Bolt looseness fault diagnosis of GIS based on vibration signal amplitude

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Abstract. The mechanical fault in gas insulated switchgear (GIS) will cause abnormal vibration of equipment. Based on the vibration signal generated by abnormal vibration, a method for mechanical fault diagnosis of GIS is presented to achieve on-line mechanical fault diagnosis. Firstly, for the typical mechanical faults of GIS, the vibration mechanical characteristics are analyzed in depth. Secondly, based on the amplitude ratio characteristics of different points in the system, which is only related to the natural frequency and the main vibration mode, a signal processing method taken amplitude ratio as a feature is presented. Finally, on a simulation experiment platform, different test points are set up to extract the vibration signal, the composite matrix with the amplitude ratio of vibration signal as a feature is constructed and the feature is input into support vector machine to realize the mechanical fault diagnosis of GIS. The experimental results show that, the feature can be recognized effectively and accurately by using the typical fault types set.

1. Introduction
Gas insulated switchgear (GIS) is one of the important equipment in power system. GIS mechanical failure refers to defects such as guide rod bending, abnormal contact contacting, fasteners loosing, and other defects that occur in GIS [1]. In the presence of mechanical fault of GIS, the abnormal vibration of the equipment will occur under the action of the ampere force generated by the alternating current in the conductor. The abnormal vibration of the GIS will affect the firmness of the grounding point of the shell, result in loosening the fastening bolts of the body and even cause more serious consequences [2]. In order to realize the diagnosis of GIS mechanical faults, it is necessary to deeply analyze the mechanical properties of GIS, and then use the characteristic information of vibration signals under different faults [3][4][5]. At present, researchers have carried out a lot of research work on the GIS mechanical fault characteristics and the vibration signal diagnosis [6][7][8].

This paper proposes a method of GIS mechanical fault diagnosis based on the vibration signal amplitude. Firstly, the vibrational mechanics of the GIS shell is analyzed theoretically. The ratio of signal amplitude at any two points of the GIS shell under different mechanical states is obtained. The ratio of the amplitude is only related to the principal mode and natural frequency of the beam. Secondly, a simulation experiment platform is built to set up different types of mechanical faults. The sensors are used to obtain the vibration signals of GIS under different faults, and the ratio of the amplitude under different vibration signals is analyzed and diagnosed. Finally, the ratio of the amplitudes of different test points is used as the feature quantity, and the support vector machine
(SVM) is input to implement the GIS fault diagnosis. The diagnosis results show that this method can effectively diagnose the mechanical faults of GIS and can be used as an effective method of GIS mechanical fault diagnosis.

2. Fault characteristics

The mechanical failure of GIS equipment is mainly due to the unbalanced internal force of the equipment. When the GIS is in a mechanical failure, it is affected to generate abnormal vibrations by the electric power. Under different mechanical conditions, the internal force of the GIS is different, which is reflected in the vibration signal of the casing. For the looseness of the fasteners in the mechanical failure, the vibration characteristics are studied and the vibration signals are taken as reference.

When analyzing vibration characteristics, the shell of GIS is approximately equivalent to the beam [9]. For a beam with a unit mass length ρ and a bending stiffness EI, the lateral bending vibration equation for the deflection \( y(x,t) \) at the x-section under free vibration is:

\[
EI \frac{d^4 y}{d^4 x} + \rho \frac{d^2 y}{d^2 x} = 0
\]  

(1)

The solution is:

\[
y(x,t) = Y(x)T(x)
\]  

(2)

Because \( T(x) \) is a harmonic function, the vibration displacement of the beam can be expressed as

\[
y(x,t) = Y(x)\sin(\omega t + \alpha)
\]  

(3)

Where \( Y(x) \) is the principal mode function of the beam’s transverse bending vibration, i.e. the displacement amplitude equation. \( \omega \) is the natural frequency of the system.

The vibration of the GIS casing under the Ampere force is essentially the forced vibration of the system under the action of the external excitation force \( p(x,t) \). Similar to the free vibration situation, the dynamic displacement of the beam under forced vibration can be expressed as [10]:

\[
y(x,t) = \sum_{i=1}^{\infty} Y_i(x)q_i(t)
\]  

(4)

Where \( Y_i \) is the i-th principal mode shape function of the beam, and \( q_i \) is the i-th principal coordinate (weight function). At any time of vibration, the displacement ratio of each particle remains unchanged, i.e. the shape of vibration unchanged. This vibration form is called vibration mode.

