Research on Performance of Grounding Conductor Based on Multi-Physics

Sun Xiangdong¹, Ding Hui², Cui Jinrui³, Wang Yanwei⁴

¹Anhui Power Engineering Quality Supervision Center, Hefei, Anhui 23000, China
²National Energy Administration Reliability and Quality Supervision Center, Xicheng, Beijing, 100000, China
³State Grid Anhui Electric Power Limited company, 23000, Hefei, Anhui 23000, China
⁴North China Electric Power University Baoding, Hebei 071000, China

*Corresponding author’s e-mail: 1351405626@qq.com

Abstract: The performance analysis of the grounding conductor is of great significance for improving the design and construction level of the grounding grid and rationally selecting the grounding conductor specifications. Based on the multi-physics analysis and calculation software COMSOL, this paper establishes a three-dimensional simulation model of the grounding conductor with the standard hexagonal M8 bolt as the research object. Firstly, the contact resistance of the grounding copper bus contact surface is calculated, and the influence of contact resistance is analyzed according to different factors. Then, the influence of different tightening torque on the maximum temperature of the contact surface under the condition of short-circuit current is calculated. Finally, the normal condition of the contact surface under different tightening moments and the pressure distribution characteristics during short-circuit are calculated. The results show that the bolt tightening torque, the surface roughness of the copper row, the selected grounding copper row material, and the overlapping area all have an effect on the contact resistance; When the grounding conductor is short-circuited, the maximum temperature on the contact surface decreases with the increase of the tightening torque. It is recommended to use copper as the material of the grounding conductor, and apply a tightening torque to the bolt at 24–28 N·m; At the same time, the distribution characteristics of the contact surface of the conductor under normal conditions are analyzed. Finally, based on the research results, the method of reducing the grounding resistance at the grounding conductor joint in practical engineering is proposed.

1. Introduction

From the beginning of power engineering construction, the grounding system of electrical equipment has been closely related to the primary and secondary circuits of electrical equipment and electrical equipment[1]. As the voltage level of the power grid continues to increase, the maximum voltage level has reached 1000kV, and the grounding short-circuit current of the system is also getting larger and larger, and the voltage of the grounding grid is getting higher and higher. In large ground current systems, the short-circuit current flowing into the ground network is generally in the range of several thousand amps to several tens of kiloamperes. Such a strong short-circuit current flows through the ground conductor and scatters into the ground, which will generate a high amount of heat in the
conductor, especially the ground conductor connection. Since the short-circuit current lasts for a short period of time, generally only a few tenths of a second, the heat generated in a very short period of time is not transferred to the surrounding soil medium, and it can be considered that all the heat is used to raise the temperature of the conductor. When the conductor temperature exceeds a certain value and is naturally cooled in the soil, the mechanical properties of the conductor will be significantly reduced, especially at the joint between the conductors. At this time, if other external forces are encountered, the conductor will be destroyed. When the short-circuit current is large and the conductor temperature is high, reaching the melting point of the metal material, the conductor will be melted. This will cause the ground wire conductor to break and the ground net to disintegrate, thereby greatly reducing the reliability of the grounding grid and causing safety hazards.

At present, in the large current grounding equipment, the grounding conductor connection is stabilized by bolt fastening, and the calculation method of the contact resistance of the bolt fastening conductor is mainly based on theory or based on engineering empirical formula. Li Zhenting et al[2] derived the calculation formula of shrinkage resistance and thin film resistance according to the conduction mechanism of mechanical electrical contact points, and obtained the calculation formula of contact resistance. Xu Jun et al[3] based on the contact resistance microscopic model, combined with the factors affecting the contact resistance, give the empirical formula and measurement method for calculating the contact resistance. Fu Liying et al[4] explored the distribution of interface pressure in small and medium-sized bolted joints of spacecraft using Fuji pressure sensing test paper. Loujiafa et al[5] carried out related calculations on the short-term and long-term heating of contact points in shrinkage resistors, mainly to solve the calculation problem of contact resistance of copper bars in the case of sliding connection of copper bars, which is to study the fixed surface of copper bars. Contact issues do not apply. Wu Nan, ZhuangJinwu et al[6] used the standard hexagonal M8 bolt as the research object, and carried out the indentation test of the relationship between different torque and contact area between cylindrical copper rows. Based on the contact size and area, the contact was studied. The relationship between area and contact resistance was used to establish a cylindrical copper row and copper row contact resistance model using ANSYS software. Zhou Tian et al[7] established a three-dimensional eddy-fluid-temperature multi-field coupling numerical calculation model of GIS isolation switch with contacts for the monitoring of temperature rise and overheat fault of GIS isolation switch contacts, with a resistivity. The variable conductor is used to simulate the contact resistance of the contact point. The current density and power loss of each part of the GIS isolating switch are calculated by electromagnetic field analysis. The power loss is substituted into the fluid-temperature field coupling calculation model to calculate the temperature field of the conductor and the outer casing distributed.

