Study on the Correlation between Partial Discharge Energy and SF$_6$ Decomposition Gas Generation

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Abstract: In this paper, the amount of SF$_6$ decomposition gases due to the partial discharge (PD) was studied in the SF$_6$ gas-insulated transformer. The long-term PD degradation experiment was performed while controlling the discharge magnitude using the surface discharge, and the gas generation amount was measured by using gas chromatography for SO$_2$F$_2$, SOF$_2$, SO$_2$, CO, and CF$_4$. In addition, to investigate the relationship between the partial discharge energy and the decomposed gas generation amount, partial discharge energy was calculated by a data processing program and converted to the unit of joule per mole. With the finite element method (FEM), the electric field distribution and SF$_6$ gas decomposition mechanism were explained for the partial discharge energy effect on the gas generation. This study helps understand the relationship between the partial discharge energy and the decomposed gas generation ratio with the experimental results and can be used for the diagnosis of PD and maintenance process for the gas-insulated transformers.

Keywords: partial discharge energy; decomposed components; gas chromatography; gas-insulated transformer

1. Introduction

SF$_6$ gas has been used broadly for different types of power apparatus due to its excellent insulation ability since the start of gas circuit breakers in 1930s. The SF$_6$ gas has also been used for gas-insulated transformers (GIT) since the 1950s [1]. GIT is non-combustible because it is composed of composite insulation using SF$_6$ gas and solid insulators. As well as it is suitable for the fire hazard prevention required for underground substations, it has merits in many aspects, such as preventing environmental pollution, preventing pollution around work, preserving and repairing buildings, and compacting buildings. Since 2003, 55 Banks of GIT (165 units on a single-phase basis) have been installed and operated in underground substations (20 locations) in Korea. Though failure reports with partial discharge are increasing accordingly, the regular inspections are just being applied due to the lack of reliable diagnosis standard for GIT.

The gas analysis standard for the oil-immersed transformer (OIT) has been established for the diagnosis of degraded oil since 1982 and regular checks for the health of transformers have been performed using it, but it has not been established for GIT [2]. In the case of OIT, gases are extracted from the insulating oil, and an analysis is mainly performed using the photoacoustic spectroscopy method. The feature gas has its own absorption wavelength band and the absorbed energy from the light source causing a local heating and a thermal expansion which create a pressure wave or noise. With the acoustic detection, it is possible to identify the gas type and its concentration [3,4]. Since the GIT has different insulation material and gas generation characteristics from the OIT, the gas analysis standard for GIT needs to be established in the near future.
analysis standard of OIT cannot be directly applied. Therefore, the degradation characteristics of insulating materials have been applied to the GIT by the thermal degradation and the partial discharge degradation. However, in this case, the gas generation mechanism should be identified. For the stable operation of GIT, establishing the gas diagnosis standard and the maintenance procedure are urgently required in the engineering field. For this reason, it is necessary to grasp the decomposed gas generation characteristics by overheating and partial discharge defects through long-term overheating and discharge degradation experiments. In this paper, we focused on the partial discharge diagnosis by measuring the decomposed gas increase trend. The decomposed gases from SF₆ have been studied under various conditions, such as spark [5], arc [6], and partial discharge [7] in SF₆ gas-insulated electrical equipment [8]. In addition, some papers have investigated the defect classification method by analyzing the composition ratio of decomposed gases [9]. Nevertheless, it has limits in the suggestion of generalized diagnostic criteria due to the non-standard shape of discharge structures and a fixed applied voltage for each defect model. To overcome the limitations, the relationship between discharge energy and decomposed gas production have been studied in this paper. The featuring gas generated by the long-term partial discharge degradation experiments of the GIT was extracted and the gas generation rate according to the partial discharge energy was analyzed for establishing the diagnostic standards and maintenance procedures.

