Analysis and application of GIS vibration principle in power system

Bin Qu\textsuperscript{1,1}, Li Zhang\textsuperscript{1}, Qiong Fang\textsuperscript{2}, Rong Chen\textsuperscript{1}, Bin Han\textsuperscript{1}, Xiaopeng Wang\textsuperscript{4}, YanHua Wang\textsuperscript{3}

\textsuperscript{1}State Grid Tianjin Electric Power Technology Institute, Tianjin, China
\textsuperscript{2}State Grid Tianjin Electric Power Company, Tianjin, China
\textsuperscript{3}State Grid Tianjin Chengdong Electric Power Supply Company, Tianjin, China
\textsuperscript{4}State Grid Tianjin Electric Power Overhaul Company, Tianjin, China

*Corresponding author e-mail: dajiangu188@126.com

Abstract. Firstly, the basic principle and characteristics of GIS vibration are analyzed and studied. It is pointed out that electromagnetic force and magnetostriction are two basic forms of GIS vibration, and both of them take 100Hz as the characteristic frequency. Then through the experiment, it is found that the frequency doubling characteristics of 200Hz and 300Hz can be excited by the loose mechanical fault. These conclusions provide an important basis for the field vibration test of GIS. Finally, a successful case of vibration test and analysis is described in detail, and the basic methods of measuring point arrangement and spectrum analysis are introduced.

1. Introduction
Gas insulated switchgear is called GIS for short. It is widely used in power system because of its strong systematization, high integration, small floor area and good reliability. However, with a large number of applications of GIS, its failure has become a problem that could not be ignored. According to statistics, mechanical faults account for the largest proportion of all kinds of faults in GIS, reaching about 40% [1]. The traditional methods for GIS fault testing, such as ultrasonic method, pulse current method, gas decomposition method, are all aimed at the discharge fault, so it is impossible to test and analyze the mechanical fault early. GIS mechanical faults are often manifested in the form of vibration. Therefore, in recent years, GIS vibration fault test and analysis methods have been paid more and more attention. In order to carry out effective vibration test and analysis, it is necessary to understand the vibration mechanism and vibration characteristics of GIS. In this paper, the basic vibration characteristics of GIS are obtained by simulation calculation and experiment, and the test and analysis process of a 220kV GIS with abnormal vibration is introduced.

2. Vibration mechanism and characteristic analysis of GIS
Electromagnetic vibration is the main vibration source in GIS operation state, and the root cause of electromagnetic vibration in GIS is electromagnetic induction phenomenon. According to different mechanism, electromagnetic vibration of GIS can be divided into two types: Ampere force vibration and magnetostrictive vibration [2]. If the shell material of GIS is ferromagnetic, such as iron and stainless steel, the alternating magnetic field will cause magnetostrictive vibration after passing
through the ferromagnetic material; however, if the shell of GIS is composed of aluminum or non-
domain steel, the electromagnetic vibration of GIS is only the vibration excited by Ampere force.

2.1. Analysis of vibration characteristics of electromagnetic force
The shell of GIS is designed as a cylinder structure, so that the electric field in the gas chamber of GIS
can be evenly distributed. For the three-phase split GIS, there is only a single conducting pole in each
gas chamber, which will generate induced current in the shell; for the three-phase community GIS,
although the conducting poles are symmetrically distributed, the difference between the geometric size
and the shell size is not big, so the induced current will still be generated in the shell. In this paper,
three-phase split GIS is taken as an example to analyze the electromagnetic force on the shell. Using
the idea of micro element, a certain diameter of GIS cylindrical shell is selected to make a section
along the axial direction, and the section is shown in Figure 1. When the alternating current flows
through the conducting rod, the induction current will flow through the upper and lower metal
rectangular blocks in the section of Figure 1. Because the upper and lower two rectangular blocks are
complete metal units, the induction current in the metal unit appears in the form of eddy current [3].
On the premise of not affecting the accuracy of the analysis, the paper simplifies the analysis and only
considers the induction current in the upper and lower edges.

Set conductor current to \( i_0 = I_0 \cos(\omega t) \), \( \omega \) is the angular frequency of the corresponding power
frequency, \( R \) is the outer diameter of the GIS cylindrical shell, \( r \) is the inner diameter of the GIS
cylindrical shell, \( i \) is the induced current of the shell (as shown in Figure 1), \( R_{eq} \) is the equivalent
resistance of the current circuit, \( \mu_0 \) is the vacuum permeability, \( \mu_r \) is the relative permeability.

