Decomposing Mechanism of SF$_6$ under Positive DC Partial Discharge in the Presence of Trace H$_2$O

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ABSTRACT: The influence of H$_2$O on SF$_6$ decomposition characteristics under positive DC partial discharge (PD) is significant. To evaluate PD fault severity in DC SF$_6$-insulated equipment using the production characteristics of SF$_6$ decomposition components, the corresponding relationship and mathematical expression between the production of SF$_6$ decomposition components and the H$_2$O content should be identified and achieved. Thus, SF$_6$ decomposition experiments under positive DC PD are performed to reflect the influence of H$_2$O on SF$_6$ decomposition components. Results show that the total discharge quantity and the discharge repetition rate averaged for 1 s decrease slightly when the H$_2$O content increases from 0 to 970 ppmv and then increase when the H$_2$O content increases from 970 to 5120 ppmv. The effective production rates of SO$_2$F$_2$, SOF$_2$, and SO$_2$ increase with the H$_2$O content, whereas that of SOF$_4$ decreases. Finally, the corresponding relationship and mathematical expression between the characteristic ratio ($c$(SO$_2$F$_2$) + $c$(SOF$_4$))/$c$(SOF$_2$) + $c$(SO$_2$)) of components and the H$_2$O content have been achieved, which can afford references for PD fault diagnosis in DC SF$_6$ gas-insulated equipment.

1. INTRODUCTION

SF$_6$ insulation devices, such as gas-insulated switchgear (GIS), are quite important to guarantee the safe operation of power systems, which are usually applied in high-voltage alternating current (AC) or direct current (DC) transmission lines. However, in a long-running SF$_6$ insulation device, partial discharge (PD) will occur inside the equipment and decompose SF$_6$ into several low-fluorine sulfides. In the presence of trace H$_2$O and O$_2$, these byproducts of SF$_6$ would further react with these impurities, thus accelerating the decomposition process, and some characteristic gases including SOF$_4$, SO$_2$F$_2$, and SOF$_2$ would be generated. Previous studies have shown that the production rate and characteristic ratio of SF$_6$ decomposition species are closely related to the type of fault and severity of PD inside the devices. Thus, the analysis of decomposition components is a workable approach to evaluate the insulation status of SF$_6$ insulation devices.

It has been reported that the potential SF$_6$ decomposition species are significantly impacted by the content of H$_2$O inside a device. Up to now, many studies have been conducted to analyze the influence of H$_2$O on the SF$_6$ decomposition mechanism under AC PD. Refs 12–14 revealed that the generation of SO$_2$F$_2$ and SOF$_2$ would be facilitated with the increase of the H$_2$O content. Zeng proposed that the relationship between $c$(SO$_2$F$_2$)/$c$(SOF$_4$) and the H$_2$O content follows the formula $f(x) = 0.27/(1 + (x/1921.33)^{1.11}) + 0.27$. When it comes to the SF$_6$ decomposition mechanism under DC PD, there have been some studies that indicate that the production of SO$_2$F$_2$ and SOF$_2$ would be largely enhanced under negative DC PD, and ref 17 showed that oxyfluoride production would not be very sensitive to the variations of H$_2$O concentrations at levels below 1%. However, few studies focused on the influence of H$_2$O on the SF$_6$ decomposition mechanism under positive DC PD. Thus, the relationships between SF$_6$ decomposition components and the H$_2$O content remain unclear, which may impact the diagnosis accuracy and validity of the faults inside the devices. According to IEC 60480-2005 and IEC 60376-2008 standards, the H$_2$O content in SF$_6$ gas should be controlled under 750 ppmv in an operating GIS, but the threshold value may be exceeded after long-term operation even when H$_2$O removal measures are taken, which may be due to the slow release of H$_2$O from the inner solid materials or the diffusion of H$_2$O from outside when the equipment is poorly sealed.

