Design and Development of Monitoring System for GIS Structural Deformation Based on Photogrammetry

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Abstract. Aiming at the current situation, main problems and the characteristics of structure monitoring of GIS equipment, the principle and method of deformation monitoring of key points in GIS are put forward based on photogrammetry technology. A non-contact monitoring and early-warning system for structural deformation of GIS equipment is designed and developed. Moreover, the monitoring results are compared with the results of finite element simulation. The reliability of the system is verified.

1. Introduction

GIS gas insulated switchgear is a fully enclosed combined metal switchgear with Sulphur hexafluoride as its insulating medium. It has the advantages of less floor area, no environmental interference, high reliability, convenient operation, less maintenance workload, quick installation and no electromagnetic interference. It has been applied to electricity all over the world for many years [1]. As an indispensable part of UHV distribution, the security of GIS equipment will become more and more important.

Generally, GIS equipment are assembled by long distance, multi-segment splicing and overhead installation. Considering the design, manufacturing, installation errors, as well as the thermal expansion and contraction caused by temperature changes during operation, bellows expansion joints are often installed at the joints of different segments of GIS to compensate for the thermal expansion and contraction of super-long GIS equipment and the expansion and contraction of foundation. However, due to the errors such as manufacturing and installation or drastic changes in environmental conditions, the deformation and stress of GIS cylinder are usually very high, which will lead to cracking of cylinder, expansion joint, bracket and other faults, SF6 gas leakage and ground discharge, as shown in Figure 1. Especially in some high-cold and high-altitude areas, there is a large temperature difference between day and night, which is easy to cause the uneven stress on the support points of the super-long GIS equipment shell, eventually resulting in migration, fracture, deformation and other problems, which seriously affect the safe and stable operation of the GIS equipment[2-3]. Meanwhile, the fluoride produced by ionization has high toxicity and high pollution, which poses a certain threat to human body and the environment.
At present, since the application of super-long GIS equipment is more and more widespread, the problem of large-scale structure deformation caused by temperature is becoming increasingly prominent. However, there lacks of effective supervision over the structure of GIS equipment.

![Figure 1. Cracking behavior of bellows, bracket and bus barrel weld of GIS equipment. (a) Failure components, (b) Bellows connection, (c) Bracket, (d) Welding seam in the bus barrel.](image)

In view of the current application situation and main problems of GIS equipment, in order to solve the shortcomings of monitoring large-scale structure status of GIS equipment, and to grasp the structure safety status of large-scale equipment in time. In this paper, a deformation monitoring and early-warning system for key points of GIS based on Photogrammetry technology is designed and developed. It mainly focuses on the non-contact displacement measurement, principle and system composition, which is suitable for the structure of GIS equipment. At the same time, the monitoring results are compared with the results of finite element simulation to verify the reliability of the system.

### 2. Demand analysis and overall design

#### 2.1. Requirement analysis and technical parameters requirements

Most of the GIS equipment are deployed for outdoors, and the external factors such as temperature are the main factors affecting the structural deformation of the GIS equipment. The metal structure of GIS equipment can be elongated and shorted flexibly in the process of environmental change. Sliding support and bellows must work normally. Monitoring the displacement (deformation) of key points such as brackets and bellows with the change of temperature can judge whether the compensation device is abnormal. Real-time monitoring and early-warning are the key to ensure the normal operation of GIS equipment.

Taking a substation in the south-eastern coastal area of China as an example, there is an obvious difference between the highest and lowest temperatures over a whole year. According to the characteristics of climate change, the environmental temperature and deformation of bus barrel of GIS equipment under normal operation conditions can be determined. The lowest limit temperature of the whole year is -20°C, the highest limit temperature of the whole year is 40°C, and the highest limit temperature of the equipment surface can reach 70°C. The loads on bus barrel of GIS equipment are bracket binding force, gravity, internal pressure and temperature load.

GIS equipment is affected by the diurnal temperature difference and seasonal temperature difference. The maximum temperature difference between day and night is more than 20°C, and the maximum annual temperature difference is more than 60°C. Because the support foundation is made of concrete
and the GIS equipment is made of metal materials such as aluminium alloy or steel, the thermal expansion coefficients of the two materials are different. The same temperature difference will lead to different thermal expansion and cold contraction of GIS equipment and foundation, which will eventually lead to the relative ground development of GIS structure.

Taking a 30-meter-long GIS equipment as an example, the formula of thermal expansion and cold contraction is as follows:

\[ D = a \cdot \Delta T \cdot L \]  

Among them, D denotes thermal expansion and contraction displacement, the unit is mm; \( a \) represents the thermal expansion coefficient of an object, \( 1^\circ C(2.3 \times 10^{-5}/^\circ C \) for GIS equipment, \( 1 \times 10^{-5}/^\circ C \) for foundation); \( \Delta T \) denotes the temperature difference, the unit is \( ^\circ C \); L denotes the length of an object, the unit is mm.

