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SIMULATION ANALYSIS OF BUNDLED CONDUCTORS AND SPACER-DAMPERS IN A TYPICAL 500kV TRANSMISSION LINE DURING DC ICE-MELTING

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Abstract: In order to reduce the danger of a high current, a conglutination phenomenon on a typical bundled transmission lines during DC ice-melting was investigated in this paper. Simulation models on four bundled LGJ-4×400/35 conductors and square 450mm×450mm spacer-dampers in a typical 500kV transmission line were presented by the three-dimension finite element method (FEM). Magnetic field distributions of the four bundled conductors and the square frame type spacer-dampers with a 10mm icing thickness, a -5℃ weather temperature, a 5m/s wind speed, and with different values of DC deicing current was investigated via ANSYS. At the same time, the force of bundled conductors and deformation of the subconductors were calculated. The rule of the electromagnetic field distribution and the form-finding analysis' results were given in this paper. Finally, the phenomenon of bundle pinch came out obviously when the range of the DC ice-melting current is from 3000A to 4000A.

INTRODUCTION

At the beginning of the years of 2008 and 2011, a large number of transmission lines were covered with ice in an extensive area of Guizhou Province, China. According to the monitoring system of China Southern Power Grid (CSPG), barely in Guizhou, in the early of January, 2011, the aggregate amount of icing lines was up to 251, including a number of 500kV Transmission lines, which resulted in enormous loss. A test carried on a specific icing thickness shows that the higher DC deicing current is, the shorter deicing time will be at the same temperature and wind speed. However, as the deicing current increases, electromagnetic forces of the transmission lines and subconductors grow step by step. The large electromagnetic forces lead the subcondctors of the bundle to pinch together, sometimes with sufficient severity to cause conglutination in bundled conductors.

1. RESULTS AND DISCUSSION

SOLID96 unit, INFANT47 unit, SOURCE36 unit are selected to simulate the spacer and subconductor, air, the current excitation respectively.

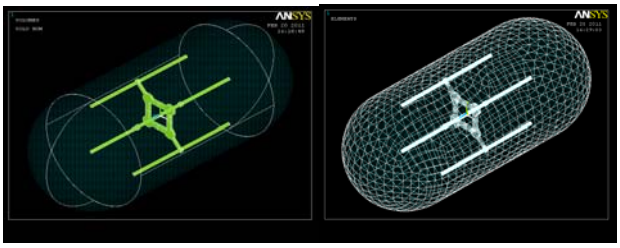


Fig.3 The 3D model and meshed grid of the four bundled conductors and spacer

Take full advantage of the symmetry of the structure of the overhead bundled transmission lines.

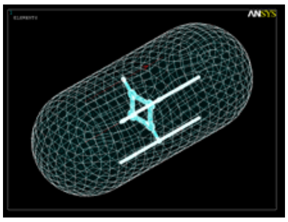
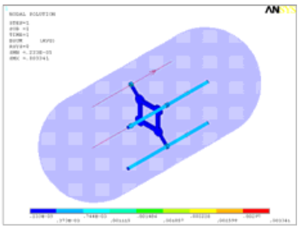


Fig.4 The model loaded with deicing current

Load the finite element model with different values of current. (1000A/2000A/3000A/4000A)



Fi.5 The magnetic field distribution of subconductor 1 and the spacer is calculated (4000A)

Link10 unit is selected to simulate Subconductor 1.

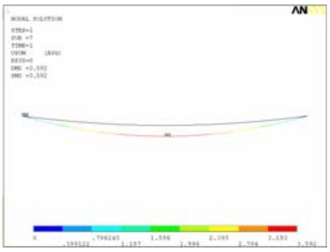


Fig.8 The vertical displacement of ice-coated subconductor 1 (4000A&Height of 5 times magnification)

The phenomenon of bundle pinch came out obviously when the range of the DC ice-melting current is from 3000A to 4000A.

3. CONCLUSION

The phenomenon of bundle pinch came out obviously when the range of the DC ice-melting current is from 3000A to 4000A.

