Research on Influencing Factors of Current-carrying Temperature Rise on Connector Terminal of Current Circuit in UHVDC Converter Station

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Abstract. Relying on the high current temperature rise test, starting from three aspects of different materials, different structural strengths, and different contact conditions, the research on the current-carrying-temperature rise characteristics of the joint terminals of ±800kV UHVDC converter stations under different conditions is carried out. The results show that, for joint terminals of the same structure type and contact area, the difference in resistivity of joint terminals of different materials has a significant impact on the temperature rise level. When the material is the same, the temperature rise level can be reduced to a certain extent after the silver (tin) layer is added to the contact surface of the terminal. When the contact resistance of the joint terminal and the current density are the same, after increasing the contact area, the temperature rise and decrease level of the aluminum alloy plate lap type joint terminal is significantly better than other types of joint terminals. The contact resistance and temperature rise of the joint terminal decrease with the increase of the bolt tightening torque, and become stable when it reaches more than 80%. When the bolt tightening torque reaches more than 90%, the surface finish of the contact surface has no obvious effect on the contact resistance of the joint terminal. By controlling the material properties, structural strength, contact conditions, significantly reduces the temperature rise of the level of the joint terminal, effectively ensuring the safety ±800kV UHVDC converter station stable operation.

Keywords: Convertor Station, Terminal Connector, Heating Mechanism, Limiting Temperature.

1. Introduction
With the rapid development of China’s national economy and the gradual improvement of people’s living standards, the demand of whole society for electricity is rapidly rising, while the reliability and quality of power supply has put forward higher requirements. Since the distribution of primary energy in China is extremely mismatching with production development level, the development of UHV power grids to achieve long-distance and large-capacity power transmission is an important way to meet electricity demand and solve energy contradictions [1-2]. The converter station is the core component of the UHVDC project, and it is also the key figure in the AC-DC conversion. The connector terminal is a fitting that is widely used for the UHVDC converter station, and its role is to connect the main equipment of the converter station to each other, forming a conductive path. The connector terminal will
inevitably generate heat during long-term operation. The main cause of heat generation is resistance heating under current-carrying conditions [3-4]. In the case of long-term heat generation, the mechanical strength of metal components will be significantly reduced and thus will easily be deformed and damaged under the action of external forces. The statistical data shows that since the beginning of summer in 2014, the connector terminals of several ±800kV UHVDC converter stations, including the Fu-Feng Line, Jin-Su Line, Tian-Zhong Line and Bin-Jin Line have been subjected to overheating, of which 114 have been abnormally hot and 10 have been seriously hot and applied for temporary shutdown. The problem of temperature rise in the terminals of UHVDC converter stations has become an important factor of endangering the safety and reliability of power transmission.

The influencing factors of temperature rise on the connector terminals of UHVDC converter stations are very complex, involving many aspects such as material characteristics, contact mode, contact area, contact conditions and environmental adjustment points [5]. As the first UHVDC project to be put into operation in the world, there is still a lack of research results on the influencing factors of temperature rise on the connector terminals of the converter station and their test methods. The research on the carrying current - temperature rise characteristics and its influencing factors of connector terminal of UHVDC converter station can provide experimental data to support the proposed measures for preventing and controlling the temperature rise on the connector terminals, which is of great guiding significance for improving the operation and maintenance of UHV grid and ensuring its safe and stable operation.

Based on the temperature rise condition of the connector terminals of the converter station in the ±800kV UHVDC transmission project that has been put into operation, this paper studies the current-temperature rise characteristics of the connector terminals of different materials, different pressing force conditions, different structure types, different contact areas, and different surface finishes and analyzes the influence of material characteristics on the current-temperature rise characteristics of the connector terminal to provide experimental and theoretical support for the selection, design and optimization of the connector terminal.

