Development of SF₆ Gas Pressure Prediction Device in Substation

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Abstract—SF₆ equipment has leakage due to various reasons. The longer the equipment operates, the more serious the leakage is. When the equipment gas leaks to the set air replenishment value, the air replenishment alarm signal will be sent. It can be seen from the SF₆ gas temperature pressure relationship table that the temperature change has a great impact on the pressure value. Although the equipment popularizes the SF₆ density meter or SF₆ density relay with temperature compensation, the compensation system needs to achieve temperature compensation through a long time, resulting in the distortion of the pressure value counted by the operation and maintenance personnel. Therefore, the temperature difference between winter and summer is large, and more alarm signals are obtained. At this time, there are great potential safety hazards in air replenishment. This paper introduces in detail a SF₆ gas leakage prediction device in substation, which can effectively solve the above problems in substation.

1.INTRODUCTION
The electrical equipment of GIS Substation is filled with SF₆ gas. SF₆ is an ideal insulating gas with excellent insulation performance and arc extinguishing performance. However, due to quality differences in manufacturing, installation and material aging, SF₆ gas leakage of high-voltage switchgear is a common phenomenon. Once SF₆ gas leaks from SF₆ indoor substation, it will not only
cause safety problems of power grid, but also cause ground air pollution and endanger personal safety. Therefore, it is urgent to design the development of \( \text{SF}_6 \) gas leakage prediction device in substation, as in [1].

2. STATE PARAMETER EQUATION AND CURVE OF \( \text{SF}_6 \) GAS

2.1. Beattie-Bridgman Equation

Within the scope of engineering application, air or general gas can be called ideal gas when the pressure is not too large compared with atmospheric pressure and the temperature is not too low compared with room temperature. Microscopic characteristics of gas model is expressed as [2]:

- There is no interaction between molecules.
- The size of molecules, like geometric points, does not occupy volume itself.

When the gas density is less than the critical density of 0.8, Beattie-Bridgman equation is more accurate. Beattie-Bridgman equation is given by (1) to (4),

\[
P = \frac{RT(1 - \epsilon_{(v,T)})}{v^2} (v + B_{(v)}) - A_{(v)} = A_0 \left(1 - \frac{a}{v}\right) \quad (1)
\]

\[
A_{(v)} = A_0 \left(1 - \frac{a}{v}\right) \quad (2)
\]

\[
B_{(v)} = B_0 \left(1 - \frac{b}{v}\right) \quad (3)
\]

\[
\epsilon_{(v,T)} = B_0 \left(1 - \frac{c}{vT^2}\right) \quad (4)
\]

Where \( A_0, B_0, a, b \) and \( c \) are 5 constants, whose values depend on the type of gas and can be fitted by the experimental values.

2.2. State Parameter Equation Of \( \text{SF}_6 \) Gas

\( \text{SF}_6 \) gas has large molecular weight and mutual attraction between molecules. When the gas pressure exceeds 0.3 MPa, especially 0.5 MPa, with the increase of density, the intermolecular distance is compressed, which significantly increases the attraction between molecules and weakens the force of molecules on the vessel wall. The actual gas state deviates from the ideal gas state equation: the increase of actual pressure is lower than the ideal. The higher the gas pressure, the more obvious the difference, as in [3]. The rated pressure of \( \text{SF}_6 \) gas used in high voltage apparatus is generally not less than 0.5 MPa, so it does not have the conditions of ideal gas and cannot be calculated according to Charlie's law.

The most commonly used empirical formula for calculating the state parameters of \( \text{SF}_6 \) gas is Beattie-Bridgman equation, as in (5) to (7).

\[
P = 56.2 \times 10^4 \rho T(1 + B) - \rho^2 A \quad (5)
\]

\[
A = 7.49 \times 10^{-5} (1 - 0.727 \times 10^{-3} \rho) \quad (6)
\]

\[
B = 2.51 \times 10^{-3} \rho(1 - 0.846 \times 10^{-3} \rho) \quad (7)
\]

Where \( P \) is the pressure of \( \text{SF}_6 \) gas, \( \rho \) is the density of the gas, \( T \) is the temperature of the gas.

2.3. Curve of \( \text{SF}_6 \) Gas

The state parameter curve of \( \text{SF}_6 \) is a family of curves, in which each curve corresponds to a density value. When the gas temperature changes, the gas pressure changes along the density curve, and the intersection of the density curve and the saturated steam pressure curve is the liquefaction point, as shown in Fig. 1.
3.COMMON SF$_6$ GAS MONITORING METHODS

3.1. Traditional Measurement Method
The traditional monitoring method used by the monitoring personnel is to measure SF$_6$ gas with a barometer and complete the monitoring work together with the density relay measurement method. The working principle of this method is to measure the pressure generated by the gas through the barometer, and then obtain the content of SF$_6$ gas in the air. However, this method has many limitations and can only be used in the environment where there is no significant change in temperature and the leakage phenomenon is very obvious, as in [4]. In addition, if the substation uses this method, it also needs to be equipped with a monitoring personnel to observe the barometer, which cannot be applied to unattended substations. In addition, this method also has great disadvantages. The density relay belongs to mechanical equipment, with low accuracy and good seismic capacity. Unless the gas leakage is still insufficient to the safety line, the change of barometer is not obvious, and it is difficult for the monitoring personnel to monitor the leakage in time.

