

Research on the Test of Transmission Line Galloping

Lichun Zhang^{1, a}, Qing Li^{2, b}, Zhongbin Lv^{2, c}, Kunpeng Ji^{1, d}, Bin Liu^{1, e}

¹China Electric Power Research Institute , beijing,100055,China

²Electric Power Research Institute of State Grid Henan Electric Power Company, Zhengzhou ,450052, China

^aE-mail: bkdzlc@126.com ^bE-mail: muzidl@163.com ^cE-mail: gylzb@qq.com ^dE-mail: jkp@epri.sgcc.com.cn ^eE-mail: liubl@epri.sgcc.com.cn

Abstract. The load of iced transmission line and the load generated by galloping after the conductor are covered by ice all may cause severe circuit faults, such as tripping, conductor breaking, armor clamp damage and even tower collapse, thus severely threatening running safety of power system. The generation and development processes of galloping of power transmission line is very complicated, and numerous factors may influence the galloping excitation, such as environmental factors, terrain factors and structural parameters of power transmission line; in which, the ice covering of conductor is one of necessary factors causing galloping. Therefore, researches on ice covering increasing test of different types of conductors under different meteorological conditions have been conducted in large-sized multi-functional phytotron, thus obtaining the relation curve of ice covering increasing of conductor along with time under different conditions, and analyzing factors influencing increasing of ice covering. The research result shows that under the same ice covering conditions, the increasing of ice covering of conductor with small diameter is relatively rapid; both environmental temperature and wind speed have obvious influence on increasing of ice covering of conductor, and the environmental temperature will decide the type of ice covering of conductor surface. Meanwhile, after wind tunnel tests targeting conductors with different ice covering shapes, pneumatic stability loss characteristics of conductors with different ice shapes have been obtained. Research results have important scientific reference value for revealing the mechanism of galloping of iced power transmission line, and have relatively high engineering practicability value for promoting realization of early warning system for galloping of iced power transmission line.

1.Introduction

The galloping of power transmission line is a kind of vibration phenomenon with low frequency but great amplitude generated by wind excitation after the conductor is covered with ice [1]. The galloping will constitute great threat to power facilities, national life and social economy. Especially, with the rapid development of power grid construction and evolution of climatic conditions, the conductor galloping becomes more and more frequent in our country. In 2008, there was large-area ice disaster in southern China, and iced galloping was a kind of important damage type in the disaster, causing severe faults of power transmission line such as tower collapse [2]. At present, the research on iced galloping of power transmission line is an important and hot research subject in the field of running safety of power transmission line [3-8]. However, the acquisition of galloping data and mechanism of data and evaluation on anti-galloping device of conductors are to be conducted by virtue of test, and the test research is conducted along with the theoretical analysis [9]. This thesis has analyzed the increasing



process of conductor ice covering as well as influence of conductor models and environmental parameters on the increasing of ice covering through conductor ice covering test. Aerodynamic parameters and response data of conductor structure under different ice shapes have been obtained via wind tunnel test. The research result can be used to verify exactness and reliability of galloping theory and numerical analysis model, or can be applied into engineering design as excitation parameter.

2. Iced Conductor Test

Adopt multi-functional phytotron to implement research on AC ice covering tests of different types of conductors, and analyze the influence of conductor models and environmental parameters on the increasing process of ice covering.

2.1 Test Device

Generally, the ice covering increasing test is conducted in a large-sized multi-functional phytotron, with the temperature ranging from -45°C to 50°C (adjustable), and with air pressure ranging from 35kPa to 103kPa (adjustable). The spraying and wind speed regulation system consists of 14 nozzles recommended in the IEC standard and 10 fans with wind speed adjustable; the diameter of fog drop particle ranges from $10\mu\text{m}$ to $120\mu\text{m}$ (adjustable), and the wind speed ranges from 1m/s to 12m/s (adjustable).

The test power supply adopts large-current generator with capacity of 30kVA and maximum output current of 5kA. The current regulation is conducted via changing tap joint or regulating input voltage with voltage regulator. The measurement of environmental parameters adopts PTU 200 type digital comprehensive measuring instrument in temperature, humidity and air pressure produced by Vaisala in Finland. The measuring instrument is characterized by temperature error of $\pm 0.2^{\circ}\text{C}$ and relative humidity error of ± 1 when the environmental temperature is 20°C ; the measurement of fog drop particle adopts the Winner 312 type laser particle analyzer produced by Jinan Winner Particle Instrument Stock Co., Ltd., with testing scope of $4.6\mu\text{m}$ - $323\mu\text{m}$ and testing error of <3 ; the wind speed measurement adopts wind speed sensor, with testing scope of 0m/s - 30 m/s and testing error of <1 .

2.2 Test Conditions

The test selects 3 different types of conductors (LGJ-240, LGJ-300 and LGJ-400) (1 piece for each type) which are 5m and 20m in length as test specimen.

