DC Traction Power Supply System For Electrified Railway With Ice Melting Function

Chuanping Wu¹, Hongzhang Zhu², Wen Wang³, and Yao Xie²

¹State Grid Hunan Electric Power Co Ltd State Key Laboratory of Disaster Prevention and Reduction for Power Grid Transmission and Distribution Equipment
²Changsha University of Science and Technology - Yuntang Campus
³Changsha University of Science and Technology

October 31, 2022

Abstract

This paper proposes a DC traction power supply system for electrified railroads with ice-melting function, which is used to solve the problems of power quality and line icing of single-phase AC traction power supply system. The proposed system consists of a multi-tap regulating transformer, a DC traction converter, a DC step-down converter, and a three-phase inverter. The DC traction converter adopts the topology of input-parallel-output-series (IPOS) uncontrolled rectifier and fully controlled converter. Its main capacity is assumed by the uncontrolled rectifier, which has the advantages of low cost, simple structure and easy to realize engineering applications. In this paper, the voltage regulating transformer is used for shifting and voltage regulation to expand the ice melting function, which can be used to solve the icing problem of the railway traction system. In order to realize the functions of harmonic compensation, DC-side voltage stabilization and power distribution in multiple parallel operation of DC traction converter, this paper proposes a compound control method for traction converter, which realizes power distribution by droop control with voltage compensation, voltage stabilization by suppressing voltage fluctuation by power feedforward control, and harmonic compensation by harmonic current compensation control. The small-signal model of the system under this control strategy is also established, and the stability of the control parameters on the system is analyzed. Finally, a simulation platform is built to verify the superiority of this topology and the feasibility of the control method.
DC Traction Power Supply System For Electrified Railway With Ice Melting Function

Chuanping WU¹,², Hongzhang ZHU¹, Wen WANG², Yao XIE²
¹ State Key Laboratory of Disaster Prevention & Reduction for Power Grid Transmission and Distribution Equipment, Changsha 410007, People's Republic of China
² College of Electrical and Information Engineering, Changsha University of Science & Technology, Changsha 410114, People's Republic of China
E-mail: jandom@126.com

Abstract—This paper proposes a DC traction power supply system for electrified railways with ice-melting function, which is used to solve the problems of power quality and line icing of single-phase AC traction power supply system. The proposed system consists of a multi-tap regulating transformer, a DC traction converter, a DC step-down converter, and a three-phase inverter. The DC traction converter adopts the topology of input-parallel-output-series (IPOS) uncontrolled rectifier and fully controlled converter. Its main capacity is assumed by the uncontrolled rectifier, which has the advantages of low cost, simple structure and easy to realize engineering applications. In this paper, the voltage regulating transformer is used for shifting and voltage regulation to expand the ice melting function, which can be used to solve the icing problem of the railway traction system. In order to realize the functions of harmonic compensation, DC-side voltage stabilization and power distribution in multiple parallel operation of DC traction converter, this paper proposes a compound control method for traction converter, which realizes power distribution by droop control with voltage compensation, voltage stabilization by suppressing voltage fluctuation by power feedforward control, and harmonic compensation by harmonic current compensation control. The small-signal model of the system under this control strategy is also established, and the stability of the control parameters on the system is analyzed. Finally, a simulation platform is built to verify the superiority of this topology and the feasibility of the control method.

Index Terms—DC traction power supply; traction network icing; DC ice melting; DC side voltage stabilization; power distribution; small signal model

1 Introduction

At present, single-phase AC power supply is commonly used in China's railroad traction system, and the electric locomotive has the non-linear characteristic of moving variable, which will cause power quality problems such as unbalance, harmonics, reactive power and negative sequence current in the traction supply network of AC power supply during operation [1-4]. Alternating phase sequence technology is generally used to alleviate the negative sequence problems of AC traction power supply systems [5-6]. For power quality problems such as unbalance, harmonics and reactive power in electrified railways, scholars have proposed a series of power quality compensation methods such as balanced traction transformers, railroad power conditioners and their improved structures, and static reactive power compensation devices [7-10].

