ICE-MELTING METHODS AND COMPARISON WITH AC AND DC CURRENTS

Jiang Xingliang[1]*, Hu Jianlin[1], Zhang Jiwu[2], Shu Daisong[2], Gong Xiaowei[2], Yi Tianzhi[2]

1: State Key Laboratory of Power Transmission Equipment and System Security and New
Technology, College of Electrical Engineering of Chongqing University
174 Shazheng Street, Shapingba District, Chongqing, 400030, China

2: Huaihua Electrical Power Design Insitute, Hunan Power Corporation
Fuxing Road 157, Huaihua City, Hunan, 418000,China
* E-mail: xljiang@cqu.edu.cn

Abstract: This paper analyses and compares between AC and DC Short-circuit-current Ice-melting methods (SCCIM) in terms of heating effect, ice-melting time, critical ice-melting current and power capacity. The ice-melting time and critical ice-melting current of AC and DC SCCIM are tested by experiments in artificial climate chamber, and the results of experiments are basically consistent with the calculation results. Both calculation and experiment show that: The ice-melting effect of AC SCCIM is the same as that of DC SCCIM in essence when the effective value of AC is equal to the DC. However, the power capacity of AC ice-melting is much greater than that of DC ice-melting because of the line inductance. Under the same conditions, the critical ice-melting current of AC is smaller than that of DC, and the ice-melting time of AC is shorter than that of DC.

1 INTRODUCTION

Being the most serious menace to power grid, ice storm has endangered the 500kV lines even the 1000kV lines shown by operational experiment. To solve this disastrous problem, after the ice-storm of 2008, short-circuit-current ice-melting (SCCIM) has been accepted as the most effective method to resist ice storm by the State Grid Corporation and the Southern Power Grid Company, therefore, a lot of human, financial and material resources are put into the research and development of the methods and equipments for the SCCIM[1,2].

SCCIM refers to short-circuiting of the single-phase, two phase or three-phase conductor to form short-circuit current to melt the ice on the conductor[3]. This method includes the AC Short-circuit-current Ice-melting Method(AC SCCIM) and the DC Short-circuit-current Ice-melting Method(DC SCCIM).The former is provided with short-circuit current by power system, easy to operate with relatively low cost, which makes itself the most widely-used Ice-melting Method[5]. To take the ice-storm of 2008 for an example, this method was executed by Hunan Electric Power Corporation for 20 times on several lines, which was proved to be quite useful to anti-icing [6]. By contrast, without line inductance influence, DC SCCIM is more suitable for overhead lines ice-melting with high voltage and long span. It follows naturally that after the ice-storm of 2008, the State Grid Corporation and the Southern Power Grid Company put a lot of human, financial and material resources into the research and development of the methods and equipments for the DC SCCIM[10] .On Dec.31, 2008, with the world’s first stationary DC Ice-melting device with large capacity (Capacity of 60MVA) designed and manufactured on our own, the heating experiment was successfully completed on 500KV fu-sha I line of Hunan Power Grid [6]. This device makes 86KM 4×LGJ-400 wire heat up to 47℃. In January 2009, with the same kind of device of the Guangdong Power Grid, the first ice-melting field experiment was accomplished on 110KV Tong-Mei line. In addition, 220kV Power Supply Bureau in Liupanshui and 500KV Transformer Station in Fuquan also successfully carried out the same experiment [9].

This paper analyses and compares between AC and DC SCCIM in terms of heating, ice-melting time, critical ice-melting current and power capacity, and the corresponding experiments are performed in the artificial climate laboratory of Chongqing University.

2 EQUIVALENCE ANALYSIS OF AC AND DC SCCIM

2.1 Analysis of Joule Heating Effect of Conductor

When the AC or DC current is switched on, the generated Joule Heating can be expressed as:

$$q_j = I^2 r_T \tag{1}$$

Where, *I* is effective DC current or AC current, A; r_T is the conductor resistivity at temperature T, Ω/m, when the AC current is switched on, r_T refers to AC resistance r_{AC}, when the DC current is switched on, r_T refers to DC resistance r_{AC}.

