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Experimental research on sealing performance of sulfur hexafluoride electrical equipment under low-temperature environment

G X Li, L Li[1], R Zhang, Z Q Jiang, X C Zhu, Z W Gao, H D Zhang and J Zhang

State Grid Heilongjiang Electric Power Company Limited Electric Power Research Institute, Harbin, Heilongjiang, 150030, China

[1] E-mail: lilin77@yeah.net

Abstract. It is discovered that the sealing performance of the sulfur hexafluoride electrical equipment worsens under low temperature, but research in the aspect is reported rarely when corresponding measures are adopted for improving the sealing performance of electrical equipment. Therefore, sealing and leakage test of sulfur hexafluoride electrical equipment was implemented under low-temperature environment according to the analysis on gas sealing methods of sulfur hexafluoride electrical equipment. Causes of gas leakage of sulfur hexafluoride electrical equipment under low temperature environment were analyzed according to test results. Effective measures were proposed for improving the gas sealing performance of the equipment, thereby providing valuable reference for gas sealing design, installation, operation maintenance and failure analysis of sulfur hexafluoride electrical equipment under low - temperature environment.

1. Introduction

Sulfur hexafluoride gas is used in high-voltage electrical equipment widely, which is applied for insulating and extinguishing arc mainly [1]. The insulation strength of sulfur hexafluoride gas is increased with gas pressure increasing. The insulation performance and arc extinguishing performance of the equipment will be reduced greatly if the gas pressure is decreased due to equipment leakage, which even can threaten safe operation of electrical equipment if the leakage is serious [2]. Moisture penetrates into the equipment due to water vapor pressure difference inside and outside the sulfur hexafluoride electrical equipment when the equipment suffers from poor sealing performance, and the humidity of sulfur hexafluoride gas is increased, thereby directly affecting the insulation performance thereof [3]. Therefore, the gas leak is serious hidden troubles to operation of sulfur hexafluoride electrical equipment.

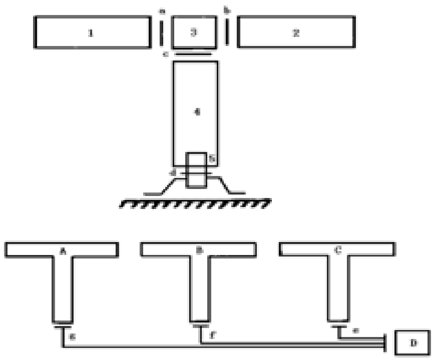
North Heilongjiang, Tibetan Plateau, Gansu, Xinjiang and Inner Mongolia partially belong to alpine region [4] in China. Winter is cold and long in the above-mentioned areas. These regions also belong to important energy bases. Therefore, it is of great significance to guarantee safe operation of sulfur hexafluoride electrical equipment in winter.

In cold regions, outdoor sulfur hexafluoride electrical equipment suffers from as liquefaction, gas leakage, actuating mechanism abnormal action and other failure [5]. The following circumstances are common during gas leakage detection of sulfur hexafluoride electrical equipment and equipment defect treatment: equipment gas leakage rate is low during daytime and high during nighttime [6], or equipment can be operated normally in summer, but gas leakage is discovered in winter. Causes are investigated, namely the circumstances are produced mainly because the sealing performance of the equipment worsens under low temperature operation environment [7]. It is discovered that research in the aspect is reported rarely when corresponding measures are adopted for improving the sealing performance of sulfur hexafluoride electrical equipment at low temperature. Therefore, it has important practical significance to conduct sealing and gas leakage test of sulfur hexafluoride electrical equipment at low temperature, investigate the sealing performance of the equipment at low temperature, analyze gas leakage causes of sulfur hexafluoride electrical equipment at low temperature, and adopt corresponding measures to improve the sealing performance of sulfur hexafluoride electrical equipment. Therefore, it is of an actual significance to improve the sealing performance of sulfur hexafluoride electrical equipment, implement sealing and gas leakage test for sulfur hexafluoride electrical equipment under low temperature environment, and investigate the sealing performance of the equipment under low-temperature environment.

2. Analysis on gas sealing methods of sulfur hexafluoride electrical equipment

Sealing methods of hexafluoride electrical equipment include static sealing and dynamic sealing [8]. Static sealing refers to sealing between two static surfaces, and sealing gaskets are used for sealing mainly, such as sealing between two flange surfaces. Dynamic sealing refers to sealing between relative moving parts, which is divided into reciprocating dynamic sealing, rotary dynamic sealing and compound motion sealing. For example, the sealing between dynamic contact draw bar and the equipment belongs to compound motion sealing.

