

Using SF₆ analysis for condition based maintenance of circuit breakers and gas insulated substations

Historical Background

Sulfur hexafluoride was first synthesized in the laboratories of the Faculté de Pharmacie de Paris in 1900 by Moissan and Lebeau. Fluorine, which had been obtained by electrolysis, was allowed to react with sulfur in a strongly exothermic reaction: $S + 3F_2 \rightarrow SF_6 + 262 \text{ kcal}$. This reaction is still used for the production of SF₆ today.

The first research into industrial applications was done by the General Electric Company in 1937 when they realized that the gas could be used for insulation in electrical equipment. In 1939 Thomson-Houston patented the principle of using SF₆ for insulating cables and capacitors. Application of SF₆ to circuit breakers would follow in the 1940's. The story of the earliest experiments of switching arcs in an atmosphere of SF₆ at Westinghouse can be found in the Lingal, Browne, and Strom patent applied for in 1951.

Large scale industrial production of SF₆ was developed in the late 1940's and early 1950's. By the late 1950's large scale commercialization of SF₆ manufacture for use in electrical plant construction coincided with the appearance of the first SF₆ circuit-breakers for high voltages and extra high voltages.

Through the 1960's, a number of designs of high voltage SF₆ circuit breakers became available. These were predominantly the "two-pressure" designs, in which a relatively low-pressure was used for insulation, and a high-pressure system was used to interrupt the current. As the experience with SF₆ in high voltage circuit breakers grew, the manufacturers introduced "single-pressure" designs and improved sealing techniques, greatly reducing leakage rates.

Today SF₆ is in use in medium voltage circuit breakers, ring main units, contactors, HV circuit breakers, EHV circuit breakers, gas insulated substations and power transformers.

Advantages and Disadvantages of SF₆

Sulfur hexafluoride has several properties that make it a preferable dielectric fluid.

It is a very good insulating medium. It has 2.5 times the breakdown strength of air and at pressures greater than three bar, it has greater breakdown strength than mineral oil. Because of the high electron affinity of fluorine, use of SF₆ raises the inception voltages for partial discharges.

It is a very good arc quenching medium. With SF₆, the high electron affinity of fluorine coupled with the abundance of fluorine in any discharge path provides for a strong interaction with high

energy electrons. This makes SF₆ about 100 times more efficient at arc quenching than air.

SF₆ is inert. SF₆ is non-flammable. Temperatures on the order of 500°C or electrical discharges are required to initiate dissociation and possible reactions. Fortunately, in the absence of any other species, the dissociation products of SF₆ naturally combine to reform SF₆ (see Figure 1). SF₆ is self-healing. This does not happen with other dielectric fluids.

SF₆ is an excellent heat transfer medium. The heat transfer coefficient for SF₆ is superior to air and improves with increasing pressure. At sufficient pressures or flows the heat transfer coefficient of SF₆ is superior to mineral oil.

SF₆ is non-toxic gas. This is attractive from a health and safety perspective.

Unfortunately, owning and operating SF₆ filled equipment is not trouble free. There are concerns about safety, the environment, the quality of gas supply and the equipment condition that can arise. Several practices to manage concerns are well established but require clear identification of the concern. Analysis of the insulating fluid can play an important role in this identification.

Environmentally, SF₆ has proven to be one of the most potent greenhouse gases. Its warming potential is 23,900 times greater than CO₂. In an effort to reduce the impact of SF₆ on environmental change, regulations to limit releases and other losses have been promulgated around the world. Many utilities now maintain detailed inventories of their supplies that allows them to report annual losses. Leakage and inaccurate records from the handling of gases account for most of the losses.

Safety concerns about arc by-products arise when chemical species other than SF₆ become involved in discharges within the equipment. When it becomes necessary, special handling is required for the gas and special procedures are required for the equipment.

Sources of SF₆ have proliferated in recent years. Some of the sources are not specific for electrical insulation, but have been supplied into electrical equipment, nonetheless. In response to environmental concerns, services for reprocessing of SF₆ have developed in several markets. The quality of reprocessing has been inconsistent. Uncertain quality of supply increases the risk of safety issues and the risk of shortened service life for equipment containing it.

