Case Study of Two Typical Transmission Line Faults due to Ice Shedding

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Abstract—Ice shedding is one of the main natural disasters threatening the safety of overhead electric transmission lines. It is a phenomenon that ice accretion is detached from electric conductors due to melting or mechanical loads, such as wind load or mechanical de-icing. As a result, large amplitude vibration and dramatic force variation will occur if large amounts of ice are shed, which may cause mechanical faults, including strands/conductor breakage, insulator rupture, tower crossarm deformation and even tower collapse. Electrical faults are also a consequence, such as flashovers or short circuits due to insufficient electric clearance among phase conductors, ground wires, tower members and the earth. Although the influence of ice shedding has been taken into consideration in the Chinese design code for overhead transmission lines, faults may still occur in certain specific conditions. However, it is rare to observe faults of the ultra high voltage (UHV) transmission lines induced by ice shedding due to their large phase-phase distance, phase-ground wire distance and tower size. Two typical faults of 1000 kV AC and ±800 kV DC UHV lines due to ice shedding are reported and investigated in this study. The first one (tripping of two-phase conductors) occurred on a double-circuit 1000 kV AC UHV transmission line section in 2019, with the design ice thickness of 15 mm and wind speed of 30 m/s. It was found that there were several discharge points on the middle phase and the upper phase conductor around the midpoint of a long span with large elevation difference. Thus, ice shedding is taken as the most suspicious cause for the fault. Then, numerical simulation and empirical formula were employed to calculate the jump height of conductor to reproduce the faults. The results confirm that the fault may be caused when excessive icing appears and then sheds off from conductors. The second event occurred on a ±800 kV DC UHV line in 2021, where the optical fibre ground wires (OPGW) ruptured after an icing event. Detailed investigation showed that short circuits occurred between the OPGW and the conductor, again in a long span with large elevation difference, for there are obvious melting marks on the strands around the rupture point. Also, numerical simulations indicate that ice shedding is the most possible reason for the fault. Several scenarios with various ice thicknesses and wind speeds are modelled and compared. The results show that the fault is unlikely to occur in still air even with excessive ice loads and wind action during the ice shedding process may have made an obvious contribution to the fault. Thus, to ensure the security of UHV lines, it is necessary to check the dynamic response of the high-risk line sections by considering the combined effects of wind and ice shedding and excessive ice loads, especially for line sections with long spans and large elevation differences. The analysis of typical faults of real UHV lines may help to understand the fault mechanism of ice shedding and improve the design code.

Keywords—***UHV, ice shedding, finite element method, wind load, jump height***

I. INTRODUCTION

UHV refers to the electric transmission technology with a voltage level of AC 1000 kV and above and DC ± 800 kV and above, which has the advantages of large transmission capacity, long distance, high efficiency and low loss. Up to now, the State Grid of China has completed and put into operation 26 UHV projects, with 14 UHV AC lines and 12 UHV DC lines. Taking into consideration of the five UHV lines under construction, the total length of UHV transmission lines will reach 41,000 km, and the substation (converter) capacity exceeds 450 million kVA (kW). Thus, it is inevitable for the line corridors to cross high-altitude mountainous areas, which are very prone to atmospheric icing that may seriously endanger the safety of the power grid.

Ice shedding refers to phenomenon that ice accretion is detached from electric conductor due to melting or mechanical loads, such as wind load or mechanical de-icing. It is one of the main natural disasters threatening the safety of overhead electric transmission lines, as it may cause mechanical faults, including strands/conductor breakage, insulator rupture, tower crossarm deformation and even tower collapse. It may also cause electrical faults, such as flashover or short circuits due to insufficient electrical clearances among phase conductors, ground wires, tower members and the earth, due to large amplitude vibration and dramatic forces [1-2]. The influence of ice shedding has been taken into consideration in the Chinese design code and large electric clearance margins have been added for UHV lines. Therefore, it is rare to find faults of the UHV transmission lines induced by ice shedding, due to their large phase-phase distance, phase-ground wire distance and tower size. However, in recent years, with the evolution of the global climate, extremely adverse meteorological events occur more frequently, and winter icing disasters in China show a trend of rapid expansion in both the scope of influence and the degree of damage to the power grid. Typical ice shedding faults of UHV lines have been reported during extreme icing events and their detailed study is needed to further improve the design practice.

