Combined application of ultrasonic and ultra high frequency
techniques in the partial discharge detection and positioning
of gas insulated switchgear

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Abstract: Partial discharge live detection of GIS can effectively find internal defects, but it is often interfered by surrounding environmental noise, which affects the correct identification and judgment of defect signals. This paper introduces the application of AE and UHF technique in the live detection of GIS, which successfully recognizes the external interference signal, analyzes the cause of abnormal partial discharge signal based on signal characteristics, and uses the method by calculating time difference to locate the source of the signal. An internal checking on the equipment were conducted based on the test results while the equipment were stopped, and verified the existence of floating fault inside GIS.

1. Introduction
The safe operation of GIS (Gas Insulated Swichgear) equipment is very important, but compared with large-scale equipment such as transformers, it has simpler structure, smaller volume, and lower insulation margin, and its detection methods for internal defects are also limited. Although some defects can be found in the power outage test, the equipment needs to be taken out of operation, and as the test cycle lengthens, the defect detection rate is very low[1]. GIS live detection technology can detect GIS equipment without power failure and find internal defects in time. Due to many factors such as design and processing, installation process, transportation and friction, the following common types of defects may exist in the GIS: tip (flaws), floating defects, free particles, insulation defects (internal and surface), fasteners Looseness can also cause mechanical vibration[2]. During operation, the electric field distortion caused by the defect will cause partial discharge, which can accelerate the deterioration of the insulation, or cause breakdown and flashover, leading to serious power outages. Partial discharge in the medium will be accompanied by physical phenomena such as electricity, heat, light, and sound. High-energy pulses will also decompose the insulating medium to produce a series of compounds[3, 4]. UHF, ultrasonic, and SF6 gas analysis methods are usually used on site to detect and locate partial discharge signals.

This paper combines a 110 kV GIS equipment abnormal partial discharge case, introduces the process of ultrasonic and UHF joint diagnosis of abnormal defects, and analyzes the causes of defects.
2. Detection method

2.1. Ultrasonic method (AE)
Partial discharge in GIS will excite ultrasonic waves, which propagate outward in the form of spherical waves from a point sound source. Usually, only longitudinal waves can propagate in SF6 gas[5, 6, 7]. The main frequency is distributed in 10~100 kHz, and the resonant sensor made of piezoelectric ceramics receives the sound wave signal. The probe has two types: contact type and non-contact type. The contact type probe is mainly used in the power system. Coupling agent is required to reduce the impact of interface attenuation and handheld vibration. As ultrasonic method has strong resistance to electromagnetic interference, and is more sensitive to defects such as free particles, suspension discharge, mechanical vibration, etc., it is widely used in actual operation and maintenance[8].

2.2. Ultra high frequency method (UHF)
Partial discharge in power equipment is a pulse discharge, which can excite electromagnetic waves with frequencies up to several GHZ. Broadband high-frequency antennas (300 MHz~ 1.5 GHz) are used to detect the electromagnetic wave signals generated by the internal partial discharge of the GIS, thereby reflecting the type and type of internal partial discharge. Approximate location. Since the field corona interference is mainly below 300 MHz, the UHF detection can effectively avoid the conventional corona interference and has high sensitivity [9, 10].

2.3. Location of interference sources by bisecting plane method
When there is an external interference signal, the bisecting plane method can be used for positioning to distinguish internal and external signals.

![Figure 1. Bisection positioning method](image)

As shown in Figure 1, moving the two UHF sensors to the positions of A and B, when the waveform and time triggered by the two sensors are the same, it can be determined that the interference signal source is located on the vertical bisecting plane P1 between A and B. Then we can move the sensor to the positions of A' and B', and a vertical bisecting plane P2 can also be determined. The intersection line of P1 and P2 is the bisector where the signal source is located. Finally, we can move the sensor on the bisector, such as A'' and B'' position, when the trigger waveform is consistent with the time, the vertical bisector P3 can be determined. The point where P1, P2, P3 intersect is the position of the discharge source.