Using the orthogonal relationship of the principal mode function to the mass and stiffness, the equation of motion is obtained as:

\[
M_i \ddot{q}_i(t) + \sum_{i=1}^{\infty} (c_i Y_i'(x) + c Y_i(x)) \dot{q}_i(t) + M_i \omega_i^2 q_i(t) = p_i^*(t)
\]  

(5)

Among them, \( c_i \) is the internal damping coefficient of the strain rate, \( c \) is the external coefficient of viscous resistance, \( M_i \) is the main mass, \( p_i^* \) is the generalized force, and \( \omega_i \) is i-th inherent frequency. The main mass and the generalized force in the formula are:

\[
M_i = \rho \int_0^l (Y_i(x))^2 dx
\]  

(6)

\[
p_i^*(t) = \int_0^l Y_i(x)p(x,t) dx
\]  

(7)

Using equation (5), the weight function \( q_i(t) \) can be obtained as:

\[
q_i(t) = \frac{\int_0^l Y_i(x)y(x,0)dx}{M_i}
\]  

(8)

In particular, when the external excitation force is a uniformly distributed harmonic force \( P \sin \theta t \), where \( \theta \) is the frequency of the excitation force, the weight function \( q_i \) without considering the damping can be expressed as:
\[ q_i(t) = \frac{P \sin \theta t}{\rho} \int_0^l Y_i(x)dx \]  
\[ q_i(t) = \frac{P \sin \theta t}{\rho} \int_0^l Y_i(x)(\omega_i^2 - \theta^2)dx \]  
\[ y(x, t) = \frac{P \sin \theta t}{\rho} \sum_{i=1}^{\infty} \int_0^l Y_i(x)(\omega_i^2 - \theta^2)dx \]  
\[ y(x, t) = \frac{P \sin \theta t}{\rho} \sum_{i=1}^{\infty} \int_0^l Y_i(x)(\omega_i^2 - \theta^2)dx \]  
\[ \frac{A(x_1)}{A(x_2)} = \frac{\sum_{i=1}^{\infty} \int_0^l Y_i(x)(\omega_i^2 - \theta^2)dx}{\sum_{i=1}^{\infty} \int_0^l Y_i(x)(\omega_i^2 - \theta^2)dx} \]  

The resulting vibrational displacement can be:

\[ y(x, t) = \frac{P \sin \theta t}{\rho} \sum_{i=1}^{\infty} \int_0^l Y_i(x)(\omega_i^2 - \theta^2)dx \]  

The ratio of amplitude \( A(x_1) \) to \( A(x_2) \) of any two points on the beam is:

\[ \frac{A(x_1)}{A(x_2)} = \frac{\sum_{i=1}^{\infty} \int_0^l Y_i(x)(\omega_i^2 - \theta^2)dx}{\sum_{i=1}^{\infty} \int_0^l Y_i(x)(\omega_i^2 - \theta^2)dx} \]

From equation (11), we can see that the ratio of the amplitude between any two points on the beam is only related to the principal mode shape and natural frequency of the beam, and for a certain system, the principal mode shape and natural frequency are only related to the system. Therefore, the ratio of the amplitudes between the two points can reflect the mechanical state of the beam system and can be used to characterize the fault information of the GIS.

3. Vibration signal acquisition

3.1. experiment platform

The GIS is filled with airtight gas and it is inconvenient to set up faults. Therefore, a certain proportion of GIS is reduced, GIS models are created, and a simulation experiment platform is built. The experimental platform consists of an experimental device and an acquisition system. The GIS model consists of a shell, a conductor, a contact pedestal, a shield, and a flange plate. When making the model, it is ensured that the natural frequency is approximately constant and that the vibration amplitude of the enclosure roughly matches the actual situation. The ratio of the thickness of the GIS shell is very small, and the internal force of the shell is distributed evenly along the thickness direction. Internal torque does not occur. When the natural frequency is calculated, it can be approximated as the beam. The internal conductor is small in size and in stiffness. The support point is a rigid support. Its natural frequency is close to the first-order natural frequency. The model produced is shown in figure 1. The GIS model has a length of 1.4m and a diameter of 0.2m. At the same time, a three-phase conduction current of 1000 A is generated by using a step-down transformer and a small resistance power resistor in series. There is a certain error between the experimental device and the actual vibration of the GIS, but it can still reflect the vibration characteristics of the GIS under different mechanical faults. The acquisition system consists of a sensor and a capture card. The 622B01 high-performance accelerometer with 50g range, 100mv/g voltage sensitivity and 1-15kHz frequency range from the United States PCB company and the NI-4472B data acquisition card from National Instruments are used.

![Figure 1. GIS model diagram.](image)
In order to collect vibration signals, accelerometers should be placed on the GIS shell where the vibration signal is obvious and accelerometers are easy to install. After many experiments, the vibration signals collected by the four test point sensors are sufficiently abundant. The location of the test points is shown in figure 2: Test Point 1 and Test Point 2 are on the side of the shell, while test point 3 and test point 4 are on the top of the shell.