Although the above methods can alleviate the electrical energy problems to a certain extent, they all require additional installations, the compensation device has large capacity but its cost is high, and can not fundamentally solve the power quality problems, which limits the electrified railroad’s high-speed, heavy-duty development. Secondly, the catenary, as an important part of the traction power supply system, is usually directly exposed to the air, and is susceptible to external factors such as climate and terrain. In high-cold and high-humidity areas, icing occurs frequently, which may cause the traction power line to break and seriously affect the safe and stable operation of the railroad [11-12].

In order to effectively solve the problem of power quality in AC power supply system, scholars proposed the concept of establishing an electrified DC railroad traction power supply system and discussed its advantages of completely eliminating electrical
splitting, increasing power supply distance, realizing power quality management, and easy access to renewable energy, which provided new ideas for electrified railroad traction system \[13-15\]. Building a railroad DC traction system with modular multilevel converters (MMC) is a typical example \[16-19\]. However, this structure is costly and also does not take into account the catenary icing problem and cannot achieve ice melting.

For the railroad catenary icing problem, the main ice-melting methods are AC and DC hot-melt deicing methods \[20-22\]. Compared with AC short-circuit ice melting, DC short-circuit ice melting has the advantages of small capacity required for ice melting power supply, high efficiency, wide available range, no need for impedance matching, good constant current characteristics, and can meet the ice melting requirements of lines with different lengths \[23-25\]. If the DC traction substation can be equipped with DC ice melting function through reasonable design and control, it can reduce the economic loss and ensure the safe operation of railroad traction system. Therefore, the study of new traction power supply system of electrified railroad with ice melting function is of great significance to promote electrified railroad and ensure the safe and stable operation of railroad system.

To solve the above problems, this paper proposes an electrified DC railroad traction system with ice melting function, and proposes a DC traction converter with topology of IPOS uncontrolled rectifier and fully controlled converter, and a regulating transformer with high position for high voltage DC traction power supply and low position for DC ice melting. After analyzing the cost and capacity of the system, the selection method of uncontrollable rectifier and fully controlled rectifier capacity is determined. The compound control method is further proposed for this topology, which realizes power distribution by droop control with voltage compensation, voltage stabilization by suppressing voltage fluctuation by power feedforward control, and harmonic compensation by harmonic current compensation control, while the small signal model of the system under the compound control strategy is established and the influence of control parameters on system stability is analyzed. Finally, the simulation platform is built to verify the superiority of the topology and the feasibility of the control method.

2 Topology of DC traction power supply system for electrified railway with ice melting function

2.1 System Structure

The structure of the DC railroad traction power supply system with ice-melting function proposed in this paper is shown in Fig. 1, which mainly consists of transformer, traction converter, DC step-down device and three-phase inverter. The transformer adopts a multi-tap regulating transformer to realize the AC voltage level adjustment, where the high-tap position is used for high-voltage DC traction power supply and the low-tap position is used for DC ice melting. The DC-DC adopts 3L-DAB (Three-level dual active bridge), which can effectively reduce di/dt and dv/dt, improve the system EMC performance and voltage carrying capacity, with high efficiency, high power density, and input and output voltage with wide range regulation \[26\]. DC-AC uses a three-phase inverter circuit.

![Fig. 1 DC railway traction power supply system with ice melting function](image)

2.2 Topology and Principle of DC Traction Converter

In this paper, the functions of DC traction converter include traction power supply and DC ice melting, so the needs of DC traction power supply and DC ice melting should be comprehensively considered for its topology.

At present, the topologies used in DC ice melting devices are mainly uncontrolled rectifier (diode) \[27-28\],
thyristor-based fully controlled rectifier and IGBT-based fully controlled rectifier. Among them, the uncontrolled rectifier is low cost and easy to realize large capacity devices, while the thyristor-based fully controlled rectifier can realize smooth regulation of output DC voltage. However, both of these two topologies have the problem of high input current distortion rate and need to be equipped with a large number of harmonic and reactive power compensation devices. The IGBT-based fully controlled rectifier has strong output voltage regulation capability and excellent power quality, but it has high cost and complex system design. These three topologies can only merely achieve ice melting function without realizing the traction power supply. Therefore, a composite structure composed of uncontrolled rectifier and full control converter is proposed in this paper.

