CALCULATION METHOD OF MAXIMUM CONDUCTOR TEMPERATURE AND MAXIMUM ALLOWABLE CURRENT IN TRANSMISSION LINE ICE-MELTING WITH SHORT-CIRCUIT

Bai Yunqing[1], Mo Wenqiang[1], Wu Bin[1], Zhou Shu[1],Liu Yu[2]
(1: Chongqing Electric Power Corporation, 400067, China; 2: State Key Laboratory of Power Transmission Equipment & System Security and New Technology, Chongqing University, Chongqing 400030, China)

***Abstract**:* Ice-melting with short-circuit in transmission line is the most effective methods of de-icing. Conductor would be damaged if rapidly rising conductor temperature exceeds the allowable temperature. A lot of laboratory experiments were carried out on both LGJ-240/30 and LGJ-400/35 conductor in the artificial climate chamber. The tests results and analysis show that the maximum temperature of conductor is determined by two factors includingthe thickness of ice and ice-melting current. simple calculation formulas of ice melting time and ice melting current are put forward in this paper. Also a method to calculate the maximum temperature of conductor and maximum allowable conductor current is deduced. Calculated and experimental results agree very well.

1. INTRODUCTION

Power transmission lines are the main components in the power transmission. Transmission Line icing is a serious threat to the safe and stable operation of power system[1-2]. This paper analyzes temperature properties, especially the maximum temperature of conductor and its influencing factors in ice melting process. Through theoretical analysis and verification experimental verification, we can effectively choose the value of current in ice melting process, control conductor temperature within its the maximum allowed temperature, and ensure that power system network safety operation.

2. THE CALCULATION OF ICE MELTING TIME AND CURRENT

In this section, approximate calculation formulas of ice melting time and ice melting current are proposed.In the ice melting process, heat balance equation as follows:

$$I^2 r_T - \pi(D_c + 2d_i)h(T_i - T_a) = \rho_i L_F \frac{dV_m}{dt} + \rho_i V_i C_i \frac{dT_i}{dt} + \rho_c V_c C_c \frac{dT_c}{dt}$$

Ignoring the absorbed heat by conductor temperature changing,and taking the inside and outside the ice layer surface average temperature as the ice layer temperature T_{i}, the ice melting time (t) and ice melting current (I) calculation formulas are expressed as:

$$t = \frac{\rho_i L_F V_m + \rho_i V_i C_i (T_i/2 - T_a)}{[I^2 r_T - 2\pi(R_c + d_i)h(T_i - T_a)]}$$

$$I = \sqrt{\frac{\rho_i L_F V_m + \rho_i V_i C_i (T_i/2 - T_a) + 2\pi(R_c + d_i)h(T_i - T_a)t}{r_T t}}$$

3. THE CALCULATION OF THE MAXIMUM TEMPERATURE AND MAXIMUM ALLOWABLE CURRENT OF ICE MELTING CONDUCTOR

In the ice melting process, to ensure that the temperature of ice-melting conductor is lower than its allowable temperature, we need to know the maximum temperature of Ice-melting conductor. the calculation formulas of the maximum temperature of conductor is given by:

$$\begin{cases} T_{\max} = \max\{T_{im}, T_n\} \\ T_{im} = e^{c_1 + c_2 I/A_c} \cdot [\ln(d_i)]^{c_3} \\ T_n = \dfrac{I^2 r_T (R_c^2 - R_x^2)}{2h_c R_c A_c} + T_a \end{cases}$$

the maximum allowable current of the conductor is decided by highest conductor current before and after the ice dropping from the conductor, namely, the maximum allowable current is the smaller of the two:

$$I_{\max} = \min\{I_{im}, I_n\}$$

Where $I_{im} = \dfrac{A_c[\ln(T_{MAX}) - c_3 \ln(\ln(d_i)) - c_1]}{c_2}$

$$I_n = \sqrt{\frac{2R_c A_c h_c (T_{MAX} - T_a)}{r_T (R_c^2 - R_x^2)}}.$$

4. CONCLUSION

In the light of the engineering application, simple calculation formulas of ice melting time and ice melting current are put forward in this paper. A method to determine the maximum conductor temperature and the maximum allowable conductor current is proposed. Although it does not take into consideration of dynamic change of conductor temperature, air gap etc parameters in ice melting process, it still can be provided reference for the choice of ice melting current.

5. REFERENCES

[1] JIANG Xing-liang,YI Hui. Transmission Line Icing and Protection[M].Bei Jing: China Electric Power Press,2002.

