Present Situation and Development of Internal Sensors for Ultra-high Frequency Detection in Gas Insulated Switchgear

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Abstract. This paper discusses the application situation of the ultra-high frequency (UHF) method and optical method in the detection of partial discharge of gas insulated switchgear (GIS), and the differences between external and internal UHF sensors. The sensor is a key technology in the PD detection method, and its performance directly affects the validity of the monitoring results. Different partial discharge detection sensors have different characteristics and working environments. UHF sensor has the advantages of wide detection range and convenient layout. Optical sensors have the advantages of high sensitivity and fast response speed. Six main types of internal sensors are evaluated and the performance indicators of internal sensors are discussed which includes disc antenna, loop antenna, dipole antenna, planar spiral antenna, conical antenna, photoelectric composite sensor. Furthermore, some problems need to be solved are proposed for further research, which is of great significance to the safe and stable operation of power equipment.

1. Introduction

The ultra-high frequency (UHF) method is used to detect the insulation status of power equipment. The research work in recent decades has made great progress in the UHF method. Its detection effect has been recognized by domestic and foreign scientists.

Partial discharge optical detection method detects by measuring the light signal excited by the partial discharge. The optical detection method is not affected by electrical signals, has complete immunity of electromagnetic interference, and has broad application prospects.

The sensor is a key technology in the UHF method, and its performance directly affects the validity of the monitoring results. Extrinsic sensors are easy to operate and maintain, require low size and mechanical performance. However, many GIS basin insulators are covered with a metal outer-ring, which further hinders the leakage of electromagnetic waves in the GIS, making it more difficult for extrinsic sensors to receive partial discharge signals. In addition, extrinsic sensors are affected by factors such as external corona discharge, and their anti-interference ability is not as good as built-in sensors. Therefore, the built-in sensors have an irreplaceable role in the UHF method.

Research on the performance of the built-in sensors has been the focus of research work at home and abroad[1-3] Foreign researchers began research on GIS built-in sensors earlier, and corresponding standards have been issued to regulate its performance, such as the National Grid Company (NGC) standard of the United Kingdom[4]. Domestic industry standards are also being formulated. Preliminary discussions in the industry have determined that the premise of the design of the built-in sensor is not to damage the reliable operation of GIS, and not to damage the sealing performance,
insulation performance and mechanical performance of GIS. On this basis, the built-in sensor should have good performance to ensure that it can detect 5pC partial discharge inside the GIS.

This paper summarizes the performance requirements and evaluation methods of GIS built-in partial discharge sensors, and reviews and evaluates various types of sensors.

2. Optical sensors
Fluorescence fiber is a kind of optical fiber, which can receive and transmit the light signal irradiated from any direction. Fluorescent fiber and ordinary optical fiber are the same in structure, composed of a core and a cladding. The core of fluorescent fiber can be selectively absorbs light signals in specific bands and emits fluorescent signals outward. This allows the fluorescent fiber to receive light signals irradiated from the side. The characteristics of fluorescent fibers are mainly related to the fluorescent substances doped. The main characterization parameters of fluorescent substances are excitation spectrum, emission spectrum, and fluorescence quantum yield. The excitation spectrum reflects the wavelength range of the optical signal that the fluorescent substance can absorb; the emission spectrum reflects the wavelength range of the fluorescent signal emitted by the fluorescent fiber.

3. Performance requirements and evaluation methods of built-in UHF sensors
The UHF built-in sensor can be regarded as an antenna working in the range of 300-3000MHz, and its characteristics can be explained by antenna theory. However, the working environment of UHF sensors and communication antennas is quite different, and the traditional antenna parameters cannot describe the characteristics of the sensors well. There is no clear conclusion on the selection of sensor performance indicators now, commonly used evaluation criteria are impedance bandwidth, sensitivity, and minimum measurable discharge.

3.1. Impedance bandwidth
The frequency band of most UHF monitoring systems is selected between 300 ~ 1500MHz. Therefore, the effective operating bandwidth of the sensor should also be within this range.

The bandwidth of a UHF sensor usually refers to the impedance bandwidth (or VSWR bandwidth). This change can be reflected by VSWR curve or S11 curve. The smaller the value of a frequency point in the curve, the less the reflection, and the higher the matching efficiency[5]. We name the frequency range less than a certain value (for example, VSWR < 3:1 or S11 < -6dB) as the impedance bandwidth. Impedance bandwidth measuring requires a network analyzer and placing the sensor in an anechoic chamber or an open space.

