Online sealing of SF6 leak for Gas insulated switchgear

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Abstract. SF6 gas leak is a common issue that needs to be addressed for Gas insulated switchgear (GIS). In this paper, typical gas leaking defects of GIS are described with the reason leading to them. A cost-effective online sealing technology based on adhesion and gas diversion is established and a case study is presented. Besides, an analytical model which can be used to predict the pressure evolution for the leaking component as well as in the sealing zone is proposed. It has been shown that this technique can be applied to sealing SF6 gas leak of GIS components with different shape and structure.

Keywords: SF6 leak; GIS; online sealing.

1. Introduction
Gas insulated switchgear (GIS) has been applied extensively in high voltage substations owing to its compact design, confined dimensions and high reliability of operation[1-4]. Moreover, it is expected that the growing investment in renewable energy and enhanced demand for safe and secure electrical distribution systems will further increase the utilization of GIS.

GIS is essentially an apparatus insulated by pressurized SF6 to make devices such as conductors and circuit breaker to be functional properly. Therefore, effective sealing of SF6 gas is a basic requirement for its safely operation. However, due to the fabrication quality issues, aging, and improper maintenance, gas leak is a common defect for GIS equipment and it is reported that SF6 leakage represents about 40% minor failures of GIS[5-7]. Gas leak may cause the deterioration of insulating properties and arc extinction of the equipment, and it may even lead to the power outage of substation. Normally, gas leak is solved by regasketing and replacement, which requires power overhaul of the substation, leading to high cost of time and maintenance. Furthermore, since SF6 is a strong green-house gas, its leaking leads to serious environmental issues.

Online sealing technology is well established in the chemical and petroleum industry[8, 9]. It is used for blocking the gas and liquid leakage while the equipment is energized. However, for GIS in electric substation, this technology has not been adopted. This is partly due to the complicated leaking characteristics of SF6 gas, and partly due to the fact that the electrical performance must be taken into
consideration when the online sealing technology is adopted. In this paper, common factors leading to SF₆ leak of GIS was analyzed, and a novel sealing technique involving adhesive joining and gas diversion is introduced. It is expected that this study will facilitate the application of online sealing technology for GIS apparatus.

2. SF₆ Gas leak defects analysis

![Fig. 1 SF₆ gas leak defects of GIS: (a) weld crack, (b) failure of flange gasket (Infrared image), (c) failure of the expansion joint flange, and (d) corrosion of aluminum shell.](image)

It is known that many factors such as improper design, poor fabrication quality and aging may lead to the SF₆ gas leak in substation. Thus SF₆ gas leak is a key issue that needs to be addressed for GIS maintenance. Specific factors causing SF₆ gas leak include weld defect, sealing failure of flange, cracking of expansion joint and corrosion of aluminum shell, as shown in Fig. 1.

Compartment of GIS is normally fabricated using the welding technology. If the welding procedure is not controlled properly, pores and cracks may form in the weld. Although nondestructive test such as ultrasonic or X-ray testing are employed during the fabrication process, defects with small size is difficult to be detected. The remaining defects may propagate and cause the SF₆ leakage during the operation of GIS equipment (Fig. 1 (a)).

Leaking at the location of flange is the most common defects of SF₆ leakage. This is normally caused by the damage of the sealing gasket or the cracking of basin-type insulator. Furthermore, aging and weather condition are also attributed to the cause of gas leak at the flanges. Gas leaking at the flange is normally characterized by high leaking rate and concomitantly puts a serious threat to the safely operation of GIS. Expansion joint is used to absorb and adjust the expansion of GIS components, especially for ones with long dimensions, such as the bus bar compartment. However, if the structure of the expansion is not designed properly or the temperature of the environment exceeds the tolerance of the designed range, failure of the expansion joint may occur, which usually arises from cracking of the bellow or failure of the gasket.