[2] HU Yi. Analysis and countermeasures discussion for large area icing accident on power grid[J]. High Voltage Engineering,2008, 34(2): 215-219..

Calculation method of maximum conductor temperature and maximum allowable current in transmission line Ice-melting with short-circuit

Bai Yunqing[1], Mo Wenqiang[1], Wu Bin[1], Zhou Shu[1],Liu Yu[2]

(1: Chongqing Electric Power Corporation, 400067, China; 2: State Key Laboratory of Power Transmission Equipment & System Security and New Technology, Chongqing University, Chongqing 400030, China)

***Abstract*—Ice-melting with short-circuit in transmission line is the most effective methods of de-icing. Conductor would be damaged if rapidly rising conductor temperature exceeds the allowable temperature. A lot of laboratory experiments were carried out on both LGJ-240/30 and LGJ-400/35 conductor in the artificial climate chamber. The tests results and analysis show that the maximum temperature of conductor is determined by two factors includingthe thickness of ice and ice-melting current. simple calculation formulas of ice melting time and ice melting current are put forward in this paper. Also a method to calculate the maximum temperature of conductor and maximum allowable conductor current is deduced. Calculated and experimental results agree very well.**

Keywords-icing, ice-melting, maximum temperature of conductor, maximum allowable current

I. INTRODUCTION

Power transmission lines are the main components in the power transmission. Transmission Line icing is a serious threat to the safe and stable operation of power system, may lead to transmission line passing load, conductor galloping, insulator string flashover incidents, and is a serious harm to the safe operation of power system[1-5]. Because of frequent ice storm accidents, power production and operation units extensively explore anti-icing measures. So far, in addition of the ice-melting with short-circuit, there is not a effective way to prevent the transmission line ice storm.

The search and application of ice-melting with short-circuit in transmission line has already had very long history. the former Soviet Union has research it since 50's in 20th century, China has started adopting AC short-circuit to melt ice since 1976, Manitoba hydroelectric office in Canada has studied DC short-circuit to melt ice since 1993. So far, ice-melting with short-circuit in transmission line has made a wealth of practical experience. There is also a lot of research about model of ice melting time and current at home and abroad. A variety of model of ice melting time and current[6-12] are proposed. But the existing model results have large errors whih practical engineering applications. Analysis shows that the reason of the situation is all the ice melting models suppose the surface conductor temperature keeping at 0 ℃ in ice melting process, but the facts and measurements show that resulting from the water film and air gap produced ice melting, the conductor temperature is above 0°C. In the process of ice melting, because of high ice melting current, the Joule heat brought by current will make conductor temperature quickly rapid to exceed the allowable conductor temperature (the maximum allowable conductor temperature in China's current standards ⩽ +70 ℃). Conductor temperature is too high and then the increase of conductor sag, this affect safety tolerance of conductor to land and conductor cross across, and also reduces the mechanical strength and life of conductor and Supporting hardware[13,14].

This paper analyzes temperature properties, especially the maximum temperature of conductor and its influencing factors in ice melting process. Through theoretical analysis and verification experimental verification, we can effectively choose the value of current in ice melting process, control conductor temperature within its the maximum allowed temperature, and ensure that power system network safety operation.

II. THE CALCULATION OF ICE MELTING TIME AND CURRENT

There are five questions frequently needed to answer in the transmission line in ice melting project: First, how much current value to make the ice melt? Second, When the ice melting current value is constant, How long is needed for the ice layer felling from the conductor? Third, how to select the ice melting current to avoid conductor being damaged by high temperature? Fourth, how to determine parameters of ice melting power source. Fifth, How to select a appropriate ice melting method.

In this section, approximate calculation formulas of ice melting time and ice melting current are proposed. In the ice melting process, the joule heat generated by the conductor current mainly consumes at a few aspects as follows: First, absorbed latent heat in the ice melting process; Second, thermal convection and thermal radiation on the outside surface of the ice layer; Third, Heating the conductor and ice layer. Heat balance equation as follows:

$$I^2 r_T - \pi(D_c + 2d_i)h(T_i - T_a) = \rho_i L_F \frac{dV_m}{dt} + \rho_i V_i C_i \frac{dT_i}{dt} + \rho_c V_c C_c \frac{dT_c}{dt} \quad (1)$$

In the formula: h is a heat dissipation coefficient, W/(m^2.℃); L_F is latent heat of ice, L_F=335000J/kg; T_{io} is the

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outside temperature of ice layer, ℃; T_i is the temperature of ice layer, ℃; V_m is the volume that the ice melts, m^3; V_c、V_i is the volume of conductor and ice layer, respectively, m^3; ρ_c、ρ_i is the density of conductor and ice layer, respectively, kg/m^3; C_c、C_i is the specific heat capacity of conductor and ice layer, respectively, J/(kg.℃).

