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# Research on Discharge Characteristic of Free Metal Particles in DC Bushing

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**Abstract.** Free metal particle was a common impurity in fault DC bushing, which was produced while its operation. This paper mainly focused on analyzing the typical fault of DC bushing, morphology and motion characteristic of mental particles. A experiment platform was built to study the discharge characteristic, and the result consistently with analysis was obtained. The mental particles would aggregate and accumulate due to the unevenly temperature distribution, and lead to distortion of electric field. The location and width of mental particles would have impact on discharge characteristic. The research result could be used as structural optimization and design of DC bushings, which was worth a further study both in academic and engineering application.

## 1. Introduction

DC transmission benefited with lower investment cost, better stability, and less active loss, and it has become the most widely used way to deliver electricity power efficiently. Since the 21st century, under the continuously updating and improving of DC transmission equipment, HVDC transmission technology has achieved a leap from extra-high voltage to ultra-high voltage<sup>[1,2]</sup>. In DC transmission system, valve side bushings of converter transformer and DC wall bushings(DC bushing) were one of the key components that connecting the converter station and the AC/DC equipment. DC bushing operated under hybrid AC/DC voltages, harmonic currents, outdoor pollution, and rain and snow. It had strict requirements on insulation, heat, machinery and sealing<sup>[3]</sup>.

In the recently DC bushing failures, there were many metal particles founded. Most of the particles were irregularly spherical, ranging from a few microns to tens of microns in diameter. Metal particles would affect the electric field inside the bushing and reduce the insulation withstand voltage. Under the influence of electric field and SF<sub>6</sub> airflow, the particles would move inside the bushing, which might lead to the damage of insulation and flashover<sup>[4]</sup>. Therefore, it is necessary to study the discharge characteristic of free metal particles in DC bushing.

Many literatures have reported the motion and discharge characteristic of millimeter metal particles present in insulation equipment. A experiment platform that can change the distance between metal particles and electrodes was designed to study the location of the particles-initial corona, current phase-charge, and corona discharge process<sup>[5]</sup>. It was concluded from the study of the triple junction of metal, solid insulation and gas interface in GIS that partial discharge occurred frequently in this area when metal particles present<sup>[6,7]</sup>. Some Chinese research showed that a slim mental impurity under negative voltage discharged more intensely, and the shape of impurity had a large impact on insulation of electrical equipment<sup>[8]</sup>. With the number of free metal particles increasing, the flashover voltage of



SF<sub>6</sub> would decrease significantly. And the flashover voltage of SF<sub>6</sub> decreased consistently with the distance between the electrodes<sup>[9]</sup>. Nevertheless, the work carried out [5-9] that the researched mental particles' diameter was in millimeter level. However, the diameter of mental particles was at micron level in the practical operation of DC bushing. The discharge characteristic was different from the carried out researches.

This paper analyzed the manifestation and causes of typical bushing failure; the simulation of electrical field of DC bushing followed. The distribution and motion of mental particles were brought out in section 3. Section 4 carried out a experiment platform of particle discharge and the experiment results. The conclusions were presented in section 5.

## 2. Typical faults analysis of DC bushing

### 2.1. Typical fault 1

An internal discharge fault occurred in a pure SF<sub>6</sub> gas insulated DC wall bushing for a ±800kV converter station in China. Three epoxy supporting insulators that uniformly distributed in the cross section of DC bushing were used to support the current carrying conductor. And SF<sub>6</sub> was used for auxiliary insulation. The inner structure of the bushing is shown in figure 1.