Like mineral oil, the use of sulfur hexafluoride does not cause equipment to be maintenance free. For equipment that is not sealed, there is a need to develop a life management program. High voltage and extra high voltage circuit breakers should be evaluated for wear out and failure modes. Gas insulated substations and SF₆ transformers should be evaluated for failure modes.

Today, services are available to help utilities manage SF₆ gas and SF₆ filled equipment by characterizing the gas and diagnosing the equipment condition. These services are very similar to those associated with mineral oil.

The Chemistry of In-Service SF₆

In the absence of an electrical discharge or extreme heat (>500°C), SF₆ is chemically inert. When a discharge occurs, fluorine atoms on the SF₆ may capture an electron and dissociate from the sulfur. When the discharge has ended, under ideal circumstances, each dissociated fluorine loses the captured electron and recombines with a dissociated SF_x species to reform SF₆ (Figure 1). This is the 'self-healing' or regenerative property of SF₆. Regardless of circumstances, this is the predominate reaction occurring in SF₆ filled high voltage electrical equipment.

A discharge does not result in each SF₆ in the discharge path being completely dissociated. Instead, a distribution of dissociation products is formed that looks something like the distribution shown in Figure 2. The amplitude of the distribution is determined by the duration of the discharge and the composition of the distribution is determined by the energy of the discharge. Discharge durations and energies can vary considerably (Figure 3).

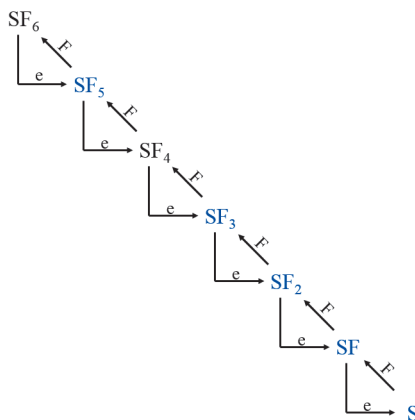


Fig. 1. The dissociation and reformation pathway of SF₆

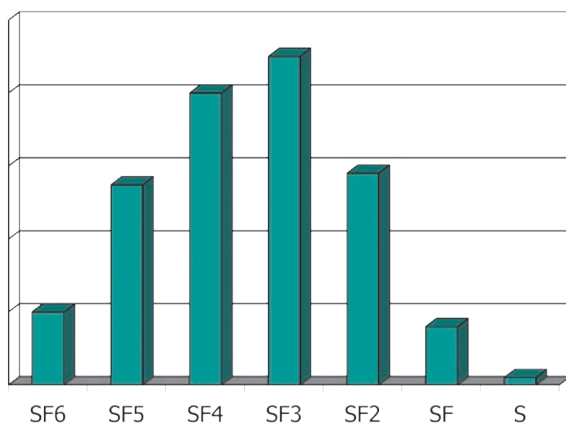


Fig. 2. Distribution of SF₆ dissociation species in a discharge

Type	Occurrence	Characteristics
Partial Discharge	Electrically floating component Free conducting particles	0.01 – 0.001 J 10 ² – 10 ⁴ Hz
Spark	Capacitive discharge Disconnect switch	0.010 – 100 J a few μs duration
Arc	Breaker switch In-service fault	10 ⁵ – 10 ⁷ J 50 – 150 ms

Fig. 3. Durations and magnitudes of discharge in SF₆

If oxygen, in the form of H₂O or O₂, is available to participate in the discharge, a new set of intermediates and products can be formed (Figure 4). The species shown in blue are highly reactive intermediates that do not persist. The products SOF₄, SOF₂, SO₂F₂ and SO₂ are stable species that provide diagnostic information about the discharge activity in the equipment. They are also toxic and when present create the need for special handling practices.

