[[1]](#footnote-1)

An Online Thermal De-icing Method for Urban Rail Transit Catenary

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*Abstract—*The frequent icing of catenary in cold areas has seriously affected the normal operation of urban rail transit. Among many de-icing methods for catenary, the thermal de-icing method which uses current Joule heat to melt ice has been widely adopted due to its efficiency and safety. However, most of the thermal de-icing methods are only applicable when the line is out of service, which cannot solve the icing problem of catenary during the operation period. In order to solve this problem, this paper proposes a novel online thermal de-icing method which takes the catenary of up and down lines as the de-icing current loop. Based on the Bolsdorf theory, the de-icing and anti-icing current of catenary are calculated, and the structure and control strategy of de-icing power unit (DIPU) are designed. The influence of online de-icing on the traction power supply system is quantitatively analyzed by the electric network model. The accurate dynamic simulation model of the traction power supply system including the DIPU is established to verify the analysis conclusion. The results show that the online thermal de-icing method has limited influence on the traction power supply system, but achieves good de-icing performance in the normal operation of the line.

*Index Terms*—Catenary, urban rail transit, thermal de-icing, online de-icing

# Introduction

U

nder the influence of low temperature, wet snow and other climatic conditions, the icing phenomenon of urban rail transit catenary occurs frequently [1]-[4]. The catenary is composed of contact wire and messenger wire, which is an important part of the traction power supply system. The train obtains electric energy through pantograph sliding contact wire. When the catenary is covered with ice, arcing will occur between the contact wire and the pantograph, which will cause the train unable to take current normally and even lead to major accidents such as contact wire breaking and pantograph striking [3]-[5]. In February 2020, affected by the temperature drop, some sections of Tianjin Line 9 had icing phenomenon in the normal operation period, which led to the train pantograph unable to take current normally and the icing sections stopped. In order to ensure the normal operation and power supply safety of urban rail transit lines in bad weather, the research on the de-icing technology of catenary becomes very urgent.

At present, the de-icing methods of catenary can be divided into mechanical de-icing method, chemical anti-icing method and thermal de-icing method [6], [7]. Mechanical de-icing usually adopts the way of the train coasting in the icing section, and uses the pantograph to scrape the ice on the contact wire passively. The friction stress and arc generated in this process usually cause great damage to the pantograph and contact wire [8]. The chemical anti-icing method prevents the contact wire from icing by applying special agent [9], [10]. However, the friction under the operation state of the line reduces the time of the agent action on the contact wire and weakens the effect. The chemical anti-icing method also causes environmental pollution. The thermal de-icing method uses a large current to generate Joule heat in the catenary to melt ice [11-16]. Compared with other methods, the thermal de-icing method has less damage, higher efficiency, no pollution, and higher practical application value.

Regarding the thermal de-icing method, the different forms of de-icing current can be divided into AC current de-icing and DC current de-icing [13], [14]. Both these forms are using short circuit [15], [16]. In this method, one end of the line requiring de-icing is short-circuited or connected in series with small impedance, and the other end is connected with the power supply to provide enough de-icing current. Due to the negative impact of the short circuit, the short-circuit method can only be used for de-icing when the line is out of service. The resistance wire heating method is also applicable to both AC and DC de-icing current. In this method, an insulated wire with large resistance is built in the contact wire for de-icing. Alstom in France and Hitachi in Japan have developed the corresponding catenary de-icing system [17], [18]. The resistance wire heating method can be used for online de-icing, but it is easy to burn off the contact wire due to the heat of the built-in insulation wire when de-icing. Moreover, the complex structure and high manufacturing cost of contact wire limit its application. In [19], [20], a skin effect de-icing method with high-frequency AC current was proposed. This method has the advantage of low de-icing power supply capacity, but it can only be used as an offline de-icing method due to high-frequency current injection and electromagnetic interference. In [21], a de-icing method was proposed to control SVG to increase the reactive current in the line. This method does not affect the load during de-icing, and is an effective online de-icing method using AC. In [22], a circulating current de-icing method based on energy feedback device was proposed. By controlling converter working states in different traction substations, DC circulating current is generated in the catenary between traction substations for de-icing. This method does not need to add an additional power supply, but requires high feeding capacity. This method can only be used during offline, because de-icing circulating current has a significant impact on catenary voltage.

