SF₆ Online Automatic Sampling Monitor Development

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Abstract. The widely used offline detection method for SF₆ in electrical equipment has disadvantages such as low real-time, complicated operation process and environment unfriendly. Therefore, SF₆ online automatic sampling device for SF₆ electrical equipment was developed, which integrated with the online chromatographic detector, to ensure the convenient and high efficient collection and analysis of SF₆. It can avoid the harm of SF₆ gas to staff, environment and equipment, provide scientific basis for equipment maintenance and condition analysis. Sampling performances of SF₆ online sampling monitor were analyzed, and the results show that the SF₆ online sampling detector can fully meet the requirements of the field use.

1. Introduction
Sulfur hexafluoride (SF₆) gas is widely used in high-voltage electrical equipment due to its excellent insulation interrupter [1-2]. An increasing number of SF₆ electrical equipment were put into operation with the rapid development of the power industry [3-4]. It is very important to keep track of the operation conditions of SF₆ electrical equipment for the stability of the power [5-6].

But under the conditions of high voltage discharge, arc and high temperature, SF₆ gas is easily decomposed into a series of highly toxic low fluoride such as sulfur tetrafluoride (CF₄), carbon disulfide (CS₂), sulfuryl fluoride (SO₂F₂), Thionyl fluoride (SOF₂), sulfur dioxide (SO₂), Hydrogen sulfide (H₂S) and so on [7-9]. It will do harm to workers’ health if SF₆ decomposition products leak into air [10-11]. A large number of studies have shown that the types, content, production rate and proportion of SF₆ decomposition products under different defect types are different [12-14]. The failure cause, discharge level, development status and danger degree of the electric equipment can be judged by detecting the components of the SF₆ decomposition products [15-16].

At present, SF₆ detecting method is to export gases regularly from the SF₆ circuit breaker charging port for detection [17]. Leak detector and density relay are commonly used to detect purity, humidity and other related parameters [18]. The offline detection method has disadvantages such as low real-time, complicated operation process and environment unfriendly [19-20].

Therefore, the purpose of this study is to develop a SF₆ online automatic sampling and detecting system for the realization of effective detection and analysis of SF₆ gas, and thus effectively monitor the quality of the gas, predict the running state of the equipment, and provide the basis for equipment operation and maintenance.
2. Methods and Materials

2.1. Structure of the system

The integrated online automatic monitoring system for SF₆ is mainly composed of sampling system module, analysis module and control module. Structure of the SF₆ online automatic monitoring system is shown in Figure 1.

The gas path control module is mainly used to control the collection and recharge of SF₆ decomposition gas, standard gas and high-purity SF₆ gas in the SF₆ equipment. The communication module is the middle control system of SF₆ online analysis and monitoring system. It is used to transfer the instructions of the host computer system (master control) to the lower computer system (SF₆ gas sampling device and SF₆ gas analyzer), so as to control the entire platform for SF₆ gas collection and detection. Also by use of communication module, the equipment status, concentration, flow, pressure and other information of the SF₆ online sampling device in the lower computer system can be fed back to the host computer system. The analysis module is mainly used to detect the concentration of gases enter into the SF₆ online monitoring system.

2.1.1. Sampling system module.

The SF₆ refilling automatic sampling platform (GPTR-C201) was developed by Guangdong Electric Power Research Institute and Shanghai LiHe Company, which can realize the automatic sampling of insulating gases of single nozzle SF₆ insulated electric equipment and refilling of sampling gases.

2.1.1. Analysis module.

The analysis module mainly consists of a dew point monitor and an online gas chromatograph. The dew point monitor installed in the sampling system, when the gas flows through the pipeline, the dew point meter monitors the dew point of the gas in the pipeline online. Taking into account the field temperature between -10°C and 50°C, we chose dew point transmitter DT242 (VALSALA). The online gas chromatograph (GPTR-S201) were developed by Guangdong Electric Power Research Institute, which is used exclusively for online detecting of insulating gas decomposition products in SF₆ electrical apparatus. It is composed of sampling system, chromatographic column, temperature control system and detector.

2.1.2. Control module.

SF₆online automatic sampling monitoring system controller is divided into two parts of hardware and software. Hardware is composed of physical components of the device, and the software achieves control function instructions and data systems relaying on hardware. The working principle of controller (STM32F103VCT6) used in the system is that the software deals with the information collected from the pressure detection switch in the sampling loop and through the hardware circuit to each operation part of the loop to send operation control command. Control system under the assistance of the PLC controller can realize the selection of SF₆ gas detection channel selection, SF₆ gas online detection, monitoring detection of data display, automatic alarm and setting of user parameters and system parameters. Its main feature is the beautiful interface and easy operation. It can choose the detection channel and setting the detection time interval, can realize the periodic detection of the selected channel according to the user's requirements, and save the detection data.