Equipment sealing structure, sealing method, sealing requirements and interrelation among the whole equipment, sub-package parts and components-sealing reciprocal diagram should be comprehended in details during supervision and inspection when sulfur hexafluoride electrical equipment is installed and after the equipment is put into operation. The equipment state should be consistent with actual operation condition as far as possible during sealing test. The sub-package parts or components can be tested if it is difficult to test the sealing performance of the whole equipment. The relationship between the allowable leakage rate of the sub-package parts or components and gas leakage rate of the equipment should be determined according to the sealing reciprocal diagram. For example, the sealing reciprocal diagram of a three-phase single-pressure porcelain knob circuit breaker produced by one manufacturer is shown in figure 1.



1- arc extinguish chamber; 2- arc extinguish chamber; 3- transmission case; 4- strut porcelain bushing; 5- operation draw bar;
A- phase A breaker; B- phase B breaker; C- phase C breaker; D- control cabinet;
a,b,c,d- O -shaped sealing ring; e,f,g-gas pipeline

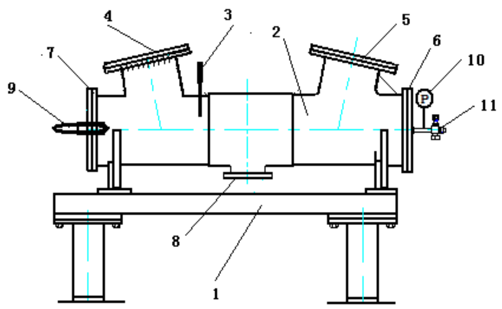
Figure 1. Sealing reciprocal diagram of sulfur hexafluoride circuit breaker.

3. Sealing and leakage test of sulfur hexafluoride electrical equipment under low-temperature environment

3.1. Low temperature sealing test of tested device

Figure 2 shows that a tank circuit breaker without casing was adopted as the tested device (effective gas volume is 250L). Flange sealing surfaces 4, 5, 6 and 7, gas charging and discharging connecting part 11, pressure gauge connecting part 10, temperature sensor 3 and breaking-closing connecting part 9 (the sealing structure is similar to that listed in figure 2) were selected for sealing test. The qualified O-shaped sealing ring was installed in the sealing groove according to the requirements of the installation technology indoors in the test (ambient temperature was between 15 and 25 ℃), and the bolt was evenly tightened to meet the tightness requirements after the sealing blind flange was installed. Then, sulfur hexafluoride gas with certain pressure was filled to the tested device. Qualitative leak detection method by quantitative leak detector and binding method were adopted for testing the sealing performance of the tested device after the device was placed statically for 12h. The tested device was pushed outdoors (the temperature was lower than -30 ℃) and maintained outdoors for 24h, and then its sealing performance was tested under low temperature. The gas leakage rate under low temperature was increased compared with that under normal temperature. However, it should not be higher than the allowable leakage rate by three times. The device was switched on and off for 50 times respectively under low temperature after the sealing test was finished. Then, the sealing performance was tested again, and the gas leakage rate of the breaking-closing connecting part should be the same as the original value.

The device was moved back indoors after the low temperature sealing test was finished. The sealing performance was tested again 48h later. Then, the device was pushed outdoors again and maintained for 24h, and the sealing performance was tested again under low temperature. The results of the tested device in low temperature sealing test are shown in table 1.



1- braced frame; 2- tested device body; 3- temperature sensor; 4, 5, 6, 7, 8-flanges of sealing junction surfaces;
9-breaking-closing connecting part; 10 - pressure gauge connecting part; 11- gas charging and discharging connecting part

Figure 2. Device for low temperature sealing test.

Table 1. Results of tested results in low temperature sealing test.

Ambient Temperature (℃)	Gas Temperature in the Equipment (℃)	Leakage Test Methods	Sulfur Hexafluoride Gas Concentration (μL/L)									
			Parts for Leakage Test									
			3	4	5	6	7	8	9 (close)	9 (break)	10	11
17.5 to 21.0	17.5 to 20.5	Qualitative leak detection method by quantitative leak detector	0	0	0	0	0	0	0	0	0	0
		Binding method	0	0	0	0	0	0	0	0	0	0
-32.2 to -38.5	-34.5 to -37.5	Qualitative leak detection method by quantitative leak detector	0	0	0	0	0	0	0	0	0	0
		Binding method	0	0	0	0	0	0	0	0	0	0
18.5 to 21.0	17.5 to 20.9	Qualitative leak detection method by quantitative leak detector	0	0	0	0	0	0	0	0	0	0
		Binding method	0	0	0	0	0	0	0	0	0	0
-33.5 to -37.5	-34.8 to -37.0	Qualitative leak detection method by quantitative leak detector	0	0	0	0	0	0	0	0	0	0
		Binding method	0	0	0	0	0	0	0	0	0	0