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Simulation Analysis of Bundled Conductors and spacer-dampers in a Typical 500kV Transmission Line during DC Ice-melting

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Keywords-*500kV transmission line; ice-melting; four bundled conductors; damping spacer; finite element method*

Ⅰ. INTRODUCTION

At the beginning of the years of 2008 and 2011, a large number of transmission lines were covered with ice in an extensive area of Guizhou Province, China. According to the monitoring system of China Southern Power Grid (CSPG), barely in Guizhou, in the early of January, 2011, the aggregate amount of icing lines was up to 251, including a number of 500kV Transmission lines, which resulted in enormous loss. For the purpose of relieving the impact of icing, the electricity sector adopts a variety of measures to prevent the lines from icing and urge the ice to melt. For now, the DC short-circuit ice-melting technology is feasible and economic in deicing, which requires a low power capacity when working, especially in the case of 500 kV transmission lines [1],[2]. A test carried on a specific icing thickness shows that the higher DC deicing current is, the shorter deicing time will be at the same temperature and wind speed. However, as the deicing current increases, electromagnetic forces of the transmission lines and subconductors grow step by step [3]-[5]. The large electromagnetic forces which arise lead the subconductors of the bundle to pinch together, sometimes with sufficient severity to cause conglutination in bundled conductors. What is worse, clash phenomenon occurs when subconductors adhere each other seriously, bringing out accidents to the conductors, such as surface attrition, broken strands, even line-disconnection. In addition, noise and heating will come into being at the contact of conductor surfaces, contributing to the loss of energy and decline of electric power.

In this paper, a conglutination phenomenon on a typical bundled transmission lines during DC ice-melting is investigated. Simulation models on four bundled LGJ-4×400/35 conductors and square 450mm×450mm spacer-dampers in typical 500kV transmission lines are presented by the three-dimension finite element method. Magnetic field distributions of the four bundled conductors and the square frame type spacer-dampers at the circumstance of 10mm icing thickness,-5℃ weather temperature, 5m/s wind speed, and different values of DC deicing current is investigated via ANSYS. At the same time, electromagnetic force is calculated responding to the transmission line. At the help of the catenary model built by form-finding analysis, deformation and stress of the transmission lines affected by icing and electromagnetic forces are calculated and analyzed. Then, the result shows that the phenomenon of bundle pinch came out obviously when the range of the DC ice-melting current is from 3000A to 4000A.

Ⅱ. CONGLUTINATION PHENOMENON

The short-circuit current is shared by the individual conductors in the conductor bundle. The current in each subconductor will thus be of the same value that is one quarter of the DC ice-melting current and the current is in the same direction. An attractive force is experienced by four parallel conductors, if the current flows in the same direction. The individual conductors are thus drawn toward one another and may impact with considerable electromagnetic force, which is given by the flollowing formula [6].

$$F = \frac{\mu_0}{2\pi} \cdot \frac{I_1 I_2}{d} \cdot L \qquad (1)$$

Where μ_0 is permeability constant, which equals $4\pi\times10^{-7}$ (H/m), L is the length of the wire, d is the spacing between wire 1 and wire 2, I_1 and I_2 are the current in wires 1 and 2 respectively. The electromagnetic forces experienced in the four bundled conductors are as shown in Figure 1.

The other subconductors apply electromagnetic forces on subconductor 1, and the relation among the forces is as the equations following show: $f_1=f_2=1.414f_3$. As the ice-melting current increases, the electromagnetic forces increase naturally. Then the spacing between subconductors reduces, which strengthens the electromagnetic force again. As the circle runs, the phenomenon of bundle pinch appears finally. Hence, the electromagnetic force, ice-melting current and spacers make interaction with each other. When the deicing appliance is in operation, bundle pinch results, not only in an obviously increase in the tension of the conductors, but also in huge compressive forces on the spacer dampers, which connect the conductors in a bundle to one another [1]. The individual strands of the conductor are also likely to be severely and permanently damaged [7], [8].

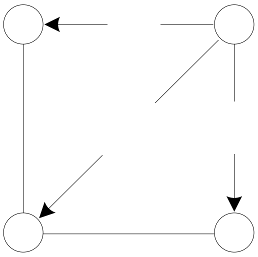


Fig.1 Forces imposed on one particular conductor

Ⅲ. CONSTRUCTING A SUITABLE FINITE ELEMENT MODEL

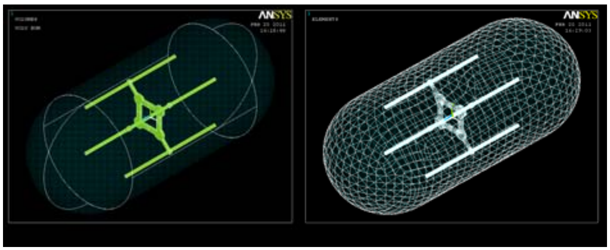
Simulation models on a 500kV transmission line of China Southern Power Grid were presented by the three-dimension finite element method (FEM). The common four bundled conductors and the ice-coated Conductors are shown in Figure 2.