Therefore, to fully understand the influence of different trace H$_2$O contents on SF$_6$ decomposition characteristics under DC PD, a series of simulation SF$_6$ decomposition experiments with different trace H$_2$O contents were conducted on a needle–plate electrode model; the model is used to simulate metal protrusion defects. Simultaneously, the production and production rate of SOF$_4$, SO$_2$F$_2$, SOF$_2$, and SO$_2$ with discharge time were obtained and analyzed in detail, including PD quantities, PD repetition...
rate, and characteristic production ratio. The results and deduction provide an experimental and theoretical basis for inner defect fault diagnosis and PD severity evaluation in SF₆ insulation equipment using the characteristics of SF₆ decomposition.

2. RESULTS AND DISCUSSION

2.1. Influence of Trace H₂O on the Process of Positive DC PD. The results of PD quantities and PD repetition rates are shown in Table 1. In this table, Nᵢ is the average value of PD repetition rates, Nᵢ = (\sum_{i=1}^{10} N_i) / 10, and Nⱼ is the pulse number of each sampling (1 s). Qᵢ is the average value of the total discharge quantity of all pulses, Qᵢ = (\sum_{i=1}^{10} (\sum_{j=1}^{N_i} Q_{j}) / 10, and Qⱼ is the single pulse discharge quantity. Qᵢav is the average value of single pulse discharge quantity, Qᵢav = Qᵢ / Nᵢ. Additionally, the total discharge quantity of pulses (>100 pC, Qt₁₀₀) and their pulse numbers Nᵢ₁₀₀ are calculated.

As shown in Table 1, Qᵢ and Nᵢ slightly decrease with the increase of water vapor below 970 ppmv, and then gradually increase as the water vapor increases from 970 to 5120 ppmv. Qᵢav, Qᵢ₁₀₀, and Nᵢ₁₀₀ continue to increase as the H₂O content increases. Some relevant results are consistent with those by Wang et al., who suggests that the average discharge quantity decreases from 550 to 100 pC when the H₂O content increases from 69 to 473 ppmv.

According to the Townsend theory and streamer theory, the electric field near the tip region is seriously distorted as the electric field and promote streamer size. Moreover, high-energy electrons affect SF₆ molecules more and cause further ionization, as shown in reaction II

\[
\text{SF}_6^- \rightarrow \text{SF}_6^- + e^- \quad (I)
\]

\[
\text{SF}_6^- + e^- \rightarrow \text{SF}_6^+ + e_i^- + e_e^-, \quad x \leq 5 \quad (II)
\]

where eᵢ⁻ represents scattered electrons and eₑ⁻ stands for ejected electron; SF₆ decomposes into SF₆⁻ when S=F bonds are broken. The new electrons promote the electron avalanche and streamer channels; positive ions at the head of the streamer channel enhance the electric field and promote streamer size. However, part of electrons are adsorbed by electronegative gases, such as SF₆⁻. The reaction is shown as follows

\[
e + \text{SF}_6 \rightarrow \text{SF}_6^- \quad (III)
\]

The discharge amplitude and the repetition rate in the discharge process are influenced by the electric field, initial electrons, gas properties (which affect the electron-avalanche growth of discharge), gas pressure, gas temperature, discharge polarity, and so on. However, they are mainly due to gas properties and initial electrons if H₂O diffuses into pure SF₆ in a relatively stable experimental environment. As reported, the effective ionization coefficient of the SF₆/H₂O mixture is different from that of pure SF₆ or pure H₂O. The approximation formulas for α (electron impact coefficient) and η (electron attachment coefficient) of a gas are given as

\[
\alpha = (N/v_q) \int_0^\infty Q_i \cdot f(v) \, dv \quad (1)
\]

\[
\eta = (N/v_q) \int_0^\infty Q_i \cdot f(v) \, dv \quad (2)
\]

where N is the number of gas molecules per unit volume and Qᵢ and Qᵢav are the electron-impact ionization cross section and electronic collision adherent section, respectively. Moreover, effective ionization coefficients of binary gas mixtures are shown as follows

\[
\alpha_m = \alpha_{H_2O} \cdot k + \alpha_{SF_6} (1 - k) \quad (3)
\]

where \(\alpha_{H_2O}, \alpha_{SF_6}\) and \(\alpha_{H_2O}\) are the effective ionization coefficients of pure H₂O, pure SF₆, and the mixture gas, respectively, and k is the volume fraction of H₂O. Therefore, the effective ionization coefficient of mixed gas changes slightly, which therefore does not exert a great effect on the formation and development of the electron avalanche.