According to formula (1), it can be used to estimate that the axial displacement of the foundation, which can reach 50 mm when the annual temperature difference is maximum, and the position displacement of the bus barrel can reach 10 mm when the temperature difference between day and night is maximum. The structural deformation and stress caused by the diurnal and annual temperature difference in the environment of GIS equipment is one of the main factors affecting the safe operation of the equipment [4-5].

The main requirement of monitoring for GIS equipment is to measure the structural deformation of the equipment. The operation status of GIS equipment can be analysed and predicted by monitoring the position deformation of GIS equipment through the operation status of bus barrel, and collecting the micro-meteorological environment parameters of substation. Since the operation of the equipment at high voltage, non-contact measurement is adopted for measurement of deformation [6]. The main technical parameters are as follows:

1) Measurement principle: non-contact deformation measurement
2) Measuring distance: 1~100m
3) Measurement accuracy: 0.2mm (50m distance)
4) Measuring range: ±200 mm (effective range, two directions)
5) Working temperature: -30 ~ +70 ℃

2.2. Overall design and main functions

In order to monitor the structural deformation and temperature change of GIS in real-time, and the deformation and damage of key components such as bellows expansion joint, cylinder and metal bracket, it is necessary to accurately measure the deformation caused by temperature, and then establish a monitoring and early-warning system for structural deformation of GIS equipment.

![Figure 2. The schematic diagram of GIS monitoring system architecture.](image)

The structure deformation monitoring system of GIS equipment is composed of three parts: sensor set data acquisition, cloud platform and monitoring terminal. As shown in Figure 2, the field sensor performs data acquisition, storage, parsing, transmission and other functions under the coordination of intelligent gateway. Cloud includes database server, background processing server and WEB server, which can analyse, store and distribute data. Intelligent terminals display, query, configure and warn
data through browsers. The structure deformation monitoring system of GIS equipment meets the following requirements:

1) It is suitable for real-time monitoring of dynamic parameters during the operation of GIS equipment. It mainly focuses on the deformation monitoring of GIS structures under external loads such as temperature, wind and vibration. Its core is to monitor the real-time changes of displacements of key points of GIS structures in all directions in a non-contact way [7].

2) It has the functions of real-time acquisition, remote transmission, over-limit alarm and data analysis.

3. Measurement principle and its application

3.1. Digital photogrammetry technology and its application

Digital Photogrammetry is based on the basic principles of digital image and photogrammetry. It uses computer technology, digital image processing, image matching, pattern recognition and other theories and methods to extract the geometric and physical information of the object in a digital way [8-9]. The basic principle is non-contact measurement based on image, which has the real-time characteristics and high precision. It is a non-contact monitoring method for dynamic and static deformation monitoring of structures [10-11].

According to the characteristics of structural deformation monitoring of GIS equipment, there are several steps to use digital photogrammetric image processing for deformation monitoring [12], as shown in Figure 3:

1) Target setting: According to the location characteristics of monitored objects, a stable target is laid out in and around the structure of GIS equipment.

2) Digital image shooting: using high-definition camera to take pictures of the target on the monitored object and obtain the frame image.

3) Digital image transmission: the collected image is uploaded to the cloud platform control center by wireless network and processed.

4) Image feature extraction: the image gray transformation, pre-processing, binarization, edge detection, circle fitting and other image processing methods are applied to the captured digital image to realize the extraction of image feature points.

5) Calibration of monitoring system: the resolution R of current monitoring system is calibrated by visual imaging.

6) Calculating displacement: the deformation of the structure to be measured is determined by using system resolution R and displacement calculation principle of frame difference method of target centre.

![Figure 3. Basic steps of deformation monitoring by digital photogrammetry.](image)

3.2. Principle of deformation measurement

According to the shape and size of the target, the original image is cut, then the image is grayscale transformed, and the centroid coordinates are calculated. To determine the two-dimensional coordinates of the target's centroid, the centroid fitting method is adopted, that is, the centroid is fitted by minimizing
the sum of the square error of the target function. The centre of mass is fitted by the circle edge points obtained by the mathematical morphological edge detection operator [13]. According to the principle of least square method, the optimized objective function is constructed as follows: Formula (2):

\[ F(a, b, c) = \sum (x_i^2 + ax_i + by_i + y_i^2 + c)^2 \]  

(2)

The centroid coordinates are fitted by calculating the parameters a, b and C to minimize the value of the objective function F(a, b, c). Because the objective function F(a, b, c) is a non-negative function, that is, the function has a minimum value and the minimum value is fixed at the extreme point, it means as long as the extreme point of the objective function is found, the unknown a, b, C can be obtained, so that the centroid coordinates (x₀, y₀) can be fitted.