Layout of specimen: place conductors with length of 20m horizontally in a surrounding way, and then fix them on the test stand. Next, input current as appropriate. During the test, only the ice recovering result of the intermediate 5m is adopted as analysis object, so as to prevent the conductor end from heating due to contacting resistor, thus influencing the test result. Meanwhile, adopt another piece of conductor of the same model, and fix it on the test stand of the same vertical plane without electrifying, and make ice covering conditions of two pieces of conductors same completely.

2.3 Ice Covering Process

Start up the current generator as per test demand, thus inputting current into the conductor to preset AC current value. Reduce the temperature in the phytotron to the preset ice covering temperature. Start up wind speed regulation system to make the wind speed reach the preset value, and start up and regulate the fog system to make the size of fog drop particles reach preset value, and then conduct ice covering to specimen and timing. The conductivity of supercooling water adopted during the ice covering of specimen refers to $80\mu\text{S}/\text{cm}$, with the temperature controlled at about 4°C . The spraying system which is used to spray fog to form ice covering conditions is 2.8m away from the specimen, and the value of sprayed fog particle is about $80\mu\text{m}$ - $120\mu\text{m}$, with the volume flow of sprayed fog about 80 L/h. See Figure 2-1 for typical ice covering shapes of galloping of the power transmission line.

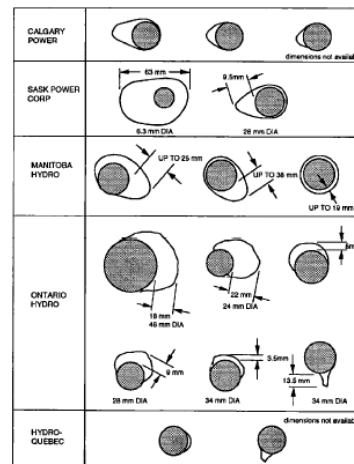


Figure 2-1 Different Ice Covering Shapes

3.Result and Analysis on Test of Icing

3.1Influence of Conductor Model on Icing Increasing

In this thesis, the research on contrast test is conducted targeting increasing processes of ice covering of different types of conductors. For example, input current of 150A, make environmental parameters of ice covering test as below: wind speed: 5m/s, temperature: -6°C, liquid water density: 80g/m³, and median volume diameter (MVD) of water drop particle: 120 μm, and then see Figure 3-1 for test result.

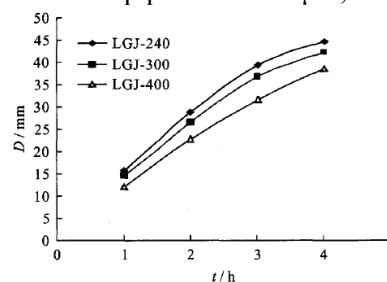


Figure 3-1 Relationship between Ice Covering Increasing and Time of Different Types of Conductors
Form Figure 3-1, it can be known that:

(1) For the 3 types of conductors in the test, with the increasing of ice covering time, the ice covering on the surface of conductor will also increase; in addition, the relationship between the increasing of ice covering on the surface of conductor and the time is non-linear.

(2) Under the same ice covering environment, with regard to different types of conductors, their relationships between the ice covering thickness and the time are different; moreover, the smaller the conductor diameter is, the faster the increasing of ice covering thickness will be. For example, in 2h of ice covering, the thicknesses of LGJ-240, LGJ-300 and LGJ-400 are 28.7mm, 26.4mm and 22.6mm respectively. The reason is that the larger the conductor diameter is, the greater the sectional area of the conductor's windward side will be. Analyzing from the perspective of fluid mechanics, the viscous force of air flow makes the small water drop's component in the direction of vertical incoming flow of acceleration deviating from the conductor increase, and then the deviation motion distance will increase. Therefore, the collision efficiency of small water drops to conductors reduces, i.e. the reduction of probability of conductor capturing water drops causes relatively less ice covering.

(3) With the increasing of ice covering time, the difference in ice covering thickness of different types of conductors is gradually reduced. For example, in 1h of ice covering, the ice covering thicknesses of LGJ-240 and LGJ-400 conductors are 15.6mm and 11.8mm respectively, and the different between two of them is 32.2mm; in 4h of ice covering; the ice covering thicknesses of LGJ-

240 and LGJ-400 conductors are 44.6mm and 38.4mm respectively, and the different between two of them is 16.1mm. The reason is that the increasing of ice covering thickness of conductor with relatively small diameter is relatively rapid, so the overall external diameter of conductor and ice layer is expanded rapidly; however, the increasing of ice covering thickness of conductor with relatively large diameter is relatively slow, so the overall external diameter of conductor and ice layer is expanded slowly. Therefore, it can be speculated that the difference value among diameters of the 3 types of iced conductors will be smaller and smaller when time goes by.