According to equation(1), the ratio between AC Joule heating power and DC Joule heating power is:

$$\kappa = \frac{r_{AC}}{r_{DC}} \tag{2}$$

Where, *κ* is the ratio between AC Joule heating power and DC Joule heating power; r_{AC} and r_{DC} refer to AC and DC resistance of conductors respectively，Ω/m.

Generally speaking, r_{AC} is not equal to r_{DC}[11] due to the skin effect of AC conductor, since the effective cross-sectional area of AC is smaller than that of DC so as to make the AC resistance bigger than the DC resistance[12,13]. The skin effect means that when the AC current is switched on, the magnetic density inside of conductor is greater than that on the surface, thus the generated self-inductance has repulsive interaction on conductor current, making the current density on the surface of conductor higher than that inside.

Overhead conductors formula for calculating the AC resistance recommended by IEC60287 is[14]:

$$r_{AC} = r_{DC}(1 + y_s) \tag{3}$$

Where, y_s is conductor's skin effect coefficient, can be calculated by the following formula:

$$\begin{cases} y_s = \dfrac{x_s^4}{192 + x_s^4} \\ x_s^2 = \dfrac{8\times 10^{-7}\pi f k_s}{r_{DC}} \end{cases} \tag{4}$$

Where, *f* is the frequency of current, k_s is the structure coefficient of conductor. As for the cylindrical conductor or the steel-cored aluminium strand conductor, k_s=1.

According to equation (3), the ratio of Joule heat-power of four conductors can be calculated. As shown by table 1, the ratio of Joule heat-power of four conductors is close to 1.

Tab.1 AC & DC resistance and Joule heat ratio

Wire type	r_{dc}(Ω/km)	r_{ac}(Ω/km)	*κ*
LGJ-240/30	0.1125	0.1132	1.0062
LGJ-400/35	0.07389	0.07499	1.0149
JTMH-120	0.242	0.242	1.0000
CTMH-150	0.203	0.203	1.0000

2.2 Thermal effects of AC electromagnetic eddy

As shown in Fig.1, an alternating magnetic field around the conductor is produced when AC current is switched on. Ice is a kind of lossy mediator, so it will generate eddy current and heat when alternating magnetic field passes it, which is how thermal effects of AC electromagnetic eddy got its name [8]. Since DC current can't generate an alternating magnetic field around the conductor, thermal effects of electromagnetic eddy is not produced for DC conductor.

As for infinitely long transmission line, magnetic induction intensity around it is[14]:

$$B = \frac{\mu_i i}{4\pi r} \tag{5}$$

Where, μ_i refers to magnetic conductivity of ice, μ_i=4π×10^{-7}H /A; *r* is radius of magnetic field lines, m; $i = \sqrt{2}I\cos(\omega t + \varphi)$ is the current of conductor.

Eddy current of ice (i_{ice})is：

$$i_{ice} = -\frac{\sqrt{2}}{4}\cdot\frac{l u_i g_i (R_i - R_c)}{\pi r}\cdot I\omega\sin(\omega t + \varphi) \tag{6}$$

Where, g_i is ice's conductivity, g_i=6.641×10^{-4}s/m； *ω* is angular frequency, *ω*=2π*f*; *l* is conductor's length,m.

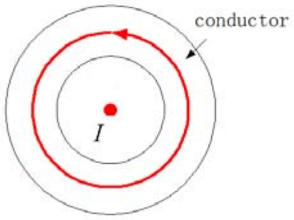


Fig.1 Magnetic field around electrified conductor

According to equation (6), effective value of eddy current is:

$$I_{ice} = \frac{l\mu_i (R_i - R_c) g_i}{4\pi r} \cdot \omega I \qquad (7)$$

Thermal power of unit length conductor is generated by eddy current(q_w):

$$q_w = I_{ice}{}^2 / g_i = \left[\frac{\mu_i (R_i - R_c)}{4\pi r}\right]^2 \cdot g_i \omega^2 I^2 \qquad (8)$$

The magnetic conductivity and electrical conductivity of ice is quite small, so the heating power of eddy current is also very small according to equation (8), with a magnitude of 10^{-8}W/m. To take LGJ-400/35 for an example, the heating power of eddy current is only 6.57×10^{-8}W/m with a current of 600 A. Therefore, for an AC current with a frequency of 50Hz, the heating power of eddy current is negligible when compared to the Joule heating effect.