The topology of the proposed DC traction converter is shown in Fig. 2. VT1~VT6 are diodes, V1~V6 are IGBTs, Lm and Ls are reactors, and capacitors C1 and C2 are DC side energy storage elements with voltage regulation and filtering functions. The uncontrolled rectifier (diodes) and fully controlled converter are input-parallel-output-series (IPOS). The fully controlled converter is adjusted to achieve power distribution among traction converters, DC-side voltage stabilization, and to eliminate harmonics caused by uncontrolled rectifier. The topological equivalent circuit is shown in Fig. 3. The system output voltage and power are:

\[
\begin{align*}
P_a + P_b &= U_{dc}^2 / R \\
U_{dc} &= U_{dca} + U_{dcb} \\
U_{dca} &= U / K_1 \alpha \\
U_{dcb} &= 2.34U / K_2 \\
I_{ph} &= I_{th}
\end{align*}
\]  

(1)

Fig. 3 Equivalent circuit

In the Eq. (1), U is the effective value of AC input voltage, K1 and K2 are the transformer ratios, U_{dc} is the total output voltage, U_{dca} and U_{dcb} are the output voltages of uncontrolled rectifier and fully controlled rectifier, U_{dca} \gg U_{dcb}, Z_r is the load equivalent impedance, \alpha is the pulse width modulation ratio, I_h is the harmonics generated by the uncontrolled rectifier, I_i is the fully controlled rectifier compensation harmonics, P_a and P_b are the output active powers of uncontrolled rectifier and fully controlled rectifier.

According to Eq. (1), adjusting the transformer ratios K_1 and K_2 can realize the switching of traction power supply and DC ice melting mode. Harmonic compensation control is achieved by controlling the fully controlled rectifier to generate harmonic compensation amount I_i to compensate for the uncontrollable harmonics I_h. In the process of load switching and power exchange, the DC side voltage U_{dc} of the traction converter can be kept stable by adjusting the fully controlled rectifier output voltage U_{dcb}.

2.3 Cost and capacity analysis

The DC traction system mainly uses uncontrolled rectifier to bear the load power, so that it can obtain high active regulation under the condition of low economic cost, realize harmonic compensation and load power dynamic regulation. The uncontrolled rectifier has the advantages of low cost, simple structure and easy to realize engineering application.

Suppose the total cost of a single DC traction converter is C, the total capacity of the fully-controlled converter is S_{C1}, the capacity of the uncontrollable rectifier is S_{C2}, and the uncontrollable rectifier price per unit of kVA is normalized to 1. The cost ratio of the controlled rectifier to uncontrollable rectifier is \delta, the harmonic of the uncontrollable rectifier is THD, and \kappa is the ratio of the active power of the fully controlled converter to the uncontrollable rectifier. The cost and capacity constraint equations

Fig. 2 Topology of traction converter
are:
\[
\begin{align*}
S_{s1} &= P_0 \sqrt{P_a^2 + Q_s^2} \\
S_{s2} &= P_a \\
P &= P_0 + P_a \\
Q_s &= P_a \times \text{THD} \\
k &= P_a / P_0
\end{align*}
\] (2)

Where \(P_0\) is the active power of the fully controlled converter, \(Q_s\) is the reactive power of the fully controlled converter, \(P_a\) is the output active power of the uncontrolled rectifier, and \(P\) is the total output active power.

Considering the existing insulation level, electrical safety distance, and the rated operating voltage of electrical equipment for economic operation, the DC side output voltage of the DC traction catenary is selected as 25 kVdc. Take \(\delta = 5\), \(\text{THD} = 20\%\), the \(k\)-value transformation law is shown in Fig. 4. Taking into account the low cost condition, if higher harmonic compensation is required, the recommended range of the uncontrolled rectifier and fully controlled rectifier capacity ratio \(k\) is: \(4 < k < 10\). In this paper, the capacity ratio of uncontrollable rectifier and fully controlled rectifier is chosen as \(22 / 3\).

2.4 DC Ice-melting

The multi-tap voltage regulating transformer is adjusted to a low position to achieve low voltage and high current output, thus realizing DC ice melting. DC ice melting technology uses the short-circuit method to short-circuit the end of the ice-covered wire, using the traction power converter to provide ice melting power to achieve DC ice melting. The principle is shown in Fig. 5.