2. Test Materials and Test Methods

2.1. Preparation of Test Samples
The equipment required for the test mainly includes a large-current generator and a DC resistance test device, and the relevant test samples are selected according to the different requirements of the test. The size of the sample used for the influence test of material property is shown in Table 1.

| Sample Used for Influence Test of Material Properties. |
|--------------------------------------------------------|
| **Aluminum Alloy** | **Copper Plate** | **Copper Plate (Silver-plated) - Aluminum Plate (Tinned) Sample 3** |
| **Sample 1** | **Sample 2** | **Sample 3** |
| Quantity of Bolt Holes | 6×4 |  |
| Overlapping Area | 330mm×220mm |  |
| Diameter of Bolt Hole | φ18mm |  |
| Hole Spacing | 50mm |  |
| Hole Edge Distance | 40mm (direction 330) or 35mm (direction 220) |  |
| Plate Thickness | 20mm | 12mm | 12mm | 20mm |
The size of the sample used for the influence test of structural characteristics is the same as the sample 1 - aluminum alloy terminal board in Table 1.

For the influence test of contact conditions, the sample 4 and sample 5 in the control group as shown in Table 2 are added on the basis of the sample 1 and sample 3 in Table 1.

**Table 2. Sample Used for Influence Test of Material Properties.**

|                  | Aluminum Alloy Sample 4 | Copper Plate (Silver-plated) - Aluminum Plate (Tinned) Sample 5 |
|------------------|-------------------------|---------------------------------------------------------------|
| Quantity of Bolt Holes | 6×4                     | Copper Plate (Silver-plated)                                  |
| Overlapping Area       | 380mm×240mm             | Aluminum Plate (Tinned)                                      |
| Diameter of Bolt Hole  | φ18mm                   |                                                              |
| Hole Spacing           | 50mm                    |                                                              |
| Hole Edge Distance     | 40mm (direction 330) or 35mm (direction 220)                  |
| Plate Thickness        | 20mm                    | 12mm                                                          |
|                     |                         | 20mm                                                          |

The quantity of the samples used for the influence test of the surface finish is: 2 aluminum alloy terminal boards with contact surface roughness of 25, 6.3, and 3.2 each, and the size of the overlapping surface is the same as that of sample 1 - aluminum alloy terminal board.

Installation requirements for test samples:
Use 200# and 400# fine sandpaper in turn to remove the dirt and oxide layer on the surface of the test samples, clean the polished surface with acetone, wipe the polished surface with absorbent cotton and blow dry. Protect the silver-plated surface of the copper plate and the tin-plated surface of the aluminum plate with oil after processing, and clean the grease on the surface before installation. For the samples used for the influence test of surface finish, clean the polished surface only with acetone, then wipe it with absorbent cotton and blow dry.

Connect the test sample to the test circuit with bolts. Keep certain distance between the test sample and other connecting parts to avoid the influence of thermal disturbance.

The temperature sensors are evenly arranged on the surface of the test sample to monitor the temperature of the test sample in real time during the test. The specific situation of the temperature measurement point layout of the terminal board is shown in Figure 2.
2.2. Influence Test of Material Characteristic

Based on the current-temperature rise test results of connector terminals of different material, this study analyzes the influence of material characteristics on the temperature rise limit of the connector terminal. The samples include aluminum plate, copper plate, copper plate (silver-plated), and aluminum plate.
(tinned). By changing the magnitude of the current, the relationship curve $K = f(J)$ between the temperature rise $K$ of aluminum plate-aluminum plate, copper plate-copper plate and copper plate (silver-plated)-aluminum plate (tinned) and the current density $J$ is obtained from the test.

The test steps are as follows:
1. Load the current to 5,000A, and after the sample temperature remains basically unchanged, record the temperature shown by the temperature sensors on the surface of the test sample, and use the highest temperature value as the stable temperature of the test sample;
2. Increase the current further to 5,750A, and record the stable temperature after the temperature of the sample remains basically unchanged;
3. Repeat the Step (2) until the current reaches 6,750A. After the temperature of the sample remains basically unchanged, record the stable temperature value.

2.3. Influence test of Structural Strength

Based on the current-temperature rise test results of the connector terminal under different pressing forces, this study analyzes the influence of the structural strength on the temperature rise limit of the connector terminal. The test sample is of an aluminum plate. The pressing force of the connector terminal is proportional to the bolt tightening torque. By changing the bolt tightening torque, the relationship curve $R = f(F)$ between the tightening torque $F$ of the sample and the resistance $R$ is obtained from the test, and the influence of the pressing force on the contact resistance is investigated.