Based on multi-physics analysis and calculation software COMSOL, a three-dimensional model of single-hole connection of grounding conductor is established. The contact resistance of the contact surface of the grounding copper strip is calculated. The effects of bolt tightening torque, copper row surface roughness, selected grounding conductor material and overlapping area on contact resistance were analyzed. According to the research results, measures to reduce the grounding resistance at the grounding conductor joint are proposed. In the study of the effect of different tightening torques on the heating of the ground conductor during a short circuit, a numerical calculation model of the electro-thermal-force multiphysics coupling of a two-hole ground conductor is established according to the actual situation. First, the application of the tightening torque in the mechanical field will change the contact resistance in the electric field. At this time, the power loss is caused by the short-circuit current. The power loss is substituted into the thermal field coupling calculation model to calculate the temperature field distribution of the conductor and the shell. The temperature value of the thermal field is brought back to the electric field to change the resistivity of the conductor, so that the electric field and the temperature field are bidirectionally coupled. The temperature of the thermal field will cause the conductor to thermally expand, which will affect the effective contact area of the contact surface, and then affect the contact resistance in the electric field.
2. Model construction and simulation calculation of contact resistance

2.1 Grounding copper bus simulation modeling
Refer to the national standard "GB/B5585.1-2005.Electrical copper, aluminum and its alloy busbars"[8] and "GB50149-2010 electrical installation engineering"[9] select conductor materials and design grounding conductor specifications and grounding conductors lap form.

The copper bar specifications built in the COMSOL software are 3mm×25mm×50mm (thickness×width×length), The lap joint is a linear lap, and the lap length is 25mm, The selected bolt is a M8 steel bolt with a bolt hole diameter of 9mm. The overlap area is 25×25-3.14×4.5×4.5=561.42mm2. The thickness of the gasket is 1mm, outer diameter is 16mm, inner diameter is 9mm.

The established model is shown in Figure 1.

![Figure 1. Ground conductor model.](image)

2.2 Simulation calculation of contact resistance
In the numerical calculation, the resistance of the contact resistance can be obtained by the following formula.

\[ R = R_1 - R_0 \]  \hspace{1cm} (1)

\( R_1 \) is the total resistance of the ground conductor model, and \( R_0 \) is the body resistance of the ground conductor model after removing the contact resistance. The calculation of the resistance is shown in Figure 2. The end of the copper row is connected to the current \( I \) and the other end is set to "ground". First calculate the potential difference \( U \) of the two end faces, then \( R_1 = U/I \) according to Ohm's law. In the COMSOL software, the model is set as a "combined body" to make all contact between the contact faces of the grounding conductor lap joints, there is no shrinkage resistance and film resistance, and the \( R_0 \) is also calculated according to the operation of Figure 2.
3. Influence of single factor on contact resistance of grounding conductor

3.1 Tightening torque
Set bolt tightening torques in the COMSOL software to 2N·m, 4N·m, 6N·m, 8N·m, 10N·m, 15N·m, 20N·m, 25N·m, 30N·m, and calculate the contact resistance, the relationship between the contact resistance and the bolt tightening torque is shown in Figure 3. It can be seen from Fig. 3 that as the tightening torque increases, the contact resistance begins to decrease. When the tightening torque exceeds 20N·m, the tendency of the contact resistance to decrease is no longer obvious, and it is almost stable. At this time, the influence of the tightening torque on the contact resistance is already small.
3.2 Contact Surface Roughness
In the COMSOL software, set the bolt tightening torque to 25N·m, and I set the roughness of the contact surface to 2μm, 4μm, 6μm, 8μm, 10μm, and 12μm. The contact resistance is calculated separately, and the relationship between contact resistance and roughness is shown in Fig. 4. It can be seen from Fig. 4 that in the case where the tightening torque is constant, the contact resistance increases as the roughness increases, and the two become nearly linear.

3.3 Material type
In the COMSOL software, set the bolt tightening torque to 25N·m, and set the material used for the grounding conductor to copper-copper, copper-aluminum, aluminum-aluminum, copper-steel, aluminum-steel, steel-steel. The contact resistance is calculated separately, and the relationship between the contact resistance and the material type is shown in Fig. 5. It can be seen from Fig. 5 that when the selected material is copper-copper, the contact resistance is the smallest. When the selected
material is steel-steel, the contact resistance is the largest. When the selected material contains steel, the contact resistance has a significant increase.

