Analysis on Influencing Maximum Temperature Factors during DC Ice-melting of Uniformly Ice-Covered Conductors

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Abstract — **Ice-melting with short-circuit in transmission line is the most effective methods of de-icing. Conductor would be damaged if the temperature of conductor rises rapidly exceeds the allowable temperature. A lot of laboratory experiments are carried out on both LGJ-240/30 and LGJ-400/35 conductor in the artificial climate chamber. Based on the tests results and analysis, the maximum temperature of conductor is determined by two factors including the thickness of ice and ice-melting current, and is not influenced by ambient temperature and wind velocity. Also the calculation formula of the maximum temperature of conductor is put forward.**

*Index Terms—***dc, ice-melting, maximum temperature of conductor, influencing factors**

I. INTRODUCTION

POWER transmission line is the main part of power network, transmission line icing is a serious threat to security and stability of power system operation, it can cause transmission lines overload, conductor galloping and insulator string flashover, thus may seriously endanger the safety of power system operation [1-5]. Because of ice disaster frequently occurring, dozens of methods have been proposed to anti-icing and de-icing by power department. So far, no method can be used to prevent the ice disaster of transmission lines effectively except short-circuit ice-melting method.

Because the conductor's ac inductive resistance is much higher than its dc resistance, ac ice-melting need 5~20 times higher power supply capacity than dc ice-melting. If ac ice-melting is performed for 500kV above and line with a length of over 100km, the system should supply the reactive power capacity of 1GVA~2GVA which exceed the scope of the normal system can bear. So it will be harmful to the stability of system. Although the dc ice-melting needs an additional power supply (at present, dc ice-melting power supply will cost 400000~600000 RMB per MW), its requirement for power

supply is lower than ac ice-melting because it does not need reactive power. The radius of ice-melting of 60MW dc ice-melting equipment can reach to 100 km. So the dc ice-melting is simple and efficient comparing to ac ice-melting. The advantage of dc ice-melting for UHV and EHV transmission lines is more obvious.

The research and application of ice-melting have a long history, the former Soviet Union have used the measure of ac ice-melting since 1950s, China have started using ac ice-melting since 1976, Manitoba Water and Power Authority in Canada has studied on dc short circuit ice-melting since 1993. So far, rich experiences of ac ice-melting have been accumulated, but dc ice-melting has not been generalized in engineering application, so there is little experience about dc ice-melting. The ice-melting of transmission line has been studied widely in the world, and many models have been proposed to calculate the ice-melting time [6-12], but relatively large error has presented between the results calculated by existing models and the actual engineering application. The analysis show, the reason of the error is that all existing ice-melting models assume that the temperature of conductor surface maintain at 0°C during ice-melting. But actual measurement and analysis show that temperature of conductor is higher than 0°C because of the effect of water film and air gap caused by ice-melting.

In the process of ice-melting, wire temperature will rise rapidly due to Joule heat generated by the large current, thus may exceed the maximum temperature (The present standards require that the maximum temperature of conductor should not exceed +70□ in China). Because the temperature of conductor is too high, the sag of conductor will increase, so the distance between conductor and the ground or crossing wires will be shortened. The mechanical strength and the impact of life of conductor, as well as electric power fittings will be affected in varying degrees due to over high temperature [13].

Thus this paper analyzes on the maximum temperature of conductor and its influencing factors. Through theoretical analysis and experimental verification, the reasonable selection of the ice-melting current is the key of ice-melting in the condition of the temperature of conductor within the allowable temperature. In this way, ice-melting current will not damage conductors so as to make power system operation safe and

stable.

II. ICE-MELTING MODEL AND MAXIMUM TEMPERATURE OF CONDUCTOR

A. Physical model of ice-melting

It is assumed that the wire is infinitely long and the icing of wires is the uniform cylindrical glaze ice. When the current pass through the conductor, the conductor is heated by joule heat, then the heat is transferred to ice layer. The outer surface of ice and air exchange the heat by convection and radiation. Hence, the temperature of conductor surface is the highest, the temperature gradually descends throughout the ice layer during ice-melting. When the surface temperature of conductor is higher than 0□, the ice contacted with the conductor begins to melt. In the process of ice-melting, the inner surface of the ice is the mixture of ice and water which maintains at 0□. The water loss through the ice porosity, thus there forms the uneven distribution of the air gap between the ice and the conductor. The ice layer gradually shifts down under gravity, and the air gap under the conductor increases gradually. Literature [12] holds that the shape of ice-melting is just a hollow pear-shaped, and literature [13] considers that the shape of ice-melting is a rectangular cross-section. In this paper, experiment results show the air gap (including the wire) is similar to oval shape, as shown in Figure 1.