In fact, the effect of H₂O on PD is primarily due to the probability of initiating electron generation in the SF₆/H₂O mixture. Van Brunt has reported that the initial electrons of PD mainly result from the ionization of SF₆⁻ to form SF₆. However, some initial electrons are generated via reaction IV when trace H₂O is added to pure SF₆. In that case, the hydrated clusters SF₆⁻(H₂O)ₙ (n = 1, 2, ...) are formed by the combinations of SF₆⁻ and the H₂O molecule, which are stable and hard to ionize. Therefore, the PD strength will be reduced, and the total discharge quantity (Q) and repetition rates (Nᵢ) decline slightly when the H₂O content is lower than 970 ppmv, as shown in Table 1.

\[
\text{SF}_6^- (H_2O) \rightarrow \text{SF}_6^- + nH_2O + e^- \quad (IV)
\]

Besides, it has been reported that the negative clusters, such as H₂O⁻, (H₂O)⁺, and O₂(H₂O)⁻, could enhance discharges because of the electrons they release. These negative ions are formed by the adsorption of low-energy electrons from the surroundings, which are unstable and easily ionized by the collision of SF₆⁻ molecules. The releasing process of electrons is presumed as

\[
\text{SF}_6^- + H_2O^- \rightarrow \text{SF}_6^- + H_2O + e^- \quad (V)
\]

\[
\text{SF}_6^- + (H_2O)_n^- \rightarrow \text{SF}_6^- + nH_2O + e^- \quad (VI)
\]

Then, the PD is promoted when the H₂O content increases.

The electron energy, pulse amplitude (means discharge quantity), and discharge repetition rates increase accordingly. Thus, Qᵢ and Nᵢ increase when the H₂O content increases from 970 to 5120 ppm, as seen in Table 1. The existence of H₂O molecules affects PD and SF₆ decomposition at the microlevel. The trace H₂O in dry SF₆
can also be decomposed by the collision of high-energy electrons. Generation reaction processes are simulated and analyzed by density functional calculations with the Dmol3 module, as shown in Table 2. From this table, we can see that the higher the H2O content, the larger the production of H2O+, O, OH, and other unknown particles in different energy states, which may result in the promotion of SOF4, SO2F2, SOF2, and SO2 production eventually. These main reactions are shown in Figure 1.

2.2. Production of SOF4 and SO2F2. Since SOF4 and SO2F2 have some pathways to be formed from SF6 with trace H2O, the relationship between the content of these two gases would be significant to analyze the influence of trace H2O on the decomposition mechanism of SF6. The production of SOF4 presents an approximately linear and negative trend with the H2O content, as illustrated in Figure 2, whereas the production of SO2F2 presents an approximately exponential trend, as shown in Figure 3.

2.3. Production of SOF2 and SO2. The influences of H2O on SOF2 and SO2 production characteristics are shown in Figures 4 and 5, respectively. Regardless of the H2O content, SOF2 and SO2 increase obviously with time increasing, and their range of increase expands when the H2O content increases. SOF2 production increases by 2.2-fold when the H2O content increases from 23 to 5120 ppmv.

As shown in Figure 1, SF3 and SF2 can react with O or OH to generate SOF4, as reaction (h), and SOF4 is consumed due to the hydrolysis process, as reaction (i). Its consumption rate is lower than its production rate due to its lower hydrolysis reaction rate \( (k = (1.0 \pm 0.3) \times 10^{-21} \text{ s}^{-1}) \), and the difference between the production rate and consumption rate decreases when the H2O content increases. In that case, the accumulated production of SOF4 decreases as the proportion of the SF6/H2O mixture increases at the same discharge time and it drops down to zero approximately when the H2O content increases to 5120 ppmv.

