Characteristic Analysis of Partial Discharge of Free Metal Particle in GIS

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Abstract. Free metal particle is one of the main defects affecting the safe and stable operation of GIS equipment. In order to further analyze the characteristics of partial discharge produced by metal particles, an independent sealed test model which can simulate real defects is designed in this paper. By adjusting applied voltage, particle size and number of particles, PRPD and n-φ pattern of partial discharge caused by particle defects are characterized. Analysis of the causes of formation of features, especially in the light of particle motion patterns, the transfer and neutralization of charges carried by particles at various stages are elaborated, which provides a reference for the follow-up research and field detection work.

1. Introduction
Gas Insulated Switchgear (GIS) has the advantages of small area, high reliability, and small occupation area. It has become more and more widely used [1-2]. During the manufacture, transportation, installation, and operation of GIS equipment, due to factors such as incomplete cleaning and vibration wear, various types of free particles, such as dust, paint, and metal particles, will inevitably appear inside GIS equipment [3]. For slightly uneven electric fields inside GIS devices, these particles, especially metal particles, are prone to distort electric field, causing internal breakdown of GIS equipment and reducing the reliability of safe power supply [4]. The influence mechanism of free metal particles on the internal insulation of GIS equipment is complex and is a research focus and hot topic, the detection and diagnosis of particle defects are mainly based on partial discharge detection techniques such as ultrasonic, ultra-high frequency and pulse current [5-10]. When the particles do not move, they will produce discharge signals similar to the tip of the shell. When the particles begin to move, the characteristics of the discharge signals are relatively complex. At present, no clear
conclusions have been formed.

To this end, this paper makes a small experimental model to simulate free metal particles in real GIS. By adjusting the applied voltage of the model to simulate the discharge development process of particle defects, the real defects in the actual operation of GIS equipment are simulated by placing different quantities and sizes of particles. Through the pulse current method to detect the discharge signal in the test process, the characteristics of PRPD (phase resolved partial discharge) and n-φ pattern under different discharge stages and different particle numbers are extracted, and the reasons for generating various characteristics are analyzed. This paper explains the discharge process of particles in the course of motion, further expounds the discharge mechanism of particle defects, and provides support for subsequent defect detection and diagnosis.

2. Design of models and test platforms

2.1 Particle Model Design

In this paper, a particle defect model (hereinafter referred to as particle model) is designed for free metal particle defects in GIS operation. The upper and lower electric plates are aluminum plates with a spacing of 150mm; The operating state of the particles can be clearly observed by installing a transparent organic glass tube between the upper and lower plates and forming a closed tank with an O-ring seal. Bolt the upper and lower plates with six nylon rods, and set the gas inlet or outlet port at the lower plates. Experiments show that the model can maintain the SF6 gas of 0.5 MPa within 72 hours; In order to make the particles produce stable discharges and prevent the particles from escaping from the high field area, high-pressure electrode plates and organic glass tubes are set up in the model. The structure is shown in figure 1.

![Figure 1. Schematic diagram of free metal particle model](image)

In order to prevent the interference signal from being generated by the model itself, the edges are diagonally treated and the shielding ring is set up on the upper and lower plates. Tests show that when no metal particles are placed inside the model, the SF6 gas of 0.35 MPa is filled inside, there is not any gas flow during the experiment, the corona discharge signal was detected when the applied voltage was raised to 40 kV. Therefore, the subsequent applied voltage is controlled below 40 kV.

During GIS operation and maintenance, metal particles with diameter of 1-3 mm are often found. Because when the diameter of metal particles is less than 1 mm, it is difficult to detect the partial discharge generated by them; when the diameter of metal particles is larger than 3 mm, it will be found in time in the process of GIS factory test and on-site commission test. Therefore, the metal particles used were spherical aluminum particles with diameters (Φ) of 1.5 mm, 2.0 mm, and 2.5 mm, respectively in this paper. Before the metal particles are put into the model for test, the surface of the metal particles is wiped with anhydrous ethanol dipped in dust-free paper to ensure that there is no moisture, pollution, etc. attached to the surface of the particles. And natural air drying is carried out to avoid the generation of other interference discharge signals.
2.2 Construction of a testing system

The test system of this paper includes: power supply device, particles model and partial discharge test device. The power supply device consists of a console, a regulator, a test transformer, and a protective resistor. The test transformer is an idling test transformer with a rated voltage of \( U_N = 200 \text{kV} \), a rated power \( S_N = 100 \text{kVA} \), and a partial discharge of less than 10pC at 200kV; The protective resistance is connected in series between the output of the test transformer and the experimental equipment. The resistance value is 5kΩ. The capacity of coupling capacitance is 500pF.