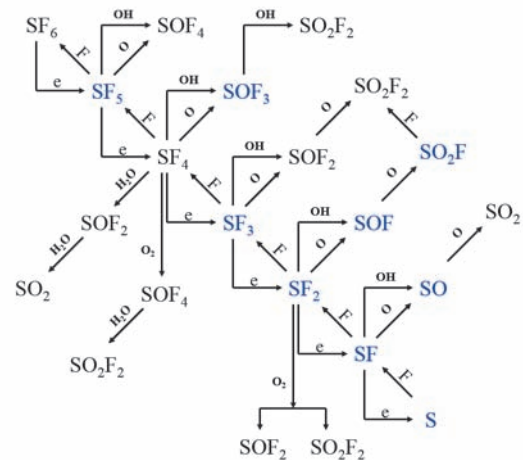


Fig. 4. SF₆ dissociation, reformation and reaction with contaminant O₂ and H₂O

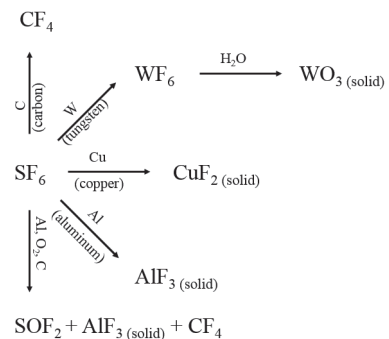


Fig. 5. Arc products formed from solid materials in circuit breakers

Solid materials within the equipment may also become involved in discharge reactions. In circuit breakers, carbon from Teflon® interrupter components, copper and tungsten from contacts and aluminum from shields are typically involved (Figure 5).

The solid products that are formed in these reactions are finely divided powders. Since they are toxic and very easily inhaled, they require special handling.

It is important to understand that the progress of many of these reactions is dependent upon the available O₂ and H₂O.

Sources of Contaminant Air

Oxygen and moisture are contaminants introduced from the atmosphere. In spite of the best efforts to eliminate contamination, some oxygen and moisture will inevitably be found in SF₆ filled equipment. Minimizing the levels of these contaminants is critical for minimizing the formation of the by-products shown in Figure 4. Because some of these by-products have deleterious effects on other materials found in the equipment, minimizing their abundance is critical for optimizing life.

Broadly, there are two ways by which these contaminants are introduced into SF₆ filled equipment: One is by incomplete removal of atmospheric gases from the equipment prior to filling with SF₆. The other is by ingress through leaks.

Prior to commissioning, equipment that will be filled with SF₆ is filled with air. Moisture in the air will adsorb onto all of the interior surfaces of the equipment. To a lesser degree moisture and oxygen will diffuse into the porous structure of materials like Teflon®. In preparation for commissioning, vacuum is applied to remove the air and moisture. Regardless of the effectiveness of this processing, some amount of atmospheric gas will remain. The amount of remaining moisture is much greater. In some applications, it is common to use desiccant bags to absorb the remaining moisture.

When there are leaks, ingress of air and moisture leads to the greatest levels of contamination. It is a common misconception that air or moisture cannot enter a leaking SF₆ compartment as long as the SF₆ pressure is above atmospheric pressure. In fact, it is the difference between the internal partial pressure and the external partial pressure of an individual gas that determines whether there will be a net flow for that gas. Graham's Law of Effusion describes the rate of ingress through a small hole (Figure 6).

$$Z_w A_o = p A_o / (2\pi m k T)^{1/2}$$

Where Z_w = Collision frequency per unit area
 A_o = Leak area
 p = differential partial pressure of the gas
 m = mass of the gas atom or molecule
 k = Boltzman constant
 T = temperature of the gas

Fig. 6. Rate of effusion according to Graham's Law

Oxygen, nitrogen, moisture and other atmospheric gases will effuse into the equipment until their individual partial pressures inside the equipment are equal to their partial pressures in the atmosphere. This is a state that can be attained more or less quickly depending on the size of the opening at the leak site. The total gas pressure in the equipment will be the sum of air and SF₆. In leak-

ing equipment that has had repeated additions of SF₆ to return the pressure to five atmospheres, the mixture of gases will become four atmospheres of SF₆ and one atmosphere of air gases.