(a)

(b)

Fig. 2 (a) The common four bundled conductors and spacer (b) the ice-coated conductors and spacer

This paper assumes that the type of bundled conductors is LGJ-4×400/35, and the size of the square-type spacer damper is 450mm×450mm. The spacer damper owns two kinds of connection, involving rigid connection and rotary connection with degrees of freedom which can be relaxed to reverse [9]. And the rigid connection is discussed in this paper. According to the material characteristics, SOLID96 unit is adopted both in the simulations of the spacer and conductors [10]. With regard to the unit area in outer layer, the air unit employs INFANT47 unit, which can obtain particular description of the far field attenuation of the magnetic field and the simulation result is more accurate than that gained by the way of using a vertical or parallel line [10]. Afterwards, the 3D model and meshed grid of the four bundled conductors and spacer are built, as are shown in Figure 3. As far as to the loading, there is no other way to define the current excitation except for SOURCE36 unit, with which a current flow area is built without any requirements of material property parameters to describe the shape and location of the current source [10]. The data of this source and others can be aware via the real constant definitions of SOURCE36 unit.



(a) (b)

Fig.3 (a) The 3D model and (b) meshed grid of the four bundled conductors and spacer

The main geometrical parameters and physical parameters occur in the analysis of magnetic field and dynamics are listed below. Distance between subconductors d is 0.45m. The relative magnetic permeability coefficient of conductors and air are 1.5 and 1 respectively. The length of subconductor 1 l is 50 m. The sectional area of the single subconductor A_0 is 425.24mm^2. The weight per unit length on a specific conductor q_1 is 13.22N/m. The icing thickness is 10 mm and the weight per unit length of the covering ice q_2 is 11.08N/m. The initial stress H is 24.68kN. The relative altitude is 0 m, and the modulus of elasticity E is 65Gpa. The DC deicing current loaded on the subconductor 1 is set to be 1000A, 2000A, 3000A, 4000A in sequence.

Ⅳ. THE ANALYSIS OF MAGNETIC FIELD

According to Formula.1, the electromagnetic force experienced in the conductor is proportional to the length of the conductor. In fact, during numerical simulating, solution process can be simplified by taking full advantage of the symmetry of the structure of the overhead bundled transmission lines [11]. Hence, the unit length of a specific wire and a half of subconductors are discussed in this paper, to probe the electromagnetic field distribution of subconductor 1 and the spacer, and to calculate the electromagnetic force loaded in subconductor 1.

Load the finite element model with different values of current (I) involving 1000A, 2000A, 3000A, 4000A. The model loaded with deicing current is shown as Figure 4. Then, the electromagnetic field distribution of subconductor 1 and the spacer is calculated, as Figure.5 shows. The magnetic flux density (B) of point A and the electromagnetic forces (F) corresponding to different values of current are presented in TABLE Ⅰ. According to Figure.5 and TABLE Ⅰ, the increasing deicing current gives rise to the magnetic flux density and electromagnetic force acting on the subconductor 1. Load the electromagnetic forces on the model which requires deformation analysis. Under the combined action of electromagnetic force, ice load and wire weight, the deformation stress and displacement of transmission lines are obtained in the chapter Ⅴ.

TABLE Ⅰ
The magnetic flux density and the electromagnetic forces of subconductor 1

I(A)	B($\times 10^{-4}$T)	F(N/m)
1000	2.33	0.07
2000	4.65	0.25
3000	6.97	0.53
4000	9.30	0.95

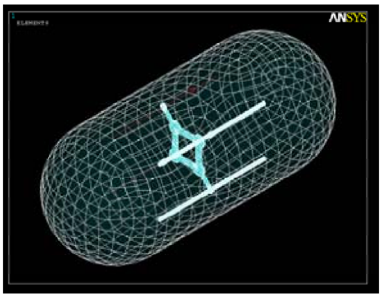
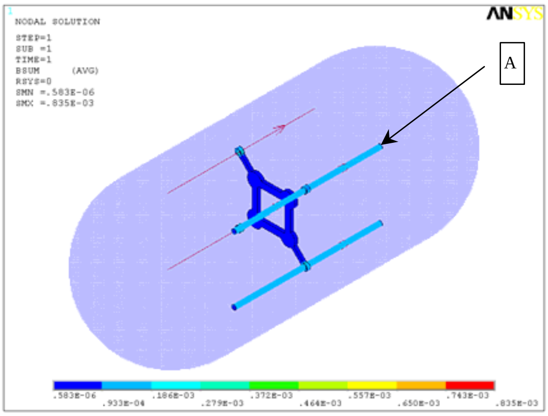