The DC power supply system is widely used in urban rail transit. If the AC de-icing current is injected into the line, it will bring the AC disturbance to the DC catenary voltage and affect the normal operation of the train. Therefore, it is more suitable to use DC current to de-ice for catenary during operation. The existing online thermal de-icing method usually adds a resistance heating wire which increases the complexity of the catenary structure. It is of great significance to design an online thermal de-icing method for urban rail transit catenary with small-scale modification, which does not affect the normal operation.

This paper proposes a novel online thermal de-icing method for catenary of urban rail transit. In Section II, the de-icing and anti-icing current of catenary under different weather conditions are calculated based on the Bolsdorf theory. In Section III, the realization and working principle of the online de-icing method are described, and the structure and control strategy of the DIPU are designed. In Section IV, the influence of this method on the traction power supply system is quantitatively analyzed, and the accurate dynamic simulation model of the de-icing system is established and verified in Section V.

# De-icing Calculation of Catenary

There are various types and shapes of ice covering for catenary, which can be generally divided into rime ice, glaze ice and mixed glaze [23]. The formation of catenary icing is affected by the meteorological conditions, for example, ambient temperature, air humidity and wind speed. Among all the factors, air humidity plays a decisive role in the type of icing [24]. When the air humidity is low, the supercooled water droplets captured by the contact wire can completely solidify on the surface. This icing process is called dry growth, and the ice formed is rime. When the air humidity is high, only part of the supercooled water droplets captured by the contact line solidifies on the surface, showing a mixed state of ice and water. This icing process is called wet growth, and the ice formed is glaze and mixed glaze [25]. The ice formed by dry growth is loose and has little adhesive force, which usually has little impact on the train operation. However, the ice formed by wet growth has high density and strong adhesive strength, which causes significant damage to the catenary and pantograph. The previous research showed that the formation conditions of wet growth icing are wind speed of 3-15m/s, temperature of 0-1.5°C and air humidity of 80%. Therefore, the de-icing of catenary aims to remove ice formed by wet growth under this meteorological condition [26].

It is necessary to ensure that the Joule heat generated by the current on the catenary is greater than the sum of the heat absorbed by the ice melting and the heat dissipated during the ice melting process. The minimum de-icing current represents the minimum current required to melt the ice covering of the catenary under the corresponding ambient temperature, wind speed conditions and air humidity. According to Bolsdorf theory [27], the formula for calculating the minimum de-icing current of wet growth icing can be derived as follows:

 (1)

 (2)

 (3)

where Δ*t* is the difference between the conductor temperature and the outside air temperature (°C), *R*0 is the resistance of the conductor per unit length at 0°C (Ω/m), *RT*0 is the equivalent ice conduction thermal resistance (°C·cm/W), *RT*1 is the equivalent convection and radiation thermal resistance (°C·cm/W), *D* is the outer diameter of the conductor after icing (cm), *d* is the conductor diameter (cm), *v* is the wind speed (m/s), and *λ* is the thermal conductivity (W/°C·cm), which is taken as 2.27×10-2 for the wet growth icing.

In order to ensure the de-icing effect, the de-icing current used in practical application should be greater than the minimum de-icing current. The de-icing time should also be considered. The relationship between de-icing current and de-icing time is as follows:

 (4)

where *I*r is de-icing current (A), *T*r is de-icing time (h), *b* is ice thickness (cm), and *g*0 is the density of ice, which is generally taken as 0.9.

The de-icing current is limited by the maximum allowable temperature of the conductor itself. Under the corresponding ambient temperature and wind speed conditions, the maximum current for the wire to reach the allowable temperature of the conductor in a short time is:

 (5)

where *I*max is the maximum allowable de-icing current (A), and *R*90 is the resistance of the conductor per unit length at 90°C (Ω/m).