The power required for DC ice melting is determined by the ice melting current and the equivalent impedance of the transmission line, and the adjacent DC traction converter is used for power supply:
\[
\begin{align*}
P_l &= (I_{dc})^2 R_s \\
U_{dc} &= I_{dc} R_s \\
P &= I_{dc} U_{dc}
\end{align*}
\] (3)

In the Eq. (3), \(P_l\) is the total power required for DC ice melting, \(I_{dc}\) is the current required for DC ice melting, \(U_{dc}\) is the output voltage of the traction converter, and \(R_s\) is the impedance of the ice melting line.


![Fig. 4 Variation law of k Value](image)

**Fig. 4 Variation law of k Value**

**Fig. 5 Principle of DC ice melting**

Usually, the current passing through the ice-melting line should be greater than the ice-melting current and less than the maximum allowable current, and the current capacity of the equipment connected in series with the ice-melting line should be taken into account, \(I_{max} \geq I_{dc} \geq I_{min}\). Therefore, the maximum allowable current and the minimum current value to ensure that the line will not freeze are:\(5\):
\[
\begin{align*}
I_{max} &= \sqrt{(C\Delta T + K) \rho_e (l-r)^2 + 2(l-r) + C(\Delta T + 2) \rho_e \pi r^2} / R_s \\
I_{min} &= \sqrt{(C\Delta T + K) \rho_e (l-r)^2 + C(\Delta T + 2) \rho_e \pi r^2} / R_s
\end{align*}
\] (4) (5)

Where \(C\) is the specific heat capacity of ice, \(\Delta T\) is the temperature rise, \(K\) is the heat of melting, \(\rho_e\) is the ice density, \(l-r\) is ice thickness, \(C\) is conductor specific heat capacity, \(\rho_e\) is conductor density, \(R_s\) is line equivalent resistance, and \(t\) is the ice melting time.

According to the above analysis, the topology proposed in this paper has the following advantages compared with the existing DC ice melting equipment:

1) The DC traction converter adopts the topology of input-parallel-output-series (IPOS) uncontrolled
rectifier and fully controlled converter. Its main capacity is assumed by the uncontrolled rectifier, which has the advantages of low cost, simple structure and easy to realize engineering applications.

2) Using the multi-tap regulating transformer, the DC side voltage can be stepless adjusted by the fully controlled rectifier, so that the proposed topology not only has the function of DC traction power supply, but also has the function of DC ice melting.

3) The topology has its own harmonic compensation function, and the fully controlled converter can compensate the harmonics generated by the uncontrolled rectifier.

3 Traction converter control method

3.1. Overall control strategies

In the traction converter topology with IPOS uncontrolled rectifier and fully controlled rectifier proposed in this paper, there are a large number of harmonics in the AC input side of the uncontrolled rectifier, which has a great impact on the grid. Therefore, fully controlled rectifier is used to eliminate AC input-side grid harmonics through harmonic compensation control to achieve power quality control. In DC traction network, DC-side voltage stability and power balance distribution are the keys to the safe and stable operation of the system [36-37]. To realize the functions of DC railway harmonic compensation, power distribution and DC side voltage stabilization, this paper proposes a compound control strategy, whose control block diagram is shown in Fig.5. In Fig. 5, \( i_{La,b,c} \) is the uncontrolled rectifier input current; \( i_{La,b,c,d} \) is the fully controlled rectifier input current; \( i_{La,b,c} \) is the uncontrolled rectifier harmonic current; \( U_{La,b,c} \) is the fully controlled rectifier input voltage; \( LPF \) is the low-pass filter and \( P_{it} \) is the fully controlled rectifier output power. It mainly contains harmonic and reactive power detection, droop control with voltage compensation, DC-side voltage control, current decoupling control, power feed-forward control and other links.

3.2 Droop control with voltage compensation

DC traction converter output power can be allocated according to the droop characteristics to realize the power allocation to the DC traction converter output power [38-39]. However, the droop control will cause the DC side voltage offset. To address this problem, the difference between the output voltage \( U_{dc} \) and the given voltage value \( U_{ref} \) is input to the PI regulator to get the output voltage compensation amount, which is added to the P-U droop control to eliminate the DC side voltage offset, and the control is expressed as:

\[
U_{dc} = U_{ref} - D_P \frac{G_i}{1+T_i s}(P_{ref} - P_{load}) + G_d(s)(U_{ref} - U_{dc})(6)
\]

The expression for the voltage compensation offset is given by:

\[
\Delta V_s = G_i(s)(U_{ref} - U_{dc}) (7)
\]

In the Eq. (6), \( U_{dc} \) is the given value of DC-side voltage; \( U_{ref} \) is the reference value of DC-side voltage and its value range is \( 0.9 U_{dc} \leq U_{ref} \leq 1.1 U_{dc} \); \( D_P \) is the droop factor; \( P_{ref} \) is the given value of output power; \( P_{load} \) is the load output power; \( G_i(s) = (K_p + K_i/s) \) is the voltage compensation regulator and \( G_d(s) / (1+T_i s) \) is the low-pass filter.

