Review on Failure of Electrical Connection Components of Transformer Bushing

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Abstract: In the actual working process, the contact resistance of transformer bushing electrical connection parts increases due to temperature changes, vibration excitation, and other factors, thereby causing the failure of the connection parts. Therefore, ensuring the normal operation of the casing electrical connection parts to realize the stability and reliability of the DC transmission system. In this review, we summarize the previous studies conducted in this field in recent years and expound on the current status of the research conducted on the contact resistance of bushing electrical connection components, considering the mechanism of the electrical contact degradation of transformer bushing electrical connection components, main factors influencing the connection failure, experimental and simulation methods, and future outlook. Additionally, we discussed the typical issues faced in this field to provide new research directions, along with useful design insights for engineers.

Keywords: Electrically connected parts, contact resistance, failure mechanisms, influencing factors

1 Introduction

Ensuring the stability of electrical connection during the operation of high-voltage appliances is crucial [1]. Contact strips have advanced significantly as an electrical connection component and are widely used in various electrical products, including combined electrical appliances, circuit breakers, transformers, switchgear, and gas-insulated buses [2].

A contact strip is a special electrical contact component that generates multiple contact points to form electrical interconnections [3]. Each contact point serves as a “bridge”, enabling the current to pass through evenly. This design comprises a simple structure, small size, and low cost and is well-suited for mass production [4]. Contact strips are widely used in high-voltage bushings and other transmission equipment. When compared with the conventional wire spring hole, twist needle, and other electrical connection structures, contact strips significantly increase the contact area, thereby reducing the current density of the contact position and doubling the flow capacity of the electrical connection device [5].

In recent years, internal flashover discharge faults caused by current heating have occurred at several domestic converter stations, presenting a single-pole block of the DC converter station, which affected the transmitting and receiving AC-DC transmission systems [6]. Further analysis demonstrated that its failure characteristics primarily manifested in the dynamic, micro, and reciprocating friction of the contact strip during the working process, which causes mechanical wear and chemical corrosion of the contact head. This ultimately increases the contact resistance of the electrical connection parts, thereby causing overheating failure [7]. The deterioration of the electrical contact performance is affected by several factors. These factors include mechanical properties, such as fretting fatigue, stress relaxation, and creep of the contact material, along with operating conditions such as the current strength [8]. Additionally, environmental conditions such as the temperature, humidity, and corrosive gases can also present a considerable impact. In practical applications, electrical connection components must withstand the combined effects of electricity, heat, and force; these factors typically work together, resulting in the accelerated degradation of the electrical contact performance [9]. Fig. 1 depicts the deterioration of the contact strip caused by various factors.

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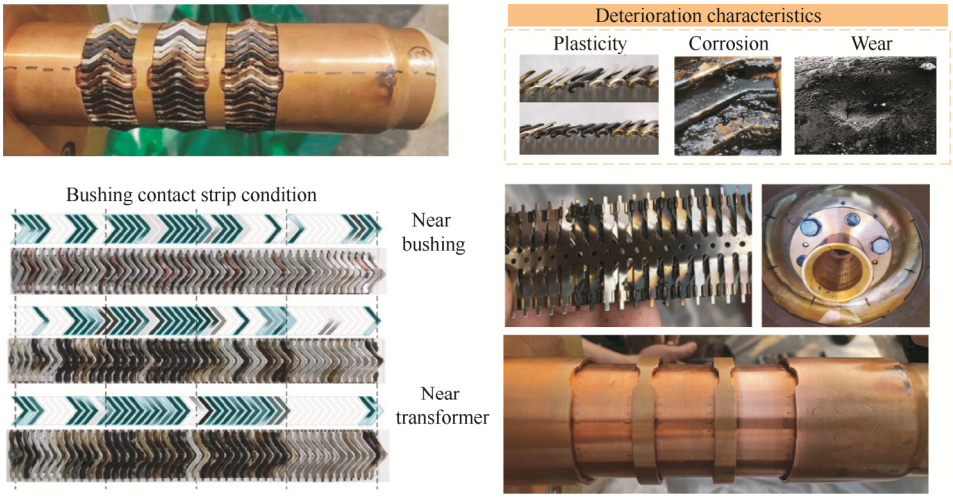


Fig. 1 Contact strips deterioration results

The increase in the contact resistance of the contact-type electrical connection parts can be attributed to two factors. One is fretting wear caused by vibrations during operation, and the other is the chemical corrosion of the electrical connection parts in the operating medium, which forms an adhesive layer. These two factors are affected in turn by the properties of the materials between the components, the stress relationship of the contact points, and other factors. Therefore, the failure of the electrical connection components involves tribology, materials science, dynamics, electronics, physical chemistry, thermodynamics, and other fields. To fully understand these complex problems, it is necessary to carry out extensive research work [10].

To this end, we summarized the existing research conducted on the electrical contact of electrical connection components based on four aspects: failure mechanism, main influencing factors, existing experimental and simulation research methods, and future research implications.

2 Mechanism of deterioration of electrical contacts of the contact strip

2.1 Mechanisms of generation and development of the contact strip connection failures

The contact strip type electrical contact component employs the deformation of the elastic plate to provide pressure of the contact point, thereby ensuring the stable transmission of current. This technology has been widely used since its introduction in the early 1960s in various environments, particularly those with strict requirements for temperature, vibration, and shock. This can be attributed to its small size, simple structure, multi-point contact, strong electrical conductivity, and excellent electrical and thermal stability. Additionally, it can withstand high currents, is suitable for high-voltage equipment, and has a large number of plug-and-unplug capabilities to satisfy the requirements of transformer assembly and switchgear life testing [11].

When the contact strip makes contact with the current-carrying conductive rod, the contact is limited to specific points on the intended surface instead of the entire surface. These points are distributed throughout the contact area, due to which the actual contact area is significantly smaller than the theoretical contact area. The difference between the actual and theoretical contact areas can vary thousands of times based on the smoothness of the surface and the applied pressure [12]. The actual contact surface primarily comprises two parts. The first is the microscopic point of direct contact between the metals, also known as the contact spot, which is formed after the contact pressure or thermal action destroys the surface film. These contact spots account for approximately 5%-10% of the actual contact area. The second comprises the points that are in contact with each other after establishing contact with the interface pollution film. Therefore, the contact resistance typically comprises two parts: the shrink resistance and film resistance [13].

The metal conducted spots were formed when the rough summit of the contact surface punctures the surface oxide film, as shown in Fig. 2 [14].

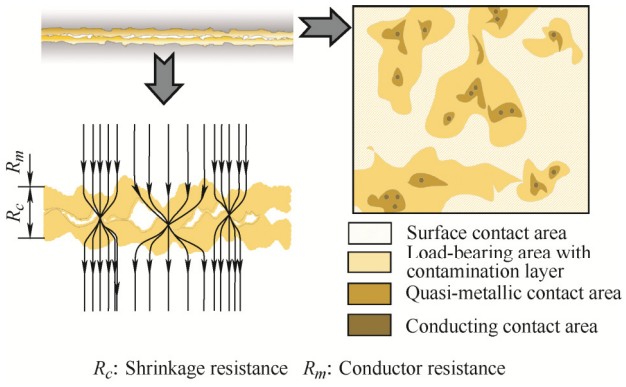


Fig. 2 Electrical contact schematic

As a key indicator for evaluating the reliability of electrical contact, the contact resistance is affected by several factors, such as the material type, roughness of the contact surface, contact mode, state of the surface film, contact pressure, current size, and duration [15].

