Feasibility study of GIS vibration testing and diagnosis method

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Abstract. In this paper, the feasibility of the fault diagnosis method based on the vibration signal in GIS is studied through the experiments of the correlation between the discharge fault and the vibration signal and the propagation characteristics of the vibration signal in GIS. The concept of pulse interval frequency is put forward. According to the experimental data, it is concluded that there is a strong correlation between the interval frequency of GIS discharge pulse and the frequency of vibration signal. At the same time, the vibration signal has regular propagation characteristics when passing through the basin insulator, cavity and T-shaped structure. The above two points strongly support the vibration test method can be used for fault diagnosis of GIS.

1. Introduction

At present, ultrasonic method, pulse current method and gas decomposition method are mature fault diagnosis methods of GIS. They can accurately and sensitively judge whether GIS has discharge fault, which plays a huge role in the safe and stable operation of GIS in power grid. However, with the continuous improvement of environmental protection and safety requirements, power companies began to pay more and more attention to the abnormal performance of GIS in other aspects, such as vibration, noise, etc. The above methods cannot play a role. We can only analyze and diagnose through the vibration test method. Vibration test method has a broad application prospect because of its advantages of convenient operation and no electrical connection with equipment [1]. The above methods cannot play a role. We can only analyze and diagnose through the vibration test method. Vibration test method has a broad application prospect because of its advantages of convenient operation and no electrical connection with equipment. However, the theoretical basis and feasibility of this method are still unknown in the industry. The key to the feasibility of GIS vibration test diagnosis method lies in whether the vibration signal can reflect the discharge fault and whether the fault point can be located by vibration test. In this paper, the relationship between vibration signal and discharge and the propagation characteristics of vibration signal in GIS are tested and analyzed to show the feasibility of vibration test and analysis technology for GIS fault diagnosis.

2. Study on the correlation between PD and vibration signal

2.1. PD pulse interval frequency

GIS spike partial discharge is a gas discharge phenomenon, PD is accompanied by many physical phenomena such as sound, light, heat, vibration, chemical decomposition and so on. The physical
phenomena associated with PD increase with the increase of discharge degree, and the pulse current can realize the quantitative characterization of discharge degree. In addition, PD exists in the form of discharge pulse [2]. The formation, development and weakening of each pulse are accompanied by the formation, development and weakening of other physical phenomena. Figure 1 shows the pulse current waveform under three test voltages.

![PD pulse waveform](image)

**Figure 1.** PD pulse waveform (a) 56.3 kV; (b) 62.7 kV; (c) 74.6 kV

It can be seen from figure 1 that PD exists in the form of pulse, and the discharge capacity increases with the increase of test voltage. At present, the national standard GB/T 7354-2003 and the International Standard IEC 60270 set pulse repetition rate (PRR) and pulse repetition frequency (PRF), in which the pulse repetition rate is the ratio of the total number of pulses recorded in the selected time interval to the selected time interval, and the pulse repetition frequency is the number of PD discharge pulses per second [3]. In this paper, a new PD characteristic parameter, pulse interval frequency (PIF), is proposed. As the name implies, for a discharge cycle, if the number of discharge pulses is more than 2, the reciprocal of the interval time of any two adjacent pulses is the pulse interval frequency. From the above definition, it can be seen that the interval frequency of pulse gives the frequency between any two adjacent pulses, which belongs to the method of discharge characteristic analysis in micro angle. The interval time TP of two adjacent discharge pulses is identified in figure 1 (a). According to the definition of interval frequency, the interval frequency PIF is

\[
PIF = \frac{1}{T_P}
\]  

(1)

Based on the connotation of the pulse interval frequency, the average pulse interval frequency (APIF) is defined, that is, the average value of the interval frequency between any two adjacent pulses in the selected time. The average pulse interval frequency APIF can be calculated as

\[
APIF = \frac{1}{n-1} \sum_{i=1}^{n-1} PIF_i
\]  

(2)
In the formula, $n$ is the number of pulses.

2.2. **PD vibration frequency mechanism**

PD discharges in the form of pulses, each of which is accompanied by a violent heating, luminescence, chemical decomposition and other physical processes. Each discharge pulse will form an exciting wave, which will generate vibration pulse and spread to the shell through the conductor and SF6 gas, thus causing the vibration of GIS shell. Considering that PD is a physical phenomenon with random characteristics, experiments were carried out to obtain the relationship between discharge characteristics and vibration characteristics.