Ignoring the absorbed heat by conductor temperature changing,and taking the inside and outside the ice layer surface average temperature as the ice layer temperature T_i, the ice melting time (t) and ice melting current (I) calculation formulas are expressed as:

$$t = \frac{\rho_i L_F V_m + \rho_i V_i C_i (T_i/2 - T_a)}{[I^2 r_T - 2\pi(R_c + d_i)h(T_i - T_a)]} \tag{2}$$

$$I = \sqrt{\frac{\rho_i L_F V_m + \rho_i V_i C_i (T_i/2 - T_a) + 2\pi(R_c + d_i)h(T_i - T_a)t}{r_T t}} \tag{3}$$

Calculate the ice melting time t and ice melting current (I) by equation (2) and (3), but need to know the volume that the ice melts V_m, the temperature of ice layer T_i.

A. The Calculation of The Volume of Melting ice

The ice sheds off from the conducting line as shown in Figure 1. Figure 1 shows, the volume of ice melting is the oval-shaped air gap volume, namely:

$$V_m = \pi ab \tag{4}$$

According to the circular outer surface of wires must be inscribed in the ellipse constraint that the air gap can be obtained b the long axis of elliptical air-gap and the short axis of a must satisfy the following relationship:

$$a \geq \sqrt{bR_c} \tag{5}$$

The formula (5 is equality, when ice fell off the conductor. Equation (5 substitutes into equation (4 can be obtained:

$$V_m = \pi b\sqrt{bR_c} \tag{6}$$

Also we can see from Figure 1, ignoring the ice melting under the surface of conductor, the long axis of ellipse Elliptical air-gap:

$$b = R_c + d_i/2 \tag{7}$$

Therefore, the ice melting volume can be expressed as:

$$V_m = \pi(R_c + d_i/2)^{3/2} R_c^{1/2} \tag{8}$$

The volume of ice layer can be expressed as:

$$V_{\text{i}} = \pi(R_c + d_i)^2 - \pi R_c^2 \tag{9}$$

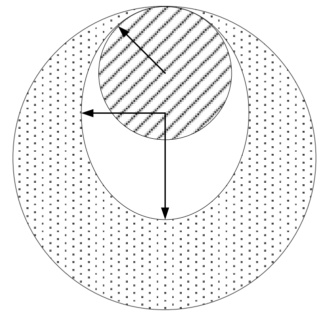

Fig.1 Cross-section of ice melting conductor at the falling off menent

B. The Calculation of Heat Exchange Coefficient (h)

Firstly, introduce the three the relative number[15] needed to be used in the calculations:

$$Re = \frac{(D_c + 2d_i)v_a}{\nu} \tag{10}$$

$$Pr = \frac{\nu}{a} \tag{11}$$

$$Nu = CRe^n Pr^{1/3} \tag{12}$$

In equation (10~(12: Re, Pr and Nu are Reynolds Number, Prandtl Number and Nusselt Number, respectively; D_c is the diameter of conductor,m; d_i is ice thickness,m; v_a is wind velocity, m/s; ν is kinematic viscosity of air, ν=1.328×10^{-5} m^2/s; a is thermal diffusivity of air, a=1.88×10^{-5} m^2/s; C and n are the coefficients, for ice Weather C=0.683, n=0.466[15].

In the ice melting process, the outer surface of the ice layer in the way of convection and radiation heat transfer heat into the surrounding environment, so heat exchange coefficient (h) is as follows:

$$h = \frac{Nu \cdot \lambda_a}{D_i} + 4\varepsilon\sigma(T_a + 273.15)^3 \tag{13}$$

In equation (13: h is heat exchange coefficient, W/(m^2.℃); λ_a is heat transfer coefficient of air, λ_a=0.0244 W/(m.℃); ε is the emissivity of the outer surface of the ice layer, ε=0.95; σ is Stefan-Boltzmann constant, σ=5.67×10^{-8} W/m^2.℃^{4}.

