# COMPARISON BETWEEN AC AND DC SHORT-CIRCUIT-CURRENT ICE-MELTING METHODS

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***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.

## 2. RESULTS AND DISCUSSION

### *A. Analysis of Joule Heating Effect of Conductor*

**Table 1:** AC & DC resistance of conductors and their Joule heat-power ratio

| Wire type | $r_{dc}$(Ω/km) | $r_{ac}$(Ω/km) | $\kappa$ |
|---|---|---|---|
| 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 |

### *B. Comparison of Critical Ice-melting Current Between AC and DC SCCIM*

**Table 2:** the critical ice-melting current of AC and DC SCCIM

| Wire type | critical ice-melting current Idc-c/A | | critical ice-melting current Iac-c/A | |
|---|---|---|---|---|
| | calculated | measured | calculated | measured |
| 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 |

As shown in table.2, under the same conditions, the critical ice-melting current of AC is smaller than that of DC.

### *C. Comparison of Ice-melting Time between AC and DC SCCIM*

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.

## 3. CONCLUSION

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, and the corresponding experiments are performed in the artificial climate laboratory of Chongqing University. Both calculation and experiment show that:

(1) 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;

(2) The power capacity of AC ice-melting is much greater than that of DC ice-melting because of the line inductance;

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

## 4. 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.

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***Key words-AC/DC; Short-circuit-current; Ice-melting (AC/DC SCCIM); heating effect; ice-melting time; critical ice-melting current; power capacity***

## I. 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.

## II. EQUIVALENCE ANALYSIS OF AC AND DC SCCIM

### A. *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; rAC and rDC refer to AC and DC resistance of conductors respectively, Ω/m.

Generally speaking, rAC is not equal to rDC[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 ys is conductor's skin effect coefficient, which 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, ks is the structure coefficient of conductor. As for the cylindrical conductor or the steel-cored aluminium strand conductor, ks=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.

TABLE 1 Ac & Dc Resistance of Conductors and Their Joule Heat-power 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 |

### B. *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 μi refers to magnetic conductivity of ice, μi=4π×10-7H /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 (iice )is:

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

Where gi is the conductivity of ice, gi=6.641×10－4s/m; ω is angular frequency , ω=2πf; l is the length of conductor, m.

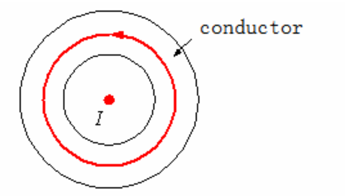


Figure 1. Magnetic field around electrified conductor

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

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

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

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

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 10-8W/m. To take LGJ-400/35 for an example, the heating power of eddy current is only 6.57×10-8W/m with a current of 600A. 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.

## III. COMPARISON OF ICE-MELTING TIME BETWEEN AC AND DC SCCIM

The process of AC ice-melting is same as the process of DC ice-melting： when the AC or DC current is switched on, the generated Joule Heating leads to ice melting. Because of the skin effect, there is more magnetic flux inside of 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, the AC resistance is bigger than the DC resistance.

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

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

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

Where α20 is temperature coefficient of resistance, for aluminum conductor α20=4.0×10-3/℃; t is temperature, ℃; rdc,t is DC resistivity at t℃, Ω/m; ys is skin effect coefficient, it can be calculated by equation (4).

The surface of the 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 :

$$r_{ac,t} = \left(1 + \frac{\left(\frac{8\pi f\times 10^{-7}}{r_{dc,t}}\right)^2}{192 + 0.8\times\left(\frac{8\pi f\times 10^{-7}}{r_{dc,t}}\right)^2}\right) r_{dc,t} \tag{11}$$

$$r_{ac,t} = \left(1 + \frac{1}{\frac{192 r_{dc,t}^2}{(8\pi f\times 10^{-7})^2} + 0.8}\right) r_{dc,t} \tag{12}$$

$$r_{ac,t} = \left(1 + \frac{1}{1.3216\times 10^{10}\times r_{dc,t}^2 + 0.8}\right) r_{dc,t} \tag{13}$$

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

$$\frac{T_{ac}}{T_{dc}} = \frac{r_{0,dc}}{r_{0,ac}} = \left(1 + \frac{1}{1.1186\times 10^{10}\times r_{dc,0}^2 + 0.8}\right)^{-1} \tag{14}$$

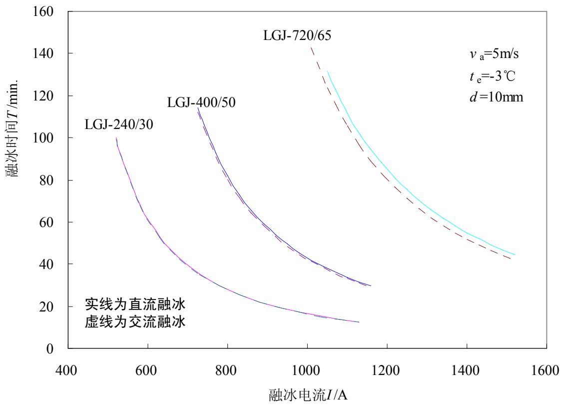


Figure 2. Influence of AC and DC SCCIM on Ice-melting Time

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.