3.2 Influence of Environmental Parameters on Icing Increasing

The ice covering of conductor is a kind of comprehensive physical phenomenon decided by temperature, humidity, cross-ventilation and circulation of cool and warm air, wind and other factors. The research shows that main factors influencing the ice covering of conductor are temperature, wind speed and liquid water content, while the influence of median volume diameter of water drop particle on ice covering is not obvious. This thesis researches the increasing process of ice covering of conductor based on the severest conditions, i.e. the environmental humidity of the test refers to saturated water status. Therefore, this thesis will mainly discuss the influence of temperature and wind speed on the ice covering of conductor.

(1) Influence of wind speed on increasing of ice covering of conductor

In this thesis, the research on contrast test is conducted targeting increasing processes of ice covering of different types of conductors. Take the LGJ-300 type conductor for example, input current of 300A, make environmental parameters of ice covering test as below: temperature: -5°C , liquid water density: 93g/m^3 , and median volume diameter (MVD) of water drop particle: $112\text{ }\mu\text{m}$, and then see Figure 3-2 for test result.

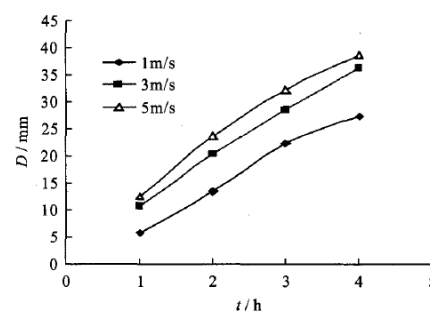


Figure 3-2 Relationship between Ice Covering Increasing and Time of Conductors at Different Wind Speeds

From Figure 3-2, it can be known that: within the same ice covering time, the greater the wind speed is ($<5\text{m/s}$), the thicker the ice covering on the surface of conductor will be. In 4h of ice covering, and when the wind speeds are 1m/s, 3m/s and 5m/s, ice covering thicknesses on the surface of conductors are 27.3mm, 36.2mm and 38.6mm respectively. The reason is that the greater the wind speed is, the more the gas streamline of water drop particle deviation will be, and then the collision with conductors will occur more easily; the limit region of conductor surface collided by water drop will be larger; the overall water drop collision coefficient on the surface of conductor and the local water drop collision coefficient will be increased due to the increasing of water drop collision amount on the same surface, that means the quantity of water drops which can be captured and frozen colliding conductors within unit time period will be more. Meanwhile, the greater the wind speed is, the heat lost on the surface of conductor will be more during the process of accelerating cross-ventilation and heat exchange of water drop particles; which is more in favor of freezing of water drop particles and accelerating the increasing of ice covering.

(2) Influence of temperature on increasing of ice covering of conductor

In this thesis, the research on contrast test is conducted targeting increasing processes of ice covering of conductors at different temperatures. Take the LGJ-300 type conductor for example, input

current of 300A, make environmental parameters of ice covering test as below: wind speed: 5m/s, liquid water density: 93g/m³, and median volume diameter (MVD) of water drop particle: 112μm, and then see Figure 3-3 for test result.

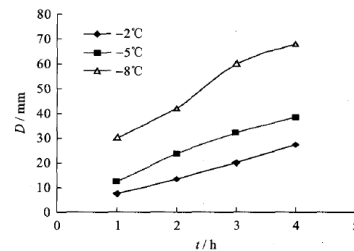


Figure 3-3 Relationship between Ice Covering Increasing and Time of Conductors at Different Temperatures

From Figure 3-3, it can be known that: the environmental temperature has influence on the increasing process of ice covering of conductor. In addition, within the same ice covering time period, the lower the temperature is (0°C to -8°C), the thicker the ice covering on the surface of conductor will be. In 4h of ice covering, thicknesses of the conductor surface at the temperatures of -2°C, -5°C and -8°C are 27.2mm, 38.6mm and 68.2mm respectively. The reason is that in the wet increasing environment, water drop particles will move from bottom to top, accompanied with the process of exchanging energy with the environment. The lower the environmental temperature is, the faster the cooling speed of water drop particles will be, and then water drop particles will freeze more easily when they move downwards from the surface of conductor.

In addition, from the test result, it can be known that the environmental temperature has influence on the forming type of ice covering. When the wind speed is 5m/s and the environmental temperature of ice covering is -5°C, there will be semitransparent ice with color of milk on the surface of conductor. After measurement, it can be known that the ice covering densities at -5°C and -8°C are 0.87g/cm³ and 0.74g/cm³ respectively, i.e. when the temperature is <-5°C, the ice covering type on the surface of conductor refers to rime; when the temperature is -8°C, the ice covering type on the surface of conductor is hard rime.

4. Test of Pneumatic Characteristics of Iced Conductor

4.1 Test Device and Specimen

The test is conducted in the wind tunnel laboratory, and pneumatic characteristics of single conductor, 2-bundled conductor, 4-bundled conductor and 6-bundled conductor are tested respectively. Figure 4-1 refers to model devices of 2-bundle and 6-bundled conductors in the wind tunnel test.