3.3 Power feed-forward and current decoupling control

In the DC railway traction power supply system, both of the rapid switching of the load and the fluctuation of the power exchange between the AC and DC systems will cause the fluctuation of the DC voltage. In this paper, power feedforward control is used to suppress DC voltage fluctuations. The specific idea is to achieve stable control of DC-side voltage by the voltage outer loop, and introduce a disturbance power feedforward link in the current inner loop to speed up the system's response to power disturbance and reduce the DC-side voltage fluctuation caused by load disturbance [40].
The current component generated through using the DC-side voltage regulator is:

\[ i_{d_{2i}} = (U'_{dc} - U_{dc}) (K_{pr} + \frac{K_{ir}}{s}) \]  

where \((K_{pr} + \frac{K_{ir}}{s})\) is the PI regulator of DC voltage loop.

Among them, the current component \(i_{di}\) generated by the feedforward decoupling control is:

\[ i_{di} = 1.5 G_i(s) \frac{P_{dc}}{u_d} \]  

In the Eq. (9), \(G_i(s)\) is the power feed-forward feedback loop, and \(P_{dc}\) is the load output power of the fully-controlled DC converter.

Thus, the given value of the d-axis component of the current control loop \(i_{d_{off}}\) is:

\[ i_{d_{off}} = i_{di} + i_{d_{2i}} + i_{di_{H}} \]  

where \(i_{di}\) is the d-axis component of harmonic current.

Since the fully controlled rectifier d and q-axis variables are mutually coupled, the current decoupling control is used and its control equation is:

\[
\begin{align*}
    u_{di} &= u_d - (K_{pr} + \frac{K_{ir}}{s}) (i_{d_{off}} - i_d) + \omega L_{di} \delta i_d \\
    u_{qi} &= u_q - (K_{pr} + \frac{K_{ir}}{s}) (i_{q_{off}} - i_q) - \omega L_{qi} \delta i_q
\end{align*}
\]  

Where \(K_{pr}\) and \(K_{ir}\) are the proportional and integral coefficients of the current regulator respectively; \(i_d\) and \(i_q\) are the d and q components of the input current of the fully controlled rectifier; \(u_d\) and \(u_q\) are the d and q-axis components of the AC side voltage of the fully controlled rectifier; \(\omega\) is the rotational angular frequency; \(i_{d_{off}}\) and \(i_{q_{off}}\) are the given values of the d and q-axis components of the AC side current.

4 System modeling and stability analysis

4.1 System modeling

To further analyze the relationship between the DC-side voltage of the traction converter and the load power, a small-signal model of the system under the compound control strategy is established. Ignoring the switching losses, the power on both sides of the fully controlled rectifier in Fig. 2 is balanced.

\[ \frac{3}{2} (u_d i_d + u_q i_q) = U_{dc} \frac{dU_{dc}}{dt} + i_{d_{as}} \]  

Using the small signal method for Eq. (12), the relationship between \(\Delta u_{dc}(s)\) and \(\Delta i_d(s)\) can be deduced as [41]:

\[ G_s = \frac{\Delta u_{dc}(s)}{\Delta i_d(s)} = \frac{3U_d}{2(CU_{dc}s + I_{do})} \]
The relationship between $\Delta u_{av}(s)$ and $\Delta i_{av}(s)$ is:

$$G_{s} = \frac{\Delta u_{av}(s)}{\Delta i_{av}(s)} = -\frac{U_{av}}{C(U_{av}s + I_{av})}$$  \hspace{1cm} (14)

$\Delta u_{av}(s)$ and $\Delta u_{t}(s)$ are related as:

$$G_{t} = \frac{\Delta u_{av}(s)}{\Delta u_{t}(s)} = \frac{3I_{t}}{2(C(U_{av}s + I_{av}))}$$  \hspace{1cm} (15)