The above analysis shows that the AC ice-melting has the same heating effect as that DC ice-melting does. When the effective value current of AC is equal to that of DC, the ratio of thermal power between AC and DC approximately is 1. For only a few conductors with relatively large cross-sectional area, the ratio of thermal power between AC and DC approximately is slightly larger than 1, so DC resistance of conductor can be replaced by AC resistance of conductor.

3 COMPARISON OF ICE-MELTING TIME BETWEEN AC AND DC SCCIM

AC ice-melting process is same as DC. When AC or DC current is switched on, generated Joule Heating leads to ice melting. Because of skin effect, there is more magnetic flux in the conductor than on the surface; inductive counter electromotive force is comparatively large, which lead to higher density on the surface of the conductor than the inside. Therefore, AC resistance is bigger than DC.

Over a wider range of temperature, resistance is linear with temperature. The DC resistance of conductor at 20℃ ($r_{dc,20}$) can be obtained from the general Electric Manual. When taking the skin effect into consideration, conductor AC resistance ($r_{ac,t}$) can be expressed as:

$$r_{ac,t} = (1 + y_s) r_{dc,t} \qquad (9)$$

$$r_{dc,t} = r_{dc,20}[1 + \alpha_{20}(t - 20)] \qquad (10)$$

Where, α_{20} is temperature coefficient of resistance, for aluminum conductor α_{20}=4.0×10^{-3}/℃; t is temperature,℃; $r_{dc,t}$ is DC resistivity at t℃, Ω/m; y_s is skin effect coefficient, it can be calculated by equation (4).

The surface of conductor is covered by a mixture of ice-water during the process of ice-melting，t=0℃, the frequency of AC is Hz，so AC resistance of the conductor is:

$$r_{ac,t} = \left[1 + \frac{1}{1.3216\times1010\times r_{dc,t}^2 + 0.8}\right] r_{dc,t} \qquad (11)$$

According to above analysis, the ratio of ice-melting duration between AC and DC is:

$$\frac{T_{dc}}{T_{ac}} = \frac{r_{0,ac}}{r_{0,dc}} = 1 + \frac{1}{1.1186\times10^{10}\times r_{dc,0}^2 + 0.8} \qquad (12)$$

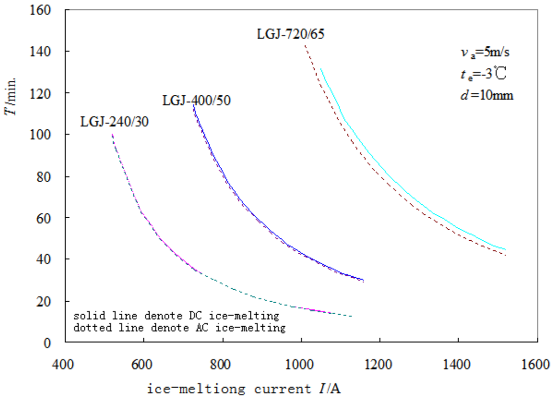


Fig.2 Influence of AC and DC SCCIM on ice-melting time

The experiments concerning this paper are carried out in the multifunctional artificial climate chamber with a diameter of 7.8 m and a height of 11.6 m. Assuming Ambient temperature t_e=-5.0℃，the ice thickness of conductor d=10mm，wind speed v_a=10.0m/s, AC and DC ice-melting time of calculation and experiment are shown in table.2. Both calculation and experiment results show that: the ice-melting time of AC is shorter than that of DC, and it is more obvious with the increasing of conductor cross-sectional area.