3.2. Ultrasonic Velocimetry
The monitoring personnel can use the ultrasonic velocimetry to measure the leakage of SF$_6$ gas. The principle is as follows: there is a difference between the molar mass of gas, and the speed of ultrasonic in it will be affected to a certain extent. Sound wave is a longitudinal wave, which propagates in an elastic medium. Ultrasonic velocity measurement method has many advantages, such as: the monitoring personnel can control the length of ultrasonic, directionally emit ultrasonic, etc. not only that, the characteristics and state of the medium are related to the propagation speed of ultrasonic. The monitoring personnel can analyze the characteristics of the medium through the measurement of ultrasonic speed. The monitoring personnel can use the difference method to eliminate the influence of temperature on the results, so the acoustic velocity is only related to the molar mass of gas. For SF$_6$ gas, its molar mass is about 5 times higher than that of air. Therefore, if SF$_6$ gas leakage occurs in the substation, the molar mass of gas in the substation is different from the previous molar mass of air, and the propagation speed of sound wave will naturally be affected. The measuring instrument can calculate the content of SF$_6$ gas in the air according to the change of sound wave propagation speed, so as to determine whether the leakage of SF$_6$ gas in the air has exceeded the standard. Compared with the traditional test method, this method is more stable, has longer service life and accurate measurement.
results. However, this method also has disadvantages, that is, it is expensive and is often used by most foreign companies, and it is only applied to areas with high concentration.

4. DEVELOPMENT OF SF₆ GAS PRESSURE PREDICTION DEVICE IN SUBSTATION

The SF₆ gas leakage prediction device in substation shall have the following functions:

- Calculate the gas chamber pressure at 20°C.
- Calculate the annual leakage rate of SF₆ in the gas chamber.
- Predict the remaining days from gas chamber leakage to pressure alarm value.
- Display various information of the air chamber and modify the setting parameters.
- Reliable operation of the device.

4.1. Scheme Implementation

In order to reduce the number of SF₆ low pressure alarm emergency defects caused by special weather in 220 kV substation, it needs to be realized from the following steps. Firstly, it is necessary to calculate the air chamber pressure at 20 °C. It is required to automatically collect the equipment ambient temperature and air chamber pressure at 5 a.m. every day and convert the air chamber pressure at 20 °C according to the SF₆ pressure ambient temperature curve. Secondly, calculate the annual leakage rate of SF₆ in the gas chamber. It is required to calculate the residual SF₆ gas in the gas chamber according to the pressure value of the gas chamber converted every day and calculate the annual leakage rate of SF₆ every day according to the formula. Then, according to the daily annual leakage rate of SF₆ and the residual SF₆ gas in the gas chamber, the remaining days from gas leakage in the outlet chamber to the pressure alarm value are predicted. Then, the information of the air chamber is displayed, and the information is displayed intuitively through the display. Finally, power shall be supplied to the device to meet the normal operation of the device. Based on the above analysis, the team proposed a specific module decomposition scheme. The tester of DC insulation detection device is divided into five modules: data transmission, data storage, logic control, power supply and display, as shown in Fig. 2.

4.2. Effect Verification

The above devices are installed in 3 chambers with SF₆ low pressure alarm emergency defects in 2020. The statistics of SF₆ low pressure alarm emergency defects are shown in Table 1.

| Number | Air chamber name                                 | SF₆ low pressure alarm occurred |
|--------|-------------------------------------------------|--------------------------------|
| 1      | 1878 line voltage transformer chamber           | No                             |
| 2      | 220kV switch phase a gas chamber                | No                             |
| 3      | Auxiliary bus voltage transformer chamber       | No                             |
5. Conclusion
The device in the substation can accurately calculate the remaining days from the leakage of the gas chamber to the low-pressure alarm of SF$_6$. The maintenance personnel can turn passivity into initiative, make decisions in advance and reasonably arrange the gas replenishment time, so as to avoid emergency gas replenishment in the environment with high air humidity such as rainstorm and late night. The operational stability of the equipment is improved to a certain extent. The prediction device also has the function of calculating the annual leakage rate. According to the standard of annual leakage rate of SF$_6$, it can judge whether there is air leakage in the gas chamber in advance. Therefore, the device can find the deterioration trend of equipment quality in advance, which greatly improve the equipment quality control ability.

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Thanks to the Taizhou power supply company of state grid for its strong support for this project. At present, the system has been applied in the debugging and work of substation in Taizhou, which has obtained a good evaluation. It can be seen that the put into use of the system greatly simplifies the on-site work process and enables on-site operation and maintenance personnel to complete on-site work with quality and quantity while improving work efficiency.

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