3.2. Low temperature sealing and leakage test of sulfur hexafluoride electrical equipment in service
The sealing performance of sulfur hexafluoride electrical equipment is always affected by low-temperature environment in winter, wherein the equipment is operated outdoors. The sealing defect of the equipment will be highlighted especially in the environment with temperature lower than -30 ℃. Therefore, 1500 sets of outdoor sulfur hexafluoride electrical equipment underwent sulfur hexafluoride gas leak detection analysis according to the natural condition of low ambient temperature in winter. The tested equipment was classified according to different equipment manufacturers, equipment types, sealing structures and sulfur hexafluoride gas inflation pressures. The distribution of 35 gas leakage points was analyzed, wherein the leakage points were discovered in the test. The test results showed that the gas leakage points were mainly discovered on flange sealing surface, dynamic sealing connecting part, density relay connecting part, tank weld sand holes, porcelain insulator cracks, etc. in the tested sulfur hexafluoride electrical equipment such as porcelain knob circuit breaker, tank circuit breaker, transformer, GIS, etc. Lower leakage was discovered in some leakage points when the ambient temperature was higher, which even cannot be discovered. However, the leakage was increased, and even safe operation of the equipment was affected under low temperature environment. For example, when a 500kV sulfur hexafluoride circuit breaker was operated at the winter environmental temperature of less than -30 ℃ for 5 hours only, the gas pressure thereof was decreased from 0.43Pa to 0.35MPa. The leakage was discovered in flange facing at the top of the circuit breaker according to inspection as shown in figure 3.

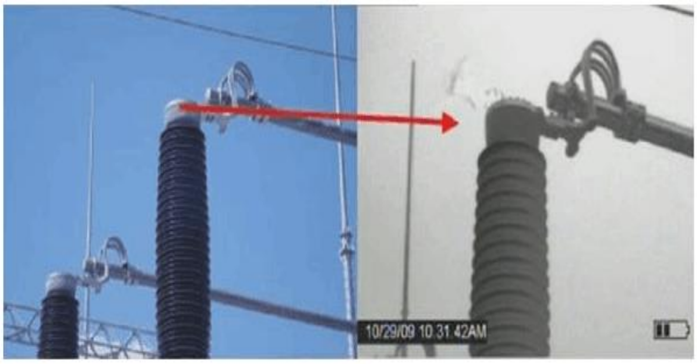


Figure 3. Infrared imaging figure of sulfur hexafluoride gas leakage test.

4. Analysis on gas leakage reasons of sulfur hexafluoride electrical equipment under low temperature environment
The sealing performance of sulfur hexafluoride electrical equipment is always affected by low-temperature environment in winter, wherein the equipment is operated outdoors. The results of electrical equipment in sulfur hexafluoride gas leakage test showed that the gas sealing performance stability of electrical equipment under low temperature was determined by the following factors.

4.1. Compression ratio of sealing ring
O-shaped sealing ring is installed in the sealing groove. An initial compression should be reserved in order to ensure its sealing performance. The pre-compression is also different corresponding to sealing surfaces with different cross section diameters in different applications. Generally speaking, the initial compression of the O-shaped sealing ring is approximately 15% ~ 30% under static sealing in a self-tight sealing structure [9], which is about 9% ~ 25% in dynamic sealing. Different requirements are proposed for the compression of O-shaped sealing rings aiming at metal-metal flange sealing and metal flange-porcelain sealing. Rational compression of O-shaped sealing rings can be controlled according to table 2 generally when the sealing ring hardness is within the scope of 65-75 in shore hardness.

Table 2. Compression ratio of O-shaped sealing ring.

Sealing Mode	Material of Sealing Surface	Compression Ratio (%)
Static sealing	Metal - metal flange	25
	Porcelain insulator - metal flange	30
Dynamic sealing and lateral sealing	Metal shaft- metallic sheath	12

The requirements of dynamic sealing assembly and requirements of controlling rotation friction resistance of motion axis are considered. Larger value should not be taken for the compression ratio of dynamic sealing, which can be limited at 12% or so generally. O-shaped sealing ring is applied for dynamic sealing since dynamic sealing has lower compression ratio, and the sealing performance of the sealing ring is poor, which should not be used in key parts.