The bandwidth of a UHF sensor depends on the form of the sensor to a large extent. For some resonant antennas, that is, narrowband antennas, the relative bandwidth is often less than 10%, and it cannot completely cover the range of 300 ~ 1500MHz, and there can only be one or more resonance points in this range.

In the early research and design of sensors, the role of impedance bandwidth was overemphasized. In fact, the impedance bandwidth only reflects the energy loss of the antenna due to impedance mismatch, not considering the sensitivity of the antenna to the electromagnetic wave signals in all directions, so it can only partially reflect the sensor performance. For a wide-band sensor with a small reflection in the bandwidth, the actual detection effect is not necessarily better than a sensor with a large reflection.

3.2. Effective height
The coaxial structure of the GIS enables the built-in sensor to couple the normal component of the electric field. the effective height $H_e$ of the UHF sensor is defined as the sensor output voltage $V_o$ divided by the normal incident electric field $E_r$.

$$H_e(\omega) = \frac{V_o(\omega)}{E_r(\omega)}$$

(1)

The unit of $H_e$ is V / (Vm$^{-1}$) or m. It was first proposed by the University of Strathclyde[6]. When
measuring the effective height, the output voltage signal has taken the loss caused by the impedance change into account, so the effective height is essentially an amplitude-frequency response function that represents the relationship between the input and output. The electric field strength near the sensor can be calculated from the measurement results. The effective height is more in line with the needs of UHF partial discharge detection. It is a parameter that can more accurately reflect the performance of the sensor than the impedance bandwidth. It is often used to characterize the sensitivity of the sensor.

Effective height can be measured using a GTEM cell with a signal generator. GTEM cell is similar to a cone-shaped coaxial transmission line. When the signal is accessed at the top of the cone, the internal field is approximately a plane wave. In the measurement, the frequency domain scanning method is a traditional method of GTEM cells, and the effective height curve is obtained by scanning point by point in the working frequency band. The time domain pulse method constructs an ultra-wideband electromagnetic field in the GTEM cavity by inputting extremely short time-domain pulses.

The British NGC standard stipulates that the average effective height of UHF sensors between 500 and 1500MHz must not be less than 6mV/Vm⁻¹[7], which is now widely accepted. However, the effective height as an indicator also has shortcomings. The main point is the lack of theoretical guidance in design. At present, there are few sensitivity models for specific types of antennas. Except for simple dipole antenna[8], the effective height of most sensors can only be detected from actual measurements. At the same time, there are few studies on the sensor structure change on its effective height, which has brought some difficulties to the design of the sensor.

3.3. Minimum measurable discharge

The severity of insulation failure on equipment can be determined by measuring the apparent discharge of partial discharge. Therefore, the minimum apparent discharge capacity that a sensor can detect is often used to illustrate its performance in the UHF method. The sensor reaches the limit of detecting partial discharge signals by adjusting the voltage. Generally choose the apparent discharge when the signal-to-noise ratio is 2:1.

It should be noted that the minimum measurable discharge is essentially the sensitivity of the entire measurement system to the partial discharge electromagnetic signal, and it is not strict to characterize the sensitivity of a single sensor. And the results obtained by the above method have low credibility and cannot be compared horizontally, because there is no stipulation and description of the measurement environment and background noise.

Therefore, CIGRE proposed a qualitative method to verify whether the GIS built-in sensor can meet the 5pC apparent discharge detection requirements, and has been widely used [9]. This method can only make qualitative judgments, and is generally used for field calibration of sensors, which is what the built-in sensor must meet when used in the field.

4. Type of sensor

The internal working environment of GIS is harsh, and the strong electromagnetic field environment requires high reliability of antenna, which makes types of built-in sensors less than external sensors. Some complex antennas are not suitable for use in GIS.

4.1. Disc antenna

![Figure 1. Structure of the disc antenna](image)
Disc antennas are the most widely used GIS built-in sensors. It was adopted by the earliest practical UHF detection system[10]. A typical disc antenna is shown in Figure 1, the diameter of which is usually between 80 and 300 mm [1].

According to the impedance bandwidth, the conventionally designed microstrip patch antenna is a narrowband antenna with a relative bandwidth of about 1% to 7%. The resonance points in all modes can be calculated from the disc radius, dielectric constant and permeability of the medium[11].

There are many ways to improve the performance of the disc antenna, such as finding a suitable dielectric constant and dielectric height. These tasks are mostly done through electromagnetic simulation and experiments. In recent years, some antenna design techniques have also been used to further improve the performance of disc antennas. Such as, applying dual-polarization technology to improve the signal receiving capability, reducing the size of the antenna in the form of a slot or a groove, widening the antenna bandwidth by multiple resonance circuit with parasitic element[12].