TABLE 2 The Ice-melting Time of Ac and Dc Sccim($t_e$=-5.0 ℃,$d$=10mm,$v_a$=5.0m/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 | —— |

## IV. COMPARISON OF CRITICAL ICE-MELTING CURRENT BETWEEN AC AND DC SCCIM

The critical ice-melting current can be calculated by the equation (15)[16,17] :

$$I_c = \sqrt{\frac{-2\lambda_{\Theta 1} R_i h T_a}{r_T R_i h \ln(R_i / R_c) + 2 r_T \lambda_{\Theta 1}}} \quad (15)$$

Where $\chi = 341.18(R_c + R_i)^{1.5} R_c^{0.5} + 3.01(R_i{}^2 - R_c^2)(\Delta T - T_a)$ , $\Delta T = T_i - T_a$, $h$ 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; $R_c$ is the radius of conductor , m; $r_T$ is conductor 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 (15), 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.

TABLE 3 The Critical Ice-melting Current of Ac and 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 |
| 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 length of conductor L=20m, the length of ice covered conductor l=1m | | | | |

## V. COMPARISON OF POWER CAPACITY BETWEEN AC AND DC ICE-MELTING

### *A. Power Capacity of DC Short-circuit Current Ice-melting*

As shown in Fig. 3, which is 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 the following formula:

$$S_{dc} = I^2 r_T L_c \quad (16)$$

Where $S_{dc}$ is DC ice-melting power capacity, V.A; $r_T$ is electrical resistivity of conductor at $T$℃, Ω/m; $L_c$ is the length of ice-melting conductor, m.

### *B. Power Capacity of AC Short-circuit Current Ice-melting*

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

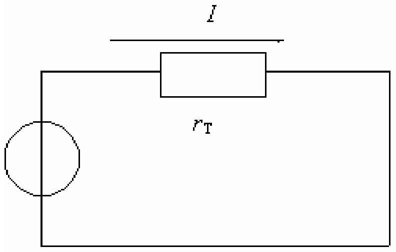


Figure 3. Equivalent Circuit of DC SCCIM

$$P = I^2 r_T L_c \quad (17)$$

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

Reactive power of AC SCCIM is:

$$Q = I^2 \omega l L_c \quad (18)$$

Where $l$ is the inductance of unit conductor, H/m; $\omega$ is angular frequency, for 50Hz current, $\omega$=314radian/s.

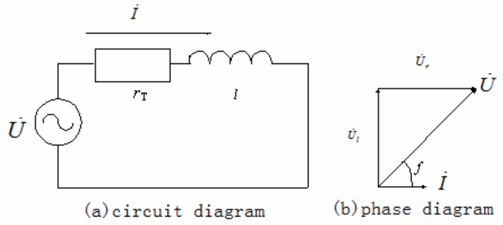
According to equation (17) and equation (18), power capacity of AC SCCIM can be acquired:

$$S_{ac} = \sqrt{P^2 + Q^2} = I^2 L_c \sqrt{r_T{}^2 + \omega^2 l^2} \quad (19)$$

Inductance of unit conductor is[15]:

$$l = \frac{\mu_0}{2\pi} \cdot \ln\left(\frac{2H_c}{R_c}\right) \quad (20)$$

Where $H_c$ is the height (m) of overhead lines, for overhead lines, $H_c$ can be approximately 20m; for contact grid, $H_c$ can be approximately 10m; $\mu_0$ is the magnetic conductivity of atmosphere, $\mu_0$=4π×10$^{-7}$H /A.



(a) circuit diagram (b) phase diagram

Figure 4. Equivalent Circuit of AC SCCIM diagram phase chart

### *C. Comparison of Power Capacity between AC and DC SCCIM*

As for 220KV and above voltage class, bundle conductor is often used, whereas for 110KV and below voltage class, single conductor is generally employed. With regard to power capacity, the requirement for bundle conductor is different from that for single conductor. Table 4 shows the power capabilities and voltages of four conductors including LGJ-4×400, LGJ-2×240, LGJ-400, LGJ-240 in AC and DC SCCIM respectively. Assuming wind speed $v_a$=5m/s, ambient temperature $T_a$=-5℃, ice thickness $d_i$=10mm, ice-melting time $t$=60min, the length of ice-melting conductor $L_c$=1km, the process of calculation is as follows: firstly, AC and DC ice-melting current can be calculated by equation (21), Then, the power capacity of DC ice-melting can be calculated by equation (16), equation (17),equation (18) and equation (19), the AC active power, the AC reactive power and the AC power capacity can be calculated.

$$I = \sqrt{\frac{\chi + 2\pi h \Delta T R_i t \times 10^{-6}}{r_T t}} \times 10^3 \qquad (21)$$

Where $\chi = 341.18(R_c + R_i)^{1.5} R_c^{0.5} + 3.01(R_i^2 - R_c^2)(\Delta T - T_a)$, $\Delta T = T_i - T_a$, $h$ is heat-transfer coefficient, W/(m$^2$.℃); $T_i$ is the temperature of ice surface, ℃; $T_a$ is ambient temperature, ℃.

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

According to table 4, as for transmission line LGJ-2 × 240 with an assumed length of 100km, the parameters of ice-melting power are: the 184.5MVA for power capacity, 180Mvar for reactive power, 40.3kV for the voltage if AC three-phase SCCIM is adopted. For LGJ-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 The 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** | ***I*ac** | ***S*dc** | ***Q*ac** | ***S*ac** | ***U*dc** | ***U*ac** |
|---|---|---|---|---|---|---|---|
| | ***A*** | ***A*** | ***KVA /km*** | ***Kvar /km*** | ***kVA /km*** | ***kV /km*** | ***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.

## VI.CONCLUSION

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, and the corresponding experiments are performed in the artificial climate laboratory of Chongqing University. Both calculation and experiment show that:

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(2) The power capacity of AC ice-melting is much greater than that of DC ice-melting because of the line inductance;

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

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

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