C. The calculation of ice layer surface temperature(T_i)

At the outer surface of the ice layer, the heat balance equation is as follows:

$$\frac{-T_i}{R_q} = h(T_i - T_a) \tag{14}$$

In equation (14): R_q is the thermal resistance of ice layer.

$$R_q = \frac{\ln[(R_c + d_i)/R_c]}{2\pi\lambda_i} \quad (15)$$

The general equation for the ice layer surface temperature(T_i) is obtained as:

$$T_i = \frac{R_q h}{1 + R_q h} T_a \quad (16)$$

D. The Calculation of The Ice Melting Time (*t*) *and Ice Melting Current* (*I*)

On substitution of Eqs. (8), (9), (16) and Eqs. (2), (3), we get the ice melting time *t* and ice melting current *I*.

$$h = (0.295R_i)^{-0.534}\, v_a^{0.466} + 4.39 \times (1 + 0.01T_a) \quad (17)$$

$$T_i = \frac{T_a}{1 + \dfrac{13.947}{h \ln(R_i / R_c)}} \quad (18)$$

$$t = \frac{\chi}{I^2 r_T - 2\pi h \Delta T R_i} \times 10^6 \quad (19)$$

$$I = \sqrt{\frac{\chi + 2\pi h \Delta T R_i t \times 10^{-6}}{r_T t}} \times 10^3 \quad (20)$$

Where

$$\chi = 341.18(R_c + R_i)^{1.5} R_c^{0.5} + 3.01(R_i^2 - R_c^2)(\Delta T - T_a)$$

and

$$\Delta T = T_i - T_a$$

Through equation (17)~(20) the ice surface convective heat transfer coefficient (*h*), the ice surface temperature (T_i), the ice melting time (*t*) which is relative to certain current and the conductor current (*I*) which is relative to certain ice melting time can be easily calculated. However, due to conductor temperature, air gap etc dynamic changes overlooked in ice melting process, calculation error is great. but, equation (17)~(20) is based on uniform cylindrical icing conductorover, its results is relatively close to the real. For eccentric elliptical icing conductor, if the impact on the thermal convection and thermal radiation on the ice layer surface of the icing conductor shape is ignored, the ice melting time can be approximately estimated. So, for eccentric elliptical icing conductor, calculation results of equation (17)~(20) only only as a reference; for irregular shapes of icing and non-synchronization ice-shedding from conductors, it can not adapt.

III. The Calculation Of The Maximum Temperature And Maximum Allowable Current Of Ice Melting Conductor

A. The Calculation of The Maximum Temperature of Ice-melting Conductor

In the ice melting process, to ensure that the temperature of ice-melting conductor is lower than its allowable temperature, we need to know the maximum temperature of Ice-melting conductor. By analysis, there are different temperature characteristics before and after the ice dropping from the conductor. The highest temperature of ice-melting conductor can be defined as:

$$T_{\max} = \max\{T_{im}, T_n\} \quad (21)$$

In equation (21): T_n is highest conductor temperature after the ice dropping from the conductor, °C. T_{im} is highest conductor temperature before the ice dropping from the conductor, °C. For the convenience of project application, fitting the numerical results based on the numerical method to get the relationship of T_{im}, current density (*J*) and ice thickness (d_i) are expressed by the following equations:

$$T_{im} = e^{c_1 + c_2 J} \cdot [\ln(d_i)]^{c_3} \quad (22)$$

In equation (22: *J* is the ice melting current density, $J = I/A_c$， A/mm^2. d_i is the ice thickness, mm; c_1、c_2、c_3 are coefficient related with the conductor type; For LGJ-400/35, c_1=-0.083 ， c_2=0.981 ， c_3=0.42; For LGJ-240/30, c_1=0.182，c_2=0.70，c_3=0.389.

By LGJ-240/30 and LGJ-400/35 two experiments testing conductor, equation (22) of the calculated results and the simulation model in Chapter 2, the basic one to the results, compared with the simulation results, equation (22) The calculated values within 10%

On substitution of equation (21), (22), the calculation formulas of the maximum temperature of conductor is given by:

$$\begin{cases} T_{\max} = \max\{T_{im}, T_n\} \\ T_{im} = e^{c_1 + c_2 I / A_c} \cdot [\ln(d_i)]^{c_3} \\ T_n = \dfrac{I^2 r_T (R_c^2 - R_x^2)}{2 h_c R_c A_c} + T_a \end{cases} \quad (23)$$

Where, $T_{\max}$ is the maximum temperature of conductor, ℃ , T_n is highest conductor temperature after the ice dropping from the conductor, °C, T_{im} is highest conductor temperature before the ice dropping from the conductor, °C, h_c is conductor surface heat transfer coefficient after the ice dropping from the conductor, h_c=1.043h， W/(m^2.℃), A_c is effective electrify area of the conductor, m^2, R_x is radiu of ACSR, m and c_1、c_2、c_3 are coefficient related with the conductor type. For LGJ-400/35, c_1=-0.083， c_2=0.981， c_3=0.42; For LGJ-240/30, c_1=0.182， c_2=0.70， c_3=0.389.