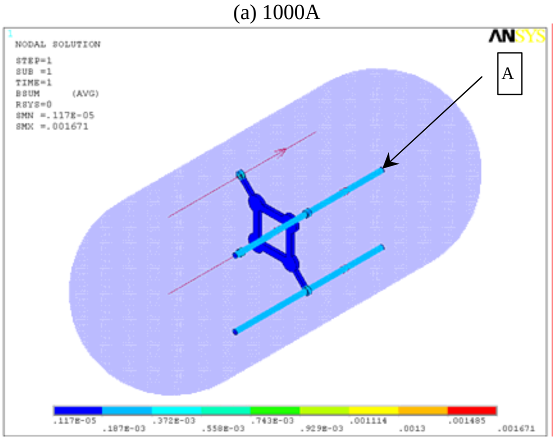
Fig.4 The model loaded with deicing current

Ⅴ. DISPLACEMENT AND STRESS ANALYSIS OF SUBCONDUCTORS

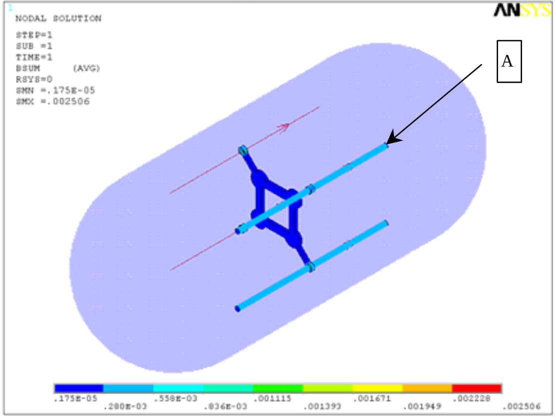
The 500 kV bundled conductors are made of steel-cored aluminium strand, which possess complex mechanical properties and significant geometric nonlinearity. Due to the arbitrary shape of the wire itself, with given boundary conditions, the pre-tension and external load imposed on subconductor 1 need to adjust the shape of the transmission line to maintain balance. Prior to the analysis of displacement and stress of the wire, its initial configuration requires being confirmed [12].



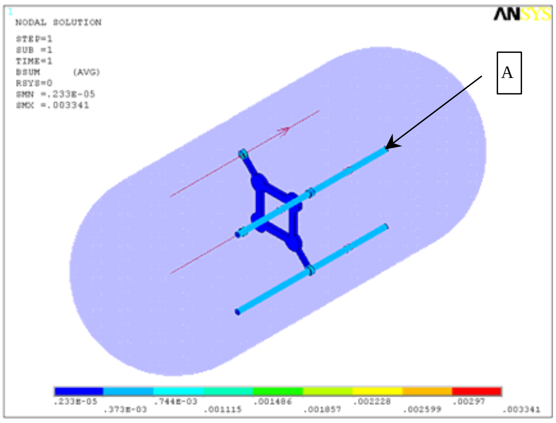
(a) 1000A



(b) 2000A



(c) 3000A



(d) 4000A

Fig.5 The magnetic flux density of subconductor 1 and the spacer

This paper adopts the finite element method from kinds of methods of form-finding analysis. The Catenary Model is applied in the process of analysis. The initial strain is imposed by LINK10 element to simulate the initial line type. The operation of the finite element method is to start from the initial state. By means of solving the nonlinear process over and over again, the equilibrium state works out gradually.

To analyze the initial configuration of the overhead transmission line, some parameters are assumed as below:

1) Ignore the ability of compressive resistance, bending resistance and torsional resistance of the transmission line. Instead, consider it as an ideal flexible cable tension which only suffers tension.

2) A tiny strain emerges when the wire deforms greatly. Only the geometric nonlinear is considered. The properties of the materials meet the Hooke’s Law.

3) The sectional area of the conductor is constant while the conductor is deforming.

