GIS vibration fault simulation experiment and analysis

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Abstract. In order to provide some theoretical and technical basis for the vibration test and analysis of GIS, this paper introduces two vibration fault simulation experiments of GIS. One is the simulation experiment of spike discharge, the other is the simulation experiment of flange bolt loosening. It includes both discharge fault and mechanical fault. The experiment shows that the vibration signal can reflect the discharge fault and mechanical fault well, and show different characteristics, which is very instructive for the field application of GIS vibration test.

1. Introduction
GIS (Gas Insulated Switchgear) can seal high-voltage equipment such as bus bar, disconnector and transformer in the pipeline filled with sulfur hexafluoride gas, which is compact and reliable, greatly saving space and significantly improving insulation performance. Therefore, it is widely used in power system. With the increasing number of applications, unavoidable design defects, aging and other problems, the fault diagnosis technology of combined electrical appliances has become an important research field. At present, ultrasonic method, pulse current method and gas decomposition method are several relatively mature GIS fault diagnosis methods, but they are all used to test the discharge fault, and there is no way for the mechanical vibration fault which accounts for the most [1]. In recent years, more and more technicians pay attention to the vibration test and analysis method, which can not only analyze the mechanical vibration fault but also the discharge fault. However, the vibration test and analysis technology started relatively late, lacking of basic experimental data as support. For this reason, this paper introduces two simulation experiments of spike discharge and flange loosening respectively, and introduces the fault characteristics of GIS vibration from two fault types of discharge and mechanical.

2. Experimental platform
In the experiment, 252kV zf-16 type GIS is used as the main body to build the test platform, which is mainly composed of the main body of the test GIS and the multi signal synchronous acquisition system, as shown in figure 1.
Figure 1. Experimental platform

The test GIS is a three-phase box type structure, which is L-shaped as a whole, including test voltage console, booster, voltage divider, protection resistance, coupling capacitance, high-voltage bushing and 252kV GIS cavity. The spike discharge fault model can be set in the experimental cavity marked with circle on the left side of figure 1. The experimental cavity is provided with quartz glass observation window, mounting hole and hand hole. The design of the visible window and mounting hole is convenient for the installation of the fault model and the observation of the test process. The position marked with circle on the right can set the failure model of loose flange bolts between air chambers.

Multi signal synchronous acquisition system consists of two parts: signal sensing and detection device and multi signal synchronous acquisition scheme.

1) Signal sensing and detection device

Sensor: Considering the high frequency of PD vibration in GIS, acceleration sensor is selected in the experiment. The performance parameters are as follows, sensitivity: 100 mV/g±10% (25℃); frequency response: 0.5 ~ 15000Hz (±3dB); maximum amplitude: ±50g.

Detection resistance: The test resistor outputs pulse voltage waveform, and the tuning range of resistance selected in this experiment is 25 ~ 400 pF (filter, preamplifier and peak detector are integrated inside)

Digital partial discharge inspection instrument: In this experiment, digital PD inspection instrument is used to measure the parameters of PD pulse signal. It can measure discharge quantity, discharge times, discharge waveform in power frequency cycle and count discharge phase in real time. The specific test parameters are: sampling frequency: 20MHz; discharge measurement sensitivity: 0.1pC; discharge range: 0.1pC ~ 10000 pC.

Vibration signal acquisition instrument: maximum sampling frequency: 105.5 kHz; input voltage range: ± 40 V; excitation current source: 4 mA.
2) Multi signal synchronous acquisition scheme

In order to quantitatively analyze the relationship between GIS shell vibration and electrical signal, the vibration acceleration signal and GIS voltage current signal are collected simultaneously. The current signal of one power frequency cycle is saved every 5 seconds, and the vibration acceleration signal is saved every 10 seconds. The collection time of vibration signal is set to 2.5 seconds.

3. Spike discharge simulation experiment

3.1. Experimental method

Spike discharge is one of the most common insulation defects in GIS, and the size of discharge model has a great influence on the research results. The size design of the model needs to consider the influence of the structure of the experimental GIS, the requirements of the vibration detection method and other factors. Figure 2 shows the structure of the test chamber. The outer diameter of the test GIS conducting rod is 70 mm, the outer diameter of the shell is 376 mm, and the thickness of the shell is 8mm. The gap between the conducting rod and the inner wall of GIS is 145 mm. In order to prevent the test voltage from being too high, the length of the spike fault model should not be too short [2]. Above all, the length of the spike is set as 60 mm, and the initial discharge voltage is 55.02 kV.