(a)Critical state of ice-melting (b)The process of ice-melting (c)Critical state of ice layer shedding

Figure 1 Schematic diagram of cross-section during ice-melting

B. The maximum temperature of conductor during ice-melting

The thermal conductivity in the process of ice-melting is heat transfer from conductor to ice layer due to temperature gradient between the ice and conductor. Because the conductor is long enough, temperature gradient in the axis direction can be neglected. R_c and D_i are conductor radius and the thickness of ice respectively; r_T is the conductor resistance when the temperature of the conductor is T; and λ is thermal conductivity that can be considered to be constant. $T(\theta)$ is the temperature of conductor surface, in which θ is shown in Figure 1(a). T_w is the temperature of inner surface of ice layer constituted by region of ABCD. $l(\theta)$ is the distance of θ corresponding the conductor surface to the inner surface of ice layer. Ice layer begins to melt, there is the state of the mixture of ice and water in inner surface of ice, the temperature keeps constant at 0℃, that is expressed by

$$T_w\big|_{ABCD} = 0 \qquad (1)$$

q is the ice-melting power per unit cross-section area (W/m^2), it can be formulated as follows:

$$q = \frac{I^2 r_T}{\pi R_c^2} \qquad (2)$$

According to Fourier law, the heat transfer equation is

$$q = \lambda \frac{T(\theta) - T_w}{l(\theta)} \qquad (3)$$

According to boundary conditions (1), equation (4) can be formulated by equation (3) as follow

$$T(\theta) = \frac{q l(\theta)}{\lambda} \qquad (4)$$

As is shown in Figure 1(b), $l(\theta)$ is less in the near surface of conductor, while $l(\theta)$ is larger near the undersurface of conductor, so the distribution of $l(\theta)$ is uneven, the temperature distribution of surface conductor $T(\theta)$ is also uneven through equation(4). When ice-melting current is determined, $T(\theta)$ increases with increasing $l(\theta)$.The temperature of surface conductor reaches the maximum when $l(\theta)$ become maximum, as is shown in Figure 1 (b) T point.

In the process of ice-melting, the ice will be detached from the conductor under its own gravity when the contact angle between ice and conductor is 0° [6]. Since the air gap becomes larger with the increasing ice thickness, the superficial area which the conductor contacts with air also increases, so does the thermal resistance of the conductor, thus joule heat speeds up the temperature of conductor rising. When the ice is just falling from the conductor, the air gap will reach the maximum, that is to say, $l(\theta)=D_i$ (T point in Figure 1(c)). So the temperature of conductor reaches to the maximum at the moment.

Steady-state heat transfer equation of "Conductor-Interface of ice layer" is

$$\int_0^{2\pi} \lambda \ R_c \frac{T(\theta)}{l(\theta)} d\theta = I^2 r_T \qquad (5)$$

So the function of surface temperature of conductor $T(\theta)$ is obtained

$$T(\theta) = f(l(\theta), I) \qquad (6)$$

When the $T(\theta)$ is T_{max}, the relationship of T_{max} is as following

$$T_{max} = f(D_i, I) \qquad (7)$$

That is to say T_{max} is not affected by wind velocity and ambient temperature, but is determined by the thickness of ice and ice-melting current.

III. EXPERIMENTAL VERIFICATION, SAMPLES AND METHODS

A. Experimental Setups

In order to verify the correctness of the model and influencing the maximum temperature factors, experiments are carried out in multi-function artificial climate chamber with the diameter of 7.8m and the height of 11.6m. The dc ice-melting power can supply current as high as 5000A.

The temperature of conductor surface is measured by DS18B20 temperature sensor produced by DALLAS Company. The measuring range of temperature is -55°C~+125°C and its accuracy is ±0.5°C. Wind velocity is

measured by using hand-held anemometer. Ambient temperature is measured with the PTU 2000 pressure-temperature-humidity transmitter. The measurement accuracy of temperature at 20 ℃ is ±0.2 ℃.