(a) 2-bundled Conductor Model (b) 6-bundled Conductor Model

Figure 4-1 Pictures of Bundled Conductor Test

To measure the overall pneumatic force of bundled conductor, it is necessary to adopt a bottom end plate to connect bundled conductor, and during the test, it is necessary to eliminate the influence of pneumatic force of connection plate itself on pneumatic force of bundled conductor. The upper end plate refers to a wooden plate with diameter of 120cm and thickness of 1cm, and the distance between

end plate and model shall be small to the greatest extent, which is below 2mm generally. The 2-bundled and 4-bundled conductors are connected with square aluminum alloy connection plate with bottom edge length of 550mm, and the 6-bundled conductor is connected with regular hexagon aluminum alloy plate with bottom edge length of 500mm, and the connection plate is connected with high-frequency force measuring balance via transfer device. There is a piece of guide plate with thickness of 1cm at the guide plate of the connection plate, and the upper part of connection plate is level with the guide plate. There is a very small gap between the connection plate and the guide plate, and when the model changes its wind direction angle, the connection plate will rotate together, while the lower guide plate will not move. To guarantee the rigidity of lower end plate and convenience of model installation, the surrounding of the lower guide plate shall adopt adjustable support screws with equal angle interval. To eliminate the boundary layer effect of wind tunnel, it is required to place a support with height of 28cm between the high-frequency balance and the rotary table; the upper end of the support shall be connected with the high-frequency balance in a rigid way, and the lower part shall be connected with the rotary table in a rigid way.

4.2 Characteristics of Pneumatic Stability Failure of Conductors with Different Ice Covering Shapes

For the interval rod constrains the relative motion among all sub-conductors of bundled conductor, the iced bundled conductor can be regarded as overall galloping generally, so compared with pneumatic force characteristics of all sub-conductors, overall pneumatic force characteristics of iced bundled conductor are more meaningful for the research on galloping. In addition, for the overall torsion frequency of bundled conductor is greatly reduced compared with single conductor, and the frequency is close to the translation frequency, so the Nigol tensional galloping may occur easily. In this case, the characteristics of overall pneumatic torque will be very important. Therefore, in this thesis, characteristics of pneumatic force related to bundled conductor are targeting overall pneumatic force. To be convenient for being compared with pneumatic force coefficient of single conductor, the overall resistance, lift coefficient and torsion coefficient of bundled conductor under the airflow shaft are defined as below:

$$C_D^N(t) = \frac{1}{N} \frac{F_D(t)}{0.5\rho U^2 DH}, \quad C_L^N(t) = \frac{1}{N} \frac{F_L(t)}{0.5\rho U^2 DH}, \quad C_M^N(t) = \frac{1}{N} \frac{M(t)}{0.5\rho U^2 DBH} \quad (4-1)$$

