unbalanced tension should be increased in the terrain with large height difference to ensure the safe operation of the transmission line.

IV. The Minimum Spacing of Ice-Shedding Conductor Under Strong Wind

Utilizing actual parameters sourced from specific segments of a transmission line in Xinjiang, we have constructed a finite element model that encapsulates a three-span, three-phase 'conductor-insulator' system, as visualized in Figure 8. The conductor type LGJ-630/45, span 400 m, insulator is type I suspension glass insulator FC7P/146, the upper end is fixed, the lower end has swing degree of freedom, and the suspension point has no height difference.

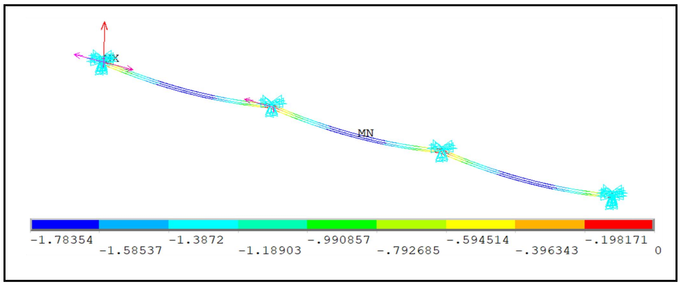


Fig. 8. Transmission line models

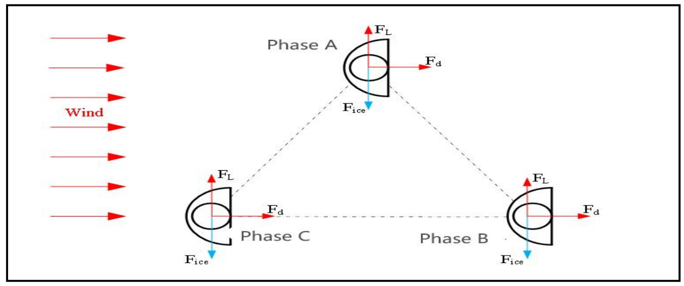


Fig. 9. Transmission line section diagram

Because the ice-shedding phenomenon of the actual line is complex and uncontrollable, in this paper, the ice load is set to be evenly distributed along the conductor during the simulated conductor ice-shedding process, and the three gears are iced. The ice-shedding position is selected as the middle gear, and the strong wind speed before and after ice-shedding is always unchanged. The additional load method is used to apply the crosswind load and lift load of each strong wind condition in the front section and the icing load with an equivalent ice thickness of 15 mm to the conductor. Before ice-shedding, wind load is applied on the transverse plane, and the longitudinal plane is the superposition of ice load and lift load. The influence of wind attack angle on iced conductor is reflected by the magnitude of load. Upon the completion of ice-shedding, the entire longitudinal icing load (equivalent to 100% icing coverage) is eliminated from the transmission line. Because there is no icing on the surface of the wire, the crosswind load and lift load of the bare wire are the same under different wind attack angles.

A. Simulated Operating Conditions

The minimum distance between phases when the power frequency voltage is working is the safe distance of operation. When the distance between phases is less than the safe distance, there is an electrical accident.In order to simplify the analysis model, it is assumed that the icing amount and ice shape of the A, B and C three-phase conductors in the ice-shedding line are exactly the same. The wind load and wind attack angle of each phase before ice-shedding are the same, and only the ice-shedding phase is selected differently. The section and stress decomposition diagram of the transmission line is shown in Figure 9. In order to facilitate the description, it is assumed that the upper phase is A phase, the left phase is C phase (upwind side), and the right phase is B phase (downwind side). The initial distances of A-B phase, A-C phase and B-C phase are 7 m, 7 m and 8.2 m, respectively. The wind attack angle before ice-shedding is 0-360° (interval 15°), the continuous wind speed is 10-25 m/s (interval 5 m/s), the equivalent icing thickness is 15 mm, and the ice-shedding rate of the middle span of each phase is 100 %.