The sealing ring for sulfur hexafluoride electrical equipment is made of G22B EPDM generally [10]. The compression ratio of the sealing ring should be controlled between 25 and 30% during design of the sealing groove. The compression ratio should be determined according to the material of the sealing surface and working ambient temperature, and the stability of the sealing performance can be affected due to too high or too low compression ratio. Rubber elasticity decreases with temperature drop, which will become vitreous if the temperature is lower than -60 ℃, thereby losing flexibility completely. The reaction of normal force vertical to the sealing surface will be formed by the atmospheric pressure in the sealing ring on the sealing ring, it can be offset by the elastic force, the sealing force will be reduced, which even can be zero or less than zero, and leakage is caused when the ambient temperature is lower if the compression ratio is lower. The compression permanent deformation will be increased when the compression ratio is too large, and the service life of the sealing ring can be reduced as a result. When the depth of the sealing ring along the circumference is not consistent, or the thickness of the sealing ring along the circumference is not uniform, too high or too low compression ratio of the sealing ring can be caused locally, thereby affecting the sealing performance stability of the product.

4.2. Strict control of surface roughness of equipment sealing surface

The sealing effect of the sealing structure may be affected by too high or too low roughness of the sealing surface of the sulfur hexafluoride electrical equipment. The sealing structure of the sulfur hexafluoride electrical equipment was tested. The results showed that the concentric circle formed by tool marks was beneficial for air tightness in suitable scope of surface roughness (Ra 1.6 to 6.3 μm) on the sealing surface processed by turning tool (boring tool). The rubber ring and the sealing ring were combined well in the scope of surface roughness Ra 1.6 to 6.3μm. The distance of SF_6 leakage path was increased by concentric circular knife grains, thereby the leakage was reduced. However, O-shaped sealing ring had poor sealing contact when the surface roughness exceeded Ra 12.5 μm; thereby gas leakage was caused easily. On the contrary, the 'resistance' effect of the concentric circular knife grain cannot be obtained if the rolling extrusion mirror surface was too smooth, and the air tightness cannot meet requirements.

The grinding cracks of the porcelain sealing surface ground by a grinding wheel are not closed concentric circles, but rambling and intermittent short lines. Considerable amount of grinding cracks are directed along SF_6 leakage path (radial direction). Therefore, porcelain insulator sealing is more difficult compared with that of metal sealing. The following effective measures can be adopted in order to achieve ideal sealing effect: (1) the sealing ring compression ratio is appropriately increased. (2) The roughness of the porcelain sealing surface is strictly controlled, and the roughness of the fitting surface is polished to Ra 1.6μm; (3) the dirt and porcelain powder are wiped by non-wool cloth (paper), and the sealing surface should be touched by hand without feeling of porcelain powder rolling, and the compression ratio of the sealing surface is increased properly.

4.3. Guarantee of sealing ring materials

Two indicators are mainly adopted for judging the material performance of the sealing ring aiming at sulfur hexafluoride electrical equipment, namely hardness and compressive permanent deformation [11]. The hardness of the sealing ring should be moderate. It is generally required that the Shaw hardness is 65 ~ 75, it is difficult to achieve excellent combination performance between the sealing ring and sealing surface due to too high hardness, insufficient contact pressure (sealing force) can be caused easily due to too low hardness, and excellent sealing performance cannot be achieved. The compression permanent deformation of the sealing ring should be lower than 20% within the working temperature scope (-55℃ to 80℃), and excellent sealing performance is available.

When materials of O-shaped rings are selected concretely, the compatibility with the working medium should be considered on the one hand, and the pressure, temperature, continuous working hours, operation cycle and other working conditions also should be comprehensively considered on the other hand. High-quality rubber rings should be adopted for sealing in order to prevent gas leakage. The sealing ring must have the features of oil resistance, SF_6 gas decomposition, low permanent deformation, and high compressive strength, tension and extension strength.

EPDM is characterized by good resistance to water, polar solvent resistance, acid resistance, and poor oil resistance. Its working temperature scope is - 55 ~ 125 ℃. Therefore, it can be used for sealing sulfur hexafluoride electrical equipment. 427 neoprene also can be selected in general regions (the lowest temperature of - 30 ℃), 518 nitrile butadiene rubber or G22B EPDM must be used in regions with low temperature (the lowest temperature of - 40 ℃).

If the sealing ring is made of poor materials, the sealing ring itself can be penetrated by SF_6 gas on the one hand, the sealing force can be reduced due to too large compression permanent deformation after being used for certain time even though the compression ratio is controlled within the rational scope on the other hand, and gas leakage can be caused.