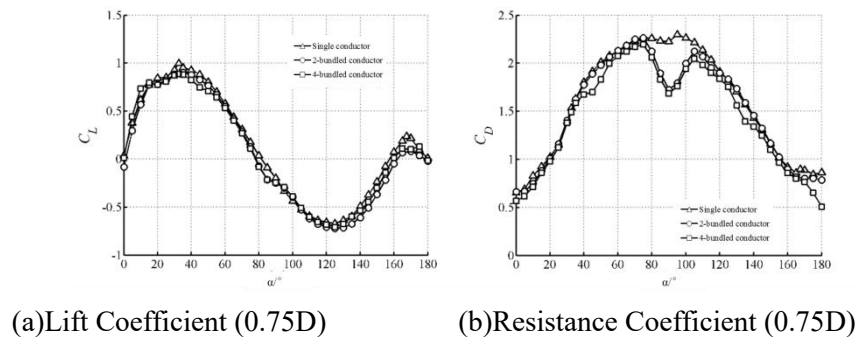
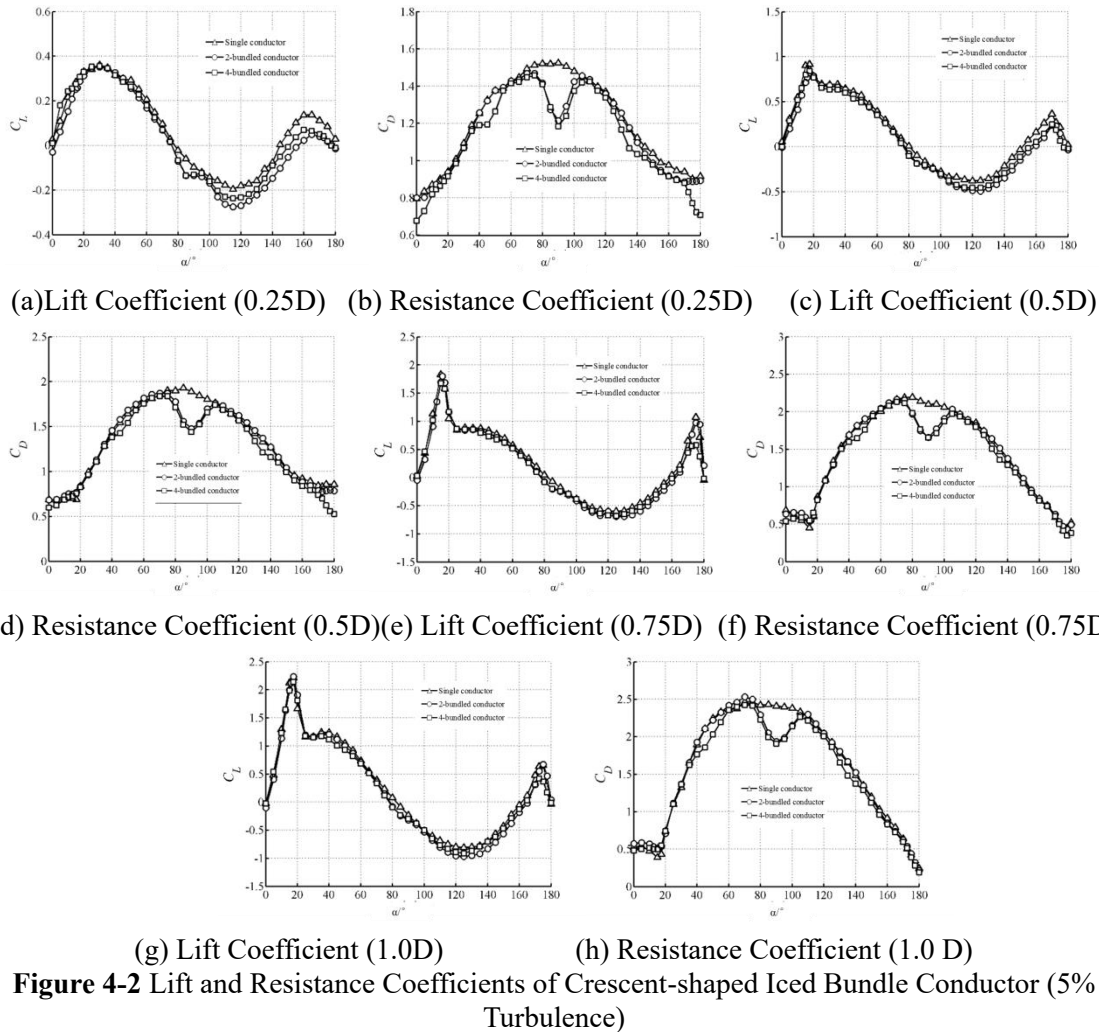
$$C_D^N(t) = \frac{1}{N} \frac{F_D(t)}{0.5\rho U^2 DH}, \quad C_L^N(t) = \frac{1}{N} \frac{F_L(t)}{0.5\rho U^2 DH}, \quad C_M^N(t) = \frac{1}{N} \frac{M(t)}{0.5\rho U^2 DBH} \quad (4-2)$$

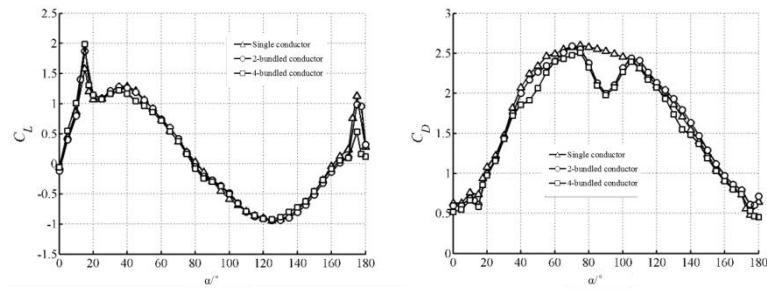
In which, $C_D^N(t)$, $C_L^N(t)$ and $C_M^N(t)$ refer to overall resistance coefficient, lift coefficient and torsion coefficient of bundled conductor respectively, N refers to quantity of bundled sub-conductors, and N=2, 4 and 6; B refers to the distance from center of bundled conductor to the rotating center; for 2-bundled conductor, B=224mm; for 4-bundled conductor, B=318mm; and for 6-bundled conductor, B=375mm. Hereby, to be compared with single conductor, we adopt B=D=26.8mm uniformly. $F_D(t)$, $F_L(t)$ and $M(t)$ refer to overall pneumatic resistance, lift and pneumatic torque of bundled conductor respectively.