On the other hand, as a result of reaction (f), the SO2F2 production rate gradually increases for the sustaining PD; although the total discharge quantity \( Q_t \) and PD repetition rates \( N_t \) decrease slightly when the H2O content range is 23–970 ppmv, the production of SO2F2 is not high. However, reaction (f) indicates that SO2F2 is generated from SF3 or SF2 upon interaction with O2, which is a new important pathway when the H2O content increases from 970 to 5120 ppmv. The following may be the reasons, the production ratios of SF3 and SF2 to SF6 increase when the H2O content is higher than 970 ppmv and the electron energy is sufficient for SF6 to decompose extensively because large-amplitude PD pulses, \( Q_{-100} \), are generated gradually, as shown in Table 1. Especially, the production of SO2F2 per unit time increases dramatically as the H2O content is 5210 ppmv. The accumulated production of SO2F2 continues to increase with discharge time as DC PD is generated steadily and SF6 decomposition proceeds continuously.

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2.3. Production of SOF2 and SO2. The influences of H2O on SOF2 and SO2 production characteristics are shown in Figures 4 and 5, respectively. Regardless of the H2O content, SOF2 and SO2 increase obviously with time increasing, and their range of increase expands when the H2O content increases. SOF2 has an approximately exponential growth trend with increased H2O, whereas SO2 presents a linear growth trend. SOF2 production increases by 2.2-fold when the H2O content increases from 23 to 5120 ppmv, and that is approximately 13 times the SO2 production under the same conditions.

Analysis of the results shows that when the H2O content is low, SOF2 is mainly generated from the combination of SF6 with H2O, as reaction (g) in Figure 1. Specifically, part of SF6 molecules spread into an ion-drifting area or the main gas volume (where E/N is low) and form into SOF2 with H2O, while they fail to combine with O and OH in the ionization area. In addition, when the H2O content increases, PD is generated with

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Table 2. Reaction Path of H2O Decomposition

| no. | reactions | reaction heat (kJ·mol⁻¹) |
|-----|-----------|-------------------------|
| 1   | \( \text{H}_2\text{O} + e^- \rightarrow \text{H} + \text{OH}^- + e^- \) | 377.6 |
| 2   | \( \text{H}_2\text{O} + e^- \rightarrow \text{H}^+ + \text{OH}^- + e^- \) | 508.0 |
| 3   | \( \text{H}_2\text{O} + e^- \rightarrow \text{H}_2\text{O}^- \) | 200.1 |
| 4   | \( \text{H}_2\text{O} + e^- \rightarrow \text{H} + \text{OH}^- + e^- \) | 507.9 |
| 5   | \( \text{H}_2\text{O}^- \rightarrow \text{H} + \text{OH}^- + e^- \) | 288.2 |

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Figure 1. Schematic of SF6 decomposition reactions under DC PD.

Figure 2. Production of SOF4 varying with trace H2O contents.

Figure 3. Production of SO2F2 varying with trace H2O contents.

Figure 4. Production of SOF2 varying with trace H2O contents.

Figure 5. Production of SO2 varying with trace H2O contents.
accumulated production of SO$_2$ would be much lower than that increases, its consumption rate would be increased, and the OH particles.

and the high hydrolysis reaction rate ($k = (1.2 \pm 0.3) \times 10^{-21}$) of reaction (g) promote the production of SOF$_2$. Piemontesi$^{28}$ has proposed a similar result that SOF$_2$ production increases 33-fold when the H$_2$O content changes from 280 to 4100 ppmv. Similarly, Van Brunt$^{30}$ has proposed that the $R_{RMS}$ of SOF$_2$ is greater than that of SOF$_2$ when the H$_2$O content ranges from 150 to 9500 ppmv under AC PD. In fact, regardless of whether the experiment is with dry SF$_6$ or the same content, whereas the $R_{RMS}$ of SOF$_4$ decreases. The results indicate that the order of the effective production rate is SOF$_2$ > SOF$_2F_2$ > SOF$_4$ > SO$_2$ when the H$_2$O content exceeds 23 ppmv. The $R_{RMS}$ of SOF$_4$ is close to the $R_{RMS}$ of SO$_2$ when the H$_2$O content is 5120 ppmv. Similarly, Van Brunt$^{30}$ has proposed that the $R_{RMS}$ of SOF$_2$ is greater than that of SOF$_2$ when the H$_2$O content