2. Partial Discharge Degradation and Measuring System

In a long-term degradation experiment, it is not easy to control the discharge state arbitrarily. The electrode oxidization and the physical and chemical change of the insulator surface during partial discharge occur, which make it difficult to maintain a constant partial discharge state. In addition, there are limitations on the discharge pattern, such as the discharge magnitude and repetition period according to the type of defects. For example, the discharge characteristic for the needle electrode shows a small partial discharge magnitude and lots of partial discharge pulses relatively. On the other hand, the particle discharge has a small discharge magnitude and a relatively sparse discharge pulse. In addition, it is difficult to sustain discharge for a long time in the case of floating discharge. Therefore, surface discharge was adopted and applied to long-term degradation in this paper, which is relatively easy to control and has a wide range of discharge magnitude.

The partial discharge degradation experiment system was set as shown in Figure 1. A capacitive voltage divider was used to measure the applied voltage, and a coupling capacitor was for the partial discharge signal measurement. To measure the species and the amount of decomposed gases due to the partial discharge degradation, the gas was extracted from the test cell and injected into the gas chromatography (GC) device (7890B Agilent). The featuring gases detected by the GC implemented in this study are SOF₂, SO₂F₂, SO₂, CF₄, and CO, and the limitation of precision was under 1ppm. The gas was extracted from the test cells after the discharge of 2, 6, 24, 48, and 72 h, and the gas component change was measured using gas chromatograph equipment. The CF₄ gas was not generated in this experiment, and major changes were mainly observed in S-series gas (SO₂F₂, SOF₂, SO₂) and CO. To generate the surface partial discharge, a 2 L-volumed test cell filled with 1 bar of SF₆ gas was used and a glass insulator was placed between the high-voltage electrode-applied AC voltage and plane-grounded electrode, as shown in Figure 1.

To record the discharge degradation process for a long time, discharge magnitude and voltage data measured by the IEC 60270-based partial discharge detector and a voltage meter were monitored through Data Acquisition System (DAS) (LabVIEW NI PXle-1071) [10]. A measurement program was designed to check the discharge state with a 10 M/s sampling rate and the partial discharge signal was superimposed 30 times for each time as shown in Figure 2.
Figure 1. (a) Schematic diagram of the partial discharge experiment, the measuring system and (b) the test cell.

Figure 2. A measurement program with a 10 M/s sampling rate for saving the partial discharge information.

3. SF₆ Decomposition Mechanism under Partial Discharge

The SF₆ decomposition mechanism under partial discharge is important to explain the reason for the rise of the decomposed gas amount during the partial discharge for each species. When partial discharge occurs in the SF₆ gas environment, it is decomposed into low fluorine sulfides and F atoms such as SF₅, SF₄, and SF₃. Most of them return to SF₆ gas after a while, but some react with the H₂O and O₂ impurities inevitably present inside the device to produce a decomposition gas that maintains a stable state for a relatively long time, such as SOF₂, SO₂F₂, and SO₂. In this paper, we focused on the effect of the partial discharge magnitude variation on the amount of decomposed gas generation, and further tried to reveal the relationship between the discharge energy and the mechanism for generating decomposition gases.

The three-zone model is widely cited as a model explaining the process of decomposition of SF₆ gas by partial discharge, which is composed of the glow region, ion drift region, and the main gas region [11]. In this paper, it is divided into two regions, the high energy region and the low energy region, for the understanding of the decomposition mechanism as shown in Figure 3. The high energy region is a relatively high electric field area in which the ionization and excitation of SF₆ gas mainly due to electron collision, the recombination of fragment species, oxidation reaction by the H₂O and O₂ of SF₆ fragments, and the loss due to diffusion are actively occurring. Though these are the most important and complex reactions for decomposed gas generation, the volume of the high energy region is relatively small. The electrons lose energy by collision and disappear by attachment outside this region. The boundary between the two regions was suggested based on (E/N)c in this paper where
(E/N)_c is the critical electric field to gas density at which the ionization rate equals that of attachment. The (E/N)_c value for SF₆ gas at 300 K is approximately 350 Td. The value is independent of temperature and pressure under 1500 K [12].