2.3.1. Influence test of pressing force on contact resistance. The test steps are as follows:
1. Tighten the bolt at the overlapping position of the test sample to the torque of 190N•m (100%), and measure the contact resistance of the test sample;
2. Turn further the bolt at the overlapping position of the test sample counterclockwise to the torque of 9.5N•m, reduce the total torque to 180.5N•m (95%), and measure the contact resistance of the test sample;
3. Repeat the Step (2) until the total torque drops to 76N•m (40%), and measure the contact resistance of the test sample.

2.3.2. Influence test of pressing force on temperature rise. The test steps are as follows:
1. Tighten the bolts at the overlapping position of the test sample to the torque of 190N•m (100%) and load the current to 6,750A. After the temperature of the sample remains basically unchanged, record the temperature indicated by the temperature sensors on the surface of the test sample. Use the highest temperature value as the stable temperature of the test sample, and reduce the current to zero;
2. Loosen the bolt, re-treat the surface, re-tighten the bolt at the overlapping position of the test sample to the torque of 161.5N•m (85%) and load the current to 6,750A. After the temperature of the sample remains basically unchanged, record the stable temperature value, and reduce the current to zero;
3. Repeat the Step (2) until the torque drops to 76N•m (40%), and load the current to 6,750A; after the temperature of the sample remains basically unchanged, record the stable temperature value, and reduce the current to zero.

2.4. Experiment on the influence of contact conditions on the heating limit of joint terminals

Based on the current-temperature rise test results of the connector terminal under different contact areas and different surface finish conditions, this study analyzes the influence of the contact conditions on the temperature rise limit of the connector terminal, where the test samples are made of aluminum plate and copper plate (silver-plated) and aluminum plate (tinned). For the influence test of contact area, by changing the magnitude of the current, the relationship curve $K = f(J)$ between the temperature rise $K$ of aluminum plate-aluminum plate and the current density $J$ is obtained from the test. For the influence test of surface finish, by changing the finish of the contact surface of the connector terminal, the relationship curve $R = f(Ra)$ between the surface finish $Ra$ of the test sample and the contact resistance $R$ is obtained from the test [6-8].
2.4.1. *Influence Test of Contact Area*. The test steps are the same as the influence test of material characteristics.

2.4.2. *Influence Test of Surface Finish*. The test steps are as follows.
(1) For the test samples with the contact surface finish of 25, 6.3 and 3.2 respectively, tighten the bolts at the overlapping position of the test sample to the torque of 190N•m (100%), and measure the contact resistance of the test sample;
(2) Loosen the bolts at the overlapping position of the test sample counterclockwise to the torque of 9.5N•m, reduce the total torque to 161.5N•m (85%), and measure the contact resistance of the test sample;
(3) Repeat the Step (2) until the total torque drops to 76N•m (40%), and measure the contact resistance of the sample.

3. *Analysis and Discussion on Test Results*

3.1. *Analysis on Influence Test Results of Material Characteristics*
According to the test program, the temperature rise test is carried out on the connector terminal samples of different materials. The test results are shown in Figures 3-5. In the figure, the abscissa represents the flow time (h), and the ordinate represents the average surface temperature (℃) of the sample.

![Figure 3. Flow Time (Current)-Temperature Rise Curve of Sample 1.](image1)

![Figure 4. Flow Time (Current)-Temperature Rise Curve of Sample 2.](image2)

![Figure 5. Flow Time (Current)-Temperature Rise Curve of Sample 3.](image3)
It can be seen from the figure that the average surface temperature of samples 2 and 3 does not exceed 80°C, and the average surface temperature of sample 1 exceeds 80°C but less than 90°C under the current of 6,250A according to the average surface temperature of the samples. Via comparing samples 2 and 3 further, it is found that the temperature rises of samples 2 and 3 are close to each other under the current of 6,250A.