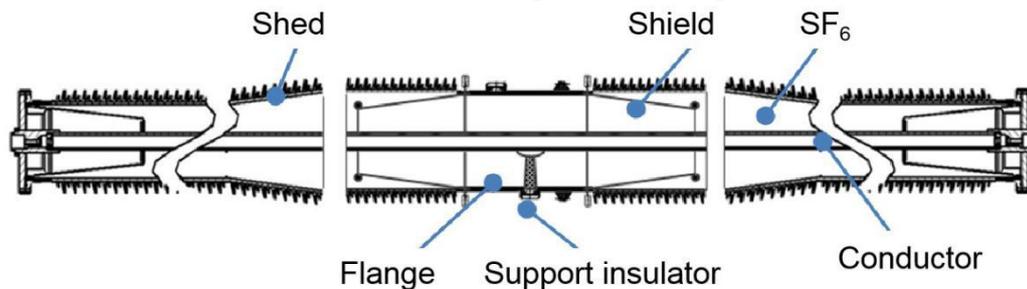


Figure 1. Inner scheme of pure SF<sub>6</sub> gas insulated DC wall bushing

When the fault occurred, the supporting insulator at 12 o'clock direction flashovered. There were many metal particles on the surface of the insulator and the conductor, and more particles were found near the fault insulator. There were obvious discharge traces on the surface of the fault supporting insulator. Under long-term and heavy-load operating conditions, the temperature of the connector that connected the indoor and outdoor conductors would increase significantly, and resulting in the uneven distribution of temperature and DC electric field on the surface of the insulator. Meanwhile, the changing of bushing temperature made the conductor stretch and rub, which might produce mental particles. Metal particles drifted to the surface of the supporting insulator under the influence of SF<sub>6</sub> airflow, and caused the electric field distorting on the surface of insulator.



Figure 2. Particles and flashover discharge traces on supporting insulator in fault bushing

### 2.2. Typical fault 2

An internal discharge fault occurred in a pure SF<sub>6</sub> gas insulated DC wall bushing for a ±800kV converter station in China, and the inner structure of the bushing is shown in figure 1. Flashover

occurred on one side of the insulator, explosion-proof membrane cracked, and flange burned. Many particles were found on the conductor, the supporting insulator, and the outer surface of shield.



Figure 3. Flashover discharge channels on supporting insulator and particles on conductor

### 2.3. Simulation analysis of bushing electric field

The COMSOL Multiphysics was used to analyze the electric field of the bushing with epoxy support insulator. 800kV DC voltage was applied to the conductor, and the result is shown in figure 4. It is clearly to see that electric field on the surface of the support insulator and the shield was concentrated. The surface of support insulator near the shield was the most concentrated area, and the field strength decreased along the surface of the insulator.

## 3. Particle morphology and motion analysis

### 3.1. Charge of particles

For a single spherical particle with a radius  $r$  on the electrode, the total charge  $q$  can calculate <sup>[10-12]</sup>

$$q = \pm \frac{2}{3} \pi^3 \varepsilon_0 \varepsilon_r E r^2 \quad (1)$$

where  $\varepsilon_0 = 8.85 \times 10^{-12} \text{F/m}$  is the vacuum dielectric constant,  $\varepsilon_r$  is the relative permittivity,  $r$  is the particle radius,  $E$  is the electric field strength at the location of the particles.

In the electric field, the Coulomb force  $F_q$  of the particle can be obtained as

$$F_q = kqE \quad (2)$$

where  $k$  is the correction factor caused by the image charge. When particles are in contact with the electrode or close to the same polarity electrode,  $k = 0.832$ , and when particles are far from the electrode,  $k = 1$ .<sup>[13,14]</sup>

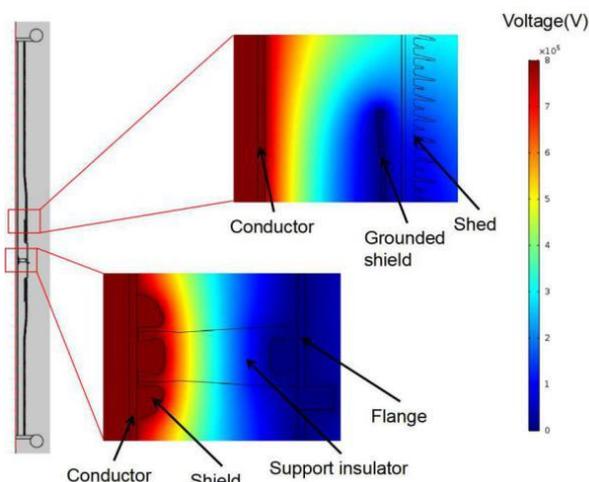


Figure 4. Electric field distribution of bushing with support insulator

Micron metal particles rarely existed independently during operation. They aggregated and accumulated multiple layers, which would have different characteristic from independent particles. Since the electric field on the electrode and epoxy mostly has axial and radial components, an increasing in the width and thickness of the particle along the direction of the electric field would result in more charge of the particles at the edge.