2.2. Performance test

2.2.1. Vacuum test.

Before sampling of the SF₆ online system, the gas in the system needs to be evacuated in order to prevent its interference on the test result, while the vacuum degree is the main index of the vacuum performance of the reaction system. An electromagnetic valve is set at the sampling port of the GIS gas chamber, a pressure gauge (KELLER, ECO1, Swiss, range 0.001 ~ 40 Mpa) is installed in the sampling line, and a pressure gauge is installed in the pipeline before the system air bag (storing SF₆ gas). When the vacuum test is done, the solenoid valve is closed, and the whole sampling system is started to vacuum, and record the numbers of two pressure gauges.
2.2.2. Gas chamber pressure test. In the case of 0.60 L sampling standard state volume, the influence of different GIS chamber pressure on the charging rate of the online sampling system is simulated.

2.2.3. Refilling rate analysis. Refilling rate is an important index of the detector to refilling efficiency. When the refilling rate is too low, it would easily cause gas leakage of SF$_6$ electrical equipment, resulting in the reduction of the pressure of SF$_6$ gas chamber, thereby affecting the insulation performance of electrical equipment. Therefore, the detection and evaluation of the refilling rate must be completed before use of the SF$_6$ online sampling platform.

In order to test the refilling effect of the online sampling system, use 1.02 L sampling bottles as simulated GIS chamber, and use SF$_6$ online sampling device for continuous sampling and refilling, to record pressure changes of the simulated GIS gas chamber in different testing conditions (different sample volume, chamber pressure and repeatability and different sizes of gas chambers) before and after sampling.

(1) Different sampling volume
In the pressure of 0.5 Mpa of simulated GIS gas chamber, to test influence of sampling volume (0.57-2.26 L) on the refilling rate of online sampling system.

(2) Repeatability
Under the condition of sampling volume was 0.91 L standard volume, and pressure simulated GIS air chamber less than 0.5 Mpa, test the effect of sampling repeatability on refilling rate of online sampling system.

(3) Effect of different gas chambers
In the standard state of 0.91 L sampling volume, and pressure simulated GIS air chamber is 0.45 Mpa, test the effect of gas chamber volume (1.02, 8, 20, 40 L) on refilling rate of online sampling system.

The refilling rate of SF$_6$ online sampling system can be calculated as follow formula:

\[ x = \left( 1 - \frac{p_1 - p_2}{p_1 - p_0} \right) \times 100 \] (1)
where, $x$ is refilling rate ($\%$), $P_1$ is the pressure of GIS air chamber before sampling (Mpa), $P_2$ is the pressure of GIS air chamber when detection of gas is complete but refilling is not yet beginning (Mpa), $P_3$ is the pressure of GIS air chamber after sampling (Mpa).

2.2.4. Accuracy test. In order to ensure the accuracy of the SF$_6$ online refilling detector, it is necessary to determine the accuracy before the actual use. In the accuracy test, 1.02 L sampling bottle was used as the simulated GIS gas chamber, standard pressure was 0.5Mpa, and SO$_2$/SF$_6$ (50ppm) standard gas was used as the standard material gas. Experimental device of the accuracy test are shown in Figure 2.

![Experimental device of the accuracy test](image)

1: high purity SF$_6$ cylinder. 2: standard gas of SF$_6$ decomposition products cylinder. 3: pressure regulating valve. 4: gas distribution instrument. 5: pressure gauge. 6: standard gas tank. 7: solenoid valve. 8: detector under test. 9: exhaust bottle. 10: vacuum pump.

**Figure 2.** Experimental device of the accuracy test

The experimental process is as follows:

1. Initialization
   Initialize the system to the starting state.

2. Vacuum pumping
   The system vacuum pumping is mainly used to remove the impurity gas in the accuracy calibration device to ensure the accuracy of gas accuracy calibration.

3. Accuracy detection
   Calculate the average value of the detection value of the instrument and the error rate:

   $\delta = \frac{C - C_S}{C_S} \times 100\% \quad (2)$

   where, $\delta$ is error rate, $C$ is instrumental values of each concentration, and $C_S$ is concentration of standard gas.

   Calculate repeatability of test values for computing instruments. According to the formula (3), the relative standard deviation of each concentration was calculated.

   $S = \frac{1}{C} \sqrt{\frac{n}{n-1} \sum (C_i - C)^2} \times 100\% \quad (3)$

   where, $C_i$ is instrumental value for the $i$th time, $n$ is total measure times, and $C$ is concentration of standard gas.
3. Results and discussion

3.1. Vacuum test
The results of vacuum test are shown in Table 1. In four experiments, pressure of pressure gauge 1 reached 0.01 MPa, the average pressure of pressure gauge 2 in pipeline system was 0.01 MPa. And when the vacuum pump stopped running, pressure values of pressure gauge 1 and pressure gauge 2 did not change for 12 h.

Table 1. The results of vacuum test.

| Times | Pressure gauge 1 (MPa) | Pressure gauge 2 (MPa) |
|-------|------------------------|------------------------|
| 1     | 0.01                   | 0.01                   |
| 2     | 0.01                   | 0.01                   |
| 3     | 0.01                   | 0.01                   |
| 4     | 0.01                   | 0.01                   |
| Mean  | 0.01                   | 0.01                   |

3.2. Gas chamber pressure test
As can be seen from Table 2, when the pressure of the GIS air chamber was greater than 0.74 Mpa, the refilling rate of the system was still 100%. It is shown that when the pressure of the simulated GIS gas chamber reaches 0.74 Mpa, the compressed air still has enough thrust to collect the SF6 gas back into the original gas chamber.