In the following reaction formula, the reactions in the high energy region are expressed as (1)–(10), and the reactions in the low energy region, (11)–(14). SO₂F₂ is mainly generated in the high energy region by the oxidation reaction of SF₂ as (6) and (7). Therefore, SO₂F₂ is affected by the partial discharge energy directly. On the other hand, SOF₂ is composed mostly in the low energy region by the hydrolysis reaction of SF₄ as (13).

\[
\begin{align*}
SF_6 + e &\rightarrow SF_X + (6 - X)F + e \\
SF_5 + O &\rightarrow SOF_4 + F \\
SF_5 + OH &\rightarrow SOF_4 + HF \\
SF_3 + O &\rightarrow SOF_2 + F \\
SF_3 + OH &\rightarrow SOF_2 + HF \\
SF_2 + O &\rightarrow SOF + F \\
SO_2F + F &\rightarrow SO_2F_2 \\
SF_2 + OH + F &\rightarrow SOF_2 + HF \\
H_2O + e &\rightarrow OH + H \\
O_2 + e &\rightarrow O + O \\
SOF_2 + H_2O &\rightarrow SO_2 + HF \\
SOF_4 + H_2O &\rightarrow SO_2F_2 + 2HF \\
SF_4 + H_2O &\rightarrow SOF_2 + 2HF \\
SF_2 + O_2 &\rightarrow SO_2F_2 
\end{align*}
\]

![Figure 3. The two regions of decomposed gas generation by partial discharge and test cell.](image-url)
4. Results

4.1. Decomposed Gas Generation According to the Partial Discharge

Figure 4 shows the measured concentration of SO$_2$F$_2$, SOF$_2$, SO$_2$, and CO for each partial discharge degradation condition. The gas amount tends to increase proportionally as the discharge magnitude increases. One of the things to pay attention to is the increasing rate of SOF$_2$ and SO$_2$F$_2$. The initial gap of the generation rate of SOF$_2$ and SO$_2$F$_2$ gas is small, but SOF$_2$ increases gradually at a relatively high rate. It can be explained that the reactions for SOF$_2$ are in the low energy region and the reactions for SO$_2$F$_2$ are in the high energy region as mentioned above. SO$_2$F$_2$ is produced by the oxidation reaction of SF$_2$ and the hydrolysis reaction of SOF$_4$, which is mainly produced by the oxidation reaction, closely related to the discharge energy. On the other hand, SF$_4$ are initially generated in the high energy region and diffuse to the surroundings, and the reactions for SOF$_2$ occur in the low energy region after sufficient diffusion. Therefore, the different volume of the region plays an important role in the different generation rates between SOF$_2$ and SO$_2$F$_2$. Though SOF$_2$ gas also reacts with H$_2$O to convert to SO$_2$ gas in the low energy region, the possibility is relatively low. In some papers, the amount of SO$_2$F$_2$ was measured to be higher than that of SOF$_2$ in the gap defect experiments, but this trend could not be observed in this paper [13].

Figure 4. Concentrations of SO$_2$F$_2$, SOF$_2$, SO$_2$, CO of (a) 100 pC, (b) 1000 pC, (c) 3000 pC, and (d) 10,000 pC.

Figure 5 shows the concentrations of the decomposed gases according to the partial discharge magnitude. From this result, CO shows a clear tendency, but it is not suitable as a feature gas because it also increases due to other factors such as thermal degradation.
The partial discharge energy was also evaluated by using the saved discharge data and compared to the decomposed gas data. The discharge was measured by overlapping 30 times with 10 M/s sampling and the discharge energy was calculated by using the average discharge magnitude ($Q_{\text{ave}}$), the number of discharges ($N_{\text{pulse}}$), and the instantaneous voltage ($V$) for each time as

$$E_{\text{PD}} = 0.5 \times Q_{\text{ave}} \times N_{\text{pulse}} \times V \ [\text{J/hour}] \ (15)$$

The discharge characteristics of each time are shown in Figure 6. It shows the trend of discharge energy during the long-term discharge degradation process. As can be seen here, it is necessary to evaluate the representative discharge energy from the discharge data for each hour, since the discharge characteristics are not constant with time and have large variability. In addition, Figure 6 shows the discharge energy accumulated over time. Though we acquired both partial discharge energy and decomposed gas amount data, it is difficult to explain the increase trends in the decomposed gas amount from the total input energy alone. The tendency varies depending on the gas pressure, discharge chamber size, defect type and electrode shape. Therefore, this study intends to analyze the correlation between the input discharge energy and the amount of gas generation over time through the gas generation mechanism and experimental results. To find the correlation between the input energy and gas generation, the calculation process was performed as shown in Figure 6.