B. Samples

In view of transmission lines of different voltage levels used in China, in this paper, two types of conductors LGJ-400/35 and LGJ-240/30 are adopted in experiment (The length of test conductors was 3m). The technical parameters are shown in table 1, which r_{20}、r_T are the rate of resistance corresponding with 20℃and T℃ respectively, the conversion relationship is following

$$r_T = r_{20}\left[1 + \alpha(T - 20)\right] \qquad (8)$$

Where α is temperature coefficient of resistance of aluminum, at $3.6 \times 10^{-3}/℃$.

TABLE 1 THE TECHNICAL PARAMETERS OF CONDUCTORS

Conductor type	D_i /mm	D_{fe}/mm	$r_{20}/(\Omega/m)$
LGJ-240/30	21.60	7.20	0.1085×10^{-3}
LGJ-400/35	27.63	6.90	0.07389×10^{-3}

C. Test Methods and Results

The uniform cylindrical glaze ice of conductor is simulated in multi-function artificial climate chamber, and ambient temperature is controlled by the refrigeration equipment, the fan is used to change wind velocity in the range of 0m/s $\leq v_a \leq$ 5m/s. In this paper, the experiment adopts the method of dc ice-melting, experimental circuit is shown in Figure 2.
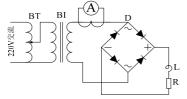

Figure 2 Experiment circuit (D: Bridge Rectifier; L: smoothing Reactor; R: sample Resistance; BT: Regulator; BI: Transformer)

TABLE 2 THE MAXIMUM TEMPERATURE T_{MAX} IN THE PROCESS OF DC ICE-MELTING

Conductor type	I/A	D_i/mm	t_e/℃	v_a/(m/s)	T_{max}/℃
LGJ-240/30	600	9.0	-1.0	1.0	9.6
	600	10.0	-6.0	1.0	9.7
	600	11.0	-3.0	1.0	9.8
	600	11.0	-3.0	4.0	9.9
	600	15.0	-5.0	3.0	10.3
	600	15.0	-1.0	3.0	10.3
	650	10.0	-3.0	3.0	11.5
	720	12.0	-5.0	3.0	14.6
	720	13.0	-6.0	3.0	14.8
	720	15.0	-1.0	1.0	15.1
	720	15.5	-1.0	1.2	15.2
	720	16.0	-7.0	1.5	15.3
	800	10.0	-3.0	3.1	17.3
	800	15.0	-3.0	3.2	18.5
	900	10.0	-3.0	3.0	21.8
	900	15.0	-3.0	3.2	23.5
LGJ-400/35	800	7.2	-3.0	5.0	8.9
	800	9.0	-3.0	4.0	9.2
	800	9.8	-3.0	1.0	9.3
	800	10.0	-3.0	5.0	9.3
	800	11.3	-7.0	5.0	9.7
	800	13.4	-7.0	3.0	10.0
	800	14.0	-7.0	1.0	10.1
	800	15.0	-1.0	4.0	10.3
	800	16.5	-1.0	5.0	10.5
	850	8.0	-5.0	1.0	10.2
	850	8.5	-5.0	1.0	10.3
	850	10.0	-5.0	3.0	10.7
	850	12.8	-1.0	3.0	11.2
	850	15.0	-3.0	3.0	11.5
	900	10.0	-5.0	2.0	11.9
	900	14.9	-5.0	2.0	12.8
	950	10.0	-5.0	3.0	13.3
	1000	15.0	-5.0	3.0	15.8

IV. ANALYSIS OF TEST RESULTS

A. The influence of wind velocity and ambient temperature on the maximum temperature of conductor

It is known from Table 2 that:

(a) T_{max} increases with increasing ice thickness during ice-melting process. That is to say, air gap, which increases with increasing ice thickness, has greater thermal resistance. Thermal resistance hampers the heat transferring to the ice surface (region of ABCD). Therefore, most of heat makes the temperature rise, the maximum temperature of conductor become higher with the thicker ice.

(b) T_{max} increases with increasing ice-melting current during ice-melting. That is to say, joule heat which make ice melted increases with increasing ice-melting current, thus raise the temperature of conductor. Under the condition that the thickness of ice is certain, T_{max} increases with increasing ice-melting current.