The advantage of the disc antenna is that it has a simple structure and can be easily installed in the hatch board of a GIS without affecting the internal electric field of the device. The performance of this antenna has also been verified during research and application. For example, a simple disc antenna with a diameter of 140mm can achieve a sensitivity of 8 mV / Vm-1 near the resonance point[13]. From the perspective of apparent discharge, the minimum measurable discharge of a disc antenna can be as low as 1pC[14].

4.2. Loop antenna

As shown in Figure 2, a typical loop antenna structure is mostly installed in the support insulator of GIS[3]. The resonant loop antennas are also narrow-band antennas.

Figure 2. Structure of the loop antenna

Among domestic universities, Chongqing University has advanced research on loop antennas. They connect the ground resistance in parallel with the ring to form a passive high-pass filter with the sensor's capacitance to earth, which can effectively suppress the coupled power frequency signal. The developed loop antenna can detect partial discharge pulse signals with a steepness of 1ns and a duration of 2ns.

Foreign countries, such as Japan, have in-depth research on such sensors. For example, TOSHIBA, in Japan, has developed a loop antenna that can detect partial discharge with an apparent charge of 1-5pC.

According to the performance, some experimental and theoretical assumptions show that the ring-shaped sensor performs better than the disc-shaped sensor, but the difference between the two is not obvious. More precisely, ring-shaped sensors are more sensitive to TEM waves propagating in GIS than disc-shaped sensors, but less sensitive to TE and TM mode waves[15]. Therefore, the detection performance of the ring-shaped sensor has a great relationship with the type of partial discharge, which is more suitable for detecting partial discharge caused by particles located on the GIS shell[16].
4.3. Dipole antenna

Hyosung company, Korea, has designed an asymmetric disc dipole antenna, as shown in Figure 3[17]. The product reached a bandwidth of 9.85% and a resonance frequency of 1.23GHz after finding the optimal size through simulation.

![Figure 3. The asymmetrical disc dipole antenna](image)

Hitachi company, Japan, has also developed a similar dipole antenna, but uses a symmetrical structure. Placed in the same white noise test environment, this dipole antenna performs better in terms of output amplitude and bandwidth, compared with other GIS built-in sensors with different structures but the same diameter[18]. In addition to disc-shaped dipoles, other forms such as printed dipoles[19] and folded dipoles[20] have also been used in UHF partial discharge measurement built-in sensor, but it is rarely used in practice.

4.4. Planar spiral antenna

The structure of planar spiral antenna does not change when the antenna is transformed at an arbitrary ratio, so its operating characteristics are independent of frequency. The planar spiral antenna with terminal truncation, its impedance characteristic remains basically unchanged over a wide frequency range. This feature allows a properly matched spiral antenna to achieve a 10: 1 octave bandwidth, which is classified as an ultra-wideband antenna. The pulse energy of the partial discharge is almost proportional to the width of the frequency band[21]. The structure is shown in Figure 4.

![Figure 4. Structure of the planar spiral antenna](image)

Spiral antennas with a size in the range of 6cm to 20cm can reach an average effective height of more than 6mm in the frequency band.

4.4.1. Equiangular spiral antenna.

![Figure 5. The planar equiangular spiral antenna](image)
The planar equiangular spiral antenna is shown in Figure 5. The minimum working frequency and the maximum working frequency can be estimated according to the following empirical formula.

\[
R_{\text{min}} = \frac{\lambda_{\text{min}}}{4}, \quad R_{\text{max}} = \frac{\lambda_{\text{max}}}{4}
\]  

(2)

\(R_{\text{min}}\) is the starting radius and \(R_{\text{max}}\) is the ending radius. The measured impedance is usually slightly smaller than this value. In order to match the coaxial feed line of 50, impedance matching circuit is usually attached.

Since the structure of the antenna is fixed, it is generally carried out by improving balun and impedance transformer. For example, Rong Mingzhe of Xi'an Jiaotong University found the optimal design parameters of the antenna by simulation, and proposes two impedance transformer designs that can reduce the antenna installation volume while keeping the original performance of the antenna as much as possible. The antenna using this transformer has a smaller power loss than the method only using balanced line feed[22].