Another factor that may cause gas leakage is the corrosion of aluminum alloy shell. This happens when the installed GIS compartment is in direct contact with the concrete wall. Since electrochemical reaction occurs for aluminum compartment in alkaline environment, GIS shell of aluminum alloy can be corroded by the concrete pore fluid which is alkaline in nature [10]. With the increasing of time, this
electrochemical corrosion will cause the thinning and ultimate penetration of the aluminum shell, resulting in the SF$_6$ gas leaking.

From the above-mentioned factors that leads to SF$_6$ leakage, it can be found that these factors consist of fabrication quality, design standard, and environment operation. Leakage can occur at different locations and in different components, which complicates the online sealing process. Thus, a robust and reliable sealing technology is necessary for dealing with this issue.

3. Online sealing procedures

Online sealing technique can be applied while the equipment is in operation. This technique is particularly suitable for solve the problem of SF$_6$ gas leak of GIS. Based on the above analysis, it can be found that SF$_6$ gas leak can occur at location of components with different shape and structure. Besides, for GIS component, the sealing technology can be applied while the apparatus is energized and no damage is caused for the apparatus during the sealing process. Therefore, a robust and versatile sealing process is needed in order to fulfill these requirements. Adhesive sealing technology uses structural adhesives to act as the sealant to stop leakage effectively. Since adhesives are polymer materials which characterized by rheological behavior, it is a suitable method for sealing the SF$_6$ gas leak in GIS component with different shapes. This sealing technique can be used to reduce the need of regasketing and components replacement and be integrated as a part of the overall maintenance. The established sealing procedures are shown in Fig. 2.

![Fig. 2 Online sealing procedure of SF6 leakage of GIS](image)

The first step for sealing SF$_6$ leakage is to find the leaking location. This can be accomplished by using infrared detection. For leakage with small amount, brushing soap lye and observing the bubble formation in the suspected areas can be adopted. After the leaking location is found, then the sealing zone for adhesive to be coated can be determined accordingly. Materials of the GIS metal components consist of carbon steel, stainless steel and aluminum alloy. These metal surfaces of the component need to be cleaned and grinded in order to provide a clean and suitable surface for the applying of adhesive. Normally, a proper surface roughness value is needed to ensure a strong bonding.

However, the adhesives cannot be applied directly to the leaking zone, because the pressure formed in the sealing zone increases very rapidly within a very short time and this may lead to the debonding of the adhesive. This is further explained in detail in the later part. Therefore, a diversion device is designed to be installed by adhesives in the leaking point firstly. The structure of the diversion device is like a fastening piece with Teflon washer. It is installed to let the gas leak from this specified path, and after the curing of the adhesive the leakage is sealed by tightening the nut. To fulfill the requirement of
long-term service, composite adhesives with reinforcements of ceramic and metal particles is applied on the surface of the sealing zone to provide high bonding strength and to withstand aging. After finishing the sealing process and curing, quality detection is needed to ensure that the whole process is properly applied and the leaking defect is eliminated.

3.1. Pressure evolution in the sealing zone

To further understand the pressure evolution of the leaking process as well as in the sealing zone, an analytical model is proposed to quantitatively describe the pressure as a function of time. Moreover a simplified gas leaking model was established to evaluate the pressure formation process in the sealing zone.

$\text{SF}_6$ gas was treated as ideal gas in this model. Based on the assumption that the leaking rate is proportional to the pressure difference between the vessel and the atmosphere or the sealing zone. The essence of this model is to predict the pressure evolution with time, because it is of importance for designing the diversion device and choosing the sealing adhesives.

The schematic of the leaking process is shown in Fig. 3 with two scenarios. The first one (Fig. 3 (a)) refers to the leaking of gas from the pressured chamber to the atmosphere; while the second one (Fig. 3 (a)) describes the leaking of gas from the pressured chamber to the sealing zone with a limited volume.