4.2.1 Characteristics of Pneumatic Force of Crescent-shaped Iced Conductor

Figure 4-2 and Figure 4-4 give the change diagram of resistance and lift coefficient curve of crescent-shaped iced bundled conductor along with angle of attack. It can be known that the lift coefficient of crescent-shaped single conductor is basically consistent with the overall lift coefficient of 2-bundled and 4-bundled conductors. Two peaks are within 15°-20° and 170°-175° respectively. The resistance coefficient of bundled conductor is different from that of single conductor. The overall resistance coefficient curve of bundled conductor shows the shape of “M”, and the peak values appear nearby angles of attack of 70°, 90° and 110°. Especially nearby the angle attack of 90°, the overall resistance coefficient of bundled conductor has the largest reduction, and this may be related to the fact that the

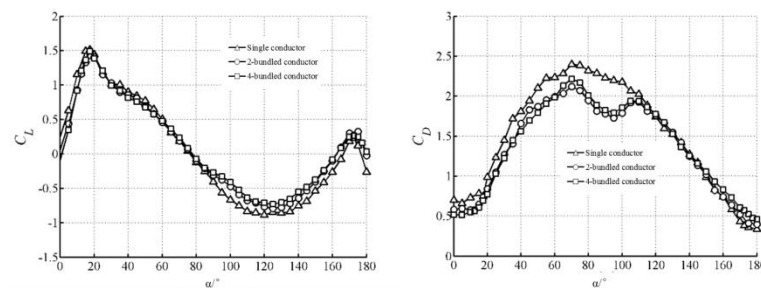
actual windward area of upper flow sub-conductor is the largest and the wake effect of lower flow sub-conductor is the most obvious at the angle of attack of 90° .





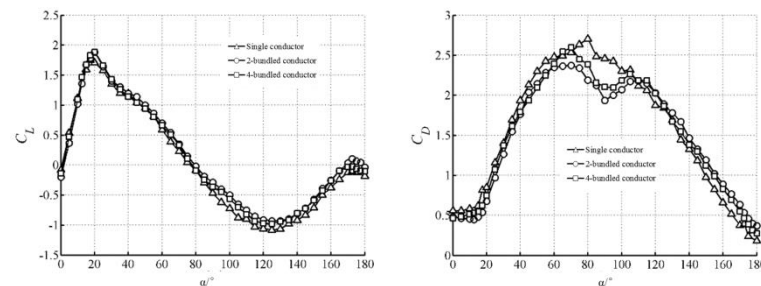
(c) Lift Coefficient (1.0D)

(d) Resistance Coefficient (1.0D)

Figure 4-3 Lift and Resistance Coefficients of Crescent-shaped Iced Bundle Conductor (Uniform Flow)

(a) Lift Coefficient (0.75D)

(b) Resistance Coefficient (0.75D)



(c) Lift Coefficient (1.0D)

(d) Resistance Coefficient (1.0D)

Figure 4-4 Lift and Resistance Coefficients of Crescent-shaped Iced Bundle Conductor (13% Turbulence)

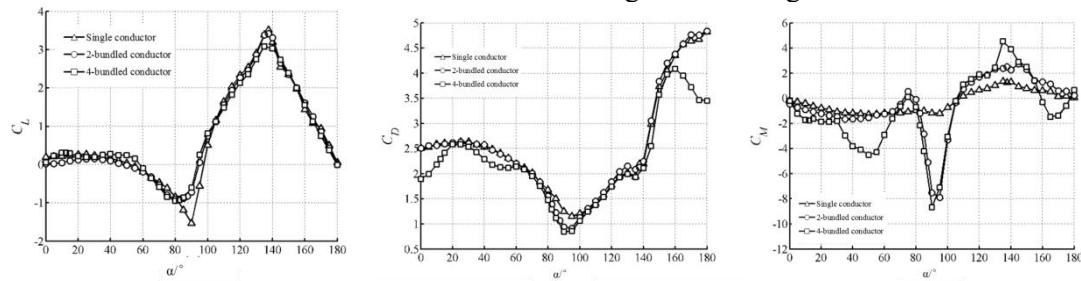
It can be known that the lift coefficient of crescent-shaped single conductor is basically consistent with the overall lift coefficient of 2-bundled and 4-bundled conductors. Two peaks are within 15° - 20° and 170° - 175° respectively. The Figure shows that the resistance coefficient of bundled conductor is different from that of single conductor. The overall resistance coefficient curve of bundled conductor shows the shape of “M”, and the peak values appear nearby angles of attack of 70° , 90° and 110° . Especially nearby the angle attack of 90° , the overall resistance coefficient of bundled conductor has the largest reduction, and this may be related to the fact that the actual windward area of upper flow sub-conductor is the largest and the wake effect of lower flow sub-conductor is the most obvious at the angle of attack of 90° .

4.2.2 Characteristics of Pneumatic Force of D-shaped Iced Bundled Conductor

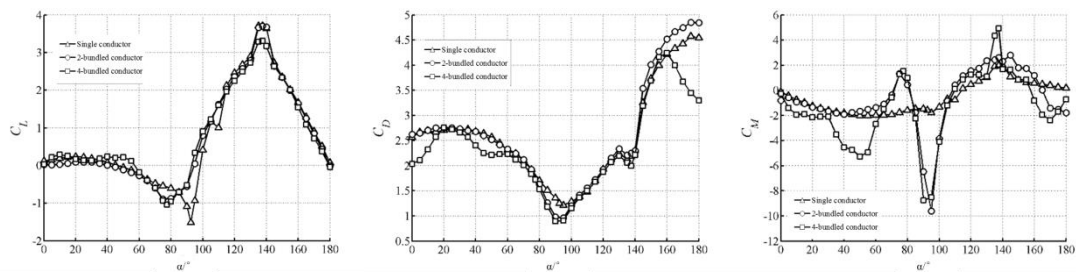
See Figure 4-5 to Figure 4-7 for the pneumatic three-component coefficient of D-shaped iced bundled conductor under 3 kinds of turbulence. From the Figure, it can be known that, with regard to standard D-shaped ice covering, except the angle of attack of 90° , the lift coefficient of bundled conductor has no large difference compared with that of single conductor. Compared with single conductor, the resistance coefficient of bundled conductor, especially 4-bundled conductor, have relatively large