The influence of material characteristics on the temperature rise of the connector terminal is manifested in that the difference in the resistivity of the connector terminal of different materials has a significant influence on the temperature rise of the connector terminal with the same structure type and contact area under the same current condition. After a silver-plated (tinned) layer is added on the surface, the temperature rise can be reduced to certain extent. The connector terminals of current circuit in UHVDC converter station shall be made of copper or silver-plated copper if possible. If aluminum material is used, the design margin shall be increased.

3.2. Analysis on Influence Test Results of Structural Strength

According to the test program, the temperature rise test of the connector terminal samples under different pressing force conditions. Figure 6 shows the tightening torque-contact resistance curve of the connector terminal. In the figure, the abscissa represents the tightening torque (N•m) of the bolt, and the ordinate represents the contact resistance (μΩ) of the connector terminal.

![Figure 6. Tightening Torque - Contact Resistance Curve of Connector Terminal.](image)

It can be seen from the figure that as the bolt tightening torque increases, the contact resistance of the connector terminal gradually decreases. When the bolt tightening torque exceeds 80% of the standard tightening torque, the contact resistance of the connector terminal basically remains stable. This is because as the pressing force increases, the effective contact area between the terminals boards increases, thereby reducing the contact resistance. When the pressing force exceeds 80% of the standard pressing force, the effective contact area between the terminal boards will be close to the maximum value, so the contact resistance remains basically unchanged.

Figure 7 shows the flow time-temperature rise curve of connector terminal under different bolt tightening torque conditions. In the figure, the abscissa represents the flow time (h), and the ordinate represents the surface temperature (℃) of the sample. Figure 8 shows the tightening torque-temperature rise curve of connector terminal. In the figure, the abscissa represents the ratio (%) of the bolt tightening torque to the standard tightening torque, and the ordinate represents the surface temperature (℃) of the sample.
Figure 7. Flow Time (Current)-Temperature Rise Curve of Aluminum Plate-Aluminum Plate Overlapped Connector Terminal under Different Bolt Tightening Torque Conditions.

Figure 8. Tightening Torque - Temperature Rise Curve of Connector terminal.

It can be seen from the figure that as the bolt tightening torque increases (from 40% of standard tightening torque to 100% of standard tightening torque), the temperature rise of the connector terminal shows a downward trend. This is basically consistent with the changing trend of the tightening torque-contact resistance curve.

For the aluminum alloy overlapped connector terminal, the contact resistance basically reaches the minimum value when the bolt tightening torque exceeds 80% of the standard tightening torque, and the temperature rise is close to the temperature rise at 100% of the standard tightening torque. Within the working temperature range of the connector terminal of current circuit in UHVDC converter station, the current-temperature rise curves of the connector terminal under different pressing force conditions all show an upward trend, and there is no inflection point. Therefore, the structural strength has no influence on the temperature rise limit of the connector terminal.

3.3. Analysis on Influence of Contact Conditions on Test Results

According to the test program, the temperature rise test is carried out on the connector terminal samples with different contact areas. The test results are shown in Figures 9-10. In the figures, the abscissa represents the flow time (h), and the ordinate represents the average surface temperature (℃) of the sample. The temperature rise test results of the connector terminals of aluminum plate-aluminum plate and copper plate (silver-plated)-aluminum plate (tinned) with the design value of the contact surface current density of 0.0936A/mm² are shown in Figure 3 and Figure 5.
According to the temperature rise test results of connector terminals with different contact areas, the current density-temperature rise characteristics of connector terminals with different contact areas are analyzed. Figures 11-12 show current density-temperature rise curves of connector terminals with different contact areas. In the figure, the abscissa represents the current density (A/mm²), and the ordinate represents the surface temperature (℃) of the sample.

Figure 9. Flow Time (Current)-Temperature Rise Curve of Sample 4.

Figure 10. Flow Time (Current)-Temperature Rise Curve of Sample 5.

Figure 11. Current Density-Temperature Rise Curves of Samples 1 and 4.
Figures 13-14 show the temperature rise retention curves of the connector terminal with different contact areas. In the figure, the abscissa represents the number of temperature measurement points on the surface of the sample, and the ordinate represents the surface temperature (°C) of the sample.