In the case of gas leak, the leaking rate can be described using the following equation:

$$\frac{dn}{dt} = K \Delta P \quad (1)$$

Where $n$ is the molar quantity transported from the vessel to the atmosphere, $t$ is the time, $K$ is the leaking coefficient which is related to the geometry of leaking defect, and $\Delta p$ is the difference of pressure between the vessel and the atmosphere. The difference of pressure is determined by the equation

$$\Delta P = P - P_0 \quad (2)$$

Where $P$ is the pressure of the vessel, $p_0$ is the pressure of the atmosphere. The pressure of the vessel can be described as following:

$$P = RT \left( \frac{n_2 - n}{V_2} \right) \quad (3)$$

Where $n_2$ is the initial pressure of the vessel, $n$ is the accumulated molar quantity of gas leaking from the vessel, $V_2$ is the volume of the vessel, $R$ is the gas constant (8.314 J/K mol), and $T$ is the temperature.

By combining (1), (2), and (3), the following expression can be gained:

$$\frac{dn}{dt} = \frac{KRT n_2}{V_2} - K \frac{P_0}{V_2} \quad (4)$$

Solving this equation gives the following expressions of $K$ and $P$ respectively:
\[ K = \frac{V_2}{RT_1} \ln \frac{P_2-P_0}{P_2-P_0} \]  
\[ P = P_0 + (P_2-P_0)e^{-\frac{KRT_1}{V_2}} \]  

Equation (5) shows that the leaking coefficient can be evaluated by using the known parameters; and equation (6) describes the pressure of the vessel. An experiment was performed to verify the analytical model with \( T = 298 \text{K} \), \( P_2 = 0.5 \text{MPa} \), \( P_0 = 0.1 \text{MPa} \), and \( V_2 = 1844 \text{cm}^3 \). It is determined experimentally that the time for a drop in pressure from 0.5 MPa to 0.2 MPa is 3240 s. The pressure evolution of the vessel evaluated from the above-mentioned model is shown in solid line while the measured value is shown by the square symbols. It is clear that the analytical model gives reasonable prediction of the pressure evolution. Thus, this analytical solution can be used for modeling the pressure variation.

\[ \Delta P = (P_2-P_1) - \frac{nRTV_1+nRTV_2}{V_1V_2} \]  

where \( P_2 \) is the pressure of the vessel, \( P_1 \) is the pressure of the sealing zone, \( n \) is the accumulated leaking molar quantity from the vessel to the sealing zone, \( V_1 \) is the volume of the sealing zone, \( V_2 \) is the volume of the vessel, \( K \) is the leaking coefficient, \( R \) is the gas constant, and \( T \) is the temperature.

Combining equation (7) and (8) gives the expression

\[ \frac{dn}{dt} = K(P_2-P_1) - \frac{(KRTV_1+KRTV_2)n}{V_1V_2} \]  

Solving this equation gives the expression of molar quantity of leaking and the pressure in the sealing zone as following:

\[ n = \frac{V_1V_2(P_2-P_1)}{RTV+RTV_2} \cdot \frac{V_1V_2(P_2-P_1)}{RTV_1+RTV_2} \cdot e^{\frac{(KRTV_1+KRTV_2)n}{V_1V_2}} \]  
\[ P = P_1 + \frac{V_1V_2(P_2-P_1)}{V_1+V_2} + \frac{V_2(P_2-P_1)}{V_1+V_2} e^{\frac{(KRTV_1+KRTV_2)n}{V_1V_2}} \]  

Fig. 4 Measured values of pressure compared to the predicted values from the analytical model. For the model of leaking from the pressured vessel to the sealing zone (Fig. 3 (b)), a similar method is adopted. The leaking rate of gas is as following:

\[ \frac{dn}{dt} = K\Delta P \]  

where \( n \) is the molar quantity transported from the vessel to the sealing zone, \( t \) is the time, \( K \) is the leaking coefficient which is related to the geometry of leaking defect, and \( \Delta P \) is the difference of pressure between the vessel and the atmosphere. The pressure difference is expressed as following.

\[ \Delta P = (P_2-P_1) - \frac{nRTV_1+nRTV_2}{V_1V_2} \]  