This study investigates two typical faults of 1000 kV AC and ±800 kV DC UHV lines. The first one occurred on a double-circuit 1000 kV AC UHV transmission line section in 2019. It was found that there were several discharge points on the middle phase and the upper phase conductor around the midpoint of one span, and ice shedding is taken as the most suspicious cause for the fault. Numerical simulation is employed to calculate the jump heights of conductors to reproduce the faults. The second case occurred on a ±800 kV DC UHV lines in 2021, where the OPGW was broken after an icing event. Detailed investigation showed that short circuits occurred between the OPGW and the conductor in a long span with large elevation difference, for there were obvious melting marks on the strands around the rupture point. Also, numerical simulation indicates that the combined loads of wind and ice shedding are the most likely reason for the fault.

II. FAULT BETWEEN PHASE CONDUCTORS OF 1000 KV AC UHV DOUBLE-CIRCUIT LINES

A. *General information on the line section*

The line section is a double circuit with design ice thickness of 15 mm and wind speed of 30 m/s. The fault occurred between the upper phase conductor (phase C, see Fig. 1) and the middle phase conductor (phase B) after an icing event around noon on February 12, in 2019 (UTC/GMT+08:00); the ambient temperature of about 1.5 ℃ was recorded by a nearby monitoring device. Several discharge points were found around the midpoint of the fourth span, with length of 531 m and elevation difference of 112.6 m, as shown in Table I. It should be noted that the possibility of galloping is excluded, which is a type of large-amplitude and long-duration vibration. Because the line has been successfully reclosed four minutes later after the fault.

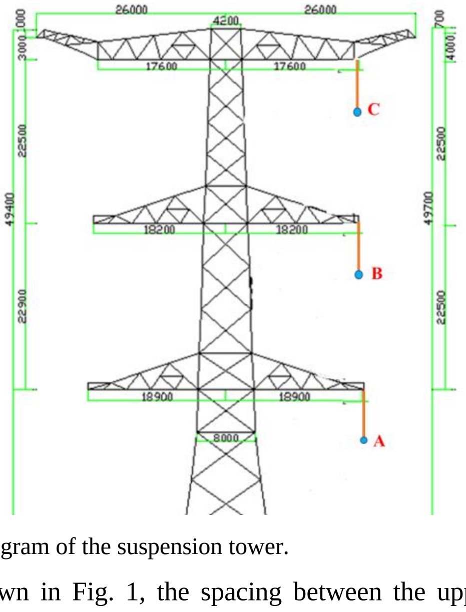


Fig. 1 Diagram of the suspension tower.

As shown in Fig. 1, the spacing between the upper and middle phase layers of the tower is 22.5 m, the spacing between the middle and lower phase layers is 22.9 m, and the height of the ground wire support is 3 m. The horizontal offset of the upper and middle phase conductors is 0.6 m, and the horizontal offset of the middle and lower phase conductors is 0.7 m.

The conductor type is 8 × JL/G1A-630/45 steel core Aluminum strands with the main characteristics listed in Table II. The ground wire type is JLB20A-185 Aluminum clad steel strand. The length of the suspension insulator string is 11.2 m.

TABLE I. SPAN ARRANGEMENT OF THE 1000 KV AC LINE SECTION

No.	Span Length (m)	Elevation Difference (m)
1	224	110.9
2	933	121.4
3	548	96.5
4	531	112.6
5	545	59.6

TABLE II.

CHARACTERISTICS OF CONDUCTORS AND OPGW

	JL/G1A-630/45	JL/G2A-1250/100	OPGW-24B1-155
Diameter (mm)	33.8	47.85	16.6
Area (mm^2)	672.81	1350.03	154.48
Young's Modulus (GPa)	63	65.2	162
Thermal Coefficient (1/°C)	0.9×10^{-6}	20.5×10^{-6}	13×10^{-6}
Rated Tension (kN)	150.45	329.85	182.1
Unit Length Mass (kg/m)	2.079	4.252	1.054

B. *Ice shedding analysis*

The line was initially designed with capability of resisting the assumed ice shedding ratio of 70% (i. e. 70% of the total ice load be removed suddenly) and ice thickness of 15 mm occurring at one span of the middle phase while the ice accretion remained on all spans of the upper phase. The allowed minimum dynamic and static clearances between conductors are 5.6 m and 10.7 m, respectively, for this line according to the Chinese design code [3].

The sudden changing density method, which has been verified by former studies, is employed to simulate the icing state and the ice shedding process [4-5]. A finite element model of the five-span conductor-insulator string was established, where the conductor and insulator are modelled by truss elements.

Varying the ice shedding ratio, wind speed during the ice shedding process, and ice thickness, a total of 12 scenarios were modelled. The minimum dynamic distance and static distance of the two phase-conductors obtained from the simulations are compared in Table III.

