GIS vibration test method and characteristic signal recognition

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Abstract. Based on the characteristics of GIS insulation and mechanical fault types and practical measurement experience, two typical vibration measurement methods, direct measurement method and natural frequency measurement method, are proposed in this paper. Then, based on the real data of experiment and field measurement, the vibration signals of typical insulation fault and mechanical fault such as spike discharge and end cover looseness are compared, analyzed and summarized, and their respective data characteristics are extracted, which can provide the basis for the determination of GIS vibration fault types.

1. Introduction

In recent years, more and more attention has been paid to the research and application of GIS vibration testing and diagnosis technology. This is because the vibration test has many advantages. Firstly, it can obtain the mechanical operation state of GIS, such as whether there are loose or damaged parts. Secondly, it can also understand the insulation operation state of GIS, such as whether there is discharge or even which discharge form, which can be analyzed and judged by the vibration signal measurement [1]. But at present, the research of GIS vibration test is still relatively preliminary, and there are still many problems to be solved. One of the more important two points is the test method and characteristic signal recognition. On the one hand, because the structure of GIS is complex and diverse, and the vibration signal is easy to conduct, so it is very important to test GIS vibration scientifically and reasonably. On the other hand, after obtaining the signal, how to identify the fault type and make the final judgment is the fundamental of vibration test. Based on the field work experience and laboratory simulation experiments, this paper introduces the commonly used GIS vibration test methods, and introduces the signal characteristics of a variety of common insulation and mechanical faults, which provides a reference for the research of the industry.

2. Test methods of typical faults

There are two kinds of vibration test methods for composite apparatus. One is direct measurement method, that is, the sensor is directly connected to the surface of the component to be tested for measurement. This test method can be used for vibration monitoring of insulation fault. Another method is the natural frequency measurement method, which needs to knock and excite the components, and use the sensor to pick up the vibration at the same time to obtain the natural frequencies of each order.
of the components, which is mainly used to judge the vibration test when the components are loose. The following two fault types of partial discharge and insulator looseness are briefly introduced as examples.

2.1. Partial discharge

The vibration signal of GIS shell is used to monitor the partial discharge fault. It involves the selection of vibration sensor, the arrangement of vibration sensor, the time and analysis method of vibration signal acquisition, the selection and determination of characteristic signal, etc.

The principle of vibration sensor placement is the strongest vibration signal. In general, the vibration signal of the flange at both ends of the gas chamber is weak, and the vibration signal at the middle of the gas chamber is strong. Therefore, the vibration sensor is generally placed in the middle of a section of air chamber [2]. Considering the difference of vibration propagation direction and vibration characteristics of each point, a vibration sensor is placed in the axial and radial position respectively. The recommended location of the sensor is shown in Figure 1.

![Suggested layout of vibration sensor](image)

Figure 1. Suggested layout of vibration sensor

Measure the vibration signal of different load current under standard voltage, the vibration signal time collected by the sensor each time should not be less than 2S, carry out fast Fourier transform on the collected vibration signal, get the vibration signal spectrum, analyze the spectrum diagram, and then get the fault type.

2.2. Signal recognition and diagnosis of seal cover looseness

The change of frequency response curve of GIS sealing cover was observed to determine whether it was loose or not. It involves the selection of vibration sensor, the arrangement of vibration sensor, the time and analysis method of vibration signal acquisition, the selection and determination of characteristic signal, etc.

In the long-term vibration environment of GIS, structural components will become loose. Taking the sealing cover as an example, the natural frequency changes before and after the sealing cover is loose are analyzed. According to the basic expression of the natural frequency $\omega = \sqrt{K/M}$, where $\omega$ is the natural frequency, $K$ is the stiffness coefficient, $M$ is the mass matrix. When the sealing cover is loose, the stiffness coefficient $K$ will decrease, resulting in the decrease of the natural frequency. The change of the natural frequency will affect the spectrum distribution of the vibration signal, which can be used as the criterion of structural looseness. Therefore, in the process of mechanical fault diagnosis, it is necessary to measure the natural frequency of the research object through experiments before feature extraction [3].

Natural frequency test: in a linear or nearly linear vibration system, we use a specific known exciting force and use a controllable way to excite the structure. At the same time, we measure the input signal
and output signal. Then, we can get the natural frequency of the system by analyzing the transfer function. The relationship between response and excitation force can be expressed as admittance:

\[
Y = \frac{X}{F} = \frac{1/k}{\sqrt{(1-u^2)^2 + 4D^2u^2}} e^{j\phi}
\]  
\[
\phi = \arctan \frac{-2Du}{1-u^2}
\]

Where: \(X\) is the vibration signal measured on the surface of the measured component, \(F\) is the force signal input by the impact hammer, \(k\) is the stiffness, \(u = \omega / \omega_0\) is the frequency ratio, \(D = \beta / \omega_0\).