Due to the great difference between the thickness of GIS shell and the radius of shell, GIS shell can
be treated as thin shell, so the magnetic field in the thin shell is considered to be uniform when
calculating the induced electromotive force.

\[
B = \frac{\mu_0 \mu_r I_0}{2\pi R} \cos(\omega t) = B_0 \cos(\omega t)
\]

In formula: \( B_0 = \frac{\mu_0 \mu_r I_0}{2\pi R} \)

Induced electromotive force:

\[
E = \frac{dB}{dt} = \frac{\omega \mu_0 \mu_r I_0}{2\pi R} (-\sin(\omega t))S = -B_0 S \omega \sin(\omega t)
\]

Electromagnetic force on upper and lower edge of metal unit:

\[
F_1 = -F_2 = 4\pi R_{eq}L \frac{\mu_0 \mu_r I_0 \cos(\omega t)}{2\pi R} - \frac{B_0 S \omega \sin(\omega t)}{R_{eq}} L = -\frac{\mu_0 \mu_r I_0 B_0 S \omega L}{4\pi R R_{eq}} \sin(2\omega t) = M_0 I_0 \sin(2\omega t)
\]
The same:

\[ F_2 = -F_3 = B_i i L = M_i I_0^2 \sin(2\omega t) \]  

(4)

In formula: 

\[ \frac{\mu_0 \mu_r l_0 \cos(\omega t)}{2\pi R} \cdot B_r = \frac{\mu_0 \mu_r l_0 \cos(\omega t)}{2\pi r} \cdot M_r = -\frac{\mu_0^2 \mu_r^2 S \omega L}{8\pi^2 R^2 r_{eq}} \cdot M_r = -\frac{\mu_0^2 \mu_r^2 S \omega L}{8\pi^2 r R_{eq}} \]

Therefore, the resultant force of each metal element is a simple harmonic force with twice of power frequency as the fundamental frequency, so the GIS shell vibration caused by electromagnetic force is a vibration with twice of power frequency as the fundamental frequency.

2.2. Analysis of magnetostrictive vibration characteristics

According to the magnetostrictive effect, the size of ferromagnetic material will change under the action of external magnetic field - lengthen or shorten. After removing the external magnetic field, it will return to its original length, and the macroscopic performance is mechanical vibration. The GIS shell is regarded as a thin shell, and the magnetic induction intensity in the shell is calculated by formula (1). Thus, the magnetic field strength in the shell is approximately equal:

\[ H = \frac{B}{\mu_0 \mu_r} = \frac{B_0 \cos(\omega t)}{\mu_0 \mu_r} \]

(5)

The relationship between the linear deformation of the thin shell and the magnetic field intensity is:

\[ \frac{1}{l} \frac{dl}{dH} = \frac{2\epsilon_S}{H_c^2} |H| \]

(6)

\( H_c \) in the formula is coercive force; \( \epsilon_s \) is the saturation magnetostriction of the thin shell. According to the definition of magnetostriction rate:

\[ \epsilon = \frac{\Delta l}{l} = \frac{2\epsilon_S}{H_c^2} \int_0^H |H| dH = \frac{\epsilon_S}{H_c^2} H^2 = CH^2 \]

(7)

In the formula, \( l \) is the initial position of the shell; \( \Delta l \) is the displacement change; \( C = \epsilon_s / H_c^2 \) is the expansion coefficient of the shell. Let \( B_s \) be the saturation magnetic induction intensity, then the magnetic field intensity in the thin shell is:

\[ H = \frac{B}{\mu} = \frac{B_s}{B_s} H_c = \frac{B_0}{B_s} H_c(\cos(\omega t)) \]

(8)

Substituting equation (8) into equation (7), the magnetostriction rate of the thin shell is obtained:

\[ \epsilon = \frac{\Delta l}{l} = \frac{2\epsilon_S}{H_c^2} \int_0^H |H| dH = \frac{\epsilon_S}{H_c^2} H^2 = \frac{\epsilon_S \mu_0^2 l_0^2}{2\pi R B_s^2} \cos^2(\omega t) \]

(9)

The magnetostrictive acceleration can be obtained by calculating the second derivative of \( \Delta l \) with \( t \) as the variable:

\[ a = \frac{d^2(\Delta l)}{dt^2} = -\frac{2\omega^2 \epsilon_S \mu_0^2 l_0^2}{\pi R B_s^2} \cos(2\omega t) \]

(10)
Therefore, the frequency of GIS shell vibration caused by magnetostriction is also 2 times of power frequency. According to the above analysis, under the stable action of electromagnetic force and magnetostriction effect, GIS shell will vibrate continuously and stably at the basic frequency of twice power frequency.

2.3. Vibration characteristic analysis of mechanical failure

The above is the theoretical analysis and calculation of GIS vibration. If we want to get more practical and perfect vibration fault frequency characteristics, we need to carry out fault simulation experiments to get real data. For this reason, the insulator looseness fault experiment is carried out to obtain the real vibration data of mechanical fault. The spectrogram is shown below.