The six simulation conditions are B phase single-phase ice-shedding, C phase single-phase ice-shedding, A phase single-phase ice-shedding, B and C ice-shedding at the same time, A and B ice-shedding at the same time, A and C ice-shedding at the same time.

B. Minimum Phase-to-phase Distance of Conductor

The ice-shedding response process of transmission lines under strong wind is a round-trip jump process in spatial dimension[12].Through numerical simulation, it is extracted that when the minimum phase-to-phase distance of the conductor during the bounce process is less than the safe operating distance, it can be determined that the conductor ice-shedding under this test condition has a discharge risk.Taking condition 1 as an example, there are many values less than the safe distance at the midpoint of the ice-shedding span of phase A and phase B of the transmission line under strong wind. For example, when V=10m/s and α= 210° , the minimum distance of phase A-B is only 1.11m, and when V=15m/s and α= 0° , the minimum distance of phase A-B is only 1.28 m.

All the conditions where the interphase distance is less than the safe distance are summarized, and the results are shown in the cube identification in Fig.10.From the ultra-safe distance (over-limit) risk condition, it can be seen that :

1) Condition 6 ice-shedding has the lowest number of problems, and condition 2 has the second lowest number of problems.

2) When the downwind side (phase B) is the ice-shedding phase, the number of safety distance over-limit risk problems is the most, and there is the greatest possibility of discharge accidents.

3) When single-phase ice-shedding, A phase and C phase ice-shedding, there is no safety distance exceeding the limit when the wind speed V=10m/s. For the two-phase ice-shedding including the ice-shedding of the upper phase (phase A) conductor, there is no risk of exceeding the safety distance when the wind speed V=10m/s.

4) When the B and C ice-shedding at the same time, the safety distance over-limit occurs when the wind attack angle α> 180° .

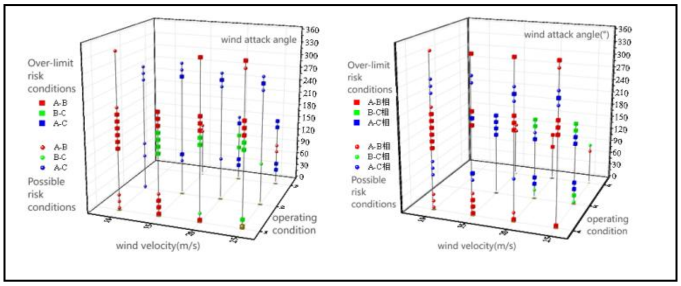
5) According to the simulation results, the minimum distance between phases can be up to 8mm, and there is a possibility of serious accidents when the conductors of two phases are close together.

In the process of conductor ice-shedding jump, although the distance between phases under some strong wind conditions is not less than the safe distance, the decrease of the distance between phases will have more than 50% of the initial distance between phases. At this time, the ice-shedding condition of transmission lines should also be paid attention to. This paper defines it as a possible risk condition and records it as a circular sign in Figure 10. From the analysis of simulation results, it can be seen that:

1) The number of significant reductions in the distance between the ice-shedding methods in condition 5 is the least.

2) There is no possible discharge risk when V=10m/s for the two-phase conductor with A-phase ice-shedding at the same time.

3) Under the condition of partial wind attack angle, there will be a situation where the phase spacing of the two side phase conductors decreases by more than 50 % of the initial distance.



(a)Single-phase ice-shedding (b)Two-phase ice-shedding

Fig. 10. Statistics of dangerous working conditions of three-phase line ice-shedding under strong wind

V. CONCLUSION

This paper takes an actual transmission line in Xinjiang as an example, establishes its three-span and three-phase "conductor-insulator" finite element model and carries out 576 ice-shedding jump simulations under six different operating conditions. Finally, the dynamic response results of ice-shedding under different working conditions of transmission lines under strong wind are obtained. The occurrence times of safety distance over-limit and possible risk conditions from condition 1 to condition 6 are 41,19,14,49,19 and 7. Therefore, if active de-icing operation is needed in windy weather, it is recommended to give priority to the ice-shedding method of operating condition 6, which is the least likely to cause electrical accidents.

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