The unique structure of the contact strip indicates that its contact point area is minimal; therefore, maintaining good contact is difficult. Typically, the resistance value of the casing current carrier system must be less than 50 μΩ, and the resistance value of the connection structure must be less than 10 μΩ [16]. However, in practice, maintaining appropriate contact pressure is difficult, which presents a contact resistance beyond the ideal range. Excessive contact resistance can lead to the overheating of the contact point. Fig. 3 summarizes the types of contact strip failures, factors affecting the state, and some research methods. From Fig. 3, it can be seen that by building an electrical contact test platform and carrying out high-temperature corrosion tests, it is possible to study the influence of contact pressure, current size, and other factors on the size of the contact resistance. At the same time, the corresponding simulation model can also be built, and the development mechanism of the fault can be studied by comparing it with the test.

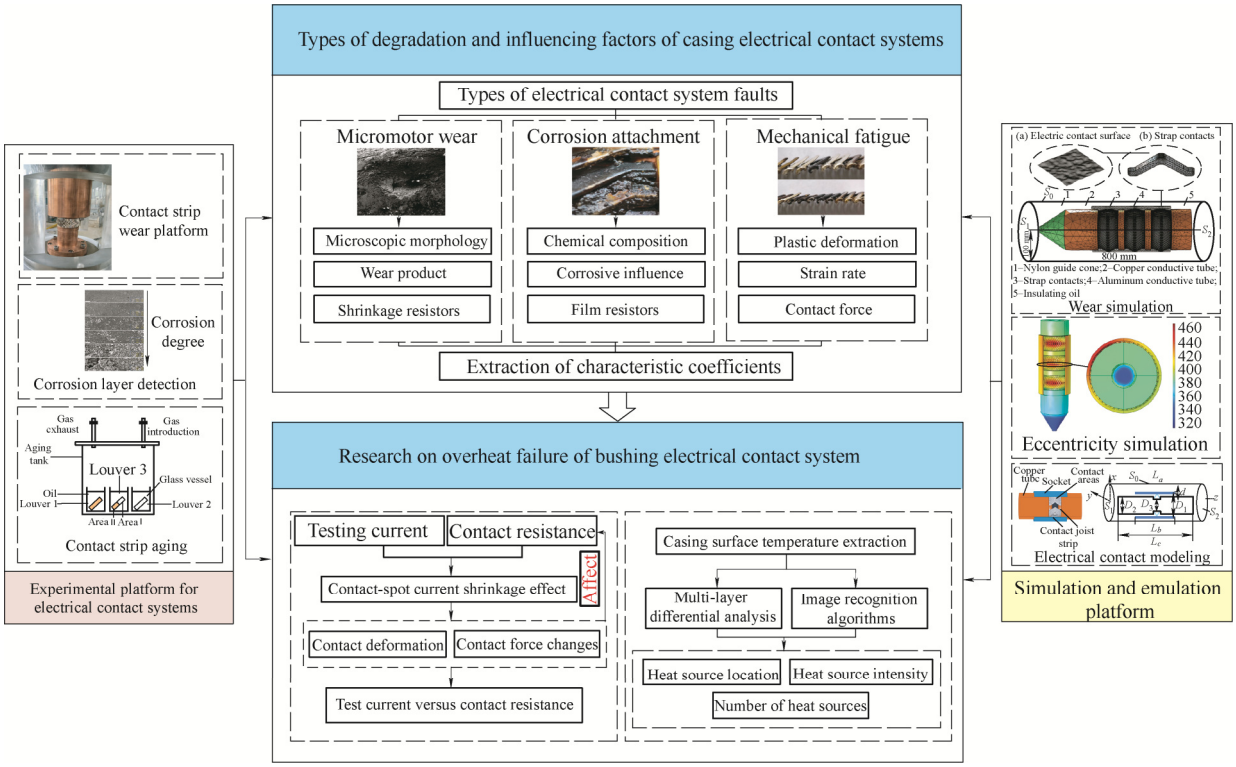


Fig. 3 Deterioration mechanism of contact strip

From the tribological perspective, the electrical contact surface exhibits copper-silver contact characteristics, as the contact surface of the copper guide rod and contact strip is not silver plated. The difference in hardness between copper and silver causes the interaction of rough peaks on the metal surface during friction, which leads to interfacial bonding. When a bond breaks, the less hard metal

(silver) is the first to produce metal debris. This metal debris fills the pores at the contact interface and serves as an abrasive, presenting a reduced contact area, increased contact resistance, and increased interface temperature. The expansion of the roughness peak of the contact interface caused an increase in the stress on the contact surface, and the metal material changed from elastic to plastic deformation and hardening, which intensifi the wear degree and formed a vicious circle [17-18].

Simultaneously, the operating environment of the contact strip is complex and long-term under the influence of high current, high voltage, and strong stress. Additionally, the surrounding medium environment includes vulcanized insulating oil and SF_6 gas. These factors presented various causes and complex developmental mechanisms for the failure of contact strips. Tian et al. [19] found that an abnormal contact strip connection is typically caused by wear and is aggravated by the corrosion of SF_6 and transformer oil and proposed a relevant deterioration mechanism. Through experiments, Jin et al. [7] revealed the wear characteristics of the contact strip under the conditions of vibration, thermal expansion, and cold contraction of the casing, along with the change law of the contact resistance in different gas environments and the characteristics of overheating corrosion.

The deterioration of the contact strip can be attributed to three main factors: eccentric deformation, fretting wear, and overheating corrosion, as shown in Fig. 4. These factors interact with each other and exhibit a strong coupling, which collectively causes the deterioration of the contact strip.

Regarding the wear characteristics of the contact interface between the contact strip and the electrode, Godfrey believes that fretting damage was caused by the bonding between the contact surfaces, and the wear debris was pushed out of the contact area and reacted with the surrounding environment, thereby increasing the contact resistance [20]. Fu et al. [21] analyzed the impact of vibration on the contact resistance of the contact strip based on their self-built vibration experiment platform. This demonstrated the correlation between the relative motion caused by vibration and the contact resistance of the contact strip in such scenarios. Furthermore, they analyzed the influence of a large current on the micromotion mechanism of the contact resistance.