![Contact resistance and material type relationship](image)

**Figure 5. Contact resistance and material type relationship**

3.4 Lap area

In the COMSOL software, set the bolt tightening torque to 25N•m, and then increase the overlap length from 25mm to 30mm,35mm,40mm,45mm,50mm. The overlapping area increased from 561mm² to 686mm², 811mm², 936mm², 1061mm², and 1186mm². The contact resistance is calculated separately, and the relationship between the contact resistance and the overlap area is shown in Fig.6. It can be seen from Fig. 6 that, with the bolt tightening torque constant, as the overlap area increases, the contact resistance also increases, and does not decrease due to the increase of the overlap area.

![Relationship between contact resistance and overlap area](image)

**Figure 6. Relationship between contact resistance and overlap area**

4. Effect of Different Tightening Torques on Thermal Effect of Short Circuit Current

The physical field of the grounding conductor in the event of a short circuit is very complicated because it needs to be combined with an electric field, a thermal field and a mechanical field. In this paper, the multi-physics model of the two-hole connected grounding conductor shown in Figure 7 is
established. The lap length is increased to 50 mm in comparison with Figure 1, and the remaining parameters are unchanged. It is used to analyze the temperature distribution and pressure distribution in the lap joint when the grounding conductor is connected to the short-circuit current.

In this paper, variables in various physical domains are coupled together and clearly described, as shown in Figure 8. The physical variables in the electrical, thermal and mechanical models are directly coupled during the simulation. In the mechanical model, by changing the magnitude of the tightening torque, the contact resistance in the electrical model is affected, and the contact thermal resistance in the thermal model is also affected. Since the short circuit process is analyzed, the heat generated by the conductor in a very short time is not transferred to the surrounding medium. Here, it is considered that all the heat is used to heat the ground conductor. Therefore, in the parameter setting of the thermal model, factors such as convection, radiation, and conduction can be ignored, so the contact thermal resistance is not considered as a research field. In the thermal model, the change in temperature causes the conductor to thermally expand and then deforms to change the contact resistance and contact thermal resistance. Electrical models and thermal models are mainly reflected by current and temperature. On the one hand, changes in current will affect temperature, and on the other hand, changes in the temperature of the conductor will affect the resistivity in the electrical model.

According to the maximum short-circuit current to ground of a substation is 23.4 kA, the short-circuit current we pass in this model is $23.4 \sqrt{2} \sin (100 \pi t) \text{kA}$, ignore the effect of the DC component when shorted. According to the provisions of Appendix C in "Grounding of AC Electrical Installations DL / T621-1997" [10], when a substation, the relay protection device of the substation has two sets of quick-action protection, near backup protection, circuit breaker failure protection and automatic reclosing protection, the time $t_e$ to remove the fault current can be as follows:

$$t_e \geq t_m + t_f + t_0$$

$t_m$-Main protective action time, s
$t_f$-Breaker failure protection action time, s
$t_0$-Breaker opening time, s

Taking the main protection action time as 0.015 s, failure protection action time as 0.3 s, and breaking time as 0.05 s, then: $t_e=0.015+0.3+0.05=0.365 \approx 0.37$ s

In the COMSOL software, copper material was chosen as the grounding conductor material and the bolt tightening torque was set to 4 N•m, 6 N•m, 8 N•m, 10 N•m, 12 N•m, 14 N•m, 16 N•m, 18 N•m, 20 N•m, 22 N•m, 24 N•m, 26 N•m, 28 N•m, 30 N•m, and calculate the maximum temperature of the
contact surface, and obtain the highest contact temperature and bolt fastening. The relationship between torque is shown in Figure 9.

It can be seen from Fig. 9 that as the tightening torque increases, the maximum temperature of the two contact surfaces decreases rapidly. When the tightening torque exceeds 20N•m, the trend of temperature decrease is no longer obvious, almost stable. The effect of the tightening torque on the temperature is already small. According to the standard "grounding DL/T621-1997 of AC electrical equipment"[10], the grounding conductor should not exceed 450 °C when short-circuited when using copper, so the tightening torque applied to the grounding conductor should exceed 16N•m, consider it is recommended to apply a tightening torque of 20–26N•m to the mechanical strength of the M8 bolt itself and the corrosion of the conductor caused by the surrounding environment.

