Application research of the partial discharge automatic detection device and diagnostic method based on the ultrasonic in long distance GIL equipment

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Abstract: Gas-insulated transmission lines are very long with the length over 100 meters for each single chamber and there are no non-metal connection parts between two chambers, which leads to a poor detect effect when using the UHF method. Because of the attenuation of the propagation process, the ultrasonic detection method has many measuring points and a large workload of manual detection. To solve these problems, an automatic detection device and diagnostic location method based on ultrasonic method for the partial discharge of GIL were proposed in this paper. By combining the ultrasonic partial discharge detection device with the inspection robot, the robot performs the partial discharge inspection and transmits the data to the background diagnostic system for analysis. The overall structure of the system, the method of automatic diagnostic and location are introduced. The effectiveness of detection, diagnostic and location of the system is verified by simulation of the discharge signal in the laboratory. The application of the system can avoid the possible limitations of manual inspection in GIL Partial Discharge Ultrasonic testing, improve the work efficiency and guarantee the safe operation of power system.

1. Introduction
GIL (Gas-insulated transmission lines) is a kind of high-current, high-voltage power transmission device which uses SF6 gas or SF6 and N2 mixed insulating gas as the insulating medium, the grounding shell and the inner tubular conductor are arranged coaxially. Compared with the GIS bus, the GIL has the characteristics of long standard unit, built-in insulator, less flanged butt joint, sealing easily, large chamber length, small amount of basin insulator, simple structure and low cost. Based on the GIL fully enclosed and long-distance structure, it is difficult to inspect quickly, maintain and overhaul the GIL in time. When the defects exist in GIL, it is probably to cause the power transmission corridor to be inoperable for a long time, which may pose a huge threat to the safety and stability of the power grid operation. Therefore, in order to ensure the safe operation of the GIL, it is of great importance to strengthen and pay attention to the live detection of the GIL equipment.

The detection of partial discharge is an essential project in the live detection of GIL equipment. Partial discharge refers to the phenomenon of partial discharge in the insulation system of power equipment caused by cracks in the insulator, air gaps, or needle-like protrusions inside the high-voltage equipment, freely movable metal particles or suspended potential bodies around them, poor contact between conductors, etc. The suspended potential body inside the GIL, the free metal particles and the
insulation defects inside the supporting insulation will lead to partial discharge, which are the main factors to reduce the insulation performance of the GIL equipment. Under certain circumstances, the partial discharge phenomenon will exist for a long time. The GIL insulation may be damaged by a single partial discharge, and the insulation level of which will be declined. When the damage accumulates to a certain limit, it will cause equipment insulation damage, equipment breakdown damage, power grid failure, and trigger the GIL out of operation ultimately, affecting power transmission [1-6].

At present, there are two main detection methods for partial discharge (PD) of gas insulated metal enclosure equipment: ultra-high frequency (UHF) detection and ultrasonic detection. Because of the GIL equipment has a long distance, the flange surface is sealed by all metal, and there is no non-metallic connection part, it is difficult to obtain the UHF signal from the external test. Therefore, UHF detection method is not effective for external testing, and the installation of built-in UHF sensor and on-line monitoring system has the problems of high cost. In addition to the UHF signal, the partial discharge also generates the ultrasonic signal [3]. By using the ultrasonic sensor which attached to the surface of the GIL metal casing closely, the ultrasonic signal generated by the partial discharge can be detected effectively. Therefore, ultrasonic sensors can be placed on the outer wall of GIL to detect partial discharge signals. Because of the large attenuation of the ultrasonic propagation process, there are many ultrasonic measuring points and a large workload of manual detection.

Aiming at the problems in the process of GIL partial discharge detection, this paper proposes an automatic detection device based on ultrasonic method for partial discharge of GIL and its diagnostic positioning method. By combining the ultrasonic partial discharge detection device with the inspection robot, the ultrasonic partial discharge inspection is carried out by the robot, and the data is transmitted to the background diagnostic system for analysis, which realizes the efficient detection of the GIL, and solves the problem of the GIL partial discharge detection effectively. The main features of the system include: the robot controls the ultrasonic partial discharge detection device through the operation arm, and the background software controls the robot to perform the inspection automatically; The robot has the ability of self-adjusting for pressure to ensure the safety of the ultrasonic sensor and the accuracy of the measurement; The robot can transmit the data collected by the ultrasonic partial discharge detecting device to the background software through the network in real time for analysis, display and diagnostic. When the diagnostic is abnormal, the robot automatically switches to the accurate detection mode to detect and locate the partial discharge more accurately, thereby realizing the intelligent inspection of the ultrasonic partial discharge of GIL equipment.