4.4. Correct use of lubricating grease

Lubricating grease is required in the sealing ring for dynamic sealing generally due to demand of relative motion among sealing surfaces of dynamic sealing. Vacuum silicone must be used for dynamic sealing in SF_6 environment. Low temperature lubricating grease can be used for the sealing ring in the operating mechanism. However, lubricating grease is not used for static sealing generally. No grease can be used for cold-proof sealing rings.

4.5. Manufacturing quality of control equipment parts

Equipment parts are not accepted and inspected strictly in procurement, processing and delivery, therefore nonconforming or defective products are transferred to next procedure or delivered, thereby gas leakage is caused after installation of whole set equipment. For example, sand holes and cracks are produced on the tank and weld in sulfur hexafluoride gas chamber, performance and materials of sealing gaskets cannot meet sealing requirements sufficiently, etc. The defects can be eliminated in two aspects: firstly, manufacturers should control quality strictly in all links of production, thereby preventing delivery of substandard products. Secondly, the delivery acceptance and test should be controlled well, equipment should be accepted and tested strictly during delivery after the equipment is installed, problems can be discovered immediately, and all related parties should be assisted for perfection.

4.6. Reduction of equipment design defects

Sulfur hexafluoride gas leakage also can be caused due to improper design of the equipment. For example, the ability of bus bars to buffer temperature changes is weakened aiming at GIS buses due to irrational quantity and layout of expansion joints, the flange surfaces are dislocated, and leakage is caused. In a 220 kV porcelain knob circuit breaker, the resin materials connected with the brass pipe or the connection part between the resin material and metal material suffer from unreasonable external force, and cracks are caused due to influence of conductor dead weight, wind swinging and other factors, thereby leading to gas leakage. Many gas chambers are connected, and one density relay is shared in some equipment. Gas leakage can be caused easily as a result due to too long connection pipeline and more contacts of the equipment. When leakage accidents occur, it is difficult to discover the leakage points due to the connection mode. Meanwhile, many gas chambers decompress as a result, thereby leading to greater hidden danger to safe operation of the equipment.

4.7. Strict control of equipment installation process and installation quality
Site installation quality of sulfur hexafluoride electrical equipment is a key factor to determine the sealing performance thereof [12]. On-site construction personnel must be familiar with GIS technology data and design drawings, make clear the relevant technical requirements and quality standards, and implement the requirements and standards in the construction strictly in order to ensure the equipment installation quality.

5. Conclusion
The sealing performance of sulfur hexafluoride electrical equipment worsens when it is operated under low temperature environment. The reasons are investigated, namely the low temperature resistance performance of equipment sealing materials is poor, equipment installation defects are exposed under low temperature, or the installation process and quality of equipment are not controlled well under low-temperature environment, etc. The follows are concluded through sealing performance test of sulfur hexafluoride electrical equipment:

(1) Natural environment in the substation installation region must be fully considered for selecting sulfur hexafluoride electrical equipment. Equipment inflation pressure, sealing structure and sealing materials should meet the requirements of equipment gas sealing performance.

(2) Sulfur hexafluoride electrical equipment should not be installed or disassembled for overhaul treatment under low temperature generally. The equipment can be installed or treated under the guidance of equipment manufacturers due to requirements on construction schedule or because the defects must be treated under low temperature.

(3) The construction organization should be scientific and rigorous for installation of sulfur hexafluoride electrical equipment and overhaul engineering. The recovery time of equipment disassembly should be shortened as far as possible.

(4) The sealing ring must be made of 518 nitrile butadiene rubber or G22B EPDM. Its compression ratio is controlled at 30%, and the lubricating grease cannot be used.

(5) Corresponding measures must be equipped for resisting wind, dust and snow. Installation personnel should wear gauze masks to prevent exhalant water vapor from condensation inside the equipment and on the sealing ring, thereby avoiding influence on sealing performance of equipment and gas humidity in the equipment.

(6) The integrity of the sealing surface with waterproof glue injection slots and exposed fastener waterproof glue should be inspected comprehensively before winter is coming. The sealing surface with poor gumming should be filled carefully. Water accumulated in the slots should be dried by blowing, thereby preventing rainwater freezing in winter, expansion force, deformation of sealing ring due to extrusion, invalid bolt pre-tightening force and gas leakage in the sealing surface, or the basin-type insulator is also partially forced by expansion force, and cracks are caused, thereby leading to gas leakage in the sealing surface.

(7) The gas leakage points should be checked and handled completely before winter is coming aiming at equipment with gas leakage, therefore sudden increase of gas leakage rate under low temperature and threat on safe operation of the equipment can be avoided.

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