4.4.2. Archimedean spiral antenna.

The Archimedean spiral antenna is shown in Figure 6. The terminal radius and the starting radius of the Archimedes antenna determine the lower and upper frequencies of the antenna, respectively, and the duty cycle has little effect on the antenna performance. Figures 7 (a) and 7 (b) are the Archimedes antennas developed and used by the Institute of Electrical Engineering of the Chinese Academy of Sciences[23] and LS Industrial Systems of South Korea[24]. The bandwidths are 300-3000MHz and 300-1500MHz, respectively. Despite the different duty cycles, both sensors have good performance over the bandwidth.

4.5. Conical antenna
Figure 8 shows a specific structural form in the conical antenna. Its transient response is better than disc-shaped antenna.

![Figure 8. Structure of the conical antenna](image)

Since the size must be limited when producing cone antennas, it is relatively difficult to achieve low frequencies performance. In general, the longer the cone length, the better the low frequency performance. The flat-topped cone antenna can also be considered as an improvement of the disc-shaped sensor, with a higher sensitivity.

4.6. Photoelectric composite sensor
The photoelectric composite sensor is a new type of partial discharge detection sensor, which is a combination of fluorescent optical fiber and GIS built-in UHF sensor. Its sensor structure is shown in Figure 9.

![Figure 9. Structure of the composite sensor](image)

The fluorescent fiber is embedded in the surface of the upper plate of the built-in sensor, and the optical signal is led out from the metal base plate through a special optical fiber sealed connector. Plastic fluorescent fiber has good flexibility. In order to increase the length of the fluorescent fiber and improve the sensitivity of the sensor to optical signals, the fluorescent fiber is arranged on the surface of the upper plate of the built-in UHF sensor according to the Archimedes spiral.

This photoelectric composite sensor implants a fluorescent optical fiber sensor into the GIS without affecting the internal electric field of the GIS and the performance of the built-in UHF sensor. The light and electromagnetic wave signals generated during the partial discharge of typical defects can be detected at the same time. Moreover, there is no obvious mathematical relationship between the UHF signal amplitude and the discharge. When detect the partial discharge by the fluorescent fiber method, the optical signal is greatly attenuated with the increase of the measurement distance.

5. Several important issues about built-in sensors design
When GIS works regularly, the compartment is filled with high-pressure SF₆ gas, and the annual leakage rate of any one compartment should be less than 0.5% a year. Therefore, after the sensor is installed in the GIS, the gas leakage caused cannot be higher than this value. The most prone to gas leakage of the built-in sensor is the RF connector that leads to the sensor signal, and it is often protected by adding a sealing ring.

In order to protect the safety of subsequent detection equipment and operators, the built-in sensor must be grounded. The common grounding method is to connect the ground electrode of the output signal with the GIS shell. On the other hand, in order to avoid the AC high voltage of GIS being directly coupled to the built-in sensors, it is common to ground metal signal electrodes at the same time. The principle is similar to forming a low-pass filter to isolate the power frequency voltage. It’s
easy to ground signal electrodes for disc antennas, loop antennas and conical antennas. Reasonably selecting the ground point can not only improve the safety of the sensor, but also suppress low-frequency interference, reduce the resonance frequency and thereby improve the sensitivity of the sensor[26].

The installation of the built-in sensor must not cause distortion of the electric field inside the GIS, so there must be no sharp structure on the sensor, and there must be no air gap in the insulating medium. In addition, although the deeper the sensor penetrates into the GIS, the higher the measured signal strength. From the perspective of security, the outer surface of the sensor can only reach a position parallel to the inner wall of the GIS, and cannot exceed the inner wall, otherwise the insulation resistance level of the GIS will be reduced.

6. Conclusion
There are currently five common GIS built-in sensors. From the perspective of sensitivity, except that there is no measurement method for loop antennas due to different installation methods, the average effective height of the other types of sensors can reach the requirement of 6mm. From the perspective of the minimum measurable discharge, these methods can detect partial discharge with the value of 5pC under laboratory conditions all. It should be pointed out that there are still some problems to be solved.

1) Improvement of sensor performance. In view of the important role of the built-in sensor, improving the performance of the sensor can greatly improve the application prospect of the UHF method.

2) Determination of sensor performance evaluation. At present, there is still a lack of an index and calibration method that can comprehensively evaluate the detection effect of the sensor, which is a key part of the standardization of the UHF method.

3) Improvement of sensor manufacturing process. The UHF partial discharge detection method has shown a rapid development trend, and some have been commercialized and applied to power equipment. Different from laboratory research, the technological requirements of the sensor are very strict in practical applications. Grounding design, signal outlet design, installation and fixing methods, and insulation sealing are all issues that require attention. Through reasonable design and processing, the failure rate of built-in GIS sensors can be reduced, and reliability and safety can be improved.

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