According to the principle of photogrammetry, the non-contact deformation measurement of GIS can be realized. Meanwhile, the system can realize self-calibration and self-calibration by the distance between two fixed targets [14].

Figure 4. Target setting and installation of GIS structure deformation monitoring system. (a) Target setting, (b) Target installation, (c) Displacement sensor installation.

4. Comparison of finite element simulation and monitoring examples

4.1. Finite element simulation of GIS equipment

Based on the actual structure of 500 kV GIS equipment in a substation, the GIS equipment is modeled by ANSY finite element analysis software. The substation GIS equipment is composed of pipe busbar, fixed support, sliding support, pressure self-balancing bellows expansion joint and common bellows expansion joint [15-17]. According to the structure of the equipment, the finite element models of six fixed supports and four sliding supports are generated. Then the connection between the models is realized by CDREAD command and the interface nodes of each segment. The linear spring element COMBIN40 and the non-linear spring element COMBIN39 are used to balance one group of common bellows expansion joints and four groups of self-balancing joints, respectively. The expansion joint is simulated and the whole finite element analysis model of GIS equipment in the substation is established. As shown in Figure 5, the total length of the equipment is 95610 mm, the diameter of the busbar is 685 mm, the wall thickness is 7.8 mm, the single length of the pressure self-balancing bellows expansion joint is 1200 mm, and the single length of the common bellows expansion joint is 760 mm. Because the axis direction (Z direction) of the busbar is 100 meters, under the influence of ambient temperature
change and solar radiation, it will be greatly deformed due to the phenomenon of thermal expansion and cold contraction.

![Figure 5: Finite element analysis model of GIS equipment in a substation.](image)

The simulation results are shown in Figure 6. For the Z-direction deformation distribution of the whole finite element model, the tubular buses on both sides of each fixed support extend to both sides when the temperature rises, which is consistent with the actual situation.

![Figure 6: Z-direction deformation and stress distribution nebula of the integral model under 22℃ temperature difference. (a) Deformation cloud image, (b) Stress cloud image.](image)

4.2. Monitoring results of actual deformation

The monitoring system has actually been installed on a substation's GIS equipment. The temperature change of one or two days in March is selected as shown in figure 7. The time range of two days is 0-2880 min, and the actual temperature fluctuates from 1 to 22℃. The deformation change data of expansion joints in GIS are monitored on the spot as shown in table 1.
Figure 7. Temperature change and deformation monitoring data of GIS equipment in a certain two-day period (expansion joint 2 axial deformation).

The deformation change data of expansion joints in GIS are monitored on the spot as shown in table 1.

| Location       | Calculated value/mm | Measured data/mm | Relative error |
|----------------|---------------------|------------------|----------------|
| Expansion joint 1 | -3.78               | -3.73            | -1.34%         |
| Expansion joint 2 | -5.27               | -5.14            | -2.53%         |
| Expansion joint 3 | -4.55               | -4.16            | -9.37%         |
| Expansion joint 4 | -3.16               | -2.78            | -13.67%        |

In the finite element model, the deformation at the monitoring point of expansion joint is calculated by applying temperature load at 22℃, and compared with the measured data, as shown in Table 1. All expansion joints are compressed, and all data in Table 1 are negative. Through comparative analysis, it can be seen that the error between the finite element simulation calculation of expansion joint of GIS equipment and the actual monitoring results is small, which shows that the actual monitoring results are consistent with the theoretical calculation results of finite element method.

5. Conclusion
In this paper, aiming at the main problems and monitoring characteristics of the structure monitoring of GIS equipment, a non-contact deformation monitoring and early-warning system for the structure of GIS equipment is designed and developed by using the deformation monitoring method of key points of GIS based on Photogrammetry technology. Meanwhile the monitoring results are compared with the results of finite element simulation to verify the system reliability.

1) Design a non-contact deformation monitoring system suitable for the structure monitoring characteristics of GIS equipment.

2) Taking the GIS equipment of a substation as the monitoring and research object, the structural deformation of the substation is simulated by finite element method. By comparing the results of finite element calculation with the actual monitoring data, the deformation trend and variation of key points are in good agreement, which shows the reliability of the monitoring method.

3) The scheme of deformation measurement of key points in GIS based on photogrammetry technology is feasible. The key parameters of equipment state can be monitored quickly and accurately in the application of structural deformation monitoring of GIS equipment. It can directly reflect the real-time change of GIS equipment structure and timely warning.

At present, there is no relevant standard and unified method to monitor and warn the structural deformation of GIS equipment. The equipment failure caused by the deformation of GIS equipment needs to be solved urgently. Therefore, the application of this system has important reference value and guiding significance.
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