3.2. Data analysis

The vibration signals of GIS shell before and after partial discharge are acquired by the test system, and the abnormal energy information of PD induced vibration spectrum is extracted to study the characteristics of PD induced vibration signals. Figure 3 shows the background vibration noise of the test GIS.

![Figure 2. Test GIS structure size](image)

![Figure 3. Background vibration noise of test GIS: (a) time domain signal, (b) frequency domain signal](image)

It can be seen from figure 3 that the vibration under normal operation of GIS is mainly concentrated in the low-frequency vibration below 500Hz, and the vibration source is electromagnetic vibration under the action of power frequency electromagnetic field and low-order natural frequency of GIS. The noise energy in the frequency band of 1000Hz and above is very small, which is less than
0.35 × 10^{-4} g, g is the acceleration of gravity. Figure 4 shows the vibration spectrum of GIS shell under different discharge levels.

![Vibration spectrum of GIS shell under different discharge levels](image)

**Figure 4.** Vibration spectrum of GIS shell under different discharge levels
(a) 56.3 kV, (b) 62.7 kV, (c) 74.6 kV

It can be seen from figure 4 that spike PD will cause abnormal vibration of GIS shell, and the abnormal vibration spectrum area has been marked red in the figure. It can be seen from the figure that the spike PD can cause high-frequency vibration. According to statistics, the high-frequency vibration energy is mainly concentrated in 1.5 kHz-4.5 kHz, and the energy and frequency range of spike PD induced abnormal vibration increase with the increase of discharge degree, which is a main feature of spike discharge vibration. In order to further obtain the vibration energy characteristics of GIS PD, the abnormal frequency range in the vibration spectrum was enlarged, as shown in figure 5.

![Energy accumulation of spike PD vibration](image)

**Figure 5.** Energy accumulation of spike PD vibration, (a) 56.3 kV, (b) 62.7 kV, (c) 74.6 kV
Figure 5 intercepts the frequency band with high abnormal vibration energy in figure 4. It can be seen from figure 5 that the abnormal vibration energy of spike PD is mainly concentrated in the frequency band of 50Hz frequency doubling, which is obviously different from other factors that cause vibration. Therefore, the energy accumulation phenomenon of 50Hz frequency doubling is another main feature of spike discharge.

4. Simulation experiment of flange bolt loosening

4.1. Experimental method

A large number of gas chambers in GIS are connected by flange bolts. The loosening of flange bolts between gas chambers is a common and easy to simulate mechanical failure. In this experiment, a flange connection in the test platform was selected for bolt loosening to simulate vibration fault, and acceleration vibration sensors were installed on the loose bolt for vibration measurement [3]. Three tightening states were set for the monitored bolts, which were normal, loosening 30% and loosening 60%.

For the above mentioned fault, the test method is to measure the electromagnetic vibration signal directly. In order to maximize the vibration characteristics of bolt looseness, this experiment adopts the great exciting effect of circuit breaker during the operation of the opening to obtain the self-excited vibration characteristics of the loose flange.

4.2. Data analysis

In order to determine the data analysis method, the vibration signal of the flange fastening bolt in the normal state was measured first, and the basic vibration characteristics of the flange bolt in the breaker opening operation were obtained.

![Image](a) Instantaneous time domain energy spectrum, (b) Frequency domain energy spectrum

Figure 6 shows the vibration signal of the flange fastening bolt in the normal state during the opening operation of the circuit breaker. It can be seen from the figure that the vibration energy of flange bolt is mainly concentrated in 0 ~ 0.1s in time and the frequency is mainly concentrated below 5000Hz.

| Serial number | Frequency/Hz          | Serial number | Frequency/Hz          |
|---------------|-----------------------|---------------|-----------------------|
| 1             | 0-1042.50             | 7             | 2560.00-2782.50       |
| 2             | 1042.50-1522.50       | 8             | 2782.50-3050.00       |
| 3             | 1522.50-1880.00       | 9             | 3050.00-3412.50       |
| 4             | 1880.00-2132.50       | 10            | 3412.50-3995.00       |
| 5             | 2132.50-2350.00       | 11            | 3995.00-5392.50       |
| 6             | 2350.00-2560.00       | 12            | 5392.50-8000.00       |

Table 1. Frequency subband
In order to analyze the characteristics of vibration signal in different time and frequency range more conveniently, according to the principle of equal energy, the signal is divided into 12 frequency sub bands and 10 time sub bands. As shown in Table 1 and table 2.