large-amplitude PD pulses, high discharge quantity, and high discharge repetition rate, and a large amount of SF$_6$, SF$_2$O, and OH would be produced. Hence, reaction (c) in Figure 1 would be much easier, which is an important and effective way to generate SOF$_2$. At the same time, the sufficient supply of H$_2$O and the high hydrolysis reaction rate ($k = (1.8 \pm 0.9) \times 10^{-19}$) of reaction (g) promote the production of SOF$_2$. Piemontesi$^{28}$ has proposed a similar result that SOF$_2$ production increases 33-fold when the H$_2$O content changes from 280 to 4100 ppmv under negative DC PD with a pulse current of 50 $\mu$A and total discharge quantity of 6 C.

Meanwhile, SO$_2$ is the reaction product of SOF$_2$ and H$_2$O, as shown in reaction (d) in Figure 1, and its production may increase slowly when SOF$_2$ production is low, where the hydrolysis reaction rate is extremely low ($k = (1.2 \pm 0.3) \times 10^{-21}$).$^{27}$ Furthermore, SO$_2$ can also be hydrolyzed to H$_2$SO$_3$, as shown in reaction (e) in Figure 1. When the H$_2$O content increases, its consumption rate would be increased, and the accumulated production of SO$_2$ would be much lower than that of SOF$_2$.

Therefore, the production of SOF$_2$, SOF$_2F_2$, SOF$_4$, and SO$_2$ changes significantly because of the various contents of trace H$_2$O, and with the increase of the H$_2$O content, the production of SOF$_2$, O, and OH under DC PD would be much more complex as well, which can also affect the interactions among SF$_6$, O, and OH particles.

The production of SF$_6$ decomposition components is the accumulated results of decomposition in a certain discharge time under a certain discharge quantity level, whereas the production rate is an obvious and essential piece of information to acknowledge the development trend of PD. Therefore, the effective production rate $R_{RMS}$ defined in ref 29 is also considered as a characteristic quantity of DC PD fault diagnosis and severity evaluation in this work, expressed as

$$R_{RMS} = \sqrt[10]{\sum_{i=0}^{10} ((C_{i+1} - C_i)/\Delta t)^2}$$

where $C_{i+1} - C_i$ is the difference in adjacent contents of decomposition components, $C_0$ is the initial content of components in new SF$_6$, and $\Delta t = 1$ h.

As shown in Figure 6, the $R_{RMS}$ of SOF$_2$, SOF$_2F_2$, and SO$_2$ keep a sustained and approximate linear growth trend with the H$_2$O content, whereas the $R_{RMS}$ of SOF$_4$ decreases. The results indicate that the order of the effective production rate is SOF$_2$ > SOF$_2F_2$ > SOF$_4$ > SO$_2$ when the H$_2$O content exceeds 23 ppmv. The $R_{RMS}$ of SOF$_4$ is close to the $R_{RMS}$ of SO$_2$ when the H$_2$O content is 5120 ppmv. Similarly, Van Brunt$^{30}$ has proposed that the $R_{RMS}$ of SOF$_2$ is greater than that of SOF$_2$ when the H$_2$O content ranges from 150 to 9500 ppmv under AC PD. In fact, regardless of whether the experiment is with dry SF$_6$ or the same experimental platform in ref 31 under DC PD, the production rate of components is in the order SOF$_2$ > SOF$_2F_2$ > SOF$_4$ > SO$_2$.

SF$