![Sensor positions](image)

**Figure 2.** Sensor positions.

**Figure 3.** The vibration signal of test point 1 in different working conditions.

### 3.2. Vibration signal

Using the experimental platform, three common operating conditions of GIS are simulated artificially, that is normal operating conditions, loosening of grounding bolts, and looseness of shields, and 40 sets of vibration signals are collected. After the experimental platform is powered on, the GIS shell generates a vibration signal, and the signal is collected to obtain the vibration signal of each test point.

Taking a preliminary analysis of the vibration signal of test point 1 under various working conditions. as shown in figure 3, the vibration signal on the GIS shell is roughly a periodic signal with a frequency of 100 Hz. The electromotive force acts on the shell, with value $F = \frac{\sqrt{3} \mu_0 I_1 I_2}{4 \pi d}$, where the electric current is 50Hz alternating current, the corresponding force should be 100Hz, the vibration signal accords with the theory. Comparing the vibration signals collected in each operating condition in the figure 3, it is found that each signal has different amplitude and phase. The vibration of each point on the GIS shell is not only related to mechanical failure factors, but also affected by the size of the electromotive force. In the GIS operating state, the current passing between the conductors fluctuates with the change of the power condition of the grid, resulting in the amplitude of the vibration signal also changing. And in the running state of the GIS, the signals are all stable periodic signals, and due to the delay characteristic of propagation, phase shift of signal phase is detected. The existence of above problems makes many signal processing methods not meet the needs of GIS diagnosis. The GIS vibration signal analysis with ratio of amplitude is independent of the size of the electromotive force, and only need to read certain signal amplitude, unaffected by the start and end of the signal. This method can effectively solve the above problems in GIS vibration signal. Therefore, the ratio of the amplitudes between two points on the GIS housing is used as a feature for the diagnosis of mechanical failures.

### 4. Diagnosis example analysis

#### 4.1. Feature Extraction and Analysis

To analyze the collected signal, the signal amplitude from test point 1 to test point 4 is extracted and divided into A1, A2, A3, A4. Then A2/A1, A3/A2, A4/A3 and A4/A1 are calculated to be features.
The relationship between the fault samples and the eigenvalues can be obtained, as shown in figure 4-7. The abscissa is the working condition sample number, followed by the normal operating conditions, the grounding bolt loosening fault and the shielding cover loosening fault, and the vertical axis is the ratio of the values of the vibration amplitude.

![Figure 4](image1.png) ![Figure 5](image2.png)  
**Figure 4.** The amplitude ratio of test points 1 and 2 in different working conditions.  
**Figure 5.** The amplitude ratio of test points 2 and 3 in different working conditions.

As can be seen in figure 4, the amplitude ratios of A2 and A1 are all close to 1 under all operating conditions. The difference between the operating conditions under this condition is not as obvious as its own dispersion, and it is impossible to distinguish between different operating conditions. Both Test Point 1 and Test 2 are test points on the side of the GIS. Loosening of the grounding bolts and loosening of the shielding cover have little effect on loosening of fasteners. In the normal operating condition and grounding bolt loosening fault in figure 5, the value of A3/A2 is below 1.5, and the value under the looseness of the shield is between 1.5 and 3. Although the value of this characteristic under various working conditions, Due to the accidental nature of the vibration signal and noise interference, all values are scattered, but there is still a certain degree of difference and the looseness of the shield can be clearly distinguished. Both test point 2 and test point 3 are test points at the midpoint of the housing. Loosening of the shield will cause vibrations at the top of the housing to increase, resulting in an increase in the amplitude of test 3 at the top of the middle.

![Figure 6](image3.png) ![Figure 7](image4.png)  
**Figure 6.** The amplitude ratio of test points 3 and 4 in different working conditions.  
**Figure 7.** The amplitude ratio of test points 1 and 4 in different working conditions.

In figure 6, the normal operating conditions and the value of the shielding cover loosening fault are all about 1 while the value under the loosening bolt condition is obviously different. Above 2 or above, the A4/A3 can clearly distinguish the loose bolt failure. The test point 3 and the test point 4 are
different points on the top of the shell. Loosening of the grounding bolt makes the amplitude of the test point 4 near the loose point increase. In the normal working condition of figure 7, the value is 1 while the bolt is loosened and the shield is loosened. The values are all above 1.5, normal operating conditions and fault conditions are more obvious. Both the grounding bolt and the shield are close to test point 1 and test point 4. Whether the grounding bolt is loose or the shield is loose, the vibration near the top of the point will be strengthened, resulting in an increase in the amplitude of test point 4.

Through the analysis of the eigenvalues under the above different operating conditions, the amplitude ratios $A_3/A_2$, $A_4/A_3$, and $A_4/A_1$ as characteristics can effectively distinguish the GIS normal working conditions, grounding bolts loosen the fault and loose the shield. Therefore, based on the ratio of the amplitude of different points can effectively extract GIS fault information.