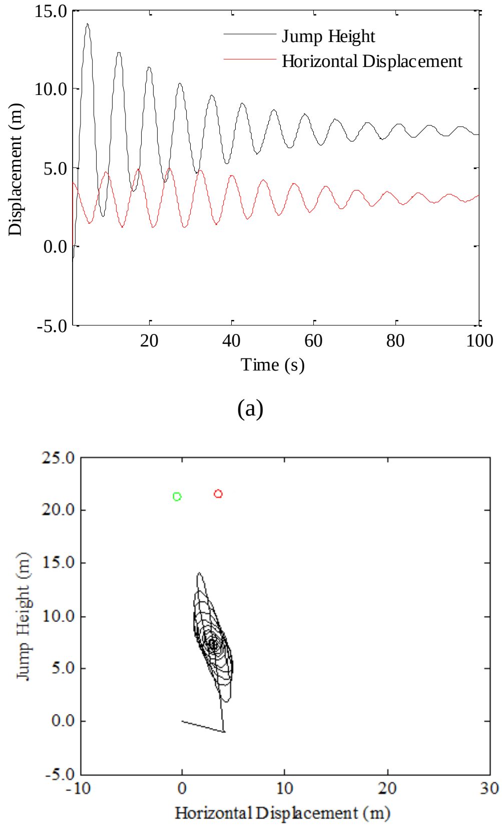
Fig.2 (a) and Fig.3 (a) show the time history of the jump height and horizontal displacement of the midpoint of the middle phase. Fig.2 (b) Fig.3 (b) show the trajectory of the midpoint and its relative position to the upper span, where the green circle is the initial position of the midpoint of the upper phase without wind and the red circle is the new position under wind loads. To be noted, the red mark coincides with the green one when there is no wind as in Fig. 3 (b).

TABLE III.

SIMULATION RESULTS OF DIFFERENT SCENARIOS FOR THE 1000 KV AC LINE

Ice Shedding Ratio (%)	Wind Speed (m/s)	Dynamic Distance (m)		Static Distance (m)	
		I.T.= 15mm	I.T.= 20mm	I.T.= 15mm	I.T.= 20mm
70	0	9.59	6.66	15.32	13.59
	10	9.55	6.81	15.44	13.65
80	0	7.57	**4.17**	14.15	12.10
	10	7.62	**4.69**	14.21	12.20
100	0	**3.50**	**0.60**	11.69	**8.96**
	10	**4.20**	**2.53**	11.78	**9.11**

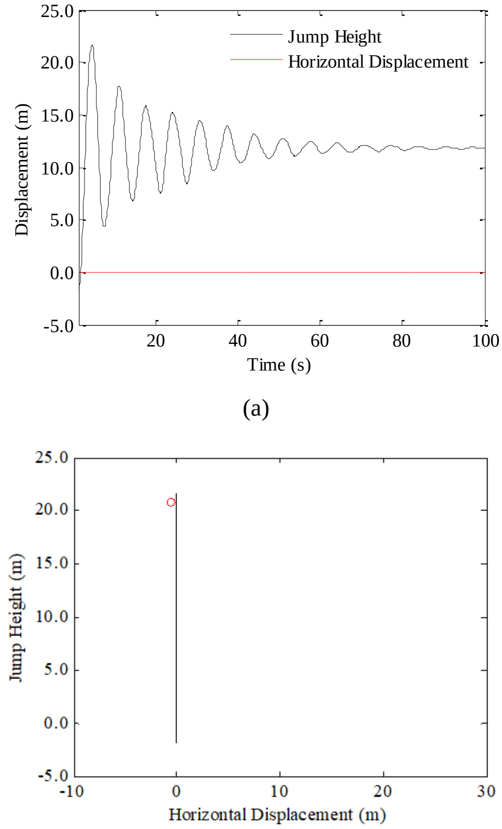
Note: I.T.=Ice Thickness. Values in bold indicate insufficient clearances.



(a)

(b)

Fig. 2 Displacement of midpoint of the ice-shedding span (15 mm, 10 m/s, 80%) (a) Jump height and horizontal displacement, (b) trajectory of the midpoint and its relative position to the upper span



(a)

(b)

Fig. 3 Displacement of midpoint of the ice-shedding span (20 mm, 0 m/s, 100%) (a) Jump height and horizontal displacement, (b) trajectory of the midpoint and its relative position to the upper span

III. 5FAULT BETWEEN PHASE CONDUCTORS AND OPGW OF ±800 KV DC UHV LINE

A. General information on the line section

The line section is 2.081 km long, and the span lengths are 706 m, 663 m, 170 m and 542 m respectively, as listed in Table IV. The conductor type is 6 × JL1-G2A-1250/100, the sub-conductor spacing is 500 mm, the OPGW is OPGW-24B1（ULL）-155; their main characteristics are listed in Table II. The design icing thickness of the conductor is 15 mm, and the design icing thickness of the ground wire and OPGW is 20 mm.