Table 2. Results of GIS gas chamber.

| No. | Pressure before sampling (Mpa) | Pressure after sampling (Mpa) | Refilling rate (%) |
|-----|-------------------------------|------------------------------|-------------------|
| 1   | 0.731                         | 0.731                        | 100               |
| 2   | 0.573                         | 0.573                        | 100               |
| 3   | 0.451                         | 0.451                        | 100               |
| 4   | 0.376                         | 0.376                        | 100               |

3.3. Refilling rate analysis

3.3.1. Different sampling volume. When pressure of simulated GIS gas chamber was 0.5 Mpa, results of refilling rate of different volumes of gas was listed in Table 3. When sampling volumes of gas was 0.57-2.26 L, the refilling rate of SF6 online sampling platform can reach 100%. It indicates that the refilling rate is not affected by the sampling volume.

Table 3. Refilling rates of different sampling volumes.

| Sampling volume (L) | Pressure before sampling (Mpa) | Pressure after sampling (Mpa) | Refilling rate (%) |
|---------------------|--------------------------------|------------------------------|-------------------|
| 0.57                | 0.573                          | 0.573                        | 100               |
| 0.91                | 0.573                          | 0.573                        | 100               |
| 1.14                | 0.573                          | 0.573                        | 100               |
| 1.55                | 0.573                          | 0.573                        | 100               |
| 1.95                | 0.573                          | 0.573                        | 100               |
| 2.26                | 0.573                          | 0.573                        | 100               |

3.3.2. Repetitive test. When the sampling volume was 0.91 L and pressure of simulated GIS gas chamber was 0.5 Mpa, the effect of sampling repeatability on the refilling rate of the online sampling system was as shown in Table 4. When times of continuous sampling was more than 20, the gas refilling
rate was 99.38%, that is, about 0.62% of the gas was leak in the 20 consecutive samplings. According to leakage rate of 0.5% per year in Test Guide of SF$_6$ Gas Tightness for High-Voltage Switchgear (GB 11023), the online sampling system can finish continuous sampling for about 2000 times. It can completely detect the change of SF$_6$ gas composition in GIS equipment.

Table 4. Results of repetitive tests.

| Times of consecutive samplings | Pressure before sampling (Mpa) | Pressure after sampling (Mpa) | Refilling rate (%) |
|-------------------------------|---------------------------------|-------------------------------|-------------------|
| 1                             | 0.562                           | 0.562                         | 100               |
| 5                             | 0.562                           | 0.562                         | 100               |
| 10                            | 0.562                           | 0.562                         | 100               |
| 15                            | 0.562                           | 0.562                         | 100               |
| 20                            | 0.562                           | 0.5621                        | 99.994            |

3.3.3. Effect of different size of gas chambers. In the standard state of 0.91 L sampling volume, and pressure simulated GIS air chamber is 0.45Mpa, effects of gas chamber volumes (1.02, 8, 20, 40 L) on refilling rate of online sampling system are listed in Table 5. The results show that, for different sizes of GIS gas chamber, using the SF$_6$ online detection device developed by this article, the single sample refilling rate can reach 100%. The smaller the gas chamber volume is, the greater the impact on gas refilling rates. The actual GIS equipment chamber is much larger than the test chamber, so the analysis shows that the SF$_6$ online sampling system can be applied to GIS chamber in different size.

Table 5. Effects of different size of gas chambers.

| Volume of gas chamber (L) | Pressure before sampling (Mpa) | Pressure after sampling (Mpa) | Refilling rate (%) |
|---------------------------|---------------------------------|-------------------------------|-------------------|
| 1.02                      | 0.465                           | 0.465                         | 100               |
| 4                         | 0.442                           | 0.442                         | 100               |
| 8                         | 0.471                           | 0.471                         | 100               |
| 20                        | 0.458                           | 0.458                         | 100               |
| 40                        | 0.439                           | 0.439                         | 100               |

3.4. Accuracy test

The results of accuracy test are as shown in Table 6, and error rates of accuracy test were within 5% in 4 different gradient tests, which can meet the requirements of field test.

Table 6. Results of accuracy test.

| No. | Standard concentration ($10^6$ μL/μL) | Measured value ($10^6$ μL/μL) | Error rate (%) |
|-----|-------------------------------------|-------------------------------|----------------|
| 1   | 30                                  | 28.9                          | 3.6            |
| 2   | 20                                  | 21.0                          | 5.0            |
| 3   | 10                                  | 10.4                          | 4.0            |
| 4   | 5                                   | 4.8                           | 5.0            |

4. Conclusion

A set of SF$_6$ online sampling monitoring system was developed to realize the online detection of SF$_6$ humidity and decomposition products by sampling and analysis. It can realize the sampling gas refilling in order to prevent the lower insulation performance of the electrical equipment and avoid harmful SF$_6$ emissions to the environment. Sampling performances of SF$_6$ online monitor were analysed, and the results show that the SF$_6$ online sampling detector can fully meet the requirements of the field use.
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