A. FORM-FINDING FOR CONDUCTORS UNDER THE DEADWEIGHT

According to the characteristic of force experienced in the conductor, LINK10 unit is selected to simulate Subconductor 1. The unit imposes initial pre-stress on the line with the help of initial strain. The real constants, such as the material properties and sectional area, are set up in accordance with practical situation. The value of the elastic module as small as possible is the key [12]. In the form-finding procedure, the length of the line varies from the straight line to the curve. The increment of length doesn’t equal to the actual elastic stretching quantity of the subconductor under deadweight. According to the horizontal stress, initial strain is obtained through the formula of stress and strain. During modeling, connect two suspension points with a straight line, which is divided into a specific numbers of LINK10 units. The two suspension points are fully restrained. Impose the gravity load. After solution, the equilibrium state comes out, which means form-finding for conductors is finished, as is shown in Figure.6. The max increasing vertical displacement of the subconductor 1 is 2.108m under the deadweight.

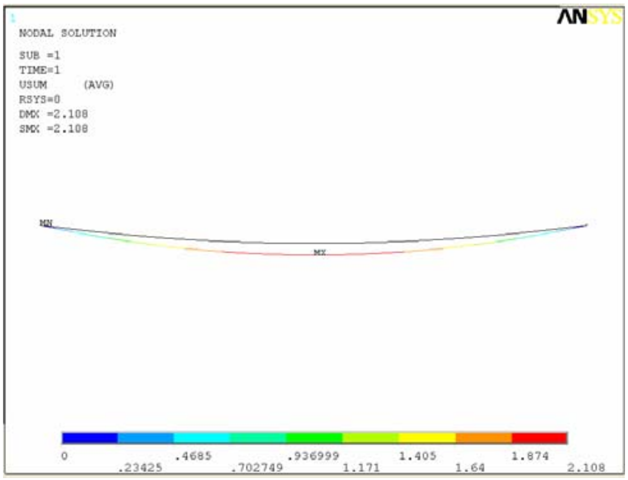


Fig.6 Form-finding for conductors under the deadweight
(Height of 5 times magnification)

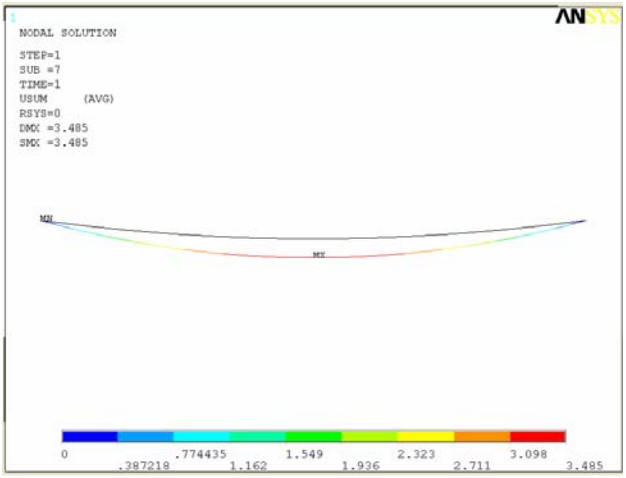


Fig.7 Sag of subconductor1 with icing
(Height of 5 times magnification)

B. VERTICAL DISPLACEMENT ANALYSISES OF ICE-COATED CONDUCTORS

Form-finding for icing conductors is on the base of static equilibrium of conductors under the deadweight. So form-finding for icing conductors proceeds after form-finding for conductors under deadweight [11]. It's difficult to simulate the sectional shape and material characteristic of the icing conductors exactly. Therefore, this paper makes the following assumptions and process to simplify the finite element model.

1) Suppose conductors are covered with ice uniformly.

2) Covering with glaze ice is regarded to be the worst situation in [2], [11]. Glaze ice is shown in Figure2.

3) Only the quality of covering ice is concerned, without the consideration of stiffness contribution. That means, the total linear density equals the sum of the linear densities of conductors and the ice covering on the conductors.

Impose ice-load on the conductor model under the deadweight. The elastic modulus of the wire needs to be modified with the actual value, because the elastic elongation of the conductors is caused by the ice load simply. After setting options of the nonlinear solution, the state of equilibrium of icing is solved, which means the form-finding for deicing is finished, as Figure.7 shows.