In addition to de-icing the catenary, Joule heat generated by the current can also be used to protect the catenary without icing. The anti-icing current can be written as follows:

 (6)

where *ε*i is the radiation coefficient, which is generally 0.6 for copper conductor, *t*1 is the temperature of unfrozen conductor which is generally 0°C, and *t*2 is the ambient temperature (°C) when the conductor is frozen.

According to the above calculation method, this paper carries out de-icing calculation for the catenary of Tianjin Line 9. The catenary of Tianjin Line 9 adopts the form of parallel connection of double messenger wires and double contact wires. The type and resistance parameters of messenger wire and contact wire are shown in TABLE I. The calculated equivalent resistance of catenary is 0.0334Ω/km.

For the worst wet growth icing meteorological conditions with a wind speed of 15m/s and a temperature of -1.5°C, according to (1)-(6), the de-icing current, maximum de-icing current, minimum de-icing current and anti-icing current of contact wire, messenger wire and catenary of Tianjin Line 9 can be calculated. When the ice thickness is 1cm and the de-icing time is 60min, the calculation results are shown in TABLE II.

TABLE I

Catenary Parameters of Tianjin Line 9

|  |  |  |
| --- | --- | --- |
| Catenary Form | Parallel connection of double messenger wires and double contact wires | |
| Messenger wire | Contact wire |
| Type | CTHA120 | JT150 |
| Wire Diameter(mm) | 13.20 | 15.80 |
| 20°C Conductor Resistance(Ω/km) | 0.1488 | 0.1213 |
| 20°C Catenary Resistance(Ω/km) | 0.0334 | |

TABLE II

Calculation Results of De-icing for Catenary

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Type | Anti-icing Current(A) | Minimum De-icing  Current(A) | Maximum De-icing Current(A) | De-icing Current(A) |
| Messenger Wire | 298.4 | 276.6 | 1388.6 | 280.6 |
| Contact Wire | 251.7 | 240.8 | 1034.8 | 243.9 |
| Catenary | 1100.2 | 1034.8 | 5122 | 1049.1 |

# Online Thermal De-icing Method

The DC traction power supply system of urban rail transit is mainly composed of traction substation, catenary and return rail. Among them, the traction substation mainly includes rectifier unit and energy feed device [28]-[32]. The DC positive feeder of the traction substation is connected to the catenary on the up and down lines for trains to collect current, and the negative feeder is connected to the rail to return current. Based on the existing traction power supply system, the online thermal de-icing method proposed in this paper adds DIPU to de-ice the icing section. The DIPU output ports are connected to the midpoint of the up and down catenary. The de-icing or anti-icing current is injected from the midpoint of the up catenary, and returns to the down catenary, as shown in Fig. 1.



Fig. 1. Schematic diagram of online thermal de-icing method of catenary

*A. Various thermal de-icing method comparison*

As a comparison, Fig. 2 shows the realization and current flow path of traditional catenary thermal de-icing methods (short-circuit and circulating current method).



(a) De-icing method for short circuit between catenary and rail



(b) De-icing method for short circuit between up catenary and down catenary



(c) Circulating current de-icing method of energy feed device

Fig. 2. Schematic diagram of traditional de-icing method of catenary

The short-circuit method with catenary and rail as de-icing current path is shown in Fig. 2(a). In this method, the catenary and rail are short-circuited at the end of the line, and a power supply is connected at the beginning to provide current for de-icing. In order to transmit the de-icing current through the whole icing section and prevent the traction substation from short circuit, the traction substations on both sides of the icing section must be disconnected, which directly limits the application of this method in de-icing of operation lines. The short-circuit method in Fig.2(b) uses the unique catenary structure by taking the up and down catenary as the de-icing current flow path. However, similar to the method in Fig. 2(a), the traction substations on both sides of the ice covered section must be disconnected due to the short-circuit effect of the line. The circulating current method shown in Fig. 2(c) makes use of the bidirectional conduction characteristics of the energy feedback device. The energy feedback devices in two traction substations work in the mode of rectification and inversion respectively, transmitting the de-icing circulating current between the catenary and the rail.