2. Design of Partial Discharge Automatic Detection Device for GIL Based on Ultrasound Method

2.1 Design of ultrasonic partial discharge detection device

The ultrasonic partial discharge detecting device is composed of ultrasonic sensor, signal conditioning unit, AD sampling unit, microcontroller unit (MCU), and communication transmission unit. The partial discharge signal output by the ultrasonic sensor is very weak in general, it must be conditioned before sent to the data acquisition unit (AD sampling unit) for analog-to-digital conversion. The signal conditioning unit mainly performs two aspects of work: on one hand, it amplifies the signal to meet the requirements of A/D sampling unit; on the other hand, it restricts the bandwidth of the signal to suppress high-frequency interference and anti-frequency domain aliasing. The actual signal conditioning unit has two signal preprocessing circuits, one is a rectification trigger circuit for detecting whether there is a discharge signal, and the other is a processing circuit which filters and amplifies the discharge signal after the trigger signal appears and then sends it to the sampling circuit. After sampling, the digital signal is transmitted to the microcontroller unit (MCU), and stored by the MCU and transmitted to the robot through the RS485 interface. The overall block diagram of the system is shown as Fig.1.
Partial discharge detection requires ultrasonic sensors with high sensitivity and strong anti-electromagnetic interference capability. Since the ultrasonic signal generated by partial discharge will produce attenuation during transmission through the SF6 gas, insulating material and metal medium, it turns to be weak when transmitted to the ultrasonic sensor shell, and the interference signal may annihilate the detected signal. At the same time, special shielding measures are needed for the filtering and amplifying circuit of the ultrasonic partial discharge detecting device, and the signal is extracted by the excellent guiding lead wire to eliminate the interference signal during signal processing, among them, the selection of the ultrasonic sensor is especially important.

According to its working principle, ultrasonic sensors can be divided into piezoelectric type, magnetostrictive type, and electromagnetic type and so on, and piezoelectric type is most commonly used. The dielectrics of piezoelectric ultrasonic sensors include quartz, piezoelectric ceramics, piezoelectric composite materials and piezoelectric films. Among them, piezoelectric ceramic sensors are the most commonly used in the research and application of ultrasonic partial discharge detection. The reasonable design of piezoelectric ceramics and the reasonable selection of detection frequency band are one of the key factors to improve the sensitivity of sensor detection. The ultrasonic partial discharge detecting device adopts an ultrasonic sensor with a frequency band ranging from 20 kHz to 80 kHz, as shown in Fig. 2, and the frequency response curve of the selected sensor is shown in Fig. 3.

The internal structure of the ultrasonic partial discharge detecting device is as shown in Fig. 4, which includes ultrasonic sensor, circuit board (signal conditioning circuit, sampling circuit, control circuit), transmission interface, support structure, etc. The ultrasonic sensor, circuit boards and transmission interface are fixed on the support structure to integrate the units into a physical structure. The ultrasonic sensor senses the ultrasonic signal generated by the partial discharge, converts the analog ultrasonic signal into a digital signal through the signal conditioning and sampling unit, and transmits the signal to the inspection robot through the transmission interface.
Fig 4. Internal structure diagram of ultrasonic partial discharge detection device

The overall appearance of the ultrasonic partial discharge detecting device is shown in Fig. 5, a fixed hole is opened in the middle of the shell of the ultrasonic partial discharge detection device to fix the robot manipulator arm. A hole is opened in the front of the shell according to the size of the probe of ultrasonic sensor, and the sensor is embedded inside the structure, only the probe of the ultrasonic sensor is exposed outside, and four screws are used to fix the sensor and the outer shell of the sensor. The installation position of ultrasonic sensor is designed with a spring device internally, which facilitates the probe of ultrasonic sensor to stick tightly to the surface of the GIL device during detection to avoid damage caused by stress extrusion. The circuit and embedded program are designed with low power consumption, and the components use low-power chips; the power supply adopts DC 24V, which is powered by the inspection robot body; sufficient storage space is reserved to store quantitative data, and the overall size is 150mm *60mm*60mm.