reduction nearby angles of attack of 0° , 45° , 90° and 180° due to the wake current disturbance and the change of actual windward area. Compared with single conductor, the overall torsion coefficient of bundled conductor is greatly different due to contributions of lift and resistance of sub-conductors; especially nearby the angle of attack of 90° , the torsion coefficient is the largest.

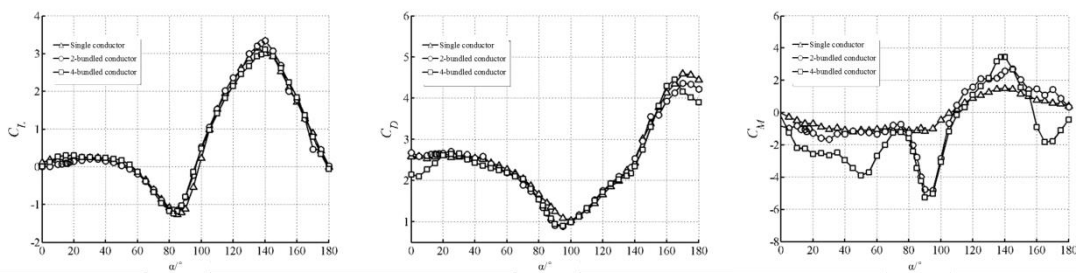
However, with regard to 6-bundled conductor, due to the disturbance of wake flow, there is a large difference in pneumatic force between single conductor and bundled conductor, and the contrast between JD-6 model and JD-1 model is as shown from Figure 4-8 to Figure 4-10.



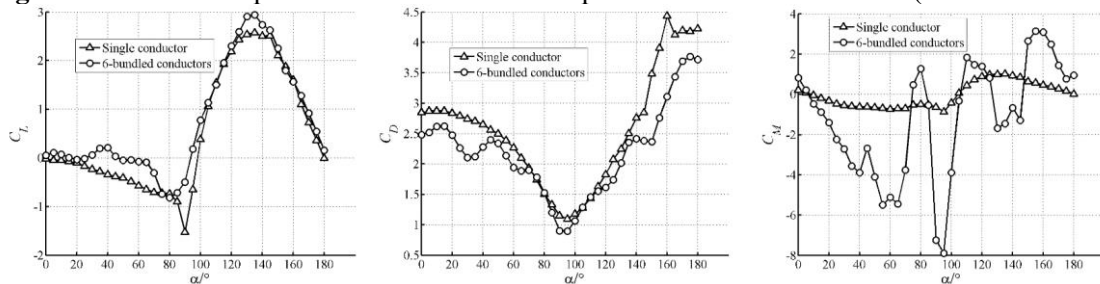
(a) Lift Coefficient (b) Resistance Coefficient (c) Torsion Coefficient
Figure 4-5 Three-component Coefficient of D-shaped Iced Bundle Conductor (5% Turbulence)



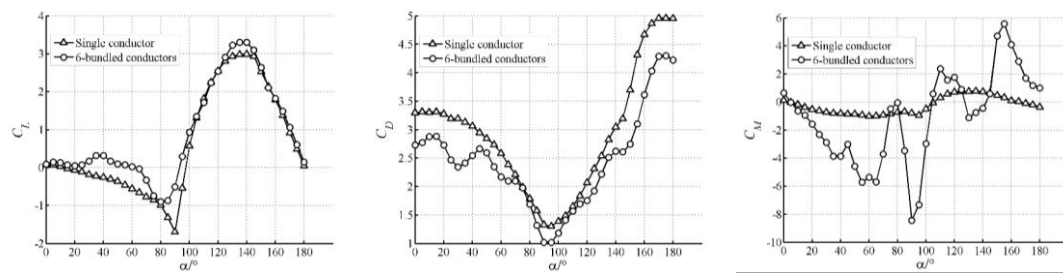
(a) Lift Coefficient (b) Resistance Coefficient (c) Torsion Coefficient
Figure 4-6 Three-component Coefficient of D-shaped Iced Bundle Conductor (Uniform Flow)