Compared with Fig. 2(a) and Fig.2 (b), the online de-icing method in Fig. 1 does not require traction disconnection caused by short circuit in de-icing section. Moreover, the DIPU is set at the midpoint of the de-icing section to ensure that the de-icing current of both sides of the catenary is the same. If it is set in other positions, the distribution of de-icing current on both sides of catenary is different, and the total output current of DIPU is larger under the same icing condition. Therefore, the optimal de-icing efficiency of DIPU can be achieved by setting it at the midpoint. Compared with Fig. 2(c), the de-icing current in Fig. 1 is not in the same flow path with the traction current, which avoids the rise of catenary voltage. This means that the traction power supply system and the de-icing system are in a relatively independent state, which makes it possible for DIPU to de-ice the catenary of the operating line. However, the de-icing current injected by DIPU will bring additional voltage drop to the catenary, and the de-icing current may still pass through the train and rail when there are trains in the up and down sections of operation. The influence of DIPU on the traction power supply system and train needs further analysis and evaluation to ensure the reliability of the online de-icing method, which will be discussed in detail in Section IV.

*B.* *DIPU structure and control*

The DIPU in the online de-icing method is composed of AC/DC converter and DC/DC converter, and its basic topology is shown in Fig. 3.



Fig. 3. Circuit topology of DIPU

AC/DC converter is a full-bridge converter with bidirectional converter capability. Its main function is to provide a suitable DC voltage for DC/DC converter. The AC side is connected to the nearby substation, and the DC side is connected to the input side of DC/DC converter. The control method of AC/DC converter adopts PI control of voltage and current double closed loop [33], as shown in Fig. 4.



Fig. 4. Control method of AC/DC converter

DC/DC converter is also a full-bridge converter with bidirectional converter capability. The control method adopts PI control of single current loop, as shown in Fig. 5. DIPU is controlled as a current source at the DC output, and its output de-icing current is

 (7)

where *I*r is the de-icing current of catenary calculated according to the actual meteorological conditions and ice thickness.



Fig. 5. Control method of DC/DC converter

*C.* *De-icing control strategy*

The de-icing control strategy of online thermal de-icing method is shown in Fig. 6. As shown, the de-icing control strategy is realized by three systems: icing monitoring and analysis system, de-icing current calculation system and DIPU control system. The icing monitoring and analysis system is mainly used to monitor the icing status of the catenary. When the wet growth ice thickness is more than 1cm, the power taking of train pantograph will be obviously affected. At this time, the icing monitoring and analysis system should issue a de-icing warning to prepare for catenary de-icing. The de-icing current calculation system mainly calculates the required de-icing current according to the ice thickness, de-icing time and weather conditions. After the de-icing current is injected into the catenary, 1cm ice coating will not grow and melt gradually. It is not necessary to reduce the de-icing time to a very short time to increase the capacity of DIPU and the impact on the traction power supply system. Therefore the de-icing time is set to 60 minutes by default. The weather conditions are subject to the detected atmospheric temperature, wind speed and humidity. After calculating the de-icing current, the DIPU control system sends out the current command to make the DIPU output the de-icing current to the catenary.



Fig. 6. Schematic diagram of de-icing control strategy

When one de-icing is completed, two modes of DIPU operation can be selected. One mode is that when the ice completely melts, according to the weather forecast or local weather regularity, if the weather conditions during the operation of the line are still easy to make the catenary icing, the DIPU anti-icing mode can be opened to protect the catenary from icing. The other mode is that the anti-icing protection is not opened after the first de-icing, then the next de-icing is the same as the first de-icing, which is determined according to the judgment of the icing monitoring and analysis system.

# Influence Analysis of Online De-icing Method

The requirement of online de-icing is that the influence of DIPU on the traction power supply system and train in operation state is within the acceptable range. In this section, the influence of DIPU on the de-icing section is quantitatively analyzed based on the electrical network model.

*A. De-icing analysis scenarios*

For the traction power supply system with DIPU and train operation on up and down lines, its equivalent electric network model is shown in Fig. 7. The up and down trains are equivalent to current sources [34]. The train current *I*1 and *I*2 are positive for traction state. The train positions are represented by *x*1 and *x*2, corresponding to nodes 3 and 4. The traction substation can be simplified as voltage source branches according to its working characteristics, with voltage of *U*dc0, corresponding to nodes 1 and 2. DIPU is represented by an equivalent current source, with current of *I*IM, and its injection node and return node are 5, 6, respectively. *R*osc represents the catenary resistance per unit length and *L* represents the total length of de-icing section.