Using PDCheck as partial discharge test device, its detection frequency band is 16kHz-30MHz, recording PRPD. At the same time, a 50Ω broadband non-inductive resistor was used to detect the impedance, and partial discharge pulse waveform is collected by the oscilloscope Tek4054. The oscilloscope bandwidth is 500MHz and the sampling rate is 2.5 GS/s. As shown in figure 2.

![Figure 2. Schematic diagram of partial discharge detection system](image)

2 Discharge Characteristic Analysis

2.1 Variation characteristics of discharge spectrum

In this paper, partial discharge tests were carried out on spherical metal particle models of \( \Phi = 1.5 \text{ mm}, 2.0 \text{ mm}, \text{ and } 2.5 \text{ mm} \) respectively. This section takes the example of the particle model of \( \Phi = 2.5 \text{ mm} \) for analysis. The initial discharge voltage of the model is 9.0 kV and the increase rate is 0.5 kV. The change of PRPD pattern with the increase of applied voltage is shown in figure 3.

![Figure 3. PRPD pattern of Discharge of Single Free Metal Particles](image)

Figure 3(a) shows the starting discharge wave pattern, at which point the particles occasionally remain
stationary or jump slightly in place. At this point, the discharge phase has spread throughout the entire power cycle, but no complete sinusoidal envelope has been formed. There is still a blank area in the sinusoidal envelope at the peak of the positive and negative half cycles. At this point, the discharge is mainly concentrated at the peak of the positive and negative half cycles, near the zero point of the power frequency, and the discharge amplitude at the peak of the positive and negative half weeks is low.

When the applied voltage continues to rise to 10.5 kV, and the frequency of motion is high, and occasionally jumps occur, but the height is small. The discharge wave pattern is shown in figure 3(b). The sinusoidal envelope is relatively complete, but obvious discharge concentration is still visible. The concentrated area is the same as the previous stage. The amplitude of the discharge signal increases significantly, from 50 mV in the previous stage to about 100 mV. In figure 3(a) (b), it is clear that wave pattern becomes pronounced at around 180° and 360°, the corresponding explanation about this part is not find yet.

The discharge spectrum with applied voltage of 15.0 kV and 18.0 kV is shown in figure 3(c) (d). In both stages of the discharge pattern, complete sinusoidal envelope features are present, and the signal amplitude is proportional to the applied voltage. However, the state of motion of the particles at two voltages is different: When the applied voltage is 15.0 kV, the metal particles frequently beat between the two polar plates, but the amplitude still does not reach the upper electrode, or quickly move horizontally on the lower polar plate in the form of "floating water"; When the applied voltage is 18.0 kV, the particles make a violent vertical beat between the two polar plates to reach the upper electrode.

In order to further analyze the characteristics of discharge pattern of particles at different voltages, the distribution of discharge times (n) and discharge phases (φ) is calculated. The distribution of n-φ is shown in figure 4.

![Figure 4. N-φ pattern of single metal particle discharge](image-url)

When the applied voltage is 9.0 kV, the n-φ spectrum has four peaks, and the discharge frequently occurs at the peak and zero point of the positive or negative half of the frequency, and the number of discharges at the zero point is higher. In contrast, the number of discharges at the peak of the positive half week is lower than the peak of the negative half week, and the discharge is most concentrated from the zero point of the positive half to the negative half week, as shown in figure 4(a).

When the applied voltage is raised to 10.5 kV, the peak value of the n-φ spectrum is reduced to two, which are located around 160° and 300° respectively. The symmetry of the positive and negative half weeks is better, as shown in figure 4(b).
When the applied voltage is 15.0 kV, the distribution of discharge times in the entire frequency cycle is relatively average. When the applied voltage continues to rise to 18 kV, the number of discharges is the largest at the peak of the positive and negative half weeks, and the n-φ spectrum peaks at the positive and negative half weeks. As shown in figure 4(c) (d).