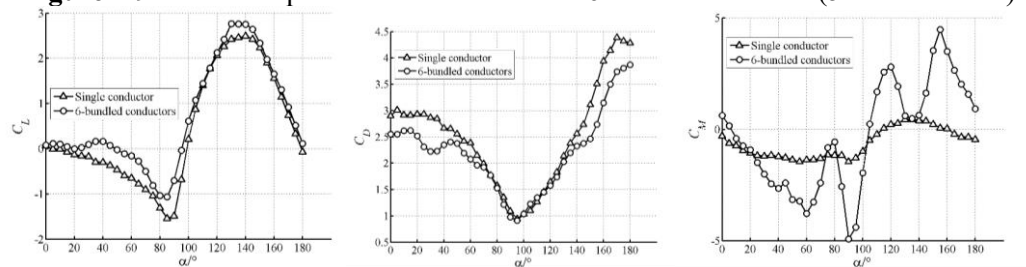
(a) Lift Coefficient (b) Resistance Coefficient (c) Torsion Coefficient
Figure 4-7 Three-component Coefficient of D-shaped Iced Bundle Conductor (13% Turbulence)



(a) Lift Coefficient (b) Resistance Coefficient (c) Torsion Coefficient
Figure 4-8 Three-component Coefficient of JD-6 and JD-1 Models (Uniform Flow)



(a) Lift Coefficient (b) Resistance Coefficient (c) Torsion Coefficient
Figure 4-9 Three-component Coefficient of JD-6 and JD-1 Models (5% Turbulence)



(a) Lift Coefficient (b) Resistance Coefficient (c) Torsion Coefficient
Figure 4-10 Three-component Coefficient of JD-6 and JD-1 Models (13% Turbulence)

5. Conclusion

Through above researches, we can obtain the following conclusions:

- 1) Under any ice covering environmental parameter, the thickness increasing of ice covering on the surface of conductor shows non-linear relationship with ice covering time;
- 2) Under the same ice covering environment, there is difference in relationship between the thickness of ice covering and the time among different types of conductors, and the smaller the diameter of conductor is, the faster the increasing of ice covering thickness will be.
- 3) Both temperature and wind speed have influence on the increasing of ice covering on the surface of conductor; within the same ice covering time, the greater the wind speed is (in case of <5m/s) and the lower the temperature is (0 to -8°C), the thicker the ice covering on the surface of conductor will be.
- 4) The overall lift coefficient of bundled conductor is basically consistent with that of single conductor along with the change curve of angle of attack. If there is lack of lift coefficient data of bundled conductor, it is allowed to adopt lift coefficient curve of single conductor to forecast the overall lift coefficient curve of bundled conductor.
- 5) The overall resistance coefficient curve of crescent-shaped iced bundled conductor shows the shape of "M". Compared with single conductor, the overall resistance of 2-bundled conductor has the largest reduction nearby the angle of attack of 90°. The 4-bundled conductor has relatively large reduction nearby the angles of attack of 45°, 90° and 145°.
- 6) Compared with single conductor and with regard to the resistance coefficient of D-shaped iced bundled conductor, only the 2-bundled conductor has slightly reduction nearby the angle of attack of 90°, while there are multiple places of fluctuation for 4-bundled and 6-bundled conductors, which have relatively great reduction nearby angles of attack of 0°, 45°, 90° and 180°.
- 7) There is a large difference between the overall torsion of bundled conductor and that of single conductor. This is related to the contributions of lift and resistance coefficients of all sub-conductors of bundled conductor to the overall pneumatic torque. Therefore, it is difficult to forecast the overall torsion coefficient of bundled conductor only by virtue of torsion coefficient of single conductor itself.

Acknowledgments

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References

- [1] State of the art of conductor galloping. CIGRE Task Force B2.11.06, 2007
- [2] ZHANG Lichun, ZHU Kuanjun. Research on the Law of Disaster Caused by Transmission Line Galloping[J]. Power System and Clean Energy. 2012, 28(9):13-17.
- [3] CIGRE.. Guidelines for Field Measurement of Ice Loadings on Overhead Power Line Conductors. TB (Technical Brochure) 179. TF 22.06.01 August. Convenor S.M. Fikke, 2000a.
- [4] Wang Shaohua, Jiang Xingliang, et al. Study Status of Conductor Galloping on Transmission Line[J]. High Voltage Engineering. 2005, 31(10):11-14.
- [5] Li Junhui, Cheng Yongfeng, et al. Improvement and Application on the Meteorological Geographical Method in the Drawing of Galloping Region Distribution Map[J]. Electric Power. 2010, 34(3):210-215.
- [6] Zhu Kuanjun, Liu Chaoqun et al. Analysis on dynamic tension of conductor under transmission line galloping [J]. Electric Power. 2005, 38(10):40-44.
- [7] Li Junhui, Wang Tao et al. Rendering Method of Galloping Distribution Map Based on Meteorological-Geographical Method[J]. Electric Power construction. 2014, 35(7):97-103.
- [8] Novak, M., A. Davenport and H. Tanaka. 1978. "Vibration of towers due to galloping of iced cables," ASCE Journal of the Engineering Mechanics Division, 104, pp. 457-473.