GIS UHF Partial Discharge On-line Monitoring Device Evaluation

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Abstract. The Ultra-high Frequency (UHF) partial discharge on-line monitoring system device is widely used in gas insulated substations (GIS), and has become one of the important detection methods for partial discharge of GIS. However, due to the lack of uniform standards within the industry, the equipment produced by the manufacturers is uneven, resulting in the performance evaluation problems of the UHF online monitoring device in the purchase and acceptance process. For this question, this paper proposes a measurement method, which has two parts: UHF sensor evaluation and complete device evaluation. A set of evaluation methods was established by using a signal simulation test method and a simulated fault evaluation method, and a more comprehensive understanding of the GIS UHF partial discharge on-line monitoring device were proposed.

1. Introduction
GIS has a very important position in electrical equipment, because of its small footprint, high efficiency, and strong anti-interference[1]. The main problem in electrical equipment is partial discharge. Common GIS internal partial discharges are caused by these metallic particles and mechanical looseness. The main types of discharges are suspended body discharges, metal tip corona discharges, and dirty discharges. In the event of an accident in GIS, maintenance is very difficult, so it is necessary to perform on-line monitoring of partial discharges in GIS equipment. Real-time control of internal discharges in GIS has important implications for GIS[2]. A set of qualified UHF partial discharge on-line monitoring system devices is indispensable.

2. UHF online monitoring works
The work process of GIS UHF PD online monitoring system can be roughly divided into: Signal acquisition, signal transmission, signal processing, data storage and signal display analysis[3]. The signal acquisition part can be completed by UHF sensors, the signal transmission is completed by the coaxial line and the optical fiber, the signal processing is completed by the signal processing unit, and the data storage and display are completed by the background server and the industrial control computer. The system flow is shown in Figure 1.:
Figure 1. Process chart of UHF online monitoring system

In this paper, two UHF online monitoring devices are mainly used for evaluation, which are denoted as Equipment I and Equipment II respectively. Each device has three UHF sensors, which are denoted as I-1#, I-2#, I-3#, II-1#, II-2#, and II-3#, respectively.

3. Another section of your paper

The UHF sensor evaluation consists of three parts: standing wave ratio evaluation, equivalent height evaluation, and sensitivity evaluation. The standing wave ratio evaluation measures the circuit parameters of the UHF sensor itself, and the equivalent height evaluation and sensitivity evaluation measure the UHF sensor's ability to receive the UHF signal[4].

3.1. Standing wave ratio evaluation

Standing wave ratio can reflect the standing wave characteristic of the sensor in the system, that is to say, when the positive wave and the reflected wave are raised, the formula (1) shows:

$$SWR = \frac{R}{r} = \frac{k + I}{k - I}$$

In the equation, $SWR$ is the standing wave ratio, $R$ is the output impedance, $r$ is the input impedance, and $k$ is the reflection coefficient.

In order to further obtain the performance of the antenna more directly, the transmission power ratio is proposed. The formula is shown in formula (2):

$$\Phi = \left[1 - \left(\frac{SWR - I}{SWR + I}\right)^2\right] \times 100\%$$

(2)
In the lab, a vector network analyzer is used to perform standing wave ratio measurements on UHF sensors, as shown in Figure 2:

Figure 2. Standing wave ratio measurement connection diagram

At the same input power, the smaller the standing wave ratio, the more power the UHF sensor can transmit. When the standing wave ratio is closer to 1, the UHF sensor can transmit the received high frequency energy through the high frequency signal cable. Conversely, when the standing wave ratio is larger, UHF sensors will transmit less high-frequency energy received through the high-frequency signal cable.

3.2. Equivalent height ratio measurement evaluation

The equivalent height ratio of UHF sensors was measured based on Gigahertz transverse electromagnetic (GTEM) cell. The calibration platform for UHF partial discharge detection systems was established using the pulsed time-domain reference method[5,6]. Considering that the electric field in the GTEM cell is not completely uniform, and the electric field at any point is difficult to measure accurately, it is still difficult to directly and accurately measure the effective height of the sensor frequency domain. A time-domain reference measurement method was proposed to solve this problem. The principle is shown in Figure 3:

Figure 3. Principle of reference measurement using GTEM cells

In the actual measurement, assume that the output voltages of the sensor under test and the reference sensor are $U_M$ and $U_{Mr}$, respectively. The transfer functions of the GTEM cell, reference sensor, and test sensor are $H_{cell}$, $H_{ref}$, and $H_{sens}$, respectively. From Figure 3, it can be seen that $H_{sens}$ is also an equivalent height expression, the unit is generally mm, and the transmission characteristic of the measurement system is $H_{sys}$. The measurement output of the reference sensor and the measured sensor is shown in the formula (3):

\[
\begin{align*}
U_{Mr} &= U_I H_{cell} H_{ref} H_{sys} \\
U_{Ms} &= U_I H_{cell} H_{sens} H_{sys}
\end{align*}
\]
Among them, $U_j$ is to inject the pulse voltage through the calibrated signal source. The equivalent height $H_{sens}$ expression (4) can be obtained from equation (3):

$$H_{sens} = \frac{U_{Ms}}{U_{Mr}} H_{ref}$$

(4)

Using the reference sensor can calculate the equivalent height from the standard, as can be seen from equation (4). By referring to the transfer function $H_{ref}$ of the sensor and the voltage response of the injected signal, the transfer function $H_{sens}$ of the desired sensor can be determined. When the field strength $E_i$ is constant, the larger the output voltage $U_o$ of the sensor, the stronger the coupling performance and the greater the equivalent height. Therefore, the equivalent height can reflect the signal receiving capability of UHF sensors. The schematic diagram and the physical map of the pulse time domain reference calibration system based on the GTEM cell are shown in Figure 4.

![Figure 4. UHF sensor time-domain pulse calibration system diagram](image)

3.3. Sensitivity evaluation

The sensor to be tested meets the standard pulse generator to establish a calibrated transient electric field in the GTEM cell. The peak value of the minimum transient electric field strength that the sensor can detect that should meet the following requirements: the monitoring device (with sensors) should not lower the signal-to-noise ratio at the peak of the transient electric field strength of 7V/m (or 17dBV/m) in the GTEM cell by less than 2 times (or 6dB).

4. Complete device evaluation

The complete device evaluation mainly includes four parts: insulation resistance, impulse voltage, pattern recognition, and anti-jamming performance [7,8]. Among them, the two parameters of insulation resistance and impulse voltage are mainly the evaluation of hardware conditions. The two parameters of pattern recognition and anti-jamming performance are the conditions of the evaluation system.

4.1. Insulation resistance and impulse voltage evaluation

Insulation resistance evaluation in accordance with the provisions of the "GB/T 7261 Basic Test Methods for Relay Protection and Safety Automatic Devices", the insulation resistance test was conducted [9]. In the normal test atmospheric conditions, the requirements of the insulation resistance between the independent circuits of the device and the exposed electrically conductive portions and between the individual circuits are shown in Table 1.

| Rated voltage $U_r$ | Insulation resistance requirements |
|--------------------|-----------------------------------|
| $U_r \leq 60V$     | $\geq 5M\Omega$ (Measured with a 250V megohmmeter) |
| $250V > U_r > 60V$ | $\geq 5M\Omega$ (Measured with a 500V megohmmeter) |

Note: The insulation resistance of the interface circuit directly connected to the secondary equipment and external circuit is $250V > U_r > 60V$.

Impulse voltage evaluation The impulse voltage test is carried out in accordance with the provisions and methods of Chapter 19 of "GB/T 7261 Basic Test Methods for Relay Protection and
Safety Automatic Devices”. Under normal test atmospheric conditions, short circuit impulse voltage tests of a standard lightning wave of 1.2 μs/50 μs shall be carried out between the individual circuits of the device and the exposed conductive parts and between the individual circuits. When the rated working voltage is greater than 60V, the open circuit test voltage is 5kV; When the rated operating voltage is not more than 60V, the open circuit test voltage is 1kV. After the test, the device should be free of insulation damage and device damage. Impact voltage requirements as shown in Table 2.

| Rated voltage Ur | Open circuit test voltage |
|------------------|--------------------------|
| Ur≤60V           | 1.0 kV                   |
| 250V>Ur>60V      | 5.0 kV                   |

Note: The interface circuit test voltage directly connected to the secondary equipment and the external circuit adopts the requirements of 250>Ur>60V.

4.2. Pattern recognition
Tip discharge and levitation discharge are used for pattern recognition evaluation. Metal tip discharge and floating potential body discharge have characteristics that it is more obvious, stable, easy to distinguish from other types of partial discharge, and easy to simulate [10,11]. As shown in Figure 5:

![a) Metal tip discharge b) Suspension potential discharge](image)

Figure 5. Metal tip discharge and suspended potential body discharge spectra

The characteristics of the metal tip discharge are: the number of discharges is more, the dispersion of the discharge amplitude is small, and the time interval is uniform. The polarity effect of the discharge is very obvious and usually occurs only during the negative half cycle of the power frequency phase.