In the field application, it is often difficult to determine the vertical bisecting plane P3 due to the high interference source or the limitation of the safety distance. Triangulation can be used for spatial positioning. As shown in Figure 2, when the bisector of the signal source is determined, the sensor 1 is placed directly below the signal source, and the other sensor 2 is placed in another location on the ground (level with sensor 1). The oscilloscope reads the time difference between the two sensors as \( \Delta t \), assuming that the height of the signal source is \( H \), the distance between the two sensors is \( L \), and the distance between the signal source and sensor 2 is \( D \). According to the Pythagorean theorem, the discharge source height \( H \) can be calculated:

\[
H^2 + L^2 = D^2 = (H + c\Delta t)^2
\]  

(1)
Among them: c is the electromagnetic wave propagation speed, $3 \times 10^8$ m/s.

![Triangular plane position method](image1)

**Figure 2. Triangular plane position method**

### 2.4. Muti-sensor positioning method for UHF (time difference method)

A nanosecond high-speed oscilloscope compares the time difference between the signals of the two detection parts to locate the signal. Since the electromagnetic wave is the speed of light, if the resolution can reach 1 ns, the positioning accuracy can reach 30 cm. This method requires high instrument performance, and at the same time, it needs a clear wave head, otherwise it will produce large errors.

Before the time difference positioning method, the amplitude method can be used to determine the approximate location of the discharge source, then the time difference method is used for positioning, and the internal structure is combined to determine the defect type and location. The positioning process is shown in Figure 3.

![UHF positioning process](image2)

**Figure 3. UHF positioning process**

When performing Muti-sensor positioning, the time domain signal of the sensors arranged around the discharge source is captured by an oscilloscope. First, it is necessary to observe the power frequency correlation of each channel signal through the multi-period graph (millisecond level) to determine whether the signal comes from the same discharge source. When the signal corresponds to each cycle one-to-one, it is the same signal source. Then we adjust the oscilloscope spectrum to the nanosecond level, observe the time delay difference between the signals, and then calculate the position of the discharge source according to the propagation speed and direction of the signal, as shown in Figure 4.

![Multi-sensor positioning method](image3)

**Figure 4. Multi-sensor positioning method**

Assuming the distance between the two sensors is L, the distance between the B1 sensor and the discharge source is x, the distance between the B2 sensor and the discharge source is Lx, the wave head time difference measured by the oscilloscope is $\Delta t$, and the electromagnetic wave propagation...
speed is $c$, $3 \times 10^8$ m/s. Then the distance $x$ between B1 and the discharge source can be calculated by the following formula to determine the position of the discharge source:

$$
\begin{align*}
\Delta t &= t_1 - t_2 = \frac{L - 2x}{c} \\
x &= \frac{L - c\Delta t}{2}
\end{align*}
$$

(2)

When $x<0$, it means that the discharge source is on the left side of the B1 sensor. When $x>L$, it means the discharge source is on the right side of the B2 sensor. At this time, the position of the sensor needs to be adjusted for secondary positioning. Three sensors can also be used to get the time difference between each sensor to locate, the efficiency and accuracy are higher.

3. Case overviews

3.1. Overview of live detection

In March 2020, during the live test of the GIS area of a 110 kV substation, it was found that the ultrasonic and UHF signals of the A-phase air chamber of the #5023 disconnector (knife) were abnormal. The amplitude of the ultrasonic signal was low about 1.0 mV and the discharge sound was obvious. The UHF signal amplitude is about 700 mV, and the pulse is characterized by a high probability of suspension discharge. At the same time, a partial discharge signal with a floating characteristic with an amplitude of about 60 dB was measured in the entire GIS room, and it was found to be an interference signal from an outdoor tower by the bisection method. A retest was performed one week later. At this time, the background noise was very small, and a floating discharge signal with a higher amplitude was measured again in the #5023 A-phase gas chamber. After disassembling and inspecting the #502 interval, it was found that the static and dynamic contacts of the #5023 A-phase disconnecting switch were not inserted in place. The static and dynamic contacts were heated and ablated for a long time and formed a floating potential. There was a large amount of white powder attached to the static contacts and the guide rod, and the surface of the guide rod was discolored. No abnormal signal was detected after repair treatment.

3.2. GIS equipment structure

The GIS of the station is a three-phase split-phase layout, in which the #502 circuit breaker interval A-phase line side equipment includes current transformers, #5023 disconnector, line side PT, lightning arresters, etc., as shown in Figure 5.