Analysis of SF₆

Analysis of SF₆ gas samples are routinely performed to determine SF₆, SOF₄, SOF₂, SO₂F₂, SO₂, CF₄, COS, CO₂, WF₆, O₂, N₂, H₂O, CCl₂F₂, and H₂ concentrations. This analysis provides information necessary to assess the condition of the gas and with an understanding of the reactions and reaction conditions provides the basis to assess the condition of the SF₆ filled equipment.

Analysis of many thousands of samples has led to the successful development of condition based maintenance programs for SF₆ filled circuit breakers, gas insulated substations and other SF₆ filled equipment.

Field Sampling

Obtaining a representative sample is essential for any analytical testing process to yield meaningful results. In SF₆ analysis, contamination of the sample with air and moisture or corruption of the sample by reactions with sampling equipment are critical issues. Special sampling equipment and procedures have been developed to address these issues. The containers are fabricated from stainless steel because of its chemical inertness to SF₆ decomposition products (Figure 7). These containers are dried and evacuated before being sent into the field. Special fittings are used for each type of equipment.

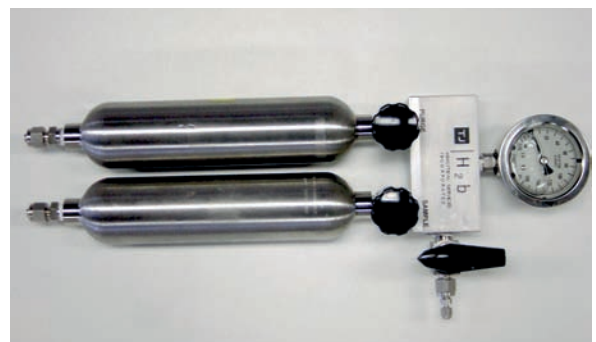


Fig. 7. Gas Sample Collection Unit (GSCU)

Application of SF₆ Analysis

The circuit breaker in Case 1 is a 161 kV, 2000 amp, SF₆ single pressure, live tank unit with a true spring operating mechanism. The breaker is operated 2 to 3 times per day to connect a 168 MVAR capacitor bank. On September 20, 1997, a remote dispatcher operated the breaker. Pole 2 failed to clear, resulting in operation of the overcurrent and breaker failure relay. The operation of these relays isolated the bus section that feeds the circuit breaker. After the clearance, the dispatcher was able to remotely energize the bus section. This failure did not result in a rupture of the interrupter.

Circuit Breaker

Compound	Pole 1	Pole 2	Pole 3
SF ₆ Sulfur Hexafluoride	998191	995848	996190
N ₂ Nitrogen	964	649	2917
O ₂ Oxygen	341	136	638
CF ₄ Carbon Tetrafluoride	504	3365	255
SOF ₂ Thionyl Fluoride	ND	1	ND
CO ₂ Carbon Dioxide	ND	1	ND

The breaker was visually inspected for damage. All gas pressures were normal. The spring assembly was recharged after the last close operation. All tests, insulation, timing, function and contact resistance were made with satisfactory results. Nothing indicated a problem with the breaker.

Gas samples were collected from all three poles. The high content of CF₄ in pole 2 indicated erosion of Teflon®. It was decided to remove the gas from the breaker and visually inspect the interrupter. Pole 2 showed arcing between the shields of the moving and stationary contacts. The arcing was not contained within the arcing contact area. Pole 2 interrupter was replaced.

Case 2

Gas Insulated Substation

Equipment	SF ₆	N ₂	CF ₄	CO ₂	SOF ₄	H ₂
Bus Segment 26	825686	173657	184	255	8	210
Bus Segment 31	820579	178674	329	254	17	146

This gas-insulated substation shown in Case 2 was constructed in conjunction with a co generation plant at a petroleum refinery and chemical manufacturing facility. The refinery developed an in-house sampling and testing program. Using their program, they successfully identified an active partial discharge emanating from a void in a gas barrier in a segment of the bus. In 1997, they decided to expand their program and contracted for a complete and more thorough survey of their system.

Samples were collected from each gas-filled component, and several were identified for further investigation. Bus segments 26 and 31 were found to be interesting, for several reasons. First, the nitrogen levels were unusually high. Investigation found that the GIS components had been filled with dry nitrogen for transport. The proportion of nitrogen to sulfur hexafluoride was what would be expected if these components had not been evacuated prior to filling with SF₆.