Fig. 7. Equivalent model of online de-icing system

According to the location relationship among the train, substation and DIPU nodes, the network topology of the de-icing section can be divided into four situations as shown in Fig. 8. For example, in the case of Fig.8 (a), the position of the up train is between traction substation 1 and DIPU, and the position of the down train is between DIPU and traction substation 2.

Fig. 8. Network topology of online de-icing system under different train positions

*B. Influence of online de-icing on train*

The influence of online de-icing on the train can be evaluated by the offset of train voltage before and after the DIPU is turned on. According to the superposition theorem, the current and node voltage of each branch of the network before and after the DIPU is turned on can be calculated under different situations. When train1 is in the section of 0 < *x*1 < *L*/2 and DIPU is turned off, the catenary current (*I*13, *I*35) on both sides of the train and the voltage drop (*U*31) of the train node relative to the traction substation are:

 (8)

 (9)

 (10)

When DIPU is turned on, it can be expressed as

 (11)

 (12)

 (13)

Therefore, for the section of 0 < *x*1 < *L*/2, the train voltage offset brought by DIPU online de-icing is

 (14)

Similarly, the offset of voltage of trains in all de-icing sections during online de-icing can be obtained as:

 (15)

As shown in (15), when the DIPU is turned on, the train voltage offset is only determined by the de-icing current, train position and de-icing section length. During the online de-icing, the train voltage on the up line increases, while the train voltage on the down line decreases. The increase or decrease of the voltage is proportional to the de-icing current and inversely proportional to the distance between the train and DIPU. When the train is at the midpoint of the section during online de-icing, the offset of train voltage brought by DIPU reaches maximum as (16).

 (16)

Taking the icing section of Tianjin Line 9 as an example, the total length of the icing section is about 3.8km. According to the parameters and calculation results in TABLE I and TABLE II, the maximum voltage offset caused by DIPU to the running train during the online de-icing is 66.6V by the (7) and (16). If the online anti-icing is carried out before the catenary is not iced, the maximum voltage offset of the train is 69.8V. For the train running under 1500V traction power supply system, this low voltage offset caused by online de-icing or anti-icing is completely acceptable.

*C. Influence of online de-icing on traction power supply system*

The influence of online de-icing on the traction power supply system can be evaluated by the influence of DIPU on the power of traction substation. In the case of *L*/2 < *x*1 < *L*, *L*/2 < *x*2 < *L*, the power and the sum of traction substations on both sides of the de-icing section is

 (17)

 (18)

 (19)

After the similar calculation, the results in other cases are the same. Equation (19) shows that the power of traction substation is only related to the train current, but not to DIPU, so DIPU will not affect the traction in the process of online de-icing.

*D. Capacity of DIPU*

The DIPU capacity calculation is of great significance in designing its structure and parameters. When train1 is in the section of 0 < *x*1 < *L*/2, the voltage at DIPU injection node is

 (20)

The DIPU injection and return node voltages of trains in different sections can be calculated, and then the DIPU terminal voltage and power can be obtained as:

 (21)

 (22)

Since the *I*IM is a given command value, the power of DIPU is proportional to its terminal voltage. Equation (22) shows that the terminal voltage of DIPU is determined by its own de-icing current command and train status when the length of de-icing section and catenary resistance are fixed.

According to the variable and inequality transformation, the power range of DIPU can be obtained as shown in TABLE III. The positive train current indicates that the train is in traction state and the negative one indicates that the train is in braking state.

TABLE III

Power Range of DIPU

|  |  |  |  |
| --- | --- | --- | --- |
| Train Position Range | Train Current Range | Power Range of DIPU | Necessary Conditions for |
|  |  |  |  |
|  |  |  |
|  |  | — |
|  |  |  |

As shown in TABLE III, the maximum de-icing power of DIPU is

 (23)

which occurs when the train on the up track is braking and the train on the down track is motoring. The minimum de-icing power of DIPU is

 (24)

which occurs when the up train is motoring and the down train is braking. According to the analysis of DIPU power range in TABLE III, except for the condition of braking of the up train and motoring of the down train, the de-icing power may be negative under other working conditions. So DIPU should have the ability of bidirectional energy flow to adapt to the different running states of the train in the section during de-icing.