B. The Calculation of Maximum Allowable Conductor Current

Maximum allowable conductor current means the maximum conductor current value of the conductor on the condition of that the conductor are not damaged under high temperature. To prevent the conductor overheat damage, almost all the state set the allowable temperature of the conductors in their electricity industry standard. In China's current standard the allowable temperature of ACSR is 70℃ [16]. The maximum allowable current is controlled by the allowable temperature of the conductors, that is to say the conductor temperature must be below the maximum allowed temperature. Equation (23) indicates that the maximum temperature of the conductor is decided by highest conductor temperatures before and after the ice dropping from the conductor. Therefore, the maximum allowable current of the conductor is decided by highest conductor current before and after the ice dropping from the conductor, namely, the maximum allowable current is the smaller of the two:

$$I_{\max} = \min\{I_{im}, I_n\} \tag{24}$$

Where, $I_{\max}$ is the maximum allowable conductor current, A, I_{im} is allowable conductor current before the ice dropping from the conductor, A and I_n is allowable conductor current after the ice dropping from the conductor, A.

By equation (22) the allowable conductor current before the ice dropping from the conductor is,

$$I_{im} = \frac{A_c[\ln(T_{MAX}) - c_3\ln(\ln(d_i)) - c_1]}{c_2} \tag{25}$$

Where, according to the provisions[17] of China's electric power industry, the allowable conductor temperature is 70 ℃, c_1、c_2、c_3 are coefficients, the same as equation (22) and A_c is effective electrify area of the conductor, m^2.

By equation (23) the allowable conductor current after the ice dropping from the conductor is,

$$I_n = \sqrt{\frac{2R_cA_ch_c(T_{MAX} - T_a)}{r_T(R_c^2 - R_x^2)}} \tag{26}$$

Where, h_c is conductor surface heat transfer coefficient after the ice dropping from the conductor, h_c=1.043h[18], W/(m^2.℃), A_c is effective electrify area of the conductor, m^2 and R_x is radiu of ACSR, m.

According to the calculation results of equation (24), in different wind speeds and under different temperature the maximum ice melting current are shown in Figure 10.2 and Figure 3, respectively. Figure 2 shows, when the wind speed is small (v_a<4m/s), the maximum ice melting current is decided by the conductor current after the ice dropping from the conductor, which increases with wind speed; when the wind speed is large (v_a>4.5m/s), the maximum ice melting current is decided by the conductor current before the ice dropping from the conductor, which has nothing to do with wind speed. Figure 3 shows, when the ambient temperature is high (for LGJ-400, T_a>-6℃; for LGJ-240, T_a>-10℃), the maximum ice melting current is decided by the conductor current after the ice dropping from the conductor, which increases with ambient temperature; when the ambient temperature is low (for LGJ-400, T_a<-6℃; for LGJ-240, T_a<-10℃), the maximum ice melting current is decided by the conductor current before the ice dropping from the conductor, which has nothing to do with ambient temperature.

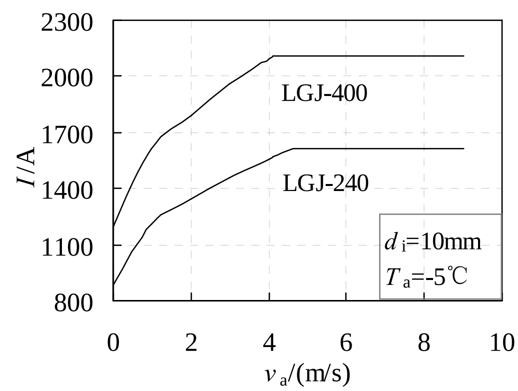

Fig.2 The maximum ice melting current under different wind speeds

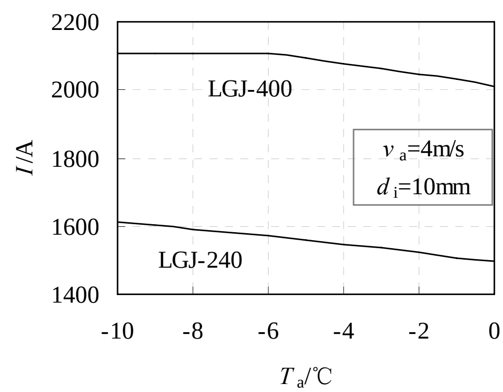

Fig.3 The maximum ice melting current under different ambient temperature

IV. CONCLUSION

In the light of the engineering application, simple calculation formulas of ice melting time and ice melting current are put forward in this paper. A method to determine the maximum conductor temperature and the maximum allowable conductor current is proposed. Although it does not take into consideration of dynamic change of conductor temperature, air gap etc parameters in ice melting process, it still can be provided reference for the choice of ice melting current.