Combining equation (7) and (8) gives the expression

\[ \frac{dn}{dt} = K(P_2-P_1) - \frac{(KRTV_1+KRTV_2)n}{V_1V_2} \]  

Solving this equation gives the expression of molar quantity of leaking and the pressure in the sealing zone as following:

\[ n = \frac{V_1V_2(P_2-P_1)}{RTV+RTV_2} \cdot \frac{V_1V_2(P_2-P_1)}{RTV_1+RTV_2} \cdot e^{\frac{(KRTV_1+KRTV_2)n}{V_1V_2}} \]  
\[ P = P_1 + \frac{V_1V_2(P_2-P_1)}{V_1+V_2} + \frac{V_2(P_2-P_1)}{V_1+V_2} e^{\frac{(KRTV_1+KRTV_2)n}{V_1V_2}} \]
A leaking case is employed to assess the pressure built up in the sealing zone. The initial pressure of the GIS chamber is 0.6 MPa, and the atmosphere pressure is taken as 0.1 MPa. The temperature is 293 K. The dimension of the chamber is 3 m in length with diameter of 1 m, corresponding to a volume of 2.355 m$^3$. The leaking process shows that after 7 days, the pressure of the chamber changes from 0.6 MPa to 0.2 MPa. According to equation (5), the $K$ value is calculated as $2.572 \times 10^{-9}$ Pa•s/mol. For a sealing zone with volume of 1 cm$^3$, the pressure evolution in the sealing zone can be calculated by equation (11), as is shown in the Fig 5.

It can be found that a rapid increase of pressure can be formed within a short time in the sealing zone. This is indicative that a diversion device is necessary for sealing the gas leakage given the fact that polymer adhesives cannot withstand such a high pressure within a short period. This model also provides a quantitative basis for the design of the dimensions of the sealing area.

4. Case study

In order to show the feasibility of this sealing technique, a case study of sealing the leak of GIS component is described. The leaking component is a flange of 220kV GIS disconnecting switch with diameter of 522 mm in a 220 kV substation. The chamber pressure is 0.52 MPa and a leaking rate of 0.05 MPa/day is recorded for this chamber.

After the gas leak detection, it is found that the leaking point is near the location of one of the bolts (Fig. 6), which may result from the failure of the sealing gasket. Following the established sealing

![Fig. 6 Case study of the SF$_6$ gas leak in a 220 kV substation: (a) leaking component after grinding and (b) component after sealing.](image)
procedure, the flange is ground mechanically and cleaned with acetone to provide a surface suitable for applying adhesive. An epoxy-based composite adhesive with reinforcements of Fe-Si alloy and carbide ceramic particles is used for the sealing process. The whole flange is sealed by adhesives except the leaking point and then the gas leaking diversion device is installed in that place. After the curing of the adhesive, the gas diversion device is sealed and then an adhesive protection layer is placed on the whole flange. A thorough gas leaking detection was performed after the sealing procedure and it is revealed that no gas leak was found, proving the feasibility of the sealing technology.

5. Conclusion
Weld pores and cracks, sealing failure of flange, cracking of expansion joint and corrosion of aluminum shell can lead to SF$_6$ gas leak of GIS. Online sealing of SF$_6$ gas leak for GIS is an efficiency and cost-effective method to eliminate the gas leak defects which can be incorporated as an integral part of the maintenance. An analytical model is proposed to predict the pressure evolution both for the leaking vessel and in the sealing zone. This model shows that gas pressure increases very rapidly in the sealing zone and it is necessary to use the diversion device during the sealing procedure. An online sealing technique based on adhesion and diversion was developed and a case study of gas leak sealing of 220 kV GIS flange is presented. It is shown that this technique is effective for addressing SF$_6$ gas leak of GIS.

Acknowledgments
This work is supported by the Science and Technology Foundation of State Grid Corporation of China (Contract No. SGZJ0000KXJS1800302): Research on metallic material Selection, Manufacturing, Installation Process for Power Transmission and Transformation Equipment and Nondestructive Detection Method for Components.

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