With the increase of the applied voltage, the n-φ spectrum has four stages of change: The spectrum of the discharge starting stage peaks at 0°, 90°, 180° and 270°. The second stage develops into two peaks at 160° and 300°. The peak characteristics of the spectrum in the third stage disappeared, and in the final stage of discharge development, there were two peaks at 90° and 270°, respectively. The number of peaks of n-φ pattern that can be summarized as four different stages of development is: 4→2→0→2 (As shown in Fig.4), the corresponding explanation about this part is not find yet.

When the applied voltage is low, there will be two types of discharge: The first is the "corona" discharge caused by the formation of the tip of the particle in the lower polar plate, which occurs at the peak of the applied voltage; The second is that free particles occur at the zero point of the applied voltage due to the charge exchange between the induced charge and the lower electrode plate during the reversal of the applied voltage polarity. Therefore, the free particle shows four peak characteristics on the spectrum.

As the applied voltage continues to rise, the particles begin to move horizontally, showing the characteristics of suspended potential discharge, that is, discharge occurs near the zero-crossing point of applied voltage, and the signal amplitude and number of discharges are larger, which makes the four peaks of the initial discharge spectrum become two.

When the applied voltage continues to rise, the particles are basically in a jumping state, and the discharge is the charge exchange between the particles and the lower plate, so the discharge occurs in the whole power frequency cycle, and the distribution is more uniform.

When the applied voltage rises to the point where the particles can jump to the upper plate, the particles exchange charge with both the lower plate and the upper plate. At the peak of applied voltage, particles are easier to reach the upper plate, which increases the number of discharges at the peak of applied voltage. Therefore, the spectrum shows two peak characteristics of 90° and 270°.

2.2 Effect of Particle Size on Discharge
It is found that the characteristics of discharge pattern of particles with diameters of 1.5 mm, 2.0 mm and 2.5 mm are similar, but the amplitudes of discharge signals of particles with different sizes change obviously. Statistical comparison of positive and negative half-cycle maximum and average values of discharge signals of three sizes of particles is shown in figure 5.

(a) Maximum of positive half-cycle discharge (b) Maximum of negative half-cycle discharge
The results show that under the same voltage, the larger the diameter, the larger the amplitude of the particle discharge signal; with the increase of voltage, the larger the diameter, the greater the trend of the maximum and average increase of the particle discharge signal amplitude.

### 2.3 Discharge characteristics of multiple particles

In the actual operation of GIS, when cash is particulate defect, there are many particulates at the same time [11-14]. In this paper, the partial discharge characteristics of multiple particles are studied experimentally. In the model shown in figure 1, multiple spherical particles with a number of particles = 2.5 mm are placed. The numbers are: 2, 5 and 10.

Compared to a single particle, the local discharge start voltage of multiple particles is lower: the initial discharge voltage of a single particle is 9kV, the initial discharge voltage of 2 particles is 8.7 kV, and the initial discharge voltage of 5 and 10 particles is 7.8 kV. It is also observed that the particles move horizontally at the beginning of discharge. This is because in the same electric field environment, different particles will induce the same polarity charge, two particles close to each other will bounce off due to repulsion, and then horizontal movement will occur, resulting in a decrease in the initial discharge voltage of particles. However, the initial discharge voltage no longer decreases with the increase of the number of particles. The reason is that the effect of the increase of the number of particles on the above phenomena has been saturated.

With the increase of applied voltage, the trend and characteristics of discharge pattern of multiple particles are basically the same as those of single particles. However, after forming a complete sinusoidal envelope, the discharge signals of multiple particles show new characteristics. The PRPD pattern of different number of particulate discharge at 16.5 kV are shown in figure 6.

The distribution of sinusoidal envelope band in the PRPD pattern of single particle is clear, and there is
no discharge point outside the sinusoidal envelope band. Although the discharge spectrum of multiple particles is also characterized by sinusoidal envelope, there are other sporadic discharge points in addition to the envelope, and with the increase of the number of particles, the number of sporadic discharge points has also increased significantly.

In order to analyze the amplitude characteristics of the signal, the confidence interval method of discharge amplitude is used to count the amplitude values of a single or multiple particle discharge sinusoidal envelope signal. The maximum and average values of the discharge signal change with the number of particles as shown in figure 7.