TABLE IV. SPAN ARRANGEMENT OF THE ± 800 KV DC LINE SECTION

No.	Span Length (m)	Elevation Difference (m)
1	706	-26.5
2	663	83.5
3	170	1.7
4	542	-54.8

The fault occurred in the first span (Table IV) between the conductor and the OPGW at 16:00 on February 28, in 2021 (UTC/GMT+08:00) after an icing event and the environmental temperature was about 0℃ as recorded by a nearby monitoring device. According to photographs of the conductor, obvious discharge points can be seen. For the OPGW, four of the 18 strands had obvious stress tensile necking morphology, and the outer surface was smooth without high-temperature burning trace. The other 14 strands had different degrees of high-temperature overheating. Therefore, ice shedding was the most suspicious cause. Discharge occurred when the conductor jumped above towards the OPGW, and 4 strands of the OPGW were burnt at high temperature, resulting in the decrease of its strength, and then large tension caused the breakage of the remaining valid strands. Typical failure modes of the strands are shown in Fig. 4. Noted that the possibility of galloping is also excluded, because the calculation shows that galloping with the same vibration level will loosen the bolts of the towers. The inspection after the fault did not find the hints.

Fig.4 Typical failure modes of the OPGW strands

B. *Ice shedding analysis*

The allowed minimum dynamic and static clearances between conductor and OPGW are 2.5 m and 6.1 m, respectively, for this line according to the design code [6]. The same numerical modelling method is used as in Section 2 for this case study.

By changing the wind speed during the ice shedding process and the ice thickness, 4 scenarios are modelled and the same ice shedding ratio of 100% is assumed. The minimum dynamic distance and static distance between conductor and OPGW are compared in Table V.

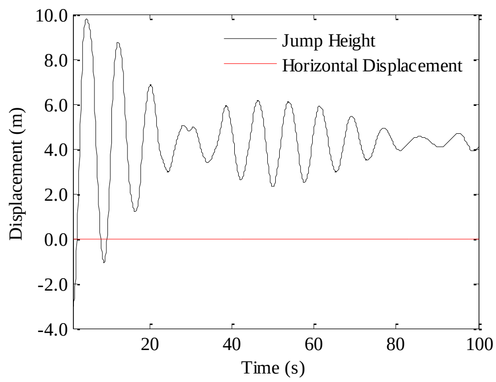
Fig.5 (a) and Fig.6 (a) show simulated time histories of the jump height and horizontal displacement of the midpoint of the conductor. Fig.5 (b) and Fig.6 (b) show the trajectory of the midpoint and its relative position to the OPGW, where the green circle is the initial position of the OPGW midpoint without wind and the red circle is the new position under wind loads. To be noted, the red mark coincides with the green one when there is no wind as shown in Fig. 5 (b).

The horizontal offset between the conductor and the OPGW is 3.2 m at the strain tower and 2.8 m at the suspension tower, both of which are greater than the minimum allowed electrical clearance value of 2.5 m. This means that even when the conductor jumps to the height of the OPGW in still air, discharge cannot happen. However, it is found from Table V and Figs. 5 and 6 that when the ice thickness and the ice shedding ratio exceed the design values, and there is wind acting at the same time, discharge may occur.

When the ice thickness is 17.5 mm, the calculated minimum dynamic clearance is 2.51 m which is close to the allowed value of 2.50 m. Wind load further exacerbates the situation because the horizontal displacements of the OPGW and the conductor are different under the same wind speed. However, in the current design code, the unequal horizontal displacements of the OPGW and the conductor during ice shedding is not considered, which is one of the possible reasons for ice shedding faults. Ice shedding-induced faults observed in transmission lines of other voltage levels also show a similar mode. Thus, in the design of transmission lines with high risk of ice shedding, it is necessary to consider the combined effects of ice and wind and more margin is needed in electrical clearances.