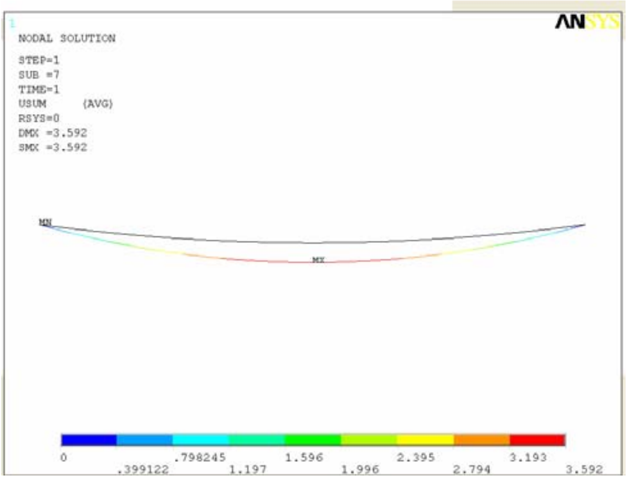
Figure.7 shows the sag with ideal uniform icing. The ice-thickness is 10mm. Compared with the form-finding for subconductor 1 under the deadweight, the max increasing vertical displacement of the subconductor 1 with icing increases 1.377m.

C. ELECTROMAGNETIC FORCES IMPACT ON THE ICE-COATED CONDUCTORS

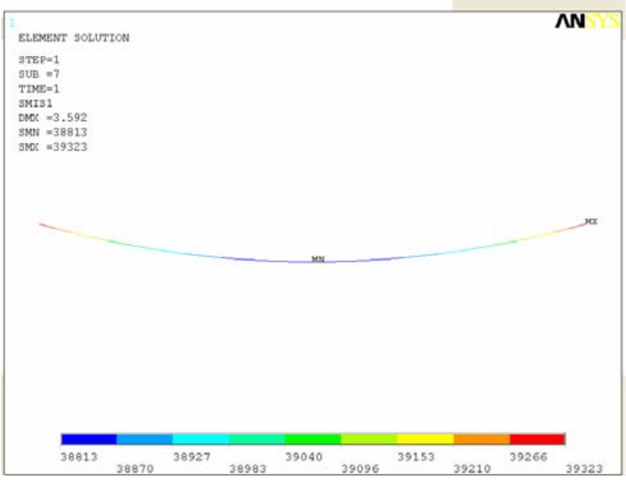
Load the subconductor 1 with the electromagnetic forces of four cases in TABLEⅠ. Afterwards, the stress and strain of the conductor, which is under the combined action of icing and electromagnetic force, are obtained. The bundle pinch in the vertical plane is concerned in this paper. According to Figure 8 and TABLEⅡ, the max increasing vertical displacement(S) of the subconductor 1 loading with four kinds of deicing currents(I) is 7mm、27mm、60mm、107mm respectively. At the same, the Max-stress (T), the increment of subconductor (Δl) and the strain (ε) is increasing respectively. The variation of vertical displacement, 60mm or 107mm, is so large. It is mean that the phenomenon of bundle pinch came out obviously. The range of DC deicing current for a type 500m transmission line is from 3000A to 4000A. The conglutination phenomenon occurred in the horizontal plane which shares the same analysis procedure with that occurred in the vertical plane [13].

TABLE Ⅱ
Electromagnetic forces impact on the ice-coated subconductor 1

I(A)	S(m)	T(N)	$\Delta l(\times 10^{-2}m)$	$\varepsilon(\times 10^{-5})$
1000	0.007	38121	0.138	2.72
2000	0.027	38360	0.139	2.74
3000	0.060	38758	0.141	2.78
4000	0.107	39321	0.144	2.83



(a) (Height of 5 times magnification)



(b)

Fig. 8 (a) The vertical displacement and (b) the stress of ice-coated subconductor 1(4000A)

Ⅵ. CONCLUSIONS

a) The magnetic flux density of the 500 kV ice-coated transmission lines strengthens in the increasing of the DC deicing current. When the DC deicing current is 1000A, 2000A, 3000A and 4000A in sequence, the electromagnetic force on the conductor per unit length is 0.07N、0.25N、0.53N、0.95N respectively.

b) At the circumstance with -5℃ temperature, 5m/s wind speed and 10 mm icing thickness, the max increasing vertical displacement of the four bundled conductors reaches 1.377m.

c) When the DC deicing current is 1000A, 2000A, 3000A and 4000A in sequence, with 10 mm icing thickness, the Max-stress of the conductor is 38.12kN, 38.36kN, 38.76kN, 39.32kN respectively, the length-increment of subconductor 1 is 1.38mm、1.39mm、1.141mm、1.44mm respectively, and the max increasing vertical displacement is 7mm、27mm、60mm、107mm respectively.

d) When the DC deicing current is up to 3000~4000A, the increasing displacement of the subconductor 1 in the vertical plane reaches 0.06~0.107m, which brings out bundle pinch. The range of DC deicing current for a type 500m transmission line is from 3000A to 4000A.

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