Next, the presence of SOF₄ indicated partial discharge. This was not unexpected, given their previous experience. Finally, the presence of H₂ and CO₂ were completely unexpected. Investigation into the materials used revealed that cast epoxy insulation was used around the conductors as well as in the gas barriers. Sometimes in the casting process, small voids can occur in the epoxy. These small voids can become sites for small discharges that can lead to formation of dendritic discharge patterns known as 'treeing'. Over time this partial discharge leads to the failure of the insulator. The presence of H₂ and CO₂ are consistent with this mechanism.

Potential Transformers

Equipment	SF ₆	N ₂	O ₂	CF ₄	CO ₂	SOF ₄	SO ₂	H ₂
Potential Tx 1	990622	7646	1203	90	391	6	11	31
Potential Tx 2	994538	4025	860	76	406	5	16	74

Similar to the bus segments, these potential transformers contained gases that indicated partial discharge and the involvement of materials that could yield H₂ and CO₂. The materials used in the construction of these devices has yet to be identified. The GIS components identified for further investigation are scheduled to be inspected at the next regular maintenance.

The unit shown in Case 4 (Figure 8) was manufactured in 1980. The unit is a live tank design. Each pole is equipped with its own operating mechanism and is set up for three pole trip and close operation. One phase had a history of leaking. Analysis of gas from this phase revealed that air was contributing approximately twenty percent of the total pressure. Oxygen and moisture were reacting with every operation and had reacted extensively for some time. The progress of the gas deterioration was accompanied by considerable deterioration of Teflon®. On inspection, this phase was found to be damaged (Figures 9, 10). The other two phases, which were leak free and saw the same duty, showed no apparent damage (Figure 11).

Case 4

245 kV Live Tank Circuit Breaker Pole 2

Compound	ppm
SF ₆ Sulfur hexafluoride	670011
N ₂ Nitrogen	144898
O ₂ Oxygen	44409
CF ₄ Carbon tetrafluoride	8719
CO ₂ Carbon Dioxide	18174
SO ₂ F ₂ Sulfuryl Fluoride	3445
SO ₂ Sulfur Dioxide	109812
COS Carbonyl Sulfide	533
H ₂ O Water	180



Fig. 8. Case 4
Live Tank Circuit
Breaker

Conclusion

Much like dissolved gas analysis, DGA, of mineral oil samples for oil filled equipment, analysis of SF₆ gas samples can provide detailed information about the wear out and failure modes for gas filled equipment.

A carefully designed testing program will cost effectively improve safety and reliability while reducing the detrimental effects of SF₆ in the environment.

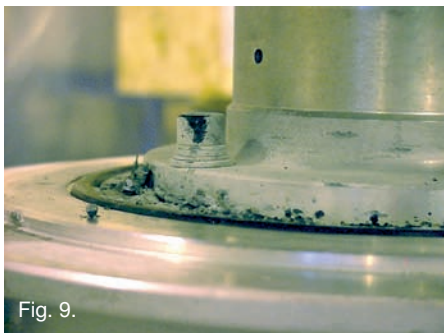


Fig. 9.



Fig. 10.

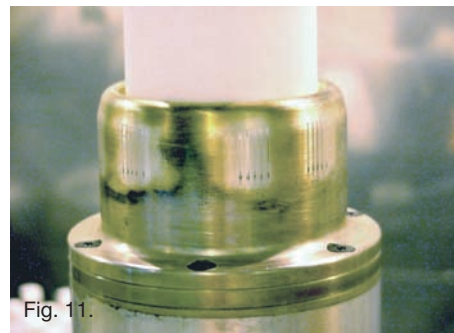


Fig. 11.

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TJ|H2b Analytical Services (Poland) sp. z o.o.

Al. Wojciecha Korfańtego 191
40-153 Katowice
tel.: +48 (32) 733 66 76 - 78
fax: +48 (32) 730 30 03
e-mail: polandlab@tjh2b.com
www.tjh2b.com



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