In order to obtain the data of different voltage levels, the method of simulating the spike discharge phenomenon by sticking wires on the surface of insulator in GIS was adopted, and three working voltages were set up, which were 56.3 kV, 62.7 kV and 74.6 kV, respectively. The probability density distribution at 1000 Hz-4000 Hz is shown in figure 2 and figure 3.

![Figure 2](image_url) **Figure 2.** Probability density distribution of PIF, (a) 56.3 kV; (b) 62.7 kV; (c) 74.6 kV
By comparing figure 2 and figure 3, it can be seen that the vibration frequency induced by PD has a strong correspondence with the distribution of pulse interval frequency. Therefore, it can be judged that PD stimulates the vibration of GIS structure in the form of discharge pulses, that is, a vibration pulse will be generated with the occurrence of each pulse, and the GIS PD vibration is the result of the excitation of discharge pulses. This conclusion well proves the correlation between the vibration signal and the discharge fault, and also proves the feasibility of using the vibration signal to test and analyze the GIS discharge vibration fault.

3. Analysis on the propagation characteristics of vibration signal in GIS
In the previous section, we found that there is a strong correlation between the frequency of GIS vibration characteristics and discharge characteristics through the experimental data, which is a strong support for using vibration method to analyze and diagnose GIS faults. But this is not enough. Because the structure of GIS is very complex, we still need to understand the propagation characteristics of vibration signal in its structure. If the vibration signal is very disordered and irregular, then the method of vibration analysis cannot locate the fault point, nor play a sufficient role.

3.1. Vibration signal propagation experiment
In order to understand the propagation characteristics of vibration signals in GIS, simulation experiments are also needed to verify. As shown in figure 4, a section of single cylinder single GIS is used as the experimental platform, which can carry out three types of vibration propagation characteristics experiments on both sides of basin insulator, linear structure and T-structure. The experimental method uses force hammer to excite vibration and sensor to pick up vibration, that is to say, using force hammer equipped with sensors to knock at different positions to generate vibration. At the same time, sensors are installed at different positions to measure vibration signals, and the force hammer signals and sensor signals at different positions are compared and analyzed to obtain the transmission characteristics of vibration.

The arrangement of experimental vibration measuring points is shown in figure 4, in which the vibration sensor is attached to the fixed nut and the sensor in the same direction is kept in the same straight line as far as possible.
In order to comprehensively study the propagation characteristics of vibration signals in GIS, 10 striking points of vibrating hammer were selected, among which A-F striking point was located on the outer wall of GIS, "conducting rod" striking point was set at the end of conducting rod in the experimental cavity, during the striking process, "horizontal" represents the striking direction along the horizontal direction, "vertical" represents the striking direction perpendicular to the ground, that was, vertical direction, and each striking point was knocked three times. Each position sensor measures the vibration signal synchronously. During the experiment, the equipment was in power off state.

3.2. Study on linear propagation of vibration signal
By using impact hammer to generate impulse excitation at the excitation point, and using sensors to collect vibration signals at each measuring point, the collected vibration signals were subject to fast Fourier transform. By comparing the spectrum characteristics of vibration signals, the linear propagation of vibration signals in GIS was studied. The following is the spectrum comparison diagram of vibration signal propagating on both sides of basin insulator and GIS cavity.

Compared with the vibration signal spectrum on both sides of the basin insulator, the shaded part in the figure is the frequency band with larger frequency deviation.
Figure 5. Frequency spectrum comparison of vibration signal
(a) At both ends of the basin insulator; (b) At both ends of GIS cavity

From the spectrum of vibration signals on both sides of the basin insulator, it can be seen that the main frequency components of the vibration signal hardly change after passing through the basin insulator, and there will be slight distortion only above 2000Hz, so it can be approximately considered that the vibration signal is transmitted linearly through the basin insulator. After GIS cavity propagation,
the frequency component of vibration signal changes to a large extent, and the longer the propagation distance, the more serious the distortion of vibration signal.