![GIS construct of #5023 disconnector](image)

Figure 5. GIS construct of #5023 disconnector

4. Detection process

Firstly, a portable ultrasonic and UHF instrument was used for general measurement, and it was found that UHF signals with higher amplitude existed in different positions of the GIS room and #5023 A-phase air chamber, and the ultrasonic signal amplitude was found to be slightly near the #5023 A-phase air chamber. If it is higher than the background signal, it is judged that there is UHF signal interference, and the external interference source location is carried out. Through the bisecting surface
method, it is found that the interference comes from the outdoor tower. After the interference signal is identified, the electric and electric joint positioning is carried out in the #5023 A-phase gas chamber. At the same time, combined with the internal structure of the gas chamber, it is judged that there may be floating discharge at the contact part of the disconnector. One week later, the retest was carried out during a period of less background interference, and the diagnosis results were consistent. Through equipment disassembly analysis, it was verified that the contacts of the #5023 A-phase air chamber disconnector had long-term floating potential. The detection process is shown in Figure 6.

4.1. Ultrasonic testing
There is an ultrasonic signal in the A-phase air chamber (yellow box) of the #5023 disconnector, the amplitude is very small, about 1.0 mV (background 0.7 mV), the earphones and ears of the detector can hear the discharge "squeaking". As shown in Figures 7 and 8, there are discharge pulses in the ultrasonic signal diagram, but the number of each cycle is unstable and has intermittent characteristics. Due to the small amplitude and no frequency correlation, the typical characteristics of the waveform diagram are not obvious, and the conditions for judging the type of discharge are not available, but it can be determined that there is an ultrasonic discharge signal inside.

4.2. UHF detection
There are partial discharge signals in the entire GIS room, with two clusters per cycle, amplitude 52–58 dB, narrow phase, with floating discharge characteristics, as shown in Figure 9(a); #5023 A-phase gas chamber basin insulators have partial discharge signals , Two clusters per cycle, the amplitude is about 60 dB, the pulse number is very dense, and it has the characteristics of metallic suspension discharge, as shown in Figure 9(b). The above two UHF signals are different, and localization of the partial discharge source is required.

Figure 6. Live detection process

![Figure 6](image_url)

4.1. Ultrasonic testing

![Figure 7](image_url)

Figure 7. AE signal source and amplitude

![Figure 8](image_url)

Figure 8. AE signal waveform

4.2. UHF detection

![Figure 9](image_url)
4.3. Bisection plane method to locate interference sources

Four channels are used to identify partial discharge sources. The blue ultrasonic sensor is placed in the #5023 A-phase gas chamber, the yellow UHF sensor is placed in the #5023 A-phase gas chamber basin, and the green and red UHF sensors are placed in the GIS indoor open space, as shown in Figure 10.

Observe the waveform of the oscilloscope. The red and green channels are typical one-to-one corresponding single-pulse floating signals. The yellow channel has two clusters of signals per cycle. The pulse size and interval in each cluster are different. It has the characteristics of insulation type discharge. The two signals have small amplitude and unknown characteristics. Through vertical and horizontal positioning, it is determined that the red and green interference sources come from outdoor towers, as shown in Figure 11.

4.4. Electric and electric joint positioning #5023 A-phase disconnector partial discharge source

Place the red sensor on the insulating basin of the #5023 disconnector on the side of the circuit breaker, the yellow sensor on the insulating basin of the #5023 disconnector on the side of the arrester, and the
green sensor on the insulating basin of the #502-current transformer on the side of the circuit breaker. The positioning waveform is shown in Figure 12.

![Figure 12. Sensor position and waveform](image1)

It can be seen from the oscilloscope graph that the green sensor waveform is the most lagging, and the red sensor waveform leads the yellow sensor waveform by 1.6 ns. The theoretical calculation is about 48 cm, which is less than the distance between the yellow and red sensors. It means that the signal source is located between the yellow and green sensors, that is, the #5023 disconnector A-phase gas chamber and close to the red sensor.

![Figure 13. Adjusted sensor position and waveform](image2)

Based on the previous step, the positions of the yellow and red sensors remain unchanged, and the green sensor is placed on the pot-type insulator on the side of the voltage transformer of the #5023 disconnector. The sensor location and oscilloscope waveform are shown in Figure 13. The green sensor waveform and the yellow sensor waveform basically overlap, indicating that the signal source is in the area between the two sensors.

Based on the comprehensive analysis of the above positioning results, the local discharge source of the #5023 disconnector is in the red circle area, as shown in Figure 14 below.