2.2 Design of robot
The schematic diagram of the inspection robot is shown as Fig. 6.

Fig 6. Schematic diagram of inspection robot
As shown in the figure, 1 is the wheeled robot base, 2 is the telescopic rotating structure unit, 3 is the robot integrated control unit, 4 is the sliding telescopic arm, 5 is the rotating arm, 6 is the silicone grease spraying and erasing unit, and 7 is the connecting mechanism. A 24V lithium battery used as the robot power supply, which is designed with full scalability in mind and equipped with a power management module.

2.3 Design of automatic detection device
The automatic detection of GIL partial discharge is realized by combining the robot and the ultrasonic partial discharge detecting device. The three-dimensional schematic diagram of the robot integrated control unit, the mechanical arm and the ultrasonic partial discharge detecting device is shown in Fig. 7. The ultrasonic partial discharge detecting device is mounted on the robot rotating arm, and the detecting
probe is installed outward, and the angle of contact is controlled by the rotating arm. Therefore, the contact of the ultrasonic partial discharge detecting device can be contacted to the various detection parts of the GIL device, thereby realizing the function of multi-point detection of the device.

The automatic detecting device includes ultrasonic partial discharge detecting device, inspection robot and background server, the system structure of the device is shown in Fig.8. The ultrasonic partial discharge detecting device is installed on the rotating arm of the inspection wheeled robot, and the wheeled robot realizes the movement in the horizontal plane. The expansion and rotation unit adjusts the height and the contact position and angle between the ultrasonic partial discharge detection device and GIL, so that the ultrasonic sensor is closely attached to the surface of the GIL device. The robot measures according to the GIL patrol monitoring points set in the software, and feeds back the data detected by the ultrasonic sensor to the background server for analysis in the background server. GIL partial discharge detection and diagnostic system software is deployed in the background server. The software function design includes creating inspection tasks, patrol test, data storage, data display and PD diagnostics.

3. Detection Method

3.1 Design of Detection Process

The layout of the robot in the pipe gallery is shown in Fig.9. The inspection is carried out in the GIL pipe gallery by the orbital robot. The robot advances along the ground or top track, and its position can be determined by the position sensor, and the ultrasonic partial discharge detection device of the robot arm is controlled to stick tightly to the test point by the laser radar.
3) The robot moves to the position of the test point of GIL equipment and keeps the position. The arm of robot moves to place the ultrasonic partial discharge detection device on the surface of the test point or the background test point of GIL equipment.

4) The body of robot carries a certain amount of silicone grease. Before testing, the robot performs the silicone grease application action, applies an appropriate amount of silicone grease to the probe of ultrasonic sensor. The robot performs the silicone grease erasing action and erases the residual silicone grease on the surface of the test point after completing the test.

5) The robot sends an acquisition command to the ultrasonic partial discharge detection device, the detection device starts to collect data after receiving the command, the data includes AE amplitude, AE waveform, AE pulse and AE phase. At the same time, the robot asks the detection device regularly whether the acquisition task has been completed. When the feedback is that the detection device has completed the acquisition task, the robot sends the acquisition data command to the detection device. After receiving the command, the detection device feeds back the collected data to the robot according to the standard data specification requirements. After receiving the data, the robot sends back to the background software through the network.

6) After receiving the data returned by the robot, the background software parses, stores, displays and diagnoses automatically. When the abnormality is diagnosed, the precise positioning command is executed immediately to inform the robot to measure and locate the current test points precisely.

7) The robot detects each detection point in turn until the last one, then the patrol task completes.

The robot can communicate with the server remotely through Wi-Fi. In the aspect of control, the mechanical arm has the function of sensing pressure and the function of smearing and erasing silicone grease. The mechanical arm can sense the pressure and flex around and around, by using it, the ultrasonic sensor probe of the ultrasonic partial discharge detection device is closely attached to the surface of the GIL device at a suitable pressure.