![Figure 7. Trend of discharge amplitude with the number of particles](image)

(a) Amplitude change of Positive half-cycle  (b) Amplitude change of Negative half-cycle

Among them, $Q_{\text{max}}^{95\%}$ refers to the largest value within 95% of the discharge signal confidence interval, $Q_{\text{max}}$ is the largest value of the discharge signal, and $Q_{\text{mean}}$ is the average amplitude of the discharge signal. As can be seen from the figure:

1. $Q_{\text{max}}^{95\%}$ and $Q_{\text{mean}}$ of multiple particles are slightly smaller than $Q_{\text{max}}$ and $Q_{\text{mean}}$ of a single particle. This is because when multiple particles exist, discharges occur between particles, and the discharge energy between particles is smaller than the discharge between the particles and the polar plate.

2. The $Q_{\text{max}}^{95\%}$ and $Q_{\text{mean}}$ of multiple particles did not change significantly with the increase of particles, while the $Q_{\text{max}}$ increased significantly with the increase of particles. The more particles, the greater the maximum value of the discharge signal. $Q_{\text{max}}$ reflects sporadic discharges outside the sinusoidal envelope in the spectrum.

According to known research results [15-18], in the electric field, particles will jump from the plate due to the electric charge they carry. When the particles move in the electric field, the charge they carry may be unevenly distributed on the surface of the particles due to the effect of the electric field. Let's call this phenomenon "polarization". When multiple "polarized" particles are in motion, if the spheres with polar opposite charges collide, they will lead to the neutralization of the charge, resulting in the increase of the residual charge of the neutralization particles. This may be one of the reasons for the increase in the maximum discharge value.

Figure 8 shows the simplest of the above processes: two polarized spherical particles collide in the electric field and increase the charge. In the non-colliding phase 1 of the particle, the particle A has a positive charge of 1 unit, and its surface charge is distributed as shown due to the electric field; The particle B is not charged, but there is a graphical charge distribution under the action of the electric field. Phase 2 represents the situation when two particles collide, and the charge of the collision sphere is neutralized; The charge distribution after the collision is shown in phase 3. At this time, the particle A has 2 units of positive charge due to the collision, that is, the charge increases due to the collision.
Figure 8. A case of charge change caused by particle collision

When a single particle exists, the above process does not occur, and when multiple particles exist, the collision probability of particles in space motion increases with the increase in the number of particles. Therefore, the more particles, the greater the maximum amount of charge that the particles can obtain, and the greater the maximum value of the locally released signal generated. In addition, when other shape particles move, the charge neutralization and transfer during the collision process should be more complicated.

During the test, it was observed that in addition to horizontal movement and up-and-down beats, multiple particles were superimposed on the lower polar plate. This situation may also lead to an increase in the amount of discharge. The specific process is shown in figure 9.

Figure 9. Another case of charge change caused by particle collision

As shown in the figure, the particle B is always on the lower polar plate, and the particle A jumps and falls on the upper end of the particle B (or does not have vertical contact with the lower particle, but touches the upper half of the particle B). At this point, two particles are superimposed, and the two particles form a combination, which is equivalent to a higher metal tip on the surface of the polar plate (relative to the tip of a single particle). Under the same electric field, the two particles obtain charge as a combination, so that the particle A may gain more charge.

At present, there is no reasonable explanation for whether metal particles are positively charged. It is only a hypothesis for readers to reference.

3 Conclusion
In this paper, the partial discharge characteristics of free metal particles in GIS are analyzed experimentally. The results show that:

- Free metal particle defects exhibit different movement characteristics at different levels of development, and they also have different manifestations in the discharge PRPD spectrum: According to the different degrees of particle motion, the phase of motion that distinguishes particles is stationary → horizontal motion → jump up and down → jump to the upper electrode; The PRPD spectrum characteristics corresponding to each stage are mainly manifested in the gradual formation of sinusoidal envelope bands, and the number of n-φ spectrum peaks corresponding to each stage has a significant change rule: 4 → 2 → 0 → 2. The reason for this change may be the different sources of discharge.

- The larger the particle size, the larger the amplitude of the discharge signal, and the larger the diameter, the greater the increase trend of the maximum amplitude and mean value of the discharge signal.

- Compared with a single particle, the initial discharge of multiple particles is low, the discharge signal
amplitude is large, and a significant discharge signal appears outside the sinusoidal envelope in the PRPD pattern.

With the increase of the number of particles, the maximum value of discharge signal increases obviously, but the average discharge signal amplitude of different quantities of particles and the maximum discharge amplitude within the 95% confidence interval do not change significantly.

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