![Figure 14. PD source position on #5023 disconnector](image3)

Analyzing the discharge type of #5023 gas chamber partial discharge source, as shown in Figure 15, the maximum signal is about 1.2 V. The pulses in the figure are mainly single, and the pulse spacing is basically the same. Combined with the structure of the GIS in the positioning area, the probability that the signal is suspended discharge is large.
5. Disintegration verification and cause analysis

5.1. Disintegration inspection
The right side of the #5023 disconnector air chamber is adjacent to the #502 TA air chamber, the upper side is the #502 A-phase line PT air chamber, the left side is the 5X15 disconnector air chamber, and the lower part is the disconnector operating mechanism, as shown in Figure 16.

![Adjacent equipment of #5023 disconnector](image1)

Figure 16. Adjacent equipment of #5023 disconnector

After disassembling the #5023 air chamber, it was found that there was a large amount of white powder on the surface of the #5023 disconnector A-phase air chamber, as shown in Figure 17.

![Inside the GIS SF6 chamber of #5023 disconnector A phase](image2)

Figure 17. Inside the GIS SF6 chamber of #5023 disconnector A phase

The conductor of the #5023 A-phase disconnector was further removed. A large amount of white powder was attached to the static contact and the guide rod of the #5023 A-phase disconnector. After erasing the powder, it was found that the surface of the guide rod was discolored and the moving and static contacts were not inserted in place. The rod only enters the shield and overlaps the contact fingers. The static contact finger oxidizes and discolors, the moving contact guide rod end has serious ablation marks, and the end diameter becomes smaller, as shown in Figure 18. After wiping the white powder on the surface, the surface of the air-chamber basin insulator and the insulating rod was smooth, and no obvious discharge point was found.
5.2. Cause analysis and defect treatment

Comparing the insertion depth of the guide rod of the normal phase moving contact, the insertion depth of the moving and static contact of the A-phase is obviously insufficient, the insertion depth of the normal phase guide rod is 3 cm, and the insertion depth of the A-phase guide rod is only 1 cm. The contact resistance of the static and dynamic contacts of the #5023 disconnector increases, which causes severe heating after the #502 interval is passed through, causing the contact parts of the guide rod to ablate, forming a metal oxide layer on the surface, as shown in Figure 19.

Figure 18. Dynamic and static contact condition of #5023 disconnector

Figure 19. Dynamic contact insertion condition of #5023 disconnector
Through the dispatch method and the energy management system, it is found that the #502 interval is in hot standby state for a long time, and only a short time will be put into operation at the end of April 2020, and it will be in hot standby state at other times in 2020, as shown in Figure 20.

![Figure 20. History operation condition of #502 interval](image)

After the #5023 disconnector moving contact guide rod was severely ablated, it further aggravated the degree of poor contact between the moving and static contacts or the tiny gap. In the long-term hot standby operation mode, the dynamic and static contact potentials are inconsistent, causing metallic floating potential discharge, which is consistent with the UHF partial discharge test map and positioning situation. The schematic diagram is shown in Figure 21.

![Figure 21. Electrical construct under hot standby state](image)

Based on the partial discharge map characteristics and GIS disintegration, it can be judged that the white powder in the A-phase gas chamber of the #5023 disconnector is the product of heat generated by the conductive rod of the moving contact and the product of partial discharge ablation and decomposition for a long time. A floating potential is formed between the moving and static contacts, generating an abnormal partial discharge signal. The disassembly verification situation is consistent with the diagnosis result of the live test.

After replacing the insulating pull rod of #5023 disconnector basin insulator and the conducting rod of the pull rod, the dust white powder products in the air chamber shall be thoroughly cleaned, and then resuming operation, no abnormal signals can be found.

6. Conclusion

Ultrasonic and UHF methods are the main methods of GIS equipment live detection, and their effectiveness has been well verified by disassembly inspection.

The UHF method is susceptible to electromagnetic interference, and the electromagnetic environment is particularly complex in the on-site operating environment. Various measures should be taken to identify and shield the interference, or avoid periods of greater interference.

Although levitation discharge has a large amplitude and high discharge energy, it is not as harmful as insulation defects and has a lower probability of causing accidents. However, its long-term development will aggravate the severity of poor contact parts, and the generated dust will cause flashover and breakdown accidents. It is dangerous when the floating discharge is formed inside the GIS, we should closely track and disassemble it for maintenance if necessary.

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