(c) When ice-melting current and the thickness of ice is determined, wind velocity has no effect on the maximum temperature of conductor T_{max}. For LGJ-240/35, under the condition of I is 600A and D_i is 11mm, T_{max} is 9.8 □ when v_a is 1m/s; while T_{max} is 9.9□ when v_a is 4m/s. The forced convection of ice surface becomes stronger with increasing wind speed, but wind speed almost has no effect on T_{max}.

(d) When ice-melting current and the thickness of ice are determinate, ambient temperature has no effect on the maximum temperature of conductor T_{max}. For LGJ-240/30 under the condition of I is 600A and D_i is 15mm, T_{max} is 10.3 □ when t_e is -5□; while T_{max} is 10.3□, when t_e is -1□.The radiation and natural convection become stronger with decreasing ambient temperature. But ambient temperature has no effect on T_{max}.

Analysis shows, before critical state of ice layer shedding, the inner surface of ice (region of ABCD) is the mixture of ice and water, the temperature of which is 0□. In this condition,

changes in wind velocity and ambient temperature only affect the speed of ice-melting. The maximum temperature of the conductor (the temperature of point T) is not affected by conditions outside the closed interval which is constituted by region of ABCD.

B. The influence of the thickness of ice on the maximum temperature of conductor

Table 2 shows that the relationship between the maximum temperature of conductor T_{max} and the thickness of ice D_i is shown in Figure 3.
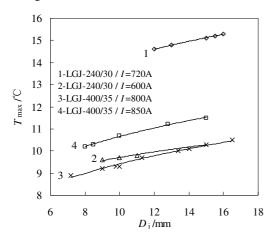

Figure 3 The relationship between the maximum temperature of conductor T_{max} and the thickness of ice D_i

Figure 3 shows that T_{max} increases with increasing D_i, and

$$T_{max} = C_1 D_i^{C_2} \qquad (9)$$

In equation (9) C_1、 C_2 are characteristic coefficients of conductor diameter, and are determined by the results of the tests, as shown in table 3, in which R is correlation coefficient.

TABLE 3 C_1 , C_2 , R^2 VALUE ON TWO TYPE OF CONDUCTORS WITH DIFFERENT THE THICKNESS OF ICE D_i

Conductor type	I/A	C_1	C_2	R^2
LGJ-240/30	600	7.022	0.141	0.98
	720	9.869	0.158	0.99
LGJ-400/35	800	5.816	0.209	0.98
	850	6.8212	0.193	0.99

C. The influence of ice-melting current on the maximum temperature of conductor

Table 2 also shows the relationship between the maximum temperature of conductor T_{max}, and ice-melting current I is shown in Figure 4.
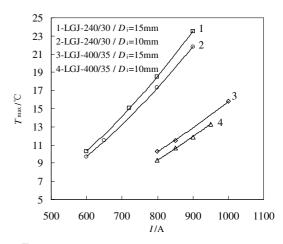

Figure 4 The relationship between the maximum temperature of conductor T_{max} and ice-melting current I

T_{max} increases with increasing ice-melting current I as seen in Fig.4, and also accords with power function as following

$$T_{max} = C_3 I^{C_4} \qquad (10)$$

In equation (10) C_3、 C_4 are characteristic coefficients of conductor diameter, and they are determined by the results of the tests, as shown in table 4.

TABLE 4 C_3, C_4 , R^2 VALUE ON TWO TYPE OF CONDUCTORS WITH DIFFERENT ICE-MELTING CURRENT I

Conductor type	D_i/mm	C_3	C_4	R^2
LGJ-240/30	10	2.89×10^{-5}	1.99	0.99
	15	2.98×10^{-5}	2.03	0.99
LGJ-400/35	10	0.94×10^{-5}	2.07	0.99
	15	3.00×10^{-5}	1.93	0.99

D. The comprehensive influence of D_i and I on T_{max}

Analysis shows that the thickness of ice and ice-melting current on the maximum temperature is independent of each other. Hence, the maximum temperature of conductor T_{max} can be expressed by the thickness of ice (D_i) and ice-melting current (I), such as equation (11):

$$T_{max} = K D_i^{m} I^{n} \qquad (11)$$

Where K is characteristic coefficient of the sample conductor; m is the characteristic index of the maximum temperature of conductor T_{max} with the thickness of ice D_i; n is the characteristic index of the maximum temperature of conductor T_{max} with ice-melting current I.