The characteristics of the floating potential body discharge are: the amplitude of the discharge pulse is stable, and the adjacent discharge time intervals are basically the same. When the suspended metal body is asymmetric, the positive and negative half-wave detection signals have polarity differences.

5. Evaluation result

5.1. UHF sensor evaluation results

5.1.1 Standing wave ratio measurement. The Standing wave ratio measurement results are similar, and the figures in the figure show the standing wave ratios of sensors I-1# and II-1#, as shown in Fig.6.
The red line in Figure 6 is the Standing wave ratios value, and more than 80% of the frequency range is within 300 MHz to 3 GHz, and other sensors are similar.

The Standing wave ratios evaluation results of the device I and device II sensors are shown in Table 3:

| Sensors | Standing wave ratios | Transmission power ratio |
|---------|----------------------|-------------------------|
| I-1#    | 7.12                 | 43.19%                  |
| I-2#    | 5.86                 | 49.81%                  |
| I-3#    | 7.58                 | 41.19%                  |
| II-1#   | 11.98                | 28.44%                  |
| II-2#   | 18.10                | 19.85%                  |
| II-3#   | 11.26                | 29.97%                  |

From Figure 6 and Table 3, it can be clearly seen that the transmission power of the sensor of Device I in the frequency range of 300 MHz to 3 GHz is better than that of Device II.

5.1.2 Equivalent height ratio measurement result. Figure 7 (a) and (b) show the test results of the typical time-domain output waveform and its equivalent height curve of a UHF sensor based on the time-domain reference method, respectively. Thus, the average equivalent height of the sensor in the 0.3-1.5GHz band is 10.62mm.
Table 4 shows that the equivalent height of the sensor of the device I is about 10 mm, the equivalent height of the device II sensor is about 6 mm, and the coupling performance of the device I is stronger than that of the device II.

5.1.3 Sensitivity evaluation. Each device uses sensors to measure sensitivity and average values. The results are shown in Table 5:

|     | Device 1 | Device II |
|-----|----------|-----------|
|     | Sensitivity (V/m) | 2.48      | 7.45      |

From Table 5 we can see that the sensitivity of device II cannot meet the requirements of GIS.

5.2. Complete device evaluation results

5.2.1 Basic Evaluation Results. (1) Prior to the evaluation of the complete set of equipment, structural and visual inspections are required, and both equipment meet the inspection requirements. (2) The connection of the two devices requires 220V AC voltage. Megohmmeter is used for insulation resistance measurement. The insulation resistance of both devices is 8MΩ, which meets the required requirements. (3) The device is injected with 5kV AC for 1min and then turn on the device. The equipment can run normally and the results meet the requirements.

5.2.2 Pattern recognition test results. In accordance with the evaluation program set the analog signal tip discharge and suspension discharge. The evaluation results are shown in Figure 8:

![Pattern recognition monitoring results](image)

The pattern recognition of the device I simulated tip discharge is based on the comparison of its existing fingerprint database. The probability that the partial discharge type is the discharge of the busbar tip is 96%, and the probability of a hole/dirty discharge is 4%; As a result of simulating the levitation discharge, the possibility that the partial discharge type is a levitation discharge is 85%, and the probability of a case corona is 15%. The pattern recognition of the device II simulated tip discharge according to its existing fingerprint library comparison results that the probability of partial discharge type for the busbar tip discharge is 60%, and the probability of hole/pollution discharge is 30%; As a result of simulated suspension discharge, the possibility of non-partial discharge is considered to be 50%, the possibility of partial discharge to be suspended discharge is 35%, and the probability of case corona is 15%. Device I has a more accurate identification capability.

6. Conclusion

The GIS ultra-high frequency partial discharge on-line monitoring device was tested and evaluated, and two devices were tested and compared.

(1) A set of evaluation and evaluation plans are designed, mainly for the evaluation of sensors and the overall evaluation of complete sets of devices;

(2) The evaluation of the sensor is mainly based on the measurement of VSWR, equivalent height and sensitivity. It is recommended that the sensor should be periodically evaluated during routine maintenance;
(3) The evaluation of complete sets of equipment is mainly for hardware and system evaluation. It is recommended to conduct evaluations during equipment purchase and acceptance.

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