The negative power of the DIPU means that it will absorb some power from the traction power supply system at this time. The source of these powers should be identified. According to the analysis conclusion of Part C in this section, there is no mutual influence between DIPU and traction substation, so the total power of the train is calculated as

 (23)

It can be found that when the up and down lines have trains at the same time, there will be power exchange between DIPU and trains. The power exchange is

 (24)

# Simulation Verification

The accurate dynamic model of catenary de-icing system including DIPU is established by MATLAB simulation software according to the actual characteristics of urban rail transit traction power supply system. The model is composed of three parts: traction calculation module, de-icing calculation module and DC power flow calculation module. The calculation process is shown in Fig. 9. The traction calculation module calculates the position and power of each train at each time according to the actual line conditions and train traction strategy. The de-icing calculation module sets the position of de-icing section, and calculates the online de-icing and anti-icing current according to the given meteorological conditions and icing thickness. The DC power flow calculation module calculates the power flow of key nodes such as each traction substation, train and DIPU ports according to the network parameters and the results provided by the traction calculation module and de-icing calculation module.



Fig. 9.Calculation process of dynamic model for de-icing of catenary

In this paper, Tianjin Line 9 is taken as an example to simulate the status of traction power supply system when the catenary is de-icing online. The whole line of Tianjin Line 9 phase I is about 44.75 km, 16 stations in total, as shown in Fig. 10. The section where catenary icing often occurs during the operation period is the section from ErhaoQiao Station to Xinli Station (S3-S5) with a total length of about 3.8km. Conduct the online de-icing of S3-S5 section as shown in Fig. 1. The system simulation parameters are shown in TABLE IV.



Fig. 10. Transportation map of Tianjin line 9 Phase I

TABLE IV

Simulation Model Parameters

|  |  |  |
| --- | --- | --- |
| Type | Parameters | Values |
| Traction Substation | No load voltage | 1650V |
| Equivalent resistance of rectifier unit | 50mΩ |
| Starting voltage of energy feedback device | 1700V |
| Train | Traction strategy | Constant acceleration traction |
| Rated power | 3MW |
| Catenary | TABLE I | |
| Rail | Single rail resistance | 24mΩ/km |
| DIPU | De-icing current | 2500A |

Fig. 11 shows power-time curve of the up and down trains in the de-icing section when the departure interval is 330s. Under this departure interval, there are many train operation conditions in the de-icing section, including up and down motoring at the same time, braking at the same time, up motoring down coasting and up coasting down motoring. Under these train conditions, the status of traction power supply system and de-icing section can be simulated comprehensively.



Fig .11. Power-time curve of up and down trains in de-icing section

Fig. 12 and Fig. 13 respectively show the current situation in the up and down catenary in the icing section before and after de-icing within a departure interval. Before online de-icing, the current in the up and down catenary is determined by the train traction and braking current. In Fig.12, the RMS of current in the catenary on both sides of the train is only 35-180A. The low RMS of current makes the catenary prone to icing during operation. Fig.13 shows the current waveform of catenary during online de-icing. It can be seen that the de-icing current is injected into the catenary, and the RMS of current is significantly increased to 1000A-1500A. The high RMS of current in catenary can achieve the expected de-icing or anti-icing effect.

Fig. 12. Current of up and down catenary in icing section before online de-icing

Fig. 13. Catenary current of up and down line in icing section during online de-icing

Fig. 14 shows the voltage of the up and down trains in the icing section before and after de-icing. After the DIPU is turned on, the voltage of the up train increases and that of the down train decreases. The amplitude of increase and decrease is not the same at each time, which indicates that the offset of train voltage is affected by the change of train state. Fig. 15 shows the relationship between the up and down train voltage offset and position during online de-icing. It can be seen that the train voltage offset is inversely proportional to the position between the train and the DIPU. Under 2500A de-icing current, the maximum voltage offset of the train at the midpoint is close to 100V. The simulation results are completely consistent with the analysis conclusion in Part B of Section IV.