Figure 9. Relationship between the maximum temperature and the tightening torque of the two contact faces of the grounding conductor (copper)

In the COMSOL software, the aluminum alloy is used as a grounding conductor material and the bolt tightening torque is set to 4N•m, 6N•m, 8N•m, 10N•m, 12N•m, 14N•m, 16N•m, 18N•m, 20N•m, 22N•m, 24N•m, 26N•m, 28N•m, 30 N•m, and calculate the maximum temperature of the contact surface, and obtain the highest contact temperature and bolt fastening. The relationship between the torques is shown in Figure 10. It can be seen from Figure 10 that the maximum temperature of the two contact surfaces decreases rapidly with the increase of the tightening torque. When the tightening torque exceeds 20N•m, the trend of temperature decrease is no longer obvious, almost stable. The effect of the tightening torque on the temperature is already small.

According to the standard "grounding of AC electrical equipment DL/T621-1997"[10], the grounding conductor should not exceed 300 °C when short-circuited when using aluminum, and within the tightening torque range that the M8 bolt can withstand, the temperature of the contact surface exceeds 300 °C, so the choice of aluminum as the grounding conductor material does not meet the requirements.
Figure 10. Relationship between maximum temperature and tightening torque of two contact faces of grounding conductor (aluminium)

5. Pressure Distribution Characteristics under Normal Conditions on the Contact Surface

In the COMSOL software, the copper material was selected as the grounding conductor material and the bolt tightening torque was set to 20N•m, and the contact surface pressure distribution under normal conditions was calculated. The pressure distribution diagram is shown in Fig. 11. It can be seen from the distribution diagram that the maximum pressure appears at the joint between the nut and the screw, and the value is 78016.2 Pa, respectively. As the distance from the joint increases, the pressure on the surface of the copper row also gradually decreasing. At the same time, it can be seen that the force portion at the lap joint occupies a small proportion of the entire lap joint and is only distributed near the bolt.

Figure 11. Pressure distribution of the grounding conductor when the tightening torque is 20 N•m

Set bolt tightening torques in the COMSOL software to 2N•m, 4N•m, 6N•m, 8N•m, 10N•m, 12N•m, 14N•m, 16N•m, 18N•m 20N•m, 22N•m, 24N•m, 26N•m, 28N•m, 30N•m, respectively.
calculate the maximum pressure on the contact surface under normal conditions, and the maximum pressure and bolt tightness of the contact surface when the grounding conductor is normal. The relationship between the solid torque is shown in Fig. 12. It can be seen from Fig. 12 that the maximum pressure of the contact surface increases with the increase of the tightening torque, and it can be seen that the relationship between the two is approximately linear.

![Figure 12: Maximum pressure at the contact surface under normal grounding conductor under different tightening torques](image)

6. Method for Reducing Contact Resistance of Ground Conductor in Practical Engineering

According to the previous analysis of the factors affecting the contact resistance, the following methods can be used to reduce the influence of contact resistance in actual engineering construction:

1. In the case of meeting the bolt strength requirements, the greater the tightening torque applied to the ground, the better, and the maximum tightening torque that the bolt can withstand. For M8 steel bolts, when copper is used as the grounding material, the tightening torque is preferably 20–26N·m.

2. Before tightening the grounding conductor with bolts, the contact resistance should be reduced by reducing the surface roughness. The surface of the grounding conductor can be ground by sandpaper to reduce the surface roughness of the grounding conductor and to remove the surface oxide film.

3. In case the construction cost permits, the grounding materials should all be made of copper.

4. Under the condition that the mechanical strength requirement is met, the overlapping area should be as small as possible.

7. Conclusion

Based on the multiphysics analysis software COMSOL, a three-dimensional simulation model of the grounding conductor is established, and the contact resistance of the grounding conductor contact surface is calculated. The related factors affecting the contact resistance and the influence of different tightening torques on the maximum temperature of the contact surface after the short-circuit current is applied are analyzed and discussed. The pressure distribution on the contact surface and the characteristics of the different tightening moments are studied. The conclusions obtained are as follows:

1. The contact resistance decreases as the tightening torque increases, increases as the roughness increases, and increases as the overlap area increases.
(2) When the material used for the grounding conductor is copper-copper, copper-aluminum, aluminum-aluminum, copper-steel, aluminum-steel, steel-steel, the copper-copper contact resistance is the smallest, and the steel-steel contact resistance is the largest.

(3) When the grounding conductor is short-circuited, the maximum temperature on the contact surface decreases as the tightening torque increases. When copper is selected as the grounding material, the recommended tightening torque is 24~28N•m. When aluminum is used as the grounding material, the short-circuit temperature is not up to standard, so aluminum is not recommended as the grounding material.

(4) In the case of normal or short circuit, the maximum stress of the contact surface appears at the joint of the nut and the screw, and as the distance from the joint increases, the pressure on the contact surface also gradually decreases. The maximum pressure of the contact surface increases as the tightening torque increases.

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