Tab.2 Ice-melting duration of AC/DC SCCIM
(t_e=-5.0℃, d=10mm, v_a=5.0 m/s)

Wire type	current /A	DC ice-melting time/h		AC ice-melting time /h	
		Theoretical calculation	experiment results	Theoretical calculation	experiment results
LGJ-70	175	Not melting	Not melting after 4hs	Not melting	——
LGJ-70	280	2.16	ice shedding after 2.5hs	2.16	——
LGJ-240	430	Not melting	Not melting after 4hs	Not melting	——
LGJ-240	600	2.24	ice shedding after 2.5hs	2.24	ice shedding after 2.5hs
LGJ-400	800	3.03	ice shedding after 3hs	2.28	ice shedding after 2.5hs

LGJ-400	1000	1.29	ice shedding after 1.5hs	1.06	ice shedding after 1h
LGJ-720	1300	2.10	ice shedding after 2hs	1.08	——

4 COMPARISON OF CRITICAL ICE-MELTING CURRENT BETWEEN AC AND DC SCCIM

The critical ice-melting current can be calculated by the equation (13) [16,17] :

$$I_c = \sqrt{\frac{-2\lambda_{\Theta 1} R_i h T_a}{r_T R_i h \ln(R_i / R_c) + 2 r_T \lambda_{\Theta 1}}} \tag{13}$$

Where, h is heat-transfer coefficient, W/(m^2.℃); T_i is the temperature of ice surface, ℃; T_a is ambient temperature, ℃; r_T is conductor resistivity at T℃, Ω/m; $\Delta T = T_i - T_a$; R_c is the radius of conductor, m; $\chi = 341.18(R_c + R_i)^{1.5} R_c^{0.5} + 3.01(R_i^2 - R_c^2)(\Delta T - T_a)$; r_T is conductor's resistivity at T℃, Ω/m; h is the heat-transfer coefficient between air and the surface of the ice, W/(m^2.℃); t is ice-melting time.

Assuming the ambient temperature t_e = -5.0℃, the wind speed v_a=5.0m/s, the ice thickness of conductor d=10×10^{-3} m, the critical ice-melting current of conductors can be calculated by equation (13), and experiment results are shown in table.3. As shown in table 3, under the same conditions, the critical ice-melting current of AC is smaller than that of DC.

Tab. 3 Critical ice-melting current of AC/DC SCCIM

Wire type	critical ice-melting current $I_{dc\text{-}c}$/A		critical ice-melting current $I_{ac\text{-}c}$/A	
	calculated value	measured value	calculated value	measured value
LGJ-70	217.5	231.21	220.2	236.1
LGJ-240	440.0	463.2	445.9	461.7
LGJ-400	602.0	650.4	571.5	590.6
LGJ-720	857.0	887.9	704.9	779.3

Notes: t_e = -5.0℃ , v_a=5.0m/s, d=10×10^{-3}m , L=20m, length of ice-covered conductor l=1m

5 COMPARISON OF POWER CAPACITY BETWEEN AC AND DC ICE-MELTING

5.1 Power Capacity of DC Short-circuit Current Ice-melting

As shown in Fig. 3, the equivalent circuit of DC SCCIM, there isn't inductive and capacitive reactance in DC ice-melting conductor. DC ice-melting power capacity (S_{dc}) can be determined by:

$$S_{dc} = I^2 r_T L_c \tag{14}$$

Where, S_{dc} is DC ice-melting power capacity, V.A; L_c is the length of ice-melting conductor, m.

5.2 Power Capacity of AC Short-circuit Current Ice-melting

As for the ice melting by AC short-circuit current, inductive resistance must be taken into consideration besides the resistance in conductor. As shown in fig.4, the equivalent circuit of AC SCCIM, active power of AC SCCIM can be acquired:

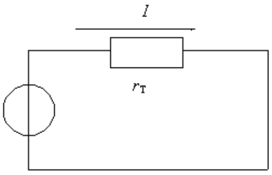


Fig. 3 Equivalent Circuit of DC SCCIM

$$P = I^2 r_T L_c \tag{15}$$

Where, P is active power of AC SCCIM, W.

Reactive power of AC SCCIM is:

$$Q = I^2 \omega l L_c \tag{16}$$

Where, l is conductor's inductance, H/m; ω is angular frequency,*equals* 314 radian/s.