3.3. Study on vibration energy propagation

(1) Energy analysis of vibration signals on both sides of the basin insulator

The energy of vibration signal is expressed by the sum of squares of vibration amplitude.

Table 1. Vibration signal energy of both sides of the basin (1)

| Percussion point | 1#     | 2#     | Attenuation percentage |
|------------------|--------|--------|------------------------|
| F-vertical       | 105.9  | 73.83  | 30.28%                 |
| A-vertical       | 608.27 | 378.64 | 37.75%                 |
| 2#-level         | 3024.7 | 1606.7 | 46.88%                 |
| F-level          | 13.61  | 9.31   | 31.59%                 |
| D-vertical       | 69.71  | 47.46  | 31.91%                 |
| E-vertical       | 54.31  | 39.38  | 27.49%                 |
| F-level          | 13.61  | 9.31   | 31.59%                 |
| Conducting rod -vertical | 37.74  | 24.94  | 33.91%                 |
| B-vertical       | 105.87 | 62.9   | 40.58%                 |

Table 2. Vibration signal energy of both sides of the basin (2)

| Percussion point | 3#    | 4#    | Attenuation percentage |
|------------------|-------|-------|------------------------|
| F-vertical       | 281.62| 219.7 | 21.98%                 |
| A-vertical       | 147.15| 101.73| 30.86%                 |
| 2#-vertical     | 125.51| 80.63 | 35.75%                 |
| F-level          | 37.81 | 27.49 | 27.29%                 |
| D-vertical       | 62.54 | 35.28 | 43.58%                 |
| E-vertical       | 249.43| 151.6 | 39.22%                 |
| F-level          | 108.7 | 76.24 | 29.86%                 |
| Conducting rod -vertical | 23.18 | 14.86 | 35.89%                 |
| B-vertical       | 5.2   | 8.54  | 8.85%                  |

Table 3. Vibration signal energy of both sides of the basin (3)

| Percussion point | 5#    | 6#    | Attenuation percentage |
|------------------|-------|-------|------------------------|
| F-vertical       | 1533.1| 1144.6| 25.34%                 |
| A-vertical       | 59.82 | 47.15 | 21.18%                 |
| 2#-vertical     | 55.76 | 40.74 | 26.93%                 |
| F-level          | 108.7 | 76.24 | 29.86%                 |
| Conducting rod -vertical | 5.2   | 4.86  | 6.53%                  |
| B-vertical       | 9.37  | 8.54  | 8.85%                  |

Table 4. Vibration signal energy of both sides of the basin (4)

| Percussion point | 7#    | 8#    | Attenuation percentage |
|------------------|-------|-------|------------------------|
| A (internal)-vertical | 4.82  | 6.04  | 20.19%                 |
| B-vertical       | 6.87  | 8.01  | 14.23%                 |
It can be seen from the energy of the vibration signals on both sides of the basin that the vibration signal on the convex side of the basin insulator is always stronger than that on the concave side. This means that when the vibration signal propagates from the concave side to the convex side, the vibration signal will be amplified, and the amplification percentage is generally no more than 50%; when the vibration signal propagates from the convex side to the concave side, the attenuation percentage will be about 2% - 80%. From table 1 to table 5, it can be seen that the attenuation degree of vibration signal is positively correlated with the total signal energy. In other words, when the energy of vibration signal is larger, the attenuation degree of vibration signal is larger. The main reason for this phenomenon is that when the vibration is stronger, the larger the vibration amplitude is, the farther the particle is away from the balance position, so that the friction path of the vibration on both sides of the balance position is longer, and the stronger the vibration signal is, the more serious the attenuation is.

(2) Energy attenuation of linear vibration

Table 5. Vibration signal energy of both sides of the basin (5)

| Percussion point | 9#   | 10#  | Attenuation percentage |
|------------------|------|------|------------------------|
| D-vertical       | 310.29 | 614.05 | 49.46%                 |
| E-vertical       | 70.44  | 113.02 | 37.67%                 |
| I0#-vertical     | 4352.3 | 15766 | 72.39%                 |
| D-level          | 117.64 | 258.1  | 54.42%                 |

Table 6. Signal energy of vibration on both sides of single section cavity in GIS (1)

| Percussion point | 2#   | 3#   | Attenuation percentage |
|------------------|------|------|------------------------|
| F-vertical       | 73.83 | 281.62 | 73.78%                 |
| A-vertical       | 88.16 | 31.09 | 64.73%                 |
| 2#-vertical     | 942.48 | 66.42 | 92.95%                 |