References

[1] JIANG Xing-liang,YI Hui. Transmission Line Icing and Protection[M].Bei Jing: China Electric Power Press,2002.

[2] HU Yi. Analysis and countermeasures discussion for large area icing accident on power grid[J]. High Voltage Engineering,2008, 34(2): 215-219.

[3] Yangchun C, Chunjie N, Chengrong L. The reliability evalua-tion method of high voltage overhead transmission lines[C] // 2008 International Conference on Condition Monitoring and Di-agnosis. Beijing, China:[s.n.], 2008.

[4] JIANG Xing-liang, MA Jun, WANG Shao-hua, et al. Trans-mission lines'ice accidents and analysis of the formative factors[J]. Electric Power, 2005, 38(11): 27-30.

[5] JIANG Xing-liang, ZHANG Li-hua. De-icing and anti icing oftransmission lines[J]. High Voltage Engineering, 1997, 23(1):73-76.

[6] Vargas J V C, Bejan A, Dobrovicescu A. The melting of an iceshell on a heated horizontal cylinder[J]. Transactions of theASME Journal of Heat Transfer, 1994(116): 702-708.

[7] Michel Landry, Roger Beauchemin, AndréVenne. De-icingEHV overhead transmission lines using electromagnetic forcesgenerated by moderate short-circuit currents[C] // Proceedingsof IEEE 9th International Conference on Transmission and Dis-tribution Construction, Operation and Live-line Maintenance.Quebec, Canada: IEEE, 2000.

[8] LIU Li, PENG Min-fang. The theory and implementation of the efficient method of the transmission lines de-icing and svc system[D]. Changsha: Hunan University, 2007.

[9] Gaydecki P, Miller G, Zaid M, et al. Detection of magneticfields highly attenuated by the skin effect through a ferrous steelboundary using a super narrow-band digital filter[J]. IEEETransactions on Instrumentation and Measurement, 2008, 57(11): 1171-1176.

[10] McCurdy J D, Sullivan C R, Petrenko V F. Using dielectriclosses to de-ice power transmission lines with 100 kHz high-voltage excitation[C] // IEEE Industry Applications Confer-ence. Chicago, USA: IEEE, 2001.

[11] Hesse K H. Ice melting systems in Manitoba hydro[C] // Canadian Electrical Association. Montreal, QC,Canada: [s.n.],1998.

[12] Huneault M, Langheit C, Caron J. Combined models for glazeice accretion and de-icing of current-carrying electrical conduc-tors[J]. IEEE Transactions on Power Delivery, 2005, 20(2):1611-1616.

[13] CHEN Shao-xin, WU Pei-sheng. Application of on-line temperature and sags monitoring device of transmission line[J].North China Electric Power, 2008(3): 14-15.

[14] REN Li-jia, SHENG Ge-hao, ZENG Yi, et al. A conductor temperature model based on dynamic line rating technology[J].Automation of Electric Power Systems, 2009, 33(5): 40-44.

[15] YANG Shi-ming,Tao Wen-shuan. Heat Transfer Theory[M]. Bei Jing: Higher Education Press, 2006

[16] JIANG Xing-liang, WANG Da-xin, FAN Song-hai, ZHANG Zhi-jing, HU Jian-lin. Experimental Research on Maximum Temperature of Ice-covered Conductors During DC Ice-melting [J]. High Voltage Engineering, 2009, 35(11): 2796-2799.

[17] XU Qing-song; JI Hong-xian; HOU Wei; WANG Meng-long. The Novel Technique of Transmission Line's Capacity Increase by Means of Monitoring Conductor's Temperature[J]. Power System Technology, 2006, 30(S1): 171-176.

[18] Z. PÉTER.Modeling and Simulation of the Ice Melting Process on a Current- Carrying Conductor[D]. UNIVERSITÉ DU QUÉBEC, 2006.