TABLE V. RESULTS OF DIFFERENT SCENARIOS FOR THE 1000 KV AC LINE

Ice Thickness (mm)		Wind Speed (m/s)	Dynamic Distance (m)	Static Distance (m)
Conductor	OPGW			
15	20	0	5.34	10.36
15	20	10	5.09	10.50
17.5	22.5	10	2.51	8.87
20	25	10	0.38	7.16



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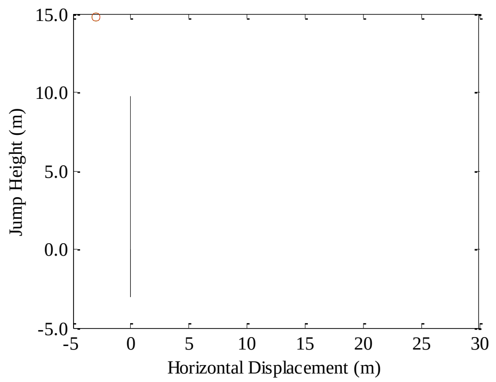
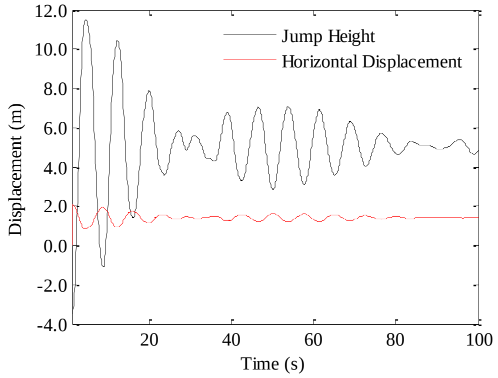
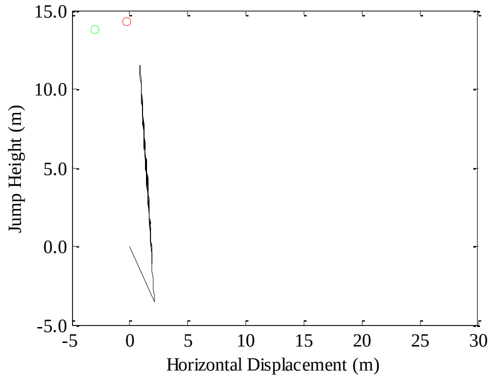


(b)

Fig.5 Displacement of midpoint of the ice shedding span (conductor ice thickness 15 mm, 0 m/s, 100%) (a) Jump height and horizontal displacement, (b) trajectory of the midpoint and its relative position to the OPGW



(a)



(b)

Fig.6 Displacement of midpoint of the ice shedding span (conductor ice thickness 17.5 mm, 10 m/s, 100%) (a) Jump height and horizontal displacement, (b) trajectory of the midpoint and its relative position to the OPGW

IV. CONCLUSIONS

Two different types of typical ice shedding faults of 1000 kV UHV AC and ±800 kV DC lines are investigated by nonlinear finite element analysis in this study. It indicates that ice shedding-induced faults may occur for UHV lines under certain conditions, although large electrical clearances have been considered in the initial design.

The analysis of the tripping fault between two-phase conductors on a double-circuit 1000 kV AC UHV transmission line section shows that a greater ice shedding ratio (above 70% as in current code) needs to be considered in design, especially for the lines prone to rime ice that is easier to shed off than glaze ice. Also, for the double-circuit line, it is not necessary to consider the wind load in ice shedding analysis for phase-to-phase distance design. The fault of a ± 800 kV DC UHV lines was characterized by a ruptured OPGW due to discharge between the conductor and the OPGW during ice shedding. It is found that for the design of vertical and horizontal offset distances between conductor and OPGW or ground wire, the effect of wind load needs to be properly considered. With the combination of wind and ice, the clearance between the conductor and the OPGW is much smaller than for the case with no wind. This study may help to improve the design of UHV and other voltage level lines and ensure the safety of lines in cold regions.

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REFERENCES

[1] G. McClure, Kc. Johns, F. Knoll, G. Pichette, *Lessons From The Ice Storm Of 1998 Improving The Structural Features Of Hydro-Québec's Power Grid*, *10th Int. Workshop on Atmospheric Icing Struc*t., 2002

[2] K. Ji, X. Rui, L. Li, C. Liu, C. Zhou, G. McClure, “The Time-Varying Characteristics of Overhead Electric Transmission Lines Considering the Induced-Ice-Shedding Effect,” *Shock Vib.*, vol. 2015, Article Number 635230, pp. 1-8, 2015.

[3] *Code for design of 1000 kV overhead transmission line*. GB 50665-2011, China Electricity Council, 2011.

[4] M. R. Fekr and G. McClure, “Numerical modelling of the dynamic response of ice-shedding on electrical transmission lines,” *Atmospheric. Res.*, vol. 46, pp. 1–11, 1998.

[5] L. E. Kollar and M. Farzaneh, *Vibration of bundled conductors following ice shedding*, *IEEE Trans. Power Del*, vol. 23, pp. 1097–1104, 2008.

[6] *Code for design of 800 kV DC overhead transmission line*. GB 50790-2013, China Electricity Council, 2013.