3.2 Installation Design of the Ultrasonic Sensor and GIL

In order to ensure the accuracy of the measurement results, the ultrasonic sensor in the detection device must be close to the surface of the measured point. If the bonding is too tight, the ultrasonic sensor will be damaged or the sensor will not be in close contact with the GIL surface, and the detection data will be inaccurate. So it is necessary to ensure that the contact pressure is within a certain range. The system adopts a feedback method of pressure recording to ensure that function. The actual method is:

1) The mechanical arm of Robot is close to the measuring point by small step;

2) A pressure sensor is installed at the probe position of the ultrasonic sensor, and the pressure value is recorded once when the mechanical arm is stepped once;

3) Step distance is required to be further reduced when the pressure value begins to be greater than zero;

4) When the pressure reaches the prescribed range, stop moving forward, record the robot position and the arm step distance;

5) When reaching the measuring point again, the robot first stretches the arm according to the step distance of the last recording plus a certain margin to ensure that the contact pressure will not be excessive in the first contact, and then repeats the steps of 1)~4) and records the position and step distance of the robot again;

6) Repeat the above process and make corrections to ensure that the ultrasonic sensor is attached to the GIL device quickly according to the appropriate pressure after the robot reaches the measuring point, so as to ensure that the sensor is close to the device without causing damage to the sensor.

4. Design of Diagnostic Method

The background software displays the partial discharge detection data uploaded by the robot in the form of spectrums and stores them. In terms of data display, the software has the functions of drawing amplitude spectrum, waveform spectrum, pulse spectrum and phase spectrum, as shown in Fig.10.
The amplitude spectrum shows four data of the RMS, the maximum (Vpeak), the frequency component 1 and the frequency component 2 of the acoustic detection data. The waveform shows the original waveform of the ultrasonic signal, and the pulse spectrum shows the flight time of particle discharge, and the phase spectrum shows the aggregation correlation of the discharge pulse in phase.

The partial discharge diagnostic method includes two parts: algorithm diagnostic and expert diagnostic. When abnormal data are found during the inspection process, it can be diagnosed by software automatically. According to the partial discharge diagnostic algorithm, the partial discharge type of insulation defect of GIL equipment is judged, and the robot is controlled to narrow the test range and enter a more accurate detection mode to locate the most obvious abnormal part of the GIL device. The diagnostic algorithm of ultrasound partial discharge judgment is designed as follows:

1) Particle discharge: if (RMS of actual measurement > RMS of background noise) & (Vpeak of actual measurement > Vpeak of background noise) & (frequency component 1 of actual measurement > frequency component 1 of background noise) & (frequency component 2 of actual measurement > frequency component 2 of background noise), it is judged that the discharge type is particle discharge. After judging that the type of PD is particle discharge, if 5dB < Vpeak ≤ 10dB, it means that the device is in abnormal state; If Vpeak > 10dB, it means that the device is in defective state.
2) Corona discharge: if \((\text{RMS of actual measurement} > \text{RMS of background noise}) \& (\text{Vpeak of actual measurement} > \text{Vpeak of background noise}) \& (\text{frequency component 1 of actual measurement} > \text{frequency component 2 of actual measurement})\), it is judged that the discharge type is corona discharge. After judging that the type of PD is corona discharge, if \(\text{Vpeak} > 2\text{mV}\), it means that the device is in defective state.

3) Suspended discharge: if \((\text{RMS of actual measurement} > \text{RMS of background noise}) \& (\text{Vpeak of actual measurement} > \text{Vpeak of background noise}) \& (\text{frequency component 2 of actual measurement} > \text{frequency component 1 of actual measurement})\), it is judged that the discharge type is suspended discharge. After judging that the type of PD is suspended discharge, if \(10\text{mV} < \text{Vpeak} \leq 20\text{mV}\), it means that the device is in abnormal state; If \(\text{Vpeak} > 20\text{mV}\), it means that the device is in defective state.

When the tester finds that there is a problem in the detection data which needs expert's judgment, the software can push multiple detection data to the designated expert by mail or message. After logging in to the system, the expert can view the data and the spectrums to be diagnosed. Experts make judgments based on experience and submit diagnostic conclusions and suggestions to the system to complete the diagnostic work. When the tester logs into the system and receives the diagnostic data record, the report can be exported. If the diagnostic result shows that the data record has typical PD feature, the data record can be imported into the system to improve the automatic diagnostic ability of partial discharge.