Fig. 14. Voltage of up and down trains in icing section before and after online de-icing





Fig. 15. Train voltage offset - position curve

Fig. 16 compares the hourly power consumption and feedback of traction station of the whole line before and after the online de-icing. It can be seen that the substation power consumption are the same when DIPU is on or off. The result verifies the analysis in Part C of section IV that the substation power is only related to the train but not to the DIPU during the online de-icing. In conclusion, the online de-icing method proposed in this paper does not affect the normal operation of the traction substation.



Fig. 16. Power consumption and feedback of traction substation in the whole line before and after online de-icing

Fig. 17 shows the power-time curve of the DIPU when the de-icing current is 2500A, 500A and 50A. The output power of the DIPU changes due to the influence of the train status in the de-icing section. When the de-icing current is 500A, the power of DIPU is negative in 50s-60s and 80s-85s. In 50s-60s, the up train in the icing section is coasting and the down train is braking. In 80s-85s, the up train in icing section is motoring and the down train is coasting. When the de-icing current is reduced to 50A, the negative power of DIPU will also occur when the up and down trains are braking at the same time.







Fig. 17 Power-time curve of DIPU

The train status in Fig. 11 does not consider the condition of one traction operation and another braking operation in the up and down trains. The power-time curve is shown in Fig. 18, which considers the conditions not shown in Fig. 11. The departure interval is to 270s. The power-time curve of DIPU corresponding to 2000A, 500A and 50A de-icing current at this departure interval is shown in Fig. 18. When the de-icing current is 500A, the power of DIPU is negative in 140s-150s and 265-280s, and the train status in the icing section within this time period is the traction of up train and the braking of down train. When the de-icing current is 50A, the power of DIPU will also be negative when the up and down trains are in traction state at the same time.



Fig. 18 Train power-time curve in de-icing section







Fig. 19. Power-time curve of DIPU at 4min30s departure interval

According to the analysis of Fig. 17 and Fig. 19, the capacity of DIPU is closely related to the current and position of the train. The smaller the de-icing current is, the more likely the negative power will occur in DIPU. In addition to the braking of the up train and the traction of the down train, the negative power of DIPU may occur in other situations, which is consistent with the analysis conclusion in Section IV. The DIPU structure in Fig. 3 can realize the bidirectional power flow phenomenon that may occur in the process of online de-icing, so the designed DIPU can meet the requirements of online de-icing.

# Conclusion

In this paper, an online de-icing method for urban rail transit catenary is proposed. This method adopts the up and down catenary as the de-icing current circuit, and sets the DIPU at the midpoint of the catenary in the icing section for thermal de-icing. Due to the negative influence on the traction power supply system, the traditional thermal de-icing method is difficult to be employed in the operation period. This method solves this problem and has little modification to the existing traction power supply system.

The analysis and simulation results of the influence of DIPU on the traction power supply system show that the proposed online de-icing method does not affect the normal operation of the traction substation. The impact on the running train in the de-icing section is within the acceptable range. In addition, the results show that the capacity of DIPU for online de-icing is affected by the running state of the train, and DIPU may output negative power. To achieve the negative power output, DIPU should have the ability of bidirectional energy flow and meet the requirements of online de-icing.

In summary, the online de-icing method proposed in this paper does not affect the normal operation of the train and traction substation. This method can be employed in the urban rail transit lines where the catenary is iced during the operation period. Compared with other existing de-icing methods, the proposed online de-icing method has high de-icing efficiency and simple structure, which has a high potential for engineering application.

Our future work is to further optimize the de-icing strategy. Due to the train operation, the power flow change of catenary will cause the fluctuation of de-icing current, which has some influence on the online de-icing effect. In order to achieve the best de-icing effect, it is meaningful to dynamically calculate the de-icing current to compensate the fluctuation according to the power flow change of the catenary.

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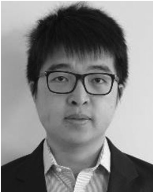
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