**Figure 5.** Concentrations of the decomposed gases according to partial discharge magnitude (a) $SO_2F_2$, (b) $SOF_2$, (c) $SO_2$, and (d) CO.
4.2. Partial Discharge Energy Calculation

From the experimental results, the decomposed gases started to be detected when the input energy was approximately 0.2 J. To understand what this value means, the input energy was converted to $E_{\text{mol}}$, of which the unit is Joule per mole:

$$n = \frac{p}{1.035 \times 10^{-19}T}$$

$n$: density [$\text{cm}^{-3}$]
$p$: pressure [Torr]
$T$: temperature [K]

$$E_{\text{mol}} = \frac{E_c}{n \times \text{vol}/N_A}$$

$E_c$: cumulative partial discharge energy [J]
$\text{vol}$: high energy region volume [$\text{cm}^3$]
$N_A$: Avogadro constant ($6.02 \times 10^{23} \text{ mol}^{-1}$)

In this paper, the volume of the high energy region was calculated by integrating a region with a higher electric field value than the critical electric field to gas density of $\text{SF}_6$, which is about 350 Td at 1 bar and 300 K. In the experiments, a 1000 pC discharge state was sustained when the applied voltage was 15 kV, and we used the input boundary conditions to conduct the electric field analysis using the finite element method (FEM) as shown in Figure 7. The high energy region can be defined where the electric field strength is over the critical electric field to gas density, whereby a volume of 0.00765 ($\text{cm}^3$) can be obtained here.
From (17), the obtained value of $E_{mol}$ is about 643 kJ/mol, which is enough energy required for the decomposition of SF$_6$ gas in the reference paper [14]. The bond dissociation energy of SF$_5$-F is about 400 kJ/mol. The average energy of active electron under corona discharge is 5–10 eV (1 eV = 96.48 kJ/mol) which is enough to dissociate SF$_6$.

As shown in Figure 8, the decomposed gases’ increasing trend for SO$_2$F$_2$, SOF$_2$, and SO$_2$ can be related to the cumulative partial discharge energy by the summation of various degradation condition results. It was found that the gas amount increases linearly according to the cumulative energy. The saturation trend was also observed in the high cumulative energy range, which may be due to the insufficient discharge chamber volume for the high partial discharge experiments. We confirmed a continuous linear increase in gas amount without saturation in the large discharge chamber.

![Figure 7](image1.png)

**Figure 7.** Finite element method electric field result (1000 pC, 15 kV applied). (a) electric field distribution, (b) high energy region.

![Figure 8](image2.png)

**Figure 8.** Cont.
5. Conclusions

In this paper, the decomposed gas generation by partial discharge effect was studied for the diagnosis of GIT. SO$_2$F$_2$, SOF$_2$, and SO$_2$ were adopted as the feature gases and measured using the GC system during long-term surface partial discharge degradation. Though the decomposed gases from SF$_6$ have been studied under various discharge conditions, including suggestions of the defect classification method by analyzing the composition ratio of decomposed gases, it is still limited in its application to the actual diagnosis of GIT. In order to establish the diagnostic standards, it needs a generalized relationship between PD and decomposed gas generation. For this purpose, the decomposed gases’ increasing trend for SO$_2$F$_2$, SOF$_2$, and SO$_2$, according to the cumulative partial discharge energy, was investigated in this paper. The generalized estimation of discharge degradation was made possible by using the correlation between the discharge energy and the decomposition gas generation from this research, which will improve the reliability of GIT diagnosis. Additionally, to verify the meaning of the critical energy value which starts to generate the decomposed gas, the conversion of energy unit to energy per mole was conducted using the electric field analysis with FEM and ideal gas law. We also tried to explain the trend of experimental results by the reactions needed for each species’ generation in the high energy region and low energy region with a gas generation mechanism. The application for diagnosis will be suggested with the additional research of the partial discharge degradation of insulators in GIT, such as PET film and pressboard in detail in future studies.

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