5. Design of Partial Discharge Location Method
The automatic detection device has two detection modes: preliminary detection and accurate detection, wherein the preliminary detection is the premise of accurate detection. When performing the preliminary detection, the detection point is fixed, and the robot is responsible for collecting data and sending it back to the background server.

In the process of carrying out preliminary detection, if a test point A is found to be abnormal, the automatic detection device will enter the accurate detection mode, taking A as the base point, measuring 8 points in the range of 0.5 m around it, and the data of eight points are sent back to the background software for diagnostic and analysis. The most severe point B is obtained, and then the B point is used as the base point, and 8 points in the range of 0.25m are measured. The 8 points data are sent back to the background software for diagnostic and analysis, and finally find the most serious point. By the method of amplitude comparison, accurate detection tasks can be completed to achieve partial discharge location.

6. Experiment
Taking the GIL pipe gallery model with a length of 30 m as an example, one test point is arranged every 5 meters, for a total of five test points, as shown in Fig.11. A suspended discharge model was placed at 0.5 m to the left of the measuring point 3 to simulate the internal suspension discharge signal of the GIL, as shown in Fig.12. The automatic detecting device performs a partial discharge inspection task, and the robot loads the ultrasonic partial discharge detection device to detect each test point and transmits the data back to the background software, and the background software diagnoses the defect accurately, and judges that the type of PD is suspended discharge, and the relevant detection data is shown in Table 1.
According to the data detected by the ultrasonic sensor, the detection signal of point 3 is the largest, and the automatic detecting device enters the accurate detection mode, and the partial discharge detection and analysis are performed on 8 points in the range of 0.5m around the point 3, and the most serious point of partial discharge is calculated. The distribution of the measured points is shown in Fig.13 and the test data are shown in Table 2.

| Test point | RMS  | Vpeak | frequency component 1 | frequency component 2 |
|-----------|------|-------|------------------------|------------------------|
| 1         | 3.5  | 4.4   | 0.7                    | 1.9                    |
| 2         | 11.7 | 15.1  | 6.7                    | 9.7                    |
| 3         | **16.7** | **27.2** | **12.5**          | **19.7**              |
| 4         | 9.4  | 12.5  | 6.5                    | 7.8                    |
| 5         | 4.6  | 6.1   | 0.5                    | 1.2                    |

### Table 2. Experimental test value (unit/mV)

| Test point | RMS  | Vpeak | frequency component 1 | frequency component 2 |
|-----------|------|-------|------------------------|------------------------|
| 3         | 16.7 | 27.2  | 12.5                   | 19.7                   |
| 3-1       | **25.4** | **32.1** | **14.2**              | **21.7**               |


|   |   |   |   |   |
|---|---|---|---|---|
|3-2| 24.3| 29.7| 14.1| 20.4|
|3-3| 15.6| 19.3| 11.5| 17.8|
|3-4| 14.1| 18.5| 12.9| 15.9|
|3-5| 13.4| 19.6| 12.1| 14.6|
|3-6| 13.6| 17.6| 13.2| 15.4|
|3-7| 14.9| 18.6| 13.7| 16.6|
|3-8| 23.8| 28.9| 13.9| 21.2|

From Table 2, it can be seen that the test value of point 3-1 is the largest, and it is judged that the point is nearest to the location of partial discharge source, which is consistent with the simulation. This confirms the validity of the detection and location of the automatic detection device.

7. Conclusion
This paper introduces the ultrasonic detection technology and diagnostic method for partial discharge of GIL equipment, develops an acoustic partial discharge detection device and diagnostic system based on robot inspection, and designs the structure which integrate acoustic detection module with robot. The method of controlling the ultrasonic sensor in close contact with GIL shell by the mechanical arm, the process of GIL ultrasonic detection based on robot, the process of data diagnostic and precise positioning measurement are studied, the validity of the whole system is verified by experiments. The system plays an important role in ensuring the stable operation of GIL equipment, which avoids the constraints that may exist in the process of manual inspection and the personal injury that operation and maintenance personnel may suffer in the field under harsh test condition, it can also improve the detection efficiency of GIL equipment effectively.

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