![Figure 2. Natural frequency test chart of GIS components](image)

As shown in Figure 2, during the test, the impact hammer made of nylon head is used to excite the measuring point, and then the force signal struck by the impact hammer and the vibration acceleration signal of the acceleration sensor adsorbed on the surface of the measured component are measured. Finally, the natural frequencies of each order of the test point can be obtained by analyzing the transfer function of the two groups of measured data. The first peak in the frequency response curve is the first order of the system, and the following peaks are other high-order natural frequencies. If the end cover is loose, the natural frequency will decrease and the amplitude will increase. The loose degree can be judged according to the transformation degree of natural frequency and amplitude.

3. Recognition of different types of fault features

In order to obtain the signal characteristics of different types of vibration fault, we use the simulation experimental platform to simulate a variety of fault types, measure the vibration signal, analyze and process the data, compare and summarize, in order to obtain the recognizable signal characteristics.

3.1. Insulation fault

Partial discharge fault is the main insulation fault of GIS equipment. Accurate identification of partial discharge type plays an important role in dealing with partial discharge fault in time. For different types of discharge faults, the vibration signals caused by different discharge pulse frequency, discharge intensity and discharge principle will have obvious differences.

3.1.1. Spike discharge. The discharge caused by spikes is mainly tip discharge, which is caused by the uneven distribution of electric field. The local electric field strength reaches the breakdown strength, which makes the dielectric around the spikes break down and lead to discharge. The spike discharge has a strong polar effect. The discharge phase is concentrated in the negative half cycle of power frequency voltage, and the significant change of vibration signal frequency caused by it is mainly concentrated in the frequency band of 1 kHz ~ 2 kHz. The bitmap is shown in Figure 3.
3.1.2. **Surface discharge.** The surface discharge of the basin is more intense, with high repetition rate and weak polarity. The positive and negative half cycle of the basin will be discharged. The pulse amplitude caused by the discharge is large, and the amplitude of the high-frequency signal in the vibration signal increases significantly. The frequency band with obvious change is the signal in 1 kHz ~ 3 kHz. The phase spectrum of the surface discharge is shown in Figure 4.

![Figure 4. Phase diagram of surface discharge](image)

3.1.3. **Free metal particle discharge.** The discharge caused by free metal particles is the most harmful to the operation of the equipment. The vibration signal caused by discharge changes most obviously. The high frequency component signal changes significantly. The discharge phenomenon is obvious. The shape of metal particles is regular. When the size is large, the positive and negative half cycle waveforms are more symmetrical, and the discharge amplitude is basically the same. There is no obvious discharge difference between the positive and negative half cycles. The difference of positive and negative half cycle discharge degree is obvious, and the discharge amplitude is also large.

![Diagram](image)
Figure 5. Vibration spectrum of GIS free metal particle discharge under different voltage, (a) 35.3 kV; (b) 52.7 kV; (c) 66.5 kV

As shown in Figure 5, the spectrum characteristics of the discharge caused by free metal particles are similar to the surface discharge characteristics of insulators, which also leads to the increase of signal energy in the frequency band of 1 kHz ~ 3.5 kHz, and the discharge characteristics are similar, because the discharge intensity and discharge phenomenon caused by the two are similar, so the spectrum characteristics are similar.

3.2. Mechanical failure

3.2.1. Loose seal end cover. Through the simulation experiment, three states of the end cover not loose, loose 0.5 mm and loose 1 mm are tested respectively for comparison. The frequency response diagram is shown in Figure 6.
Figure 6. Natural frequency of seal cover before and after loosening. (a) not loose; (b) loose 0.5 mm; (c) loose 1 mm

The natural frequency values are listed in Table 1:

| State       | Fifth order | Sixth order | Seventh order | Eighth order |
|-------------|-------------|-------------|---------------|--------------|
| Not loose   | 461 Hz      | 482.5 Hz    | 692 Hz        | 751.5 Hz     |
| Loose 0.5 mm| 460 Hz      | 482.5 Hz    | 676 Hz        | 749.5 Hz     |
| Loose 1 mm  | 454 Hz      | 480 Hz      | 669.5 Hz      | 737 Hz       |

From the natural frequencies of each point at the sealing cover, it can be seen that the low order natural frequencies are little affected by the looseness of the end cover, and the 5-8 order natural frequencies gradually decrease with the increase of the looseness. Therefore, under the action of 100Hz and its double frequency excitation force, the vibration response will change obviously in the frequency band of 400-900Hz, which can be used as the basis for GIS seal cover looseness diagnosis.