4.2. Fault classification

The characteristics of the vibration signal input classifier above are classified. Support vector machine (SVM) is a common classifier, which solves practical problems such as small sample, nonlinear and high-dimensional pattern recognition, and has the advantages of complete theory, strong adaptability, global optimization, training time, and generalization performance [11][12], suitable for GIS fault diagnosis. The basic idea is shown in figure 8.

![Figure 8. Support vector machine diagram.](image)

In fault diagnosis, the core idea of state classification using SVM is to transform nonlinear problems in low-latitude space into linear problems in high-latitude space through kernel functions. This paper uses the "one-to-one" (OAO) classification algorithm. After the feature quantity is imported into the support vector machine, the fault is classified, normal operating conditions and fault conditions are distinguished in turn, the loosening of the grounding bolt and the shielding cover are loosened, and the classification process is shown in figure 9.

Select 25 normal samples of GIS normal working conditions, grounding bolt loosening fault and shield loosening fault to form a training sample set, establish a vibration amplitude ratio SVM fault diagnosis model for sample training, and use another 15 groups of samples for testing. The results obtained are as follows: Table 1 shows.

| Condition type                | Training samples | Measure samples | accuracy (%) | Average accuracy (%) |
|------------------------------|------------------|-----------------|--------------|----------------------|
| Normal conditions            | 25               | 15              | 100          |                      |
| Grounding bolt loosening     | 25               | 15              | 100          | 100                  |
| Shield loosening             | 25               | 15              | 100          |                      |
According to table 1, the support vector machine can use the characteristic quantity of the ratio of the amplitude to complete the normal operation of the GIS, the grounding bolt loosening fault, and the shielding cover looseness fault diagnosis. The accuracy of the three types of diagnosis is close to 100%. The ratio of amplitudes can be used as a feature to diagnose GIS mechanical faults.

5. Conclusions
Based on the GIS vibration characteristics, this paper presents a method to diagnose mechanical faults. The vibration characteristics of GIS under different mechanical conditions are analyzed in depth. The experiment is conducted to simulate the mechanical failure and extract the ratio of the amplitude of each point of the shell as a feature for case diagnosis. The effectiveness of the method is verified, and the conclusions are as follows:

(1) The mechanical state of the GIS affects the natural frequency and the main vibration mode of the casing, so the amplitude ratio between the two points on the casing is different. This feature can be used for GIS mechanical fault diagnosis.

(2) The method using amplitude ratio to analyze the vibration signal of GIS does not depend on the start-end points and the absolute amplitude of the signal. It is applicable to the on-line mechanical fault diagnosis of GIS under operating condition.

(3) For some common conditions of GIS, that is normal operating conditions, grounding bolt looseness fault and shielding case looseness failure, the experimental results show its excellent results of fault diagnosis.

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References
[1] Kai L, Honghua X, Binbin C, Yangliu C and Hongzhong M 2007 Electrical measurement and instrumentation Study on the vibration mechanism and natural frequency of GIS 54(3) 14-18
[2] Yangliu C, Hongzhong M, Taoyun W, Nin J, Kai L, Binbin C, Chunlin W and Honghua X 2015 High Voltage Apparatus Fault analysis of GIS based on fault tree theory 51(07) 125-129
[3] Jiali Q, Li S, Weidong L, Honghai Z, Xiongfei X and Feiyin S 1990 High Voltage Apparatus Vibration phenomena and detection of the shell of GIS 6 3-9
[4] Bihua G and Hanhua Z 1989 Power system technology detection of internal latent faults by using the frequency characteristic of typical vibration of GIS shell. 2 44-50
[5] Yalin Z and Jiali Q 1989 High Voltage Apparatus Experimental study on shell vibration caused by internal partial discharge in GIS 4 13-16
[6] Zhe Y, Qianran Z, Yang G and Biao C 2015 ShangDong Industrial Technology Review of GIS mechanical fault vibration detection 17 261-263
[7] Linyuan W and Di B 2017 ShangDong Industrial Technology Study on the characteristics of the mechanical vibration signal of GIS noise 21 171
[8] Tianle X, Hongzhong M, Kai C, Chunning W and Kai L 2013 Electric Power Fault diagnosis of GIS equipment based on HHT method of vibration signal 46(03) 39-42
[9] Ruitang Y 2001 Hua Tong Technology Analysis of GIS vibration 2 11-14
[10] Guanmo X 2011 Vibration mechanics (Beijing)
[11] Xu C, Yonggang G and Wenpeng Z 2005 Transactions of China electro technical society Diagnosis method on the mechanical failure of high voltage circuit breakers based on factor analysis and SVM 25(15) 26-32
[12] Laijun S, Xiaoguang H and Yanchao J 2006 Transactions of China electro technical society Mechanical fault classification of high voltage circuit breakers based on Support Vector Machine 21(8) 53-58