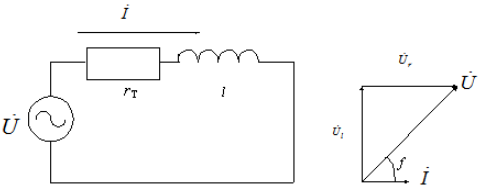
According to equation (15) and equation (16), power capacity of AC SCCIM can be acquired:

$$S_{ac} = \sqrt{P^2 + Q^2} = I^2 L_c \sqrt{{r_T}^2 + \omega^2 l^2} \tag{17}$$

And the inductance per meter conductor is[15]:

$$l = \frac{\mu_0}{2\pi} \cdot \ln\left(\frac{2H_c}{R_c}\right) \tag{18}$$

Where, H_c is the height (m) of overhead lines, for overhead lines, H_c can be approximately 20 m; for contact grid, H_c can be approximately 10 m; μ_0 is the magnetic conductivity of atmosphere, μ_0=4π×10^{-7}H /A.



(a)circuit diagram (b)phase diagram

Fig.4 Equivalent Circuit of AC SCCIM

5.3 Comparison of Power Capacity between AC and DC SCCIM

As for 220KV and above system, bundle conductor is often used, whereas for 110KV and below, single conductor is generally employed. With regard to power capacity, the requirement for bundle conductor is different from that for single conductor. Tab.4 shows the power capabilities and voltages of four conductors including 4*400, 2*240, 400, 240 in AC and DC SCCIM respectively. Assuming v_a=5m/s, T_a=-5℃, d_i=10mm, t=60min，and L_c=1km, the calculation process is as follows: firstly, AC and DC ice-melting current can be calculated by equation (19), Then, the power capacity of DC ice-melting can be calculated by equation(14), equation (15), equation (16) and equation (17), the AC active power, the AC reactive power and the AC power capacity can be calculated.

$$I=\sqrt{\frac{\chi+2\pi h\Delta TR_i t\times10^{-6}}{r_T t}}\times10^3 \qquad (19)$$

According to Tab.4, for the ice-melting of a length of 200km 4*400 transmission line, if AC three-phase SCCIM is adopted, needed power capacity power is 1.532GVA, reactive power 1.52Gvar, voltage 113.6kV. However, it is difficult to find an appropriate power source for AC three-phase SCCIM, so it isn't suitable for 4*400 or any transmission line with bigger cross-sectional area.

And for transmission line 2*240 with a length of 100 km, ice-melting power are: 184.5MVA for power capacity，180Mvar for reactive power，40.3kV for the voltage if AC three-phase SCCIM is adopted. For 2*240 or any transmission line with smaller cross-sectional area, three-phase SCCIM can be adopted with advanced ice-melting devices under appropriate conditions.

Table 4 Power capability and voltage of AC or DC SCCIM

(T_a=-5℃，d_i=10mm，v_a=5m/s，t=60min)

Wire type	I_{dc} **A**	I_{ac} **A**	S_{dc} **KVA /km**	Q_{ac} **Kvar /km**	S_{ac} **kVA /km**	U_{dc} **kV /km**	U_{ac} **kV /km**
LGJ-4×400	4524	4490	378	2525	2553	0.084	0.568
LGJ-2×240	1531	1526	132	601	615	0.086	0.403
LGJ-400	1131	1123	95	631	638	0.084	0.568
LGJ-240	765	763	66	301	308	0.086	0.403

Where, I_{dc} - DC short-circuit ice-melting current ; I_{ac} - AC short-circuit ice-melting current ; S_{dc} - the power capacity of DC SCCIM per kilometer transmission line ; Q_{ac} - the reactive power of AC SCCIM per kilometer transmission line ; U_{dc} - the voltage loss of DC SCCIM per kilometer transmission line ; U_{ac} - the voltage loss of AC SCCIM per kilometer transmission line ; S_{ac} - the power capacity of AC SCCIM per kilometer transmission line.

6 CONCLUSION

The ice-melting effect of AC SCCIM is the same as that of DC SCCIM in essence when the effective value of AC is equal to the DC.

The power capacity of AC ice-melting is much greater than that of DC ice-melting because of the line inductance.

Under the same conditions, the critical ice-melting current of AC is smaller than that of DC.

Under the same conditions, the ice-melting time of AC is shorter than that of DC.

7 ACKNOWLEDGMENTS

This work was supported by National Basic Research Program of China (973 Program: 2009CB724501).