Equation (11) is treated by mean of the linearization process:

$$\ln T_{max} = \ln K + m \ln D_i + n \ln I \qquad (12)$$

According to least square method [14], as long as the guarantee of square of deviance M is the smallest, absolute deviation between test data and the results of equation (12) is extremely small.

$$M = \sum_{i=0}^{n}[\ln T_{\max i} - (\ln K - m\ln D_i - n\ln I)]^2 \qquad (13)$$

Where M is square of deviance; $T_{\max i}$、D_i and I are the maximum temperature of conductor, the thickness of ice and ice-melting current respectively in Table 2.

M is a ternary function of independent variables K and m as well as n, when the function $M=M(K,m,n)$ obtains the minimum value, K、m and n are determined, so it can be integrated the expression equation of $T_{\max}$.

The minimum point of square of deviance M can be obtained by calculation for extreme value of multivariate function. Equation (14) can be obtained by solving the partial derivative equations of equation (13) available, and it is formulated as follows：

$$T_{\max} = \begin{cases} 1.67\times10^{-5}I^2 D_i^{0.17} & (LGJ-240/30) \\ 1.18\times10^{-5}I^2 D_i^{0.19} & (LGJ-400/35) \end{cases} \qquad (14)$$

Therefore, equation (14) can calculate $T_{\max}$ of LGJ-400/35 and LGJ-240/30 in the following circumstances that the thickness of ice is less than 16mm and ice-melting current is less than 1000A. When the thickness of ice and ice-melting current exceed the scope, we can also find the corresponding m and n value in the same way to calculate the maximum temperature of conductor. According to engineering practice, this calculation formula can give certain guidance to select ice-melting current to guarantee for the conductor in normal working state.

V. Conclusions

1) The distribution of the temperature of conductor surface is uneven during ice-melting, where the conductor relatively close contact with the ice, the temperature maintain at 0°C; The temperature of the undersurface of conductor increases with increasing air gap. The conductor reaches to the highest temperature when the ice is falling from the conductor.

2) During dc ice-melting the maximum temperature of conductor is determined by the thickness of ice and ice-melting current, and is not influenced by ambient temperature and wind velocity.

3) The calculation formula of the maximum temperature of conductor, which includes both LGJ-240/30 and LGJ-400/35, is proposed in this paper. And the calculation formula can be used to calculate and analyze the maximum ice-melting current.

VI. References

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VII. Biographies

Zhijin Zhang was born in Fujian Province, China, in July 1976. He received the B.Sc., M.Sc and Ph.D. degrees from Chongqing University, Chongqing, China, in 1999, 2002and 2005 respectively.
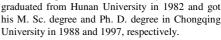He has been a Teacher with the College of Electrical Engineering, Chongqing University, since 1999. His research interests include high voltage, outdoor insulation, and numerical modeling and simulation. He is the author or coauthor of several technical papers.

Jianlin Hu was born in Hubei province, China, in 1978. He received the B.Sc. and M.Sc. degrees from Chongqing University, Chongqing, China, in 2001 and 2003, respectively. He is now working toward the Ph.D. degree in the College of Electrical Engineering, Chongqing University. He has been a Lecturer in the College of Electrical Engineering, Chongqing University since 2003. His main research interests include high voltage external insulation.

Xingliang Jiang was born in Hunan province, China, on July 31, 1961. He graduated from Hunan University in 1982 and got his M. Sc. degree and Ph. D. degree in Chongqing University in 1988 and 1997, respectively.
His employment experiences include the Shaoyang Glass Plant, Shaoyang, Hunan Province, Wuhan High Voltage Research Institute, Wuhan, Hubei province, and College of Electrical Engineering, Chongqing University, Chongqing China. His special fields of interest include high voltage external insulation, transmission line's icing and protection.

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Wenxia Sima was born in Henan province, China, on 13 July 1965. She graduated from Chongqing University in 1988 and obtained the Ph.D. degree in 1994 from Chongqing Univeristy. Her employment experience includes the college of Electrical Engineering of Chonging University. Her fields of interest include high voltage outdoor insulation and overvoltage protection.