![Vibration spectrum of simulation experiment](image)

Figure 2. Vibration spectrum of simulation experiment

The left figure shows the vibration spectrum under normal operation, and the right figure shows the vibration spectrum under loose insulator. The comparison shows that the spectrum under normal and fault conditions is mainly below 1000Hz. In normal state, only 100Hz is most prominent, and 200Hz and 300Hz are also excited under loose fault. It is concluded that the high harmonic component is derived from the conduction of vibration in the complex structure of GIS.

3. Application of vibration fault test and analysis

The GIS equipment of a certain 220kV substation had problems of excessive vibration and noise during operation. No abnormality was found in the field through UHF and ultrasonic partial discharge detection, and no problem was found in the moisture and component detection of SF6 gas. In order to find out the cause of the fault, vibration test and analysis are decided.

After preliminary observation in the field, it was found that the abnormal vibration and noise were mainly concentrated on the arrester combination equipment with 224a spacing, so the test focused on this equipment. As shown in the figure below, the GIS is a three-phase separated structure. The upper part of the arrester is equipped with a voltage transformer (PT), which is connected by a T-tube and the lower part is supported by a steel frame base. So it was decided to test the vibration of Pt, arrester and bracket. The test points are arranged as follows: Number 1-2 measurement points are placed at the lower end of Pt, Number 3-5 measurement points are located near the T-shaped pipe connecting the arrester and Pt, and Number 6-8 measurement points are located at the connection between the arrester and the base. See figure 3 for details.
Figure 3. Location of measurement points

The spectrogram obtained from the test is shown in the following figure:

Figure 4. Spectrogram

The channel number of the spectrum is the measurement point number. It can be seen from the figure that the spectrum components of each measurement point are mainly 100Hz and 200Hz. The vibration data can be obtained by averaging the amplitude of each measurement point, as shown in the following table.

Table 1. Vibration data list unit: mm/s²

| Measurement point      | Amplitude of 100Hz | Amplitude of 200Hz |
|------------------------|-------------------|--------------------|
| PT                     | 6                 | 8                  |
| Arrester               | 25                | 8                  |
| Steel frame base       | 9                 | 150                |

Using the conclusion of the previous section on GIS vibration frequency characteristics, the graph and data can be analyzed. It can be seen that the 100Hz and 200Hz values of Pt vibration are similar,
in which 100Hz should come from the electromagnetic force generated by its own coil. However, due to the high position and vertical installation of Pt, it is obviously affected by other vibration sources such as transformer and capacitor, so the 200Hz component is also significant. The 100Hz amplitude of the arrester is relatively large due to the influence of the vibration of the bus connected to it, while the 200Hz amplitude is the same as that of Pt. The 100Hz amplitude of the bracket is only 9 mm/s², but the 200Hz amplitude is 150 mm/s², which is nearly 20 times of that of other components. However, the vibration of the ground around the bracket is only 1 mm/s². Therefore, it can be concluded that there is a problem in the support stiffness of the bracket. Therefore, the support was inspected and it was found that several bolts were loose, and one of them had completely lost its tightening force. After retightening the bolts, the vibration measurement was conducted again, and the vibration data is shown in Table 2.

**Table 2. Vibration data list unit: mm/s²**

| Measurement point   | Amplitude of 100Hz | Amplitude of 200Hz |
|---------------------|--------------------|--------------------|
| PT                  | 7                  | 2                  |
| Arrester            | 25                 | 6                  |
| Steel frame base    | 10                 | 19                 |

After fastening the bracket, the 100Hz vibration amplitude of each part did not change much, but the 200Hz amplitude of the bracket decreased to 19 mm/s², the noise also became much smaller, and the amplitude of Pt and arrester was also reduced correspondingly. The vibration test and analysis had achieved good results.

4. Conclusion

(1) The internal sources of GIS vibration are mainly electromagnetic force and magnetostrictive effect. The electromagnetic force can occur in the bus bar sleeve and the equipment containing the coil. Magnetostriction occurs in GIS whose shell is made of ferromagnetic materials such as iron and stainless steel, while it does not occur in GIS with aluminum shell.

(2) The characteristic frequency of vibration produced by electromagnetic force and magnetostriction is twice the power frequency 100Hz. For the loose fault, the structure itself may produce resonance, so the frequency doubling components of 200Hz and 300Hz may appear.

(3) The structure of GIS is very complex. In the field test and analysis, it is necessary to make a concrete judgment on the actual situation. Find out the prominent position of vibration, and gradually narrow the range of abnormal vibration through testing and observation to find out the fault point. At the same time, the interference of other equipment in the substation, such as transformer and capacitor, should also be considered comprehensively.

The current situation of GIS vibration test and analysis technology is still relatively primary, and there are still many problems to be studied and clarified. I hope this article can provide some help for readers who are concerned about this field.

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