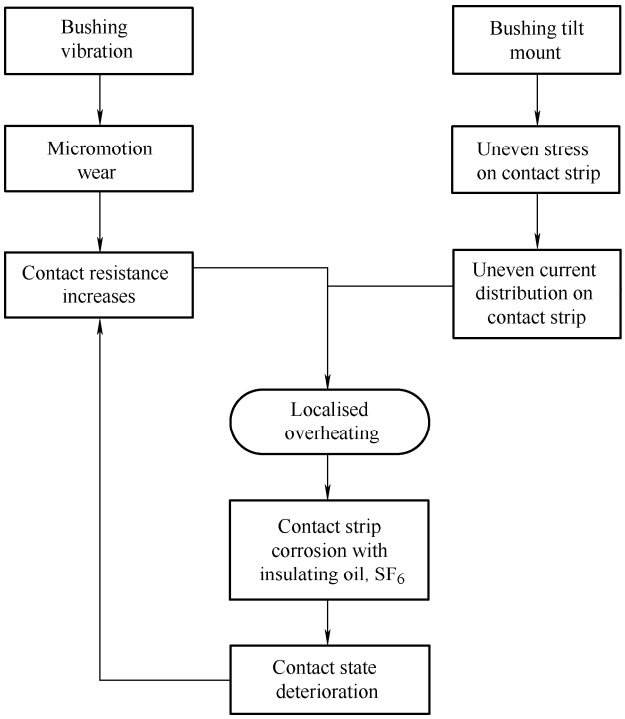


Fig. 4 Contact strip deterioration process

The fretting wear of the contact strip exhibits multi-factor coupling behavior. To determine the influence of various parameters on the contact interface, Liu [22] analyzed the differences in the fretting wear mechanism of the electric connectors under different experimental parameters, and highlighted the three stages of electric contact fretting wear. Yang et al. [23] analyzed the commonly used contact strip models and used a self-built test platform for electrical contact degradation analysis to investigate the current-carrying contact wear characteristics of contact strip. The law of change in contact resistance with normal pressure was determined by measuring the static contact characteristics of the contact strip. The effects of the plate surface coating, current amplitude, and electrode material on the current-carrying wear performance of the contact strip structure were also analyzed.

It can be seen that the fretting wear behavior of the contact strip under eccentric stress is the main reason for the increase in contact resistance, the uneven shunt of the contact strip, and the phenomenon of local overheating. However, the corrosive substances formed after the surrounding insulating medium is overheated and decomposed adhere to the contact surface and affect the contact resistance owing to the environmental problems in which the contact strip is located.

To analyze the mechanism of copper sulfur corrosion reaction and its influencing factors, ABB [24-25] proposed that mercaptan is the primary corrosive sulfide in insulation oil, and proposed the corrosion mechanism of "mercaptan-Cu_2S". This mechanism is primarily based on the presence of oxygen; essentially, copper reacts with the oxygen in the insulation oil, which causes it to be oxidized to Cuprous oxide (Cu_2O). It then reacts with mercaptan to form copper mercaptan (CuSH), which then decomposes to form Cu_2S under certain conditions. Scatiggio et al. [26] analyzed the global transformer sulfur corrosion prevention measures and found that dibenzyl disulfide (DBDS) in insulation oil is an inactive sulfide and a natural antioxidant, which is widely present in various brands of insulation oil.

However, the results indicated that DBDS is the primary vulcanizing substance that causes the corrosion of insulating oil and sulfur [27]. The corrosion of copper windings by DBDS causes a reduction in the insulation performance of the transformers, and some transformers face insulation failures after six months of operation. He et al. [28] employed different insulating oils to conduct thermal aging experiments at different temperatures. They observed that the formation of Cu_2S in the oil was affected by the temperature, variety of insulating oil, and aging time. The greater the DBDS content in the insulating oil, the faster the corrosion rates of copper and sulfur. A comparison of the formation rate of Cu_2S at different temperatures indicated that the higher the temperature, the faster the corrosion rate of copper sulfur. Additionally, the degree of corrosion increased with an increase in the aging time.

The reaction mechanism of DBDS sulfur corrosion was analyzed based on the analysis of DBDS sulfur corrosion insulation accidents. The DBDS-Cu_2S mechanism was proposed by the Mitsubishi Company in Japan [24, 29]; that is, DBDS was first combined with copper to form the DBDS-Cu complex, which was then decomposed to produce Cu_2S, bibenzyl, dibenzyl sulfide, and other DBDS degradation products. The DBS in the degradation products continues to react with copper to form Cu_2S.

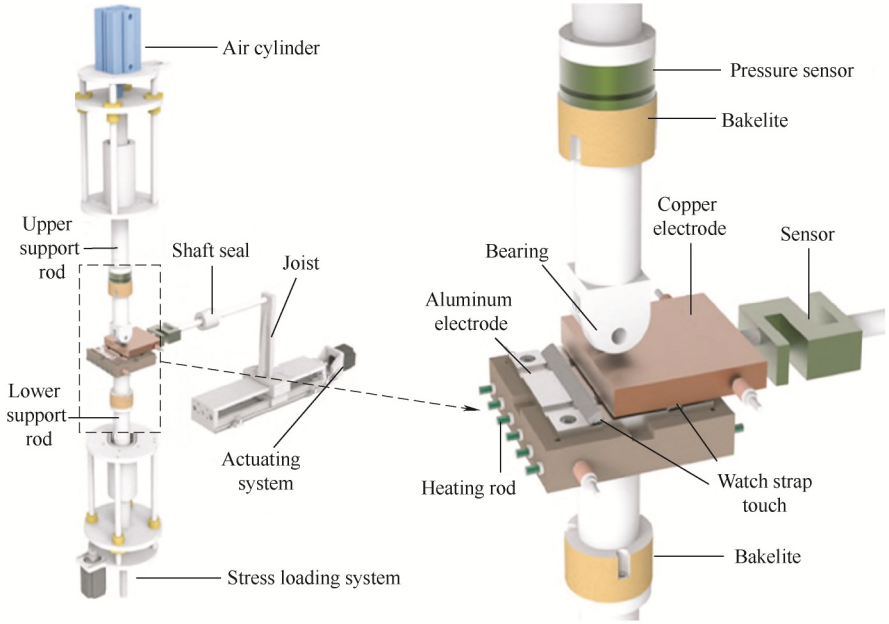
The space around the contact strip in the copper-aluminum transition zone was filled with SF_6 gas. According to the SF_6 decomposition theory [30-31], when the temperature exceeds a certain threshold, SF_6 can react with the trace moisture and oxygen to produce acidic gases, such as SO_2F and HF. These gases are highly corrosive and react chemically with metals. Dakin analyzed the decomposition of SF_6 in the presence of epoxy resin and aluminum [32] and observed that the decomposition rate of SF_6 was 1.3% at 200 ℃ and 5.5% at 225 ℃ within 28 days. When the ambient temperature exceeds 200 ℃, there are signs of metal fluoride and sulfide on the surface of the cavity. Tian et al. [33] conducted a simulation calculation, which demonstrated that when the surface temperature of the umbrella skirt increases by more than 10 ℃, the temperature in the contact area of the contact strip exceeds 200 ℃, and SF_6 begins to decompose, causing corrosion on the contact strip. The density of the small molecules produced by SF_6 decomposition is lower than that of SF_6. Therefore, these small molecules increase along the inner cavity of the inclined valve-side bushing, thereby causing local gas accumulation, which makes it impossible to effectively extract gas from the gas production port

near the flange for detection.

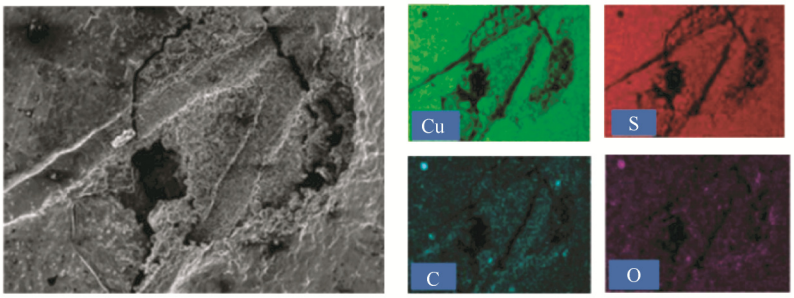
In summary, although the influence of factors such as eccentricity, wear, and corrosion on the contact connection failure of the contact strip was analyzed in previous studies, as shown in Fig. 5 the specific mechanisms and patterns remain unclear. Therefore, a more comprehensive analysis must be conducted and effective improvement measures must be developed to prevent the occurrence of bushing connection defects on the side of the UHV rheological valve during the high annular temperature and heavy load operation in the summer.

2.2 Main factors affecting connection failure

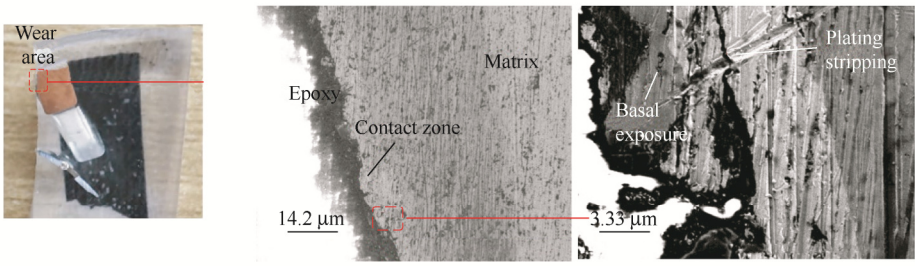
The high-voltage and high-power electrical interconnections are primarily achieved using the contact strip structure. The urgent requirement for the current flow ability and system reliability presents considerable potential for continuous increase in the electrical contact capacity of the contact strip structure. The occurrence of overheating defects was primarily attributed to a decrease in the electrical contact performance, and the contact resistance is significantly increased.



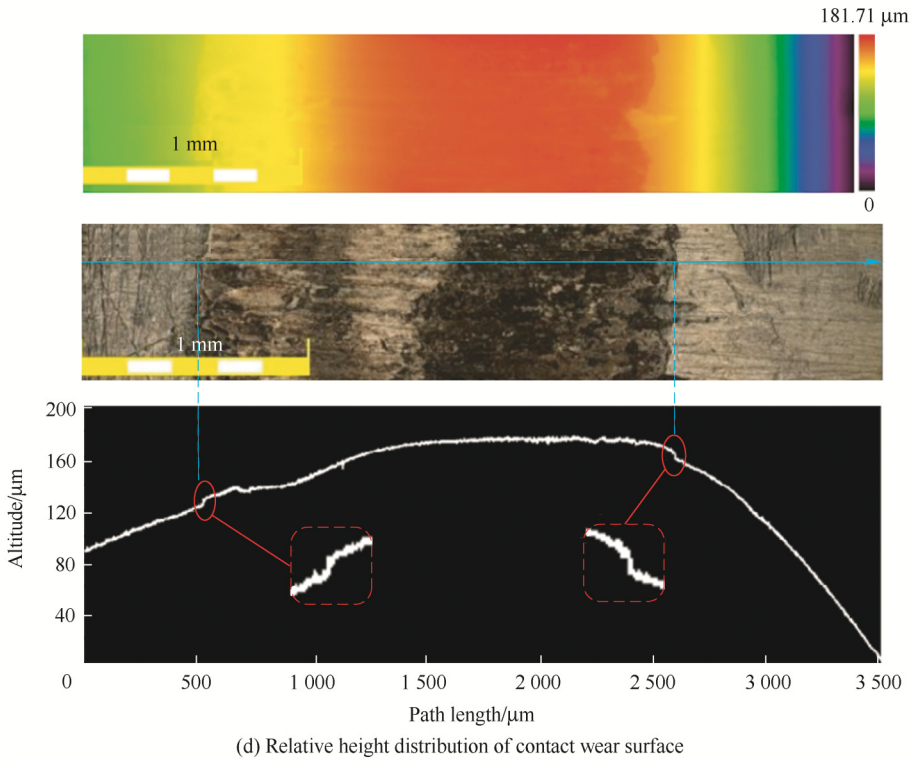
(a) Schematic diagram of current-carrying fretting friction experimental system



(b) Surface morphology and elemental distribution



(c) SEM micrographs of cross-sectional morphology of the strap contact area



(d) Relative height distribution of contact wear surface

Fig. 5 Example of contact strip deterioration mechanism [7, 23]

The contact resistance of a bushing contact strip is affected by various factors, including, the properties of the material itself, such as its electrical conductivity, hardness, wear resistance, and corrosion resistance, and so on. Insufficient material hardness can cause deformation or wear, which, increases the contact resistance. Excessive stress or high vibration frequency can cause poor contact and increase the contact resistance. The extensive research conducted on the factors affecting the contact resistance of the electrical connection components helped in elucidating the mechanism of each factor. Currently, the known factors are primarily divided into three categories: material properties, contact conditions, and environmental conditions.

2.2.1 Material properties

(1) The influence of materials. Electrical contact materials are subjected to various mechanical forces, thermal stresses, and environmental factors, which directly affect their electrical contact performance [34]. The mechanical properties of a material depend on the Young's modulus and Poisson's ratio. Conversely, the conductivity and resistivity affect the contact resistance, and the coefficient of thermal expansion and thermal conductivity affect the operating temperature of the electrically connected parts. Metal materials are widely implemented to establish electrical contact; they be divided into four categories: copper base, silver base, gold base, and new electrical contact materials [35]. Among these, copper, aluminum, and their alloys are primarily used in high-current environments, precious metals and their alloys are primarily used in low-current environments, and pure precious metals are typically used as coating materials.

The mechanical properties of the metal materials were reduced under the continuous application of high temperature. This affects the elasticity of the contact strip contacts and the microscopic morphology of the contact interface, along with the contact resistance. The mechanical properties of the metal materials include elasticity, stiffness, strength (such as yield strength, ultimate strength, and fatigue strength), hardness, plasticity, and toughness [36]. The requirements of mechanical designs vary based on the mechanical properties of the metal materials. The same metal material exhibits different mechanical behaviors under different working and environmental conditions.

Periodic temperature changes may cause the thermal expansion and contraction of the material, thereby

causing wear and metal fatigue. In the use of bushing, the contact strip may be in a state of abnormal stress for a long duration due to the long period of thermal expansion and cold contraction, which increases the contact tightness. The microscopic cracks inside the material continue to expand, until the material breaks suddenly when the critical size is reached, causing a sharp deterioration of the material properties.

To protect the electrical contact materials, Zhang et al. [37] developed a new TiBN powder material using the boron infiltration sintering method, which significantly improved the electrical conductivity, oxidation resistance, hardness, and arc erosion resistance of the Cu-based electrical contact materials. Fan et al. [38] reported that NiO additives significantly enhanced the mechanical and electrical contact properties of highly dense Ag-SnO_2 materials.

(2) Influence of surface coating. Protective and wear-resistant coatings are being increasingly used in the electronic and electrical fields. These coatings help in reducing the costs, and provide various functions such as preventing corrosion and wear, creating diffusion barriers, building conductive paths, and creating passive components on the insulating surfaces [39]. The performance of the electrically connected components was primarily affected by the surface conditions such as contamination, oxidation, reoxidation, vulcanization, and corrosion. These surface contaminants can increase the contact resistance and reduce the connection reliability [40]. However, despite the benefits of the coatings, there are also challenges, such as the porosity of the coating, hardness adhesion to the substrate, oxidation resistance, thickness of the silver coating, surface roughness, and sensitivity to corrosive environments, which can affect the performance of the electrical connection of the coating.

Theoretical and experimental analyses of the coating parameters of the electric contact parts. Sheng et al. [41] analyzed the influence of the silver coating parameters on the contact resistance through finite element analysis. Xu et al. [42] employed a hard silver coating on the electrical connections of a high-voltage switchgear to reduce the costs and improve the efficiency. Chen et al. [43] reported that a silver coating could significantly improve the wear resistance of a copper matrix under different lubrication conditions, particularly under grease lubrication.

However, the relationship between the fixed lap conductivity and the thickness, roughness, and hardness of the silver coating has not been comprehensively analyzed. To obtain a better understanding of the effect of these parameters on the performance of the electrical contact components, future works must systematically analyze the interactions between these physical properties and the underlying mechanisms to improve the performance of the electrical contact components.

The oil-immersed silver-plated copper contact is prone to pitting under high temperature and poor oil flow, which increases the defects in the silver coating based on the progress of pitting. Corrosion products are formed on the outside of the silver plating layer, the copper base, and the weak area of the coating, which induce special corrosion patterns that may cause delamination or even complete stripping of the silver plating layer. This results in an increase in the contact resistance of the contact point and causes the deterioration of the electrical contact performance [44]. The silver plating of the conductive tube during the actual operation of the elastic electrical contact parts significantly affects the contact resistance of the single contact strip, as shown in Fig. 6. Under the same amount of compression, the contact resistance of the contact strip of the non-silver-plated conductive tube was 1.4-1.8 times or even twice that of the silver-plated conductive tube.

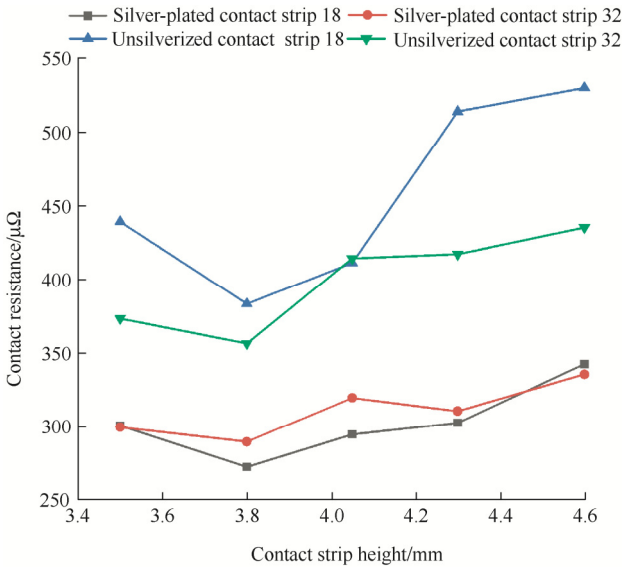


Fig. 6 Effect of silver plating on contact resistance of contact strips

2.2.2 Contact condition

(1) The effect of force. The contact strip bears the tension and pressure generated by its weight and the bushing weight due to the self-weight of the bushing, which varies with the position and direction of the bushing, causing the deformation and compaction degree of the touch. This affects the area and quality of contact between the contact strip and the electrode, which affects the contact resistance. The contact strip is a parallel channel with several pieces connected in series. Therefore, the uneven force increases the contact resistance of the entire contact strip. Simultaneously, a long-term mechanical load increases the roughness of the contact surface, accelerates the degradation of material properties, and causes an increase in the contact resistance.

Based on the conventional contact theory, only elastic deformation occurs on the contact surface under low pressure, whereas plastic deformation begins to occur with an increase in the pressure until the contact surface is completely deformed or destroyed [45-48]. However, the comprehensive analysis of the microscopic contact theory demonstrated that the deformation of the contact surface closely concurs with the behavior of the surface roughness peaks [49]. More rough peaks participate in the contact with an increase in the pressure, whereas the rough peaks that have been flattened can not be further deformed. The contact points must rely on the elastic deformation of their matrix to withstand pressure to realize the transition from plastic deformation to elastic deformation.

The contact deterioration rate caused by fretting corrosion typically decreases with an increase in the contact load. The contact resistance was primarily determined by the contact force and contact area. Increasing the force of the fretting interface can limit the adverse effects of fretting. In the contact strip, increasing the normal load increases the retaining force and reduces the potential of fretting. However, increasing the contact load only delays the occurrence of fretting corrosion, and long-term fretting may cause fatigue and surface layer fracture.

For the relationship between the stress and contact resistance, Zhang et al. [50] analyzed the relationship between the contact resistance and load force of $AgSnO_2$ contact surface topology through experimental and theoretical analysis. Jin et al. [7] analyzed the variation characteristics of the contact resistance of a single contact strip under different pressures on an electrical contact test platform. The results indicated that the number of contact spots that could effectively conduct the current increased, and the actual contact area increased following an increase in the contact pressure, which causes a decrease in the contact resistance. Conversely, the contact resistance increased when the contact pressure was reduced.

The contact pressure and contact resistance exhibit a monotonically decreasing relationship, as shown in Fig. 7. However, the reduction in the contact resistance gradually slows down with an increase in the contact pressure.

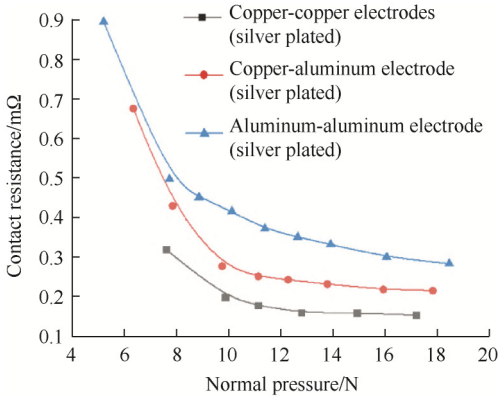


Fig. 7 Effect of pressure on contact resistance [23]

(2) The effect of fretting. Fretting corrosion was caused by the reciprocating motion of the contact at a specific speed, and its frequency is a key factor in controlling the fretting corrosion. For non-precious metal coatings, the fretting corrosion at different frequencies causes an increase in the resistance and metal volume ratio with an increase in the fretting period. At low frequencies, the performance deteriorated faster due to the accumulation of oxides. At high frequencies, the resistance increased more slowly. Fig. 8 depicts the influence of the amplitude of the fretting displacement on the electrical contact resistance. The larger the amplitude, the larger the contact resistance; beyond a certain value, the contact resistance increases significantly, and fewer number of cycles are required to achieve the same increment in the contact resistance. The factors affecting the amplitude of the fretting displacement include the chemical and physical properties of the surface contact, such as easy

oxidation, metallographic structure, surface hardness, and thickness of the matching material.

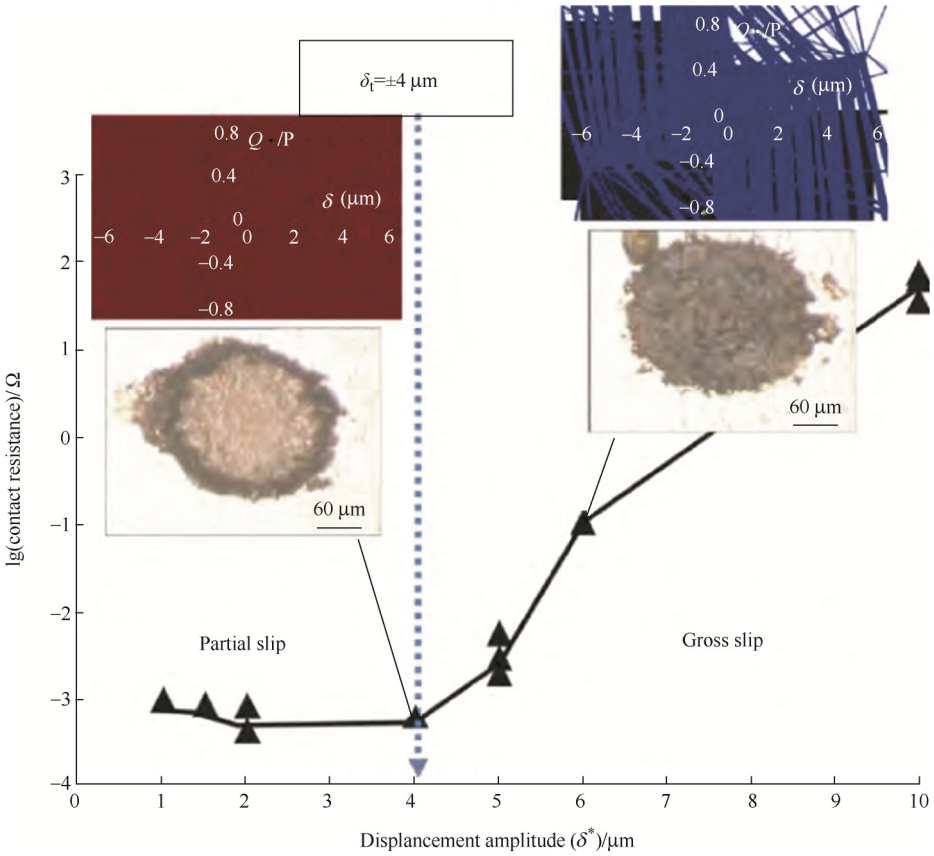


Fig. 8 Effect of the displacement amplitude on the contact resistance [51]

The contact strip inevitably vibrates due to the operating conditions, which causes micromotor wear at the contact interface between the contact strip and conductive rod. This causes the deterioration of the contact condition and significantly affects the contact resistance. The variation in the contact resistance can be attributed to the dynamics of the debris movement and the formation and partitioning of the oxidation spots in the contact area. The short fretting amplitude reduced the number of contact points for oxidation and delayed the growth of the contact resistance. The increase in amplitude intensified the oxidation and accelerated the increase in contact resistance.

(3) The effect of current. The influence of the current flowing through the electrically connected parts is multi-dimensional. It is affected by the law of the operating conditions, and can also change based on real-time variations in the system. Braunovic [52] analyzed the effect of current loads on the fretting behavior of electrical contact systems, whereas Sun et al. [53] demonstrated the significance of the current density in conductive films and its influence on the interface tribological behavior. Poljanec et al. [54] reported that the effect of the current density on the contact interface depends on the material properties of the friction pair.

When a large current flows through the contact strip, the contact is softened by the heat, presenting an increase in the conductive area and a reduction in the current contraction phenomenon, which significantly reduces the contact resistance. Simultaneously, heating the contact area also accelerates the oxidation rate of the contact area, along with the oxidation of the abrasive in the contact area. This may cause the fluctuation and sharp increase in the contact resistance [55]. However, the contact resistance demonstrated a downward trend with the increase of the current, indicating that the high current can also effectively break down the oxide film on the surface of the material, eliminate the film resistance, and establish a stable electrical contact. Conversely, it also affects the formation of oxide particles, and the electrical breakdown of these particles can reduce the contact resistance.

Fouvry et al. [56] also reported that there was no significant difference in the contact resistance between AC and DC conditions. Under the AC condition, fretting forms loose sheet fragments outside the contact area, whereas under a DC condition, the fretting fragments are denser, and the surface is more adherent.

2.2.3 Environmental condition

(1) The influence of temperature. The temperature of the contact interface directly affects the number of contact spots, along with the contact resistance. The change in the contact resistance changes the Joule heat generation, which affects the electrical contact interface temperature, thereby forming a coupling relationship. The conductive spot and the surrounding metal soften or melt when the temperature of the spot reaches the softening or melting point of the material. The temperature affects the corrosion rate and mechanical properties of the materials. As the temperature of the contact point increases, the metal resistivity increases, the hardness of the material decreases, and the effective contact area and number of contact points increase. The former causes an increase in the shrinkage resistance, whereas the latter causes a decrease in the shrinkage resistance to decrease; the two cancel each other. However, a current exceeding the short-circuit current causes a sharp increase in the temperature, accelerates the oxidation of the contact surface and growth of the oxide film, which increases the film resistance, and forms a vicious cycle. To maintain the stability of contact resistance, the long-term working temperature of the electrical contact must be controlled to avoid the overheating defects.

Angadi [57] reported that an increase in contact resistance was attributed to the increase in temperature, fretting wear, and fretting corrosion using a comprehensive environmental stress test device built using an electric shaker and thermostat. Ren et al. [58] analyzed the effect of temperature on the fretting corrosion properties of gold-plated copper alloy contacts. They reported that gold softening causes the expansion of the low contact resistance region and the reduction of the failure rate at high temperatures. However, the copper oxide particles formed at high temperatures exacerbate the deterioration of the contact resistance owing to their high hardness and poor electrical conductivity.

(2) The influence of the insulating medium. Mineral oil is the most commonly used insulating oil for power transformers. This oil is extracted from mineral crude oil and primarily comprises alkanes, cycloalkanes, and aromatic hydrocarbons, along with trace elements such as sulfur, oxygen, and nitrogen [59]. The sulfides in the mineral crude oil primarily comprise organic sulfur compounds, and include small amounts of elemental sulfur and hydrogen sulfide. Corrosive sulfur is typically derived from the residual sulfur components of the oil refining process. These sulfur-containing compounds can be dissolved in transformer oil to release highly reactive elemental sulfur in a complex decomposition reaction. Elemental sulfur is very reactive and can react with several metals, particularly at high temperatures. Furthermore, it can react with copper conductors to form metal sulfides, such as cuprous sulfide. Previous studies reported that DBDS concentrations as low as 1×10^{-6} corrode the copper conductors [60]. These corrosion products form black deposits that encompass the surfaces of the elastic electrical contact parts, thereby affecting their electrical contact and heat-dissipation properties.

To determine the specific formation of the black adhesive layer on the contact strip surface and its influence on the contact resistance, Huang et al. [44] employed simulation tests and various detection methods to determine the corrosion mechanism of the silver-plated copper contact strip. Cheng et al. [61] employed XRD to determine the material composition of the corrosion product, which primarily comprised cuprous sulfide, and conducted a high-current comparison experiment before and after cleaning the corrosion layer of the contact strip. The results indicate that cuprous sulfide is the main corrosion product, which causes an increase in the contact resistance.

In summary, the failure of the contact strip connection can be attributed to various factors in an electric-thermo-mechanical coupling environment. However, this failure is typically based on eccentricity and wear and gradually deteriorates under long-term, high-current operating conditions.

Contact strip wear exists in the operation cycle over a long duration due to the transformer self-vibration

and varies significantly with time. The contact strips are mainly composed of silver-plated materials based on copper. The contact strips are mainly made of silver-plated materials based on copper. The double-end inserts in the bushing elevating the base area of the converter station have been silver-plated at present; therefore, the contact performance of the contact strip is still good under short-term wear. However, the contact part was gradually damaged under a large contact pressure, thereby exposing the copper base due to the uneven eccentric force. With further development, the metal wear particles may synthesize new crystals to increase the wear on the contact surface. Furthermore, the contact resistance increases abruptly, thereby causing obvious overheating defects between the contact strip and the sleeve. Simultaneously, the environment around the contact strip primarily comprises sulfur-containing transformer oil and SF_6 gas. When the local temperature of the contact strip exceeds 150 ℃, the transformer oil gradually reacts with the metal. When the temperature exceeds 200 ℃, SF_6 gas begins to decompose, thereby forming metal sulfide and metal fluoride with the contact strip metal material, along with corrosion products with the contact strip, presenting more overheating defects.

Therefore, the failure mechanism of the contact strip is complex and is affected by several factors. Fig. 9 summarizes the factors influencing the failure of the contact strip.

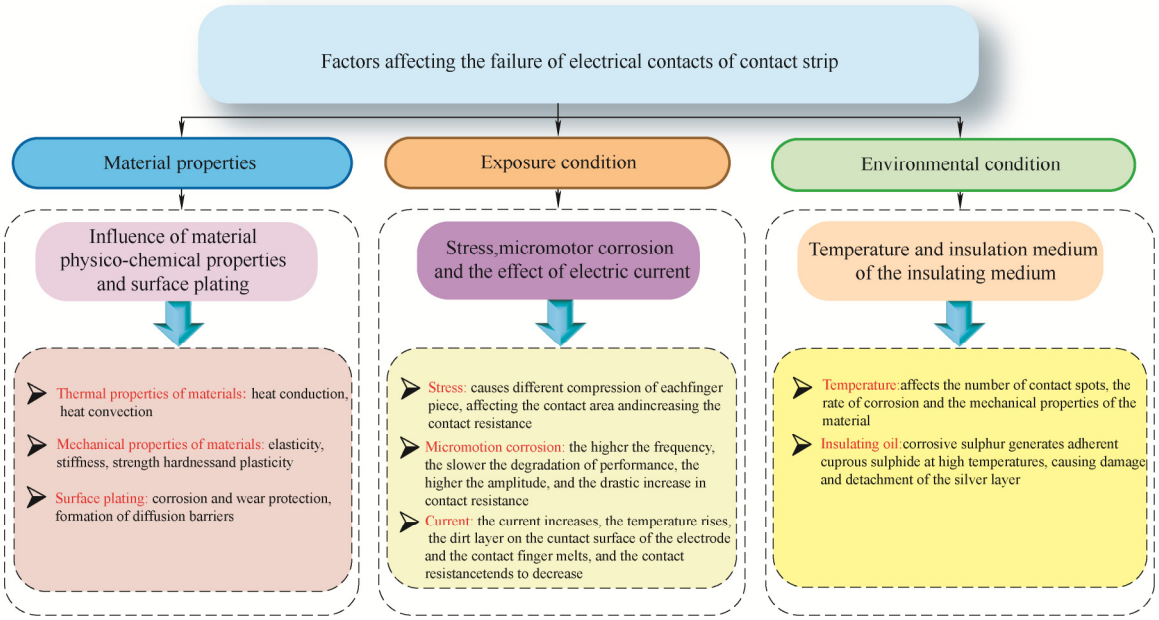


Fig. 9 Analysis of factors affecting the failure of the electrical connection of the contact strip

3 The main research methods of electric contact deterioration of contact strip

3.1 Experimental analysis method

The field condition cannot be directly tested because of the unique nature of the bushing structure and high voltage during operation. Therefore, the method of constructing an experimental sample platform is used to simulate and analyze the contact resistance of the contact strip, and how some factors affect the tribological characteristics, circuit signal characteristics, and fatigue failure characteristics of the contact interface is mainly discussed.

Vibration is a commonly observed issue in UHV equipment operation, which causes fretting wear between the contact strips and the current-carrying conductor. Fretting damage is typically caused by various wear mechanisms such as layered wear and debris accumulation [62].

Li et al. [63] analyzed the relationship between the friction, wear, and contact resistance of silver-plated electric connectors by establishing a sphere-plane contact test bench. Ren et al. [64] established a contact test bench and analyzed several factors, such as the materials, environment, and vibration, which provided an important reference for the material selection and

failure mechanism of connectors. Fouvry et al. [56] employed two circular friction pairs to simulate the contact state of the connector. Additionally, they analyzed the effects of the coating characteristics, environmental factors, and vibration factors on the micro-dynamic friction and wear behavior of the connector and established the criteria for connector failure.

Simple ball-plate and ball-ball models have been used in most of the above research on contact strip deterioration damage. The fretting wear test platform was constructed as shown in Fig. 10; however, limited research has been conducted on the electrical contact structures used in actual electrical equipment in power systems.