3.2.2. Signal recognition and diagnosis of insulator looseness fault. The failure of basin insulator caused by loose fastening bolt is a common mechanical failure in GIS. The frequency response curve of the fixed bolt of GIS basin insulator is measured by hammering method, and the natural frequency of the measured bolt is calculated. If the bolt of the fixed basin insulator is loose, the natural frequency decreases and the amplitude increases. The degree of loosening can be judged according to the transformation degree of the natural frequency and amplitude.
Figure 7. Frequency response curve of basin insulator bolt, (a) Not loose; (b) Lose 30%; (c) Loose 60%

The first five natural frequencies of each state are listed in Table 2:

| State          | Frequency /Hz | First order | Second order | Third order | Fourth order | Fifth order |
|----------------|---------------|-------------|--------------|-------------|--------------|-------------|
| Not loose      | 1021          | 1392        | 1727         | 1881        | 2225         |             |
|                | Amplitude     | 0.5029      | 0.9182       | 0.9962      | 0.9691       | 0.2789      |
| Loose 30%      | Frequency /Hz | 1010        | 1389         | 1634        | 1707         | 2205        |
|                | Amplitude     | 0.7593      | 2.465        | 2.471       | 2.593        | 6.426       |
| Loose 60%      | Frequency /Hz | 1010        | 1388         | 1632        | 1707         | 2187        |
|                | Amplitude     | 0.9295      | 2.877        | 2.865       | 3.039        | 5.616       |

3.2.3. Signal recognition and diagnosis of circuit breaker fault. (1) Normal vibration signal analysis and processing

As shown in Figure 8a, it is the closing vibration signal of GIS circuit breaker under normal state. Each peak in the figure corresponds to an event of high voltage vacuum circuit breaker at this time one by one, and there is a certain noise signal mixed in it. As shown in Figure 8b, the frequency spectrum of the closing vibration signal in normal state. According to the frequency spectrum of closing vibration signal, the energy of closing action is concentrated from 1000Hz to 4000Hz. The short-time Fourier transform of the normal closing vibration signal is shown in Figure 8c. It can be clearly seen from the
short-time Fourier spectrum of the closing vibration signal that the vibration energy is mainly concentrated at the closing moment, and the frequency bandwidth at the closing moment is very large.

![Short time Fourier spectrum](image)

**Figure 8.** Normal closing vibration signal, (a) Time domain diagram; (b) Spectrogram; (c) Short time Fourier transform

(2) Analysis and processing of vibration signal of transmission rod jam

The opening and closing operation of GIS circuit breaker is completed by the transmission function of the transmission rod. Repeated opening and closing operation can easily lead to the occurrence of wear and even jam fault, and then cause serious faults such as GIS circuit breaker refusing to operate or misoperation. The acceleration sensor collects the time domain signal of GIS circuit breaker transmission rod jam fault, as shown in Figure 9a. It is found that the peak value (maximum value) of the closing vibration time domain signal decreases and the vibration energy decreases after the transmission rod is jammed.
Figure 9. Closing vibration signal of transmission rod jam, (a) Time domain diagram; (b) Spectrogram; (c) Short time Fourier transform

Figure 9b shows the frequency spectrum of the vibration signal of the transmission rod stuck on. It is found that the vibration energy of more than 5000Hz in the frequency spectrum is significantly reduced, that is, the high-frequency energy attenuation is larger. Figure 9c shows the short-time Fourier transform of the vibration signal of the transmission rod jamming closing. Also compared with the normal state, the short-time Fourier spectrum of the closing vibration signal shows that the vibration energy is still concentrated in the closing moment, but the high-frequency energy has a large attenuation.

4. Conclusion
(1) For insulation faults, the direct method can be used for measurement. Generally, the sensor is placed in the middle of the gas chamber where the vibration signal is strong, and a vibration sensor is placed in the axial and radial position respectively. The time of each signal acquisition is not less than 2s, and the frequency spectrum of vibration signal is obtained by fast Fourier transform, and the fault type is identified.

(2) For mechanical faults, the natural frequency measurement method can be used. It needs to knock and excite the components, and use the sensor to pick up the vibration at the same time to obtain the natural frequency of each order of the components. It is mainly used to judge the vibration test when the components are loose.

(3) In insulation fault, the characteristic frequency of spike discharge is mainly concentrated in the frequency band of 1kHz ~ 2kHz; the characteristic frequency of surface discharge is mainly in the frequency band of 1kHz ~ 3kHz; the characteristic frequency of free metal particle discharge is in the frequency band of 1kHz ~ 3.5kHz.
(4) In mechanical faults, the looseness of the seal cover is characterized by low order natural frequency which is little affected by the looseness of the end cover, 5-8 order natural frequency gradually decreases with the increase of looseness, and 400-900Hz frequency band changes obviously. The characteristics of insulator looseness are that the first five natural frequencies decrease and the amplitude increases. Compared with the normal state, the frequency spectrum of the circuit breaker driving rod jam vibration signal is greater than 5000Hz, and the vibration energy is significantly reduced, that is, the high-frequency energy attenuation is larger, and the vibration energy is still concentrated in the closing moment, but the high-frequency energy has a larger attenuation.

This paper introduces two typical GIS vibration measurement methods: direct measurement method and natural frequency measurement method, and summarizes the vibration signal characteristics of typical discharge fault and mechanical fault based on the experimental data, which provides a preliminary reference for GIS vibration technology research.

Acknowledgments
This work was supported by “Science and Technology Project of State Grid Tianjin Electric Power Company (KJ19-1-19 Analysis of abnormal vibration of GIS in substation and study of its control method)”.

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