8 REFERENCES

[1] G.Peng Xiangyang, Zhou Huamin. Frost Disaster and Its Defense of Power Network[J]. Electric Power Science and Engineering, 2009, 25(07): 16-19.

[2] LU Jia-zheng; JIANG Zheng-long; ZHANG Hong-xian; LEI Hong-cai; PENG Ji-wen .Technical analysis of Hunan power grid ice disaster in 2008[J]. Hunan Electric Power,2008, 3(03): 1-9.

[3] K. H. Hesse. Ice melting systems in Manitoba hydro[J]. Canadian Electrical Association, Montreal, QC, Canada, Mar., 1998.

[4] B.W.Webb, M. K. Moallemi, R.Viskanta. Experiments on melting of unfixed ice in a horizontal cylindrical Capsule[J]. Transactions of the ASEM, Journal of Heat Transfer, 1987, 109(7): 454-459.

[5] M. Huneault, C. Langheit, R. S. Arnaud, J. Benny, J. Audet, J. C. Richard. A dynamic programming methodology to develop de-icing strategies during ice storms by channeling load currents in transmission networks[J]. IEEE Transactions on Power Delivery, 2005, 20(2): 1604-1610.

[6] LU Jiazheng; LI Bo; ZHANG Hongxian; FANG Zhen; JIANG Zhenglong .Application of New-Type AC and DC De-Icers in Hunan Power Grid[J]. Southern Power System Technology, 2009, 4(04): 77-79.

[7] LIU Gang; ZHAO Xue-zeng; CHEN Yong-hui; JIANG Shi-jin; WANG Dong; LIU Zhi-ping. An Ice-Melting Method of Adjusting Electric Load Based on Controllable Inductor and Capacitor Compensation[J]. Power System Technology, 2008, 32(S2): 99-102.

[8] J. D. McCurdy, C. R. Sullivan, V. F. Petrenko. Using dielectric losses to de-ice power transmission lines with 100 kHz high-voltage excitation[C]. Conference Record of the 2001 IEEE Industry Applications Conference, Vols 1-4, 2001, 2515-2519.

[9] XU Shu-kai; LI Xiao-lin; RAO Hong; TANG Ya-jun; YAN Shu-gang; FU Chuan. Development and Test of 500 kW DC De-Icer in China Southern Power Grid[J]. Southern Power System Technology, 2008, 2(04): 32-36.

[10] JIANG Xing-liang; FAN Song-hai; SUN Cai-xin; SHU Li-chun. Analysis on Application of the Magnetic Material of Low Curie Point to Deicing of Transmission Lines. Southern Power System Technology, 2008, 2(2): 19-22.

[11] ZHANG Xiao-lin; XU Jing-hua. Discussion of the Skin Effect in Transmission Line for Signals[J]. Jiangxi Science, 2008, 26(06): 873-875.

[12] LEI Gui-lin; QU Hong-bin. The Theoretical Explanation of Skin Effect[J]. Journal of Gansu Sciences, 2005, 17(01): 28-29.

[13] LI Jian-bing; NIU Zhong-xia; ZHOU Dong-fang; SHI Yu-jie. Numerical Analysis of the Skin Effect in Long Rectangle Conductor[J]. Journal of Information Engineering University, 2006, 7(02): 167-171.

[14] Liang Canbin; Qin Guangrong; Liang Zhujian. electromagnetism[M]. Beijing: Higher Education Press,2004.

[15] Zhou Zecun; Shen qigong;Wang dazhong, high voltage technique[M]. Beijing: China Electric Power Press,2004.

[16] Xingliang Jiang, Songhai Fan, Zhi-jin Zhang, Cai-xin Sun, Li-chun Shu. Simulation and Experimental Investigation of DC Ice-Melting Process on an Iced Conductor[J]. IEEE Transactions on Power Delivery,2010,25(02): 919-929.

[17] JIANG Xing-liang; FAN Song-hai; HU Jian-lin; ZHANG Zhi-jin; SUN Cai-xin. Analysis of Critical Ice-melting Current for Short-circuit DC Transmission Line[J]. Proceedings of the CSEE, 2010,30(1): 111-116.