Table 7. Signal energy of vibration on both sides of single section cavity in GIS (2)

| Percussion point | 4#   | 5#   | Attenuation percentage |
|------------------|------|------|------------------------|
| F-vertical       | 219.7 | 1533.1 | 85.66%                 |
| A-vertical       | 27.02 | 11.51 | 57.40%                 |
| 2#-vertical     | 47.02 | 29.66 | 36.92%                 |

When the vibration signal propagates along the straight line in the GIS cavity, it will attenuate to a large extent. In the case of equal distance, when the vibration signal energy is small, the attenuation degree will decrease, that is to say, the attenuation rate of the vibration signal propagating in the GIS cavity is positively related to the vibration signal energy, which is consistent with the propagation characteristics of the vibration signal in the basin.

(3) Vibration signal propagates along T-tube

Table 8. Energy transmission of vibration signal of GIS-T structure

| Percussion point | 2#   | 3#   | 9#   | Attenuation percentage | 2#-9# | 3#-9# | 2#-3# |
|------------------|------|------|------|------------------------|-------|-------|-------|
| D-vertical       | 49.93 | 102.92 | 431.11 | 88.41% | 76.12% | /     |
| E-vertical       | 30.05 | 170.77 | 49.28  | /       | 71.14% | 82.40% |
| A-vertical       | 74.94 | 50.19  | 66.89  | 10.74% | /       | 33.02% |
| I0#-vertical     | 65.21 | 173.32 | 1994.5 | 96.73% | 91.31% | /     |
| D-level          | 13.51 | 14.94  | 72.31  | 81.31% | 79.33% | /     |
The vibration signal propagates in T-type structure, and its propagation path is more than that in straight line. From table 8, it can be seen that the attenuation degree of vibration signal in T-type structure is more serious, generally reaching more than 70%, and the distribution of vibration energy in T-type structure also has a certain symmetry according to the symmetry of structure, that is, when the vibration signal propagates from longitudinal to transverse of T-type structure, the transverse parts on both sides the vibrational energy of the fraction is approximately equal.

The above test data shows that the propagation of vibration signal in various structures of GIS, such as basin insulator, cavity and T-shaped structure, has certain regularity. If we study this regularity enough, it can guide us to locate and identify the fault point very well. Therefore, it can be said that the propagation characteristics of vibration signal also support the feasibility of vibration test and analysis method.

4. Conclusion

(1) The concept of pulse interval frequency is put forward. The relationship between the pulse interval frequency of GIS spike PD and the frequency of its vibration signal is obtained by experiments. The spectrum of the two under different voltage levels is obtained. It is found that they have very strong correlation, which shows that the partial discharge can be obtained by analyzing the vibration signal.

(2) The propagation characteristics of vibration signals in different structures of GIS were obtained through the knock pick-up experiment. It was found that the vibration signal on the convex side of the basin insulator is always stronger than that on the concave side. This means that when the vibration signal propagates from the concave side to the convex side, it will be amplified; when the vibration signal propagates from the convex side to the concave side, it will be attenuated to a large extent. When the vibration signal propagates along the straight line in the GIS cavity, it will attenuate to a large extent, and the attenuation rate is positively related to the vibration signal energy. The attenuation degree of vibration signal in T-type structure is more serious, and the vibration energy distribution in T-type structure also has certain symmetry according to the symmetry of structure.

(3) The characteristic relationship between GIS discharge and vibration signal and the propagation characteristics of vibration signal fully show that the vibration signal can well represent the discharge and signal propagation, which not only shows that the vibration method has a strong feasibility for GIS fault analysis and diagnosis, but also provides a strong basis for the effective application of this method.

This paper demonstrates the function and significance of vibration test method in GIS fault diagnosis from two aspects of signal correlation and signal propagation characteristics. However, there are many other types of fault in GIS, and the structure of GIS is also different. If we want to realize the comprehensive and effective application of vibration analysis method, we need to do a lot of work, such as studying the vibration characteristics of various types of fault and the vibration signals in GIS The propagation characteristics between building structures.

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