**Figure 12.** Current Density-Temperature Rise Curves of Samples 3 and 5.

**Figure 13.** Temperature Rise Retention Curves of Samples 1 and 4.

**Figure 14.** Temperature Rise Retention Curves of Samples 3 and 5.
It can be seen from Figures 11-14 that the temperature rise of the aluminum alloy overlapped connector terminal is significantly reduced, but the change in temperature rise of the copper plate (silver-plated)-aluminum plate (tinned) connector terminal is not obvious with the increase of the contact area under the current of 6,250A.

Figure 15 shows the tightening torque-contact resistance curve of aluminum plate-aluminum plate overlapped connector terminal under different surface finish conditions. In the figure, the abscissa represents the ratio (%) of the bolt tightening torque to the standard tightening torque, and the ordinate represents the contact resistance (μΩ) of the sample.

![Figure 15. Tightening Torque-Contact Resistance Curve of Connector Terminals under Different Surface Finish Conditions.](image)

It can be seen from Figure 15 that the contact resistance of the connector terminals with different surface finishes remains basically unchanged when the bolt tightening torque exceeds 80% of the standard tightening torque. When the surface finish is poor, the contact resistance measurement value of the connector terminal has more dispersed. When the surface finish reaches 3.2μm, the measured value of contact resistance of the connector terminal has less dispersed.

For the influence of the contact area on the temperature rise of the connector terminal: Under the same current condition, the temperature rise of the aluminum plate-aluminum plate overlapped connector terminal is significantly reduced, but the temperature rise of other connector terminals is not obviously changed with the increase of the contact area. Increasing the design margin has a significant influence on the current-temperature rise characteristics of the aluminum plate-aluminum plate overlapped connector terminal, and can effectively reduce the temperature rise of the connector terminal.

For the influence of surface finish on the temperature rise of the connector terminal: When the bolt tightening torque reaches 90% of the standard tightening torque, the difference in the contact resistance of the connector terminal is small under different surface treatment process conditions. At 90% of standard tightening torque, the requirements of engineering applications can be met as long as the surface finish of the connector terminal is not more than 25μm.

4. Conclusions
Based on the temperature rise condition of the connector terminals of the converter station in the ±800kV UHVDC transmission project that has been put into operation, this paper studies the current-temperature rise characteristics of the connector terminals of different materials, different pressing force conditions, different structure types, different contact areas, and different surface finishes and analyzes the influence of material characteristics on the current-temperature rise characteristics of the connector terminal. The main conclusions obtained are as follows.
(1) The difference in the resistivity of the connector terminal of different materials has a significant influence on the temperature rise of the connector terminal with the same structure type and contact area under the same current condition. After a silver-plated (tinned) layer is added on the surface, the temperature rise can be reduced to a certain extent. The connector terminals of current circuit in UHVDC converter station shall be made of copper or silver-plated copper if possible. If aluminum material is used, the design margin shall be increased.

(2) When the current density is the same, the temperature rise of the aluminum alloy plate overlapped connector terminal decreases significantly, and the change in the temperature rise of the copper plate (silver-plated)-aluminum plate (tinned) type connector terminal is not obvious with the increase of the contact area. Increasing the design margin has a significant influence on the current-temperature rise characteristics of the aluminum alloy plate overlapped connector terminal, and can effectively reduce the temperature rise of the connector terminal.

(3) As the bolt tightening torque increases, the contact resistance and temperature rise of the connector terminal gradually decrease and stabilize at 80% of the tightening torque. Therefore, the bolt tightening torque shall not be less than 80% of the standard tightening torque, and the bolts shall be tightened regularly when the connector terminals are installed.

(4) When the bolt tightening torque is the same, the contact resistance of the connector terminal will drop as the surface finish of the contact surface decreases. When the bolt tightening torque exceeds 90% of the standard tightening torque, the surface finish of the contact surface has no obvious influence on the contact resistance of the connector terminal. Therefore, the requirements of engineering applications can be met as long as the surface finish of the connector terminal is not more than 25μm at 90% of standard tightening torque.

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