**Table 2. Time subband**

| Serial number | Time/s       | Serial number | Time/s       |
|---------------|--------------|---------------|--------------|
| 1             | 0-0.0146     | 6             | 0.0511-0.0626|
| 2             | 0.0146-0.0211| 7             | 0.0626-0.0773|
| 3             | 0.0211-0.0296| 8             | 0.0773-0.1171|
| 4             | 0.0296-0.0399| 9             | 0.1171-0.1919|
| 5             | 0.0399-0.0511| 10            | 0.1919-0.3500|

Table 1 and table 2 show the frequency subband and time subband of flange fastening bolt looseness according to the principle of energy equal division. According to the division of table 1 and table 2, the time-frequency energy distribution of the flange fastening bolt in the normal and loose state is plotted to get figure 7.

![Figure 7. Time-frequency division of flange fastening bolt under normal and fault conditions](image)

(a) Normal condition, (b) Loosening 30%, (c) Loosening 60%
It can be seen from figure 7 that based on the idea of energy equalization, the energy of each grid in normal state is basically the same, while the energy distribution in the same grid in fault state no longer satisfies the feature of energy equalization. The colors that appear in the same grid in each graph have changed. According to the division of time-frequency subband in figure 7, the excitation experiment of the circuit breaker was carried out, 5 times for each fault state, and the energy of each frequency subband and time subband was extracted, and the specific results are shown in figure 8.

Figure 8. Trend of time-frequency subband energy change under normal and fault of flange fastening bolt, (a) Frequency subband energy variation trend, (b) Time subband energy variation trend

Figure 8 shows the change trend of time-frequency subband energy under the normal and fault of flange fastening bolt. In the figure, black (-□-) indicates the normal state, green (-◊-) indicates the bolt loosening 30%, and red (-Δ-) indicates loosening 60%. It can be seen from figure 8 (a) that when the flange fastening bolt is loose by 30%, the energy from 1500hz to 2800hz will decrease, and the energy of other frequency bands will increase; but when the flange fastening bolt is loose by 60%, the energy of each frequency band will increase. Generally speaking, the energy above 4000Hz increases significantly after bolt loosening, which becomes a significant feature of bolt loosening in frequency domain. It can be seen from figure 8 (b) that when the flange fastening bolt is loose, the vibration shows an increasing trend in the time domain, and the energy increases significantly in a short time (0.05s) when the excitation occurs. This becomes another significant feature of bolt loosening in time domain. The reason for this phenomenon is that when the fastening bolts are loose, the structural connection is no longer firm. Under the excitation of the circuit breaker, the vibration amplitude of the mechanism at the loose part increases.

5. Conclusion
(1) The discharge fault and mechanical fault of GIS will be displayed by vibration signals with different characteristics.
(2) Through the simulation experiment of spike discharge, it is found that when spike discharge occurs, there will be 1.5 kHz-4.5 kHz high-frequency vibration components in the vibration spectrum of GIS, and the peak value of vibration is all times frequency of 50Hz.

(3) According to the experiment of vibration excitation by the loose bolts of the connecting flange of the air chamber, it is found that the loose flange bolts will show a significant increase of the vibration component above 4000Hz in the frequency domain and the amplitude will increase with the increase of the loosening degree in the time domain, and the amplitude will increase significantly in the short time (0.05s) when the excitation occurs.

There are many advantages in the vibration fault test and analysis method of GIS. The vibration sensor is easy to install and has no electrical connection with the equipment. It can analyze both discharge fault and mechanical fault. But this method needs a lot of research and practice as accumulation, simulation experiment is a good method, hope to provide some reference for the readers.

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