Small signal decomposition is also performed to P-U droop control with compensation to get:

$$\Delta u_{av}^{*} = -D_{f} \frac{G_{s}}{1+Ts} + G_{s} \Delta u_{av}(s)$$  \hspace{1cm} (16)

According to Eq. (12) ~ Eq. (16), the control small signal model of the traction converter can be shown in Fig. 7: $\Delta u_{av} = k \Delta u_{kw}$; $G_{s}(s)$ is the DC voltage regulator; $G_{t}(s)$ the current regulator and $G_{d}(s)$ is the voltage compensation regulator.

According to Fig. 7, the closed-loop transfer function of the compound control can be deduced as:

$$\Delta u_{av}(s) = \frac{1}{A(s)} \left[ \frac{-kG_{s}(s)B(s)G_{t}(s)G_{d}(s)}{1+Ts} \Delta P_{s}(s) \right]$$

$$A(s) = \frac{1}{1+Bs} + B(s)G_{s}(s)G_{t}(s)G_{d}(s)k - kB(s)G_{t}(s)G_{d}(s)G_{s}(s)$$

$$B(s) = \frac{G_{s}(s)K_{PWM}}{L_{s}s + R_{a} + G_{s}(s)K_{PWM}}$$  \hspace{1cm} (17)

Ignoring the effect of grid voltage disturbance, to suppress the DC voltage fluctuation, the power feedforward feedback $G_{f}(s)$ needs to offset the effect of $\Delta i_{av}(s)$ on $\Delta u_{av}$ through $G_{d}(s)$, so the relationship $G_{f}(s)$ needs to satisfy is:

$$G_{f}(s) = -\frac{k \Delta i_{av}(s)G_{t}(s)\Delta u_{t}(s)}{B(s)G_{t}(s)1.5\Delta P_{s}(s)}$$  \hspace{1cm} (18)

In the voltage and current double closed loop, the current loop $G(s) K_{PWM} \gg L_{s}s + R_{a}$, the Eq. (18) can be simplified as:

$$G_{f}(s) = -\frac{\Delta i_{av}(s)G_{t}(s)\Delta u_{t}(s)}{kG_{t}(s)1.5\Delta P_{s}(s)}$$  \hspace{1cm} (19)

Ignoring the effect of grid voltage disturbance and introducing power feedforward feedback, the closed-loop transfer function of output voltage and power under compound control can be simplified as:

$$\Delta u_{av}(s) = \frac{1}{A(s)} \left[ \frac{-kG_{s}(s)B(s)G_{t}(s)D_{f}(s)G_{d}(s)}{1+Ts} \right]$$  \hspace{1cm} (20)

4.2 Influences of droop coefficient $D_{f}$ on system stability

Fig. 8 shows the Nyquist curve of the system when $D_{f}$ varies. In Fig. 8, when $D_{f}$ gradually increases from 0.0003 to 0.0006, the Nyquist curve of the system always does not contain the point (-1, j0), which indicates that the system is always in stable operation under the compound control. And the Nyquist curve contains point (0,0), and as $D_{f}$ decreases, the curve moves away from point (-1, j0), indicating that the output voltage responds slowly to the power, which suppresses the DC side voltage fluctuation well.

4.3 Influence of voltage compensator parameters on system stability

Fig. 9 shows the Nyquist curve of the system when the voltage compensator parameters are varied. From Fig. 9(a), it can be seen that keeping the voltage compensator’s proportional coefficient $K_{PWM}$ constant, the Nyquist curve always does not contain the point (-1, j0) during the gradual increase of $K_{PWM}$ from 0.5 to 2, so the system is always in a stable working condition. As $K_{PWM}$ increases, the curve moves away from the point (-1, j0), indicating that increasing the $K_{PWM}$ within a certain range is beneficial to the system stability.

![Fig. 8 Nyquist curve of system when $D_{f}$ changes](image)
so the system is always in a stable working condition, and the distance from (-1, j0) remains basically unchanged when increasing the $K_{ia}$, so $K_{ia}$ has little effect on the stability of the system.

From Fig. 10(b), it can be seen that $K_{pv}$ of the voltage compensator is maintained constant, and the Nyquist curve always does not contain point (-1, j0) during the gradual increase of $K_{iv}$ from 20 to 80, so the system is always in a stable working condition, meanwhile, increasing $K_{iv}$ to a certain extent is beneficial to the system stability.

5 Simulation results

To verify the feasibility and superiority of the proposed DC traction substation topology and control algorithm, a DC railroad traction system simulation experimental platform is established in this paper. The main circuit, controller, switching frequency and other main parameters of the system are shown in Table 1.

Table 1 Setting of main simulation parameters
### Parameters Values

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Three-phase input voltage</td>
<td>220kV</td>
</tr>
<tr>
<td>Uncontrolled rectifier filter inductor</td>
<td>2mL</td>
</tr>
<tr>
<td>Uncontrolled rectifier filter capacitor</td>
<td>800uF</td>
</tr>
<tr>
<td>Fully controlled rectifier filter inductor</td>
<td>0.1mL</td>
</tr>
<tr>
<td>Fully controlled rectifier filter capacitor</td>
<td>4000uF</td>
</tr>
<tr>
<td>3L-DAB leakage inductor</td>
<td>5*10^-4mL</td>
</tr>
<tr>
<td>3L-DAB Isolated ratio</td>
<td>250:8</td>
</tr>
<tr>
<td>3L-DABFilter Capacitor</td>
<td>40mF</td>
</tr>
<tr>
<td>Three-phase inverter filter inductor</td>
<td>0.01mL</td>
</tr>
<tr>
<td>Three-phase inverter filter capacitor</td>
<td>500uF</td>
</tr>
<tr>
<td>Switching frequency</td>
<td>10kHz</td>
</tr>
<tr>
<td>Droop control parameters</td>
<td>$D_p=0.0003$</td>
</tr>
<tr>
<td>Voltage compensation control parameters</td>
<td>$K_v=2$</td>
</tr>
<tr>
<td>DC side voltage controller parameters</td>
<td>$K_v=0.8$</td>
</tr>
<tr>
<td>Current decoupling controller parameters</td>
<td>$K_v=1000$</td>
</tr>
</tbody>
</table>

### 5.1 DC ice-melting mode

Modulate the multi-tap transformer to a lower position: $K_1$ and $K_2$ are 220/3.4 and 220/0.5 respectively. Taking CTMH150 copper-magnesium contact wire of the electrified railroad catenary as an example, assuming that it is a circular wire, ice-melting line length $L = 25$km, ice-melting time $t = 3600$ s. Based on calculations and tests, it can be concluded that the suitable ice-melting current is 1000A, the equivalent DC impedance is 4.62Ω, and the total DC side output voltage $U_{dc1}$ is 4625Vdc.

The simulation results are shown in Fig. 11. The uncontrolled rectifier and fully controlled rectifier in Fig. 11(a) bear the DC side voltages $U_{dca}$ and $U_{dcb}$ of 4000Vdc and 625Vdc, respectively, and the ice melting current is stabilized at 1000A as shown in Fig. 11(b), so the proposed topology can realize the DC ice melting function.

### 5.2. DC traction power supply mode

1) Single traction converter operation

In order to realize DC traction power supply, the multi-tap transformer is set to high position, $K_1$ and $K_2$ are 220/16.8 and 220/1 respectively, the output power of 0–0.5 is 12.5MVA, and the output power of 0.5–1s is 25MVA. The output power ratio of uncontrolled rectifier to fully controlled rectifier is 22:3, and the DC output voltage of the DC traction substation is 25kVdc, where the 3L-DAB realizes the step-down of DC 25kVdc to 800Vdc, and the three-phase inverter inverts 800Vdc to phase voltage 220Vac.

The simulation results of DC traction substation are shown in Fig. 12. Fig. 12(a) shows the DC side output voltage waveform, the DC side voltage $U_{dca}$ and $U_{dcb}$ borne by uncontrolled rectifier and fully controlled rectifier are 22kVdc and 3kVdc respectively. When the load power changes, the DC side output voltage $U_{dc1}$ is stabilized at 25kVdc after using power feedforward decoupling control, which can suppress the DC side voltage fluctuation very well. Fig. 12(b) shows the uncompensated input side current, and Fig. 12(c) shows the input side current with harmonic compensation control. Comparing Fig. 12(b) and Fig. 12(c), it can be seen that harmonic compensation can be achieved by using harmonic compensation control to reduce the harmonic content of the input current. Fig. 12(d) shows the output power of DC traction substation, after adopting droop control with compensation, the total active power $P$ can be realized to follow the change of load power, and the output active power ratio of uncontrolled rectifier $P_a$ to fully controlled rectifier $P_b$ is always kept as 22:3.

3L-DAB and three-phase inverter simulation results are shown in Fig. 13. Fig.13(a) shows the DAB primary and secondary voltages, $U_{dab1}$ and $U_{dab2}$ represent the primary and secondary voltages respectively; Fig.13 (b) shows the leakage current, through Fig.13 (a) and (b), it can be seen that 3L-DAB...
can be converted from DC high voltage (25kVdc) to DC low voltage (800Vdc). Fig. 13(c) shows the output voltage of the three-phase inverter, and Fig. 13(d) shows the output current of the three-phase inverter, which supply power to the three-phase AC load after inverting.

Fig. 12 Simulation results of DC Traction Substation: (a) DC side voltage, (b) Uncompensated input-side current, (c) Uncompensated input side current, (d) Output power

2) Multi-traction converter operation

In order to verify that the DC traction substation can achieve power equalization according to the load power, two 35MVA DC traction systems with a distance of 30km and a DC output voltage of 25kVdc are used. When the locomotive load is in the middle of the two DC traction substations, the load power is carried by the traction substations #1 and #2 together. The initial load active power is 50MW, which increases to 60MW at 0.5s, as shown in Fig. 14(a), the #1 DC traction power $P_1$ and #2 DC traction power $P_2$ always keep the same, and the power equalization is realized; the DC side voltage is shown in Fig. 14(b), the DC side voltages of #1 and #2 traction substations are maintained at 25kVdc.

If the capacity of #1 traction substation is 20MVA, the capacity of #2 traction substation is 30MVA, the distance between #1 and #2 is 30km, and the DC output voltage is 25kVdc. When the locomotive load
is 50MW in the middle of the two DC traction substations, the load power is borne by #1 and #2 together. As shown in Fig. 15, traction substations #1 and #2 bear 3/5 and 2/5 power respectively, which satisfy the requirements of assuming load power and realizing power distribution according to the rated capacity ratio.

![Simulation results of power sharing of DC traction substations with the same capacity](image)

**Fig. 14** Simulation results of power sharing of DC traction substations with the same capacity: (a) Output power, (b) DC-side output voltage

![Simulation results of power sharing of DC traction substations with different capacities](image)

**Fig. 15** Simulation results of power sharing of DC traction substations with different capacities: (a) Output power, (b) DC-side output voltage

### 6. Conclusion

This paper proposes a DC traction power supply system for electrified railroad with ice melting function. Through cost and capacity analysis, the capacity ratio of fully controlled rectifier to uncontrolled rectifier is determined, and harmonic compensation, voltage stabilization and power distribution are realized by adjusting the fully controlled rectifier. This topology has the advantages of low cost, simple structure and easy to realize engineering application. By adjusting the ratio of the regulator, the traction power supply and DC ice melting mode can be switched to realize DC ice melting. Meanwhile, for this topology, this paper proposes a compound control algorithm, and establishes the control strategy under the small signal model of the system and analyzes the control parameters on the system stability. Properly reducing droop coefficient $D_k$ and $K_v$ coefficient of DC side voltage controller and increasing $K_{pu}$ coefficient of voltage compensator and $K_v$ coefficient of DC side voltage controller, can make the Nyquist curve of the system away from point (-1, j0), so as to achieve system stabilization.

Two issues deserve further investigation in future research: i) DC traction system is connected to energy storage system and distributed renewable energy power generation system. How to coordinate traction substation, renewable energy power generation system and energy storage system to maintain the stability of DC voltage of traction network and the balance of system energy supply and demand is the key to ensure the safe and efficient operation of the system. ii) Optimization design method of the main circuit parameters of the system to reduce the operation loss and improve the system efficiency.

**Acknowledgment**

This work was supported by the National Natural Science Foundation of China (No. 51907010)

**REFERENCES**


[6] Li L, Wu M. A three-phase symmetric converter in AC electric railway systems for power quality and energy efficient
improvement\cite{[7]}.