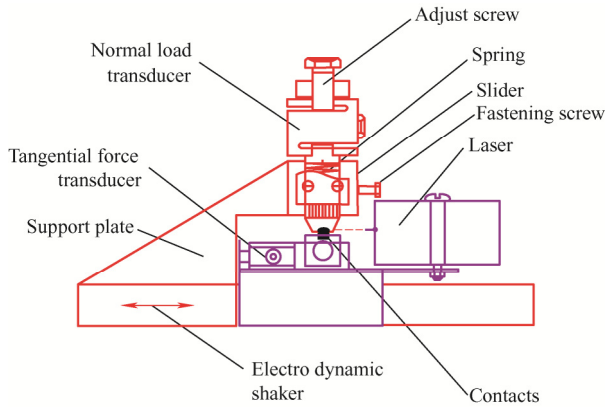


Fig. 10 Micromotion test bench [55]

Jin et al. [7, 65] elucidated the wear characteristics of a contact strip under vibration, thermal expansion, and cold contraction of the bushing, along with the change law of the contact resistance and overheating corrosion characteristics of the contact strip under different gas environments by conducting wear and gas corrosion tests. The results demonstrated that the contact resistance of the contact strip increased by approximately 14% when the copper substrate interacted with the fluoride produced by SF_6 after the wear of the contact plate. Gatzsche et al. [66-67] analyzed the applicability of the potential-temperature relationship in high-current contact systems. They observed that the *V-T* relationship of the contact system is biased under obvious environmental heat dissipation; however, it can still be used to effectively evaluate the maximum temperature rise of the contact strip.

The studies presented above demonstrate that establishing a sample test platform provides a significant analytical approach for understanding the failure mechanism of the electrical connection components. Additionally, the results obtained using this approach can positively affect the engineering applications. However, the various failure mechanisms of the contact strip and its development process remain unclear. Furthermore, the extent and mechanism of the various factors affecting the electrothermal performance of the contact strip and the overall temperature distribution of the bushing have not yet been comprehensively analyzed. Therefore, further testing and analysis must be conducted to accurately evaluate the connection status of the contact strip.

3.2 Simulation analysis method

Finite element simulations can provide high-precision analysis results, considering the nonlinearity of the material, inhomogeneity of the structure, and complex load conditions. Therefore, the simulation results are closer to the actual conditions. Finite element simulation ensures the repeatability and verifiability of the analysis results through parametric design and model verification, and enhances the reliability of the analysis [68].

Fretting and corrosion are transient processes that are accompanied by nonlinear changes in the geometry and materials. The incremental method is typically employed when the finite element method was used to overcome a problem, and the model state was updated iteratively. When addressing contact problems, the penalty function, Lagrange multiplier, and augmented Lagrange multiplier methods are commonly employed, which transform the constrained optimization problems into unconstrained optimization problems. The challenge in fretting corrosion simulation involves establishing a finite element model with multiple physical field couplings as thermal cycling and vibration cause fretting corrosion. Furthermore, the accompanying fatigue, wear, and corrosion can also cause surface damage [69-71].

Finite element simulation is being increasingly implemented to simulate the behavior of electrical contact parts in the running state. The existing studies are primarily aimed at establishing a multi-physical coupling model of a bushing and contact strip to calculate the temperature variation of the contact strip under different working conditions.

For an SF_6 gas-insulated wall bushing of ±800 kV, Lei et al. [72] established a fine bushing and contact strip structure model and performed temperature simulation calculation using the three-dimensional electromagnetic heat flow coupling method. Zhang et al. [73] analyzed the temperature field distribution of the bushing under the heating condition of the splicing structure and the influence of the contact resistance deterioration on the thermal field distribution of the bushing by coupling multiple physical fields, such as the electromagnetic, heat, and flow fields, using three-dimensional finite element analysis.

Zhuang et al. [74] established a finite element model of the contact strip type electrical connection structure under earthquake action by conducting a dynamic contact response analysis. Additionally, they reported that the failure risk of the contact strip type electrical connection structure in an earthquake must not be ignored. Duan et al. [75] established a three-dimensional electrothermal simulation model of the valve-side bushing and bushing tail plug of the converter transformer and determined the influence of the resistance distribution of the contact strip on the temperature distribution in this area. The results provide a theoretical basis for the repair strategy of abnormal resistance in the increased area of the converter transformer valve side. Furthermore, they provide theoretical support and guidelines for the development of domestic electrical connection components that are suitable for UHV and high-current environments in future works.

To numerically calculate the contact resistance and increase in the contact temperature, Rong et al. [76-77] established the Joule thermal model of contacts and employed the finite difference method to calculate the temperature distribution at the contacts. Furthermore, they considered the influence of multiple physical fields on the contacts. Additionally, they established an electrothermal multi-physical field coupling calculation model for closed contacts using a two-dimensional finite element method. Wang et al. [78-79] employed a three-dimensional electromagnetic-heat-flow coupling field analysis method to calculate the temperature field distribution of the dry bushing of the converter transformer. Subsequently, they experimentally verified the accuracy of the simulation method; however, they did not consider the thermal effect of the contact resistance.

In summary, the existing studies cannot simultaneously consider all the factors and the coupling effect between all the factors. This is due to the complex deterioration mechanism of the contact strip under the influence of high current, high voltage, strong stress, and multiple insulating media. Most of them start from the angle of electrical contact theory and obtain the contact resistance values of the contact strips under different contact states through fractal theory and numerical calculations. However, currently, the contact resistance values exist only at the theoretical level, which varies significantly from the actual measured values. Furthermore, real-time contact states cannot be obtained during the actual operation of the contact strip, and there is a certain lag.

4 Challenges and outlooks

This study begins with the failure mechanism of the contact strips, existing experimental methods, and factors affecting the contact resistance. Subsequently, it elucidates the current status of the research on the contact resistance of bushing contact strips. This is crucial for analyzing and handling equipment failures triggered by contact strips and for improving the reliability of the equipment operation.

We proposed effective protection methods to overcome the problem of contact strip failure, which can be divided into the following categories.

(1) Reducing the contact resistance. Future research and technological developments focus on reducing the contact resistance. By optimizing factors such as the material selection, surface treatment, and contact forces, the resistance can be reduced at contact points, thereby improving the efficiency of the equipment and power systems and reducing the energy losses.

(2) Stability in high-temperature and high-pressure environments. Future studies conducted on the transformer bushing contact strip contact resistance technology must focus on stability in high-temperature and high-pressure environments. Therefore, efforts are made to develop high-temperature and high-pressure resistant contact materials and structures to ensure the stability and reliability of the contact resistance.

(3) Sustainable and renewable materials. Contact resistance technologies must be developed in the

future must focus on sustainability and environmental protection. Replacing the conventional contact materials with renewable or recycled materials can help in reducing the dependence on limited resources, along with the environmental impacts.

(4) Self-healing and self-adaptability. The future contact resistance technology may comprise self-healing and self-adaptability. Automatic repair or adjustment can be realized when the contact is damaged or changed by introducing self-healing materials or adaptive structures, thereby extending the life and performance of the contact.

Overall, the contact resistance technology developed in the future must focus on reducing the resistance, improving stability, promoting sustainability, and determining the potential for self-healing and adaptability. These advances will facilitate the performance and reliability of the electronic devices and power systems and promote technological innovation and adoption.

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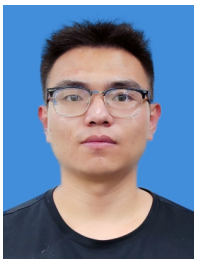
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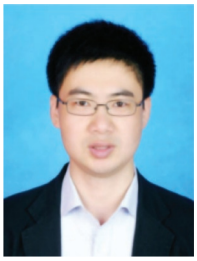
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