### 3.2. Observation and analysis of particles inside bushing

Particles were mainly distributed in the location where the electric field was concentrated inside the DC bushing, which was consistently with the simulation results. In bushing with epoxy support insulator, particles were mainly attached to the surface of support insulator, conductor near insulator, and grounded shield. In bushing with epoxy capacitor core, particles were mainly attached to the surface of capacitor core and the junction of conductor. In DC bushing, the conductor was usually segmented, connected with spring finger strap. The metal particles inside the bushing mainly originated from the metal friction at the current carrying conductor and the defects in the manufacturing process. In general, the particles were spherical, with a few microns to tens of microns in diameter.

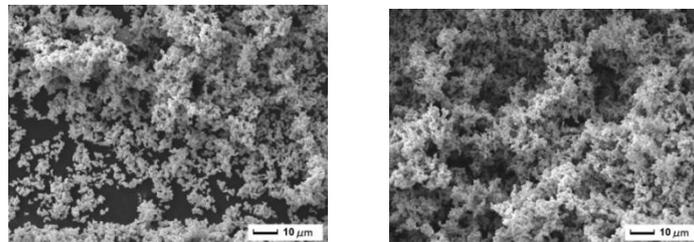


Figure 5. Microstructure of particles collected in a fault bushing

### 3.3. Analysis of the motion characteristic of particles in DC bushing

In DC bushing, SF<sub>6</sub> gas would flow because of uneven temperature inside the bushing while operating. Metal particles inside the bushing would move with the SF<sub>6</sub> airflow, and adsorb in positions where electric field was concentrated. Due to electrostatic induction, a certain amount of charge was induced on the particles attached to the surface of electrode or epoxy. These charged particles would move by the affect of the electric field force. They might move horizontally on the surface of electrode or epoxy, jump up and drift in the medium, or move from one side of electrode to the other. Motion characteristic of particles in actual bushing would be affected by multiple factors such as the influence of SF<sub>6</sub> airflow and mechanical vibration. Free mental particles had greater impact on insulation than stable ones<sup>[15,16]</sup>.

## 4. Procedure and results of particle discharge characteristic experiment

An experiment platform was built in order to study the influence of free metal particles on the discharge characteristic of DC bushing. In the experiment, 1 $\mu$ m, 1000 meshes (about 13 $\mu$ m), and 400 meshes (about 38 $\mu$ m) spherical copper particles were selected.

### 4.1. experiment device and experiment method

The experiment platform was made of Polytetrafluoroethylene (PTFE). The particle discharge characteristic experiment was carried out on the platform. The epoxy sample board was placed on the platform, and the particles were arranged on the board. High voltage electrode and ground electrode were arranged above the board. The ground electrode structure was hemispherical, and the high voltage electrode structure was cylindrical, with a diameter of 25 mm and a distance of 35 mm. When a 10kV DC voltage was applied to the high voltage electrode, the electric field distribution is shown in figure 6.

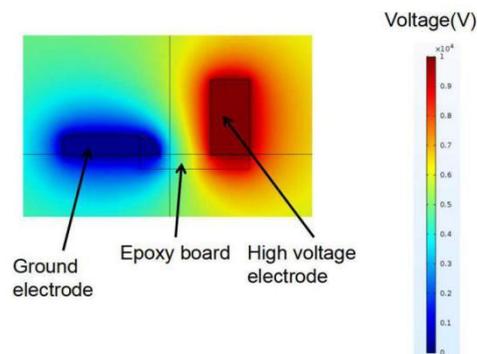


Figure 6. experiment electrode electric field distribution

During the experiment, a positive DC voltage was applied to the board, and a step-up method was used. Voltage boost speed was 0.2kV/s, and maintained for 5min after boosting 2kV. Repeated the procedure until flashover occurred, and recorded flashover voltage. For each set of experiments, repeated 10times under the same condition, and the average was taken for data analysis and processing. The 1 $\mu$ m, 13 $\mu$ m, and 38 $\mu$ m particles were arranged at different positions and different widths to verify the impact of particles on flashover characteristic.

#### 4.2. Analysis of experiment results

Three kinds of single layer particles were arranged in different positions on the board, with a parallel width of 10mm and a perpendicular width of 30mm. The flashover voltage of each distribution is shown in figure 7. It is obviously to see that the closer the particle was to the electrode, the more obvious the effect of the particle was on the insulation performance. The phenomenon can be explained that the electric field between the experiment electrodes is an uneven field, and led to the concentration of electric intensity at the position close to the electrode. The electric field were seriously distorted by particles. Besides, the particles near the electrode position were more likely to move under the impact of the electric field force, and the discharge path was easily formed during the movement.

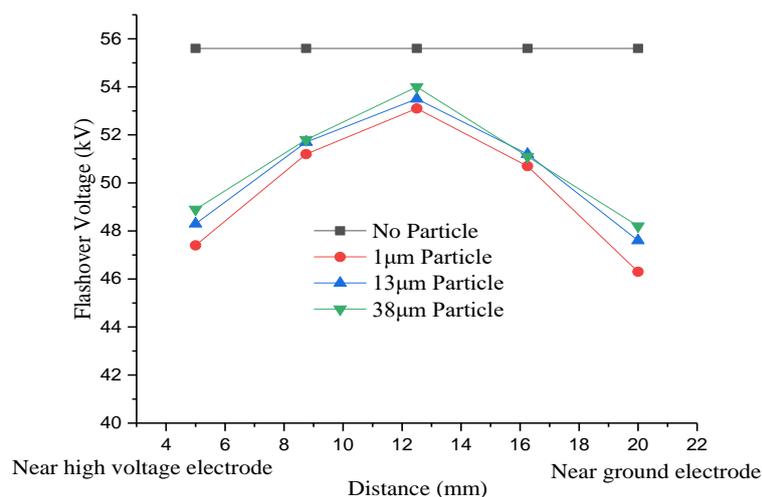


Figure 7. Flashover voltage of different particle positions

Three kinds of single layer particles were arranged in the center of the two electrodes, with a parallel width of 10-25mm and a perpendicular width of 30mm. The flashover voltage of each distribution is shown in figure 8. It is clearly to see that the wider the particle was, the more obvious the effect of the particle was on the insulation performance. It can be explained that the presence of particles reduced the insulation properties of the epoxy surface. The coverage of particles would

seriously impact the insulating property. Meanwhile, the charge of particles in the edge was consistently increasing with the particles' width, and these particles were more likely to move in the electric field.

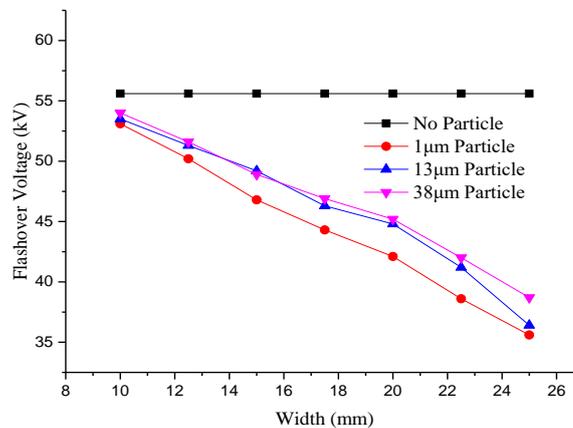


Figure 8. Flashover voltage of different particle width

## 5. Conclusion

In this paper, the experimental study and analysis of the discharge characteristic of micron metal particles in the bushing were carried out, and the following conclusions were obtained:

- Micron metal particles were generated during the operation of DC bushing. The metal particles were easily adsorbed at the positions where the electric field was concentrated, such as the support insulator and the grounded shield, and the presence of the metal particles would have a certain influence on the insulation performance of DC bushing.
- The smaller the size of the particles, the more obvious the effect on the insulation properties. As the diameter of the particles increases, the flashover voltage between the electrodes increased. The 1µm particle flashover voltage was the lowest, but the difference between each particle on the flashover voltage was small.
- The closer the particle distribution to the electrode, the more obvious the effect on the insulation performance. When the particles were distributed in the middle of the electrodes, the flashover voltage was the highest, and it was about 10% higher than close to the electrodes.
- The wider the particle distribution, the more obvious the effect on insulation performance. When the distribution area of the single layer particles exceeded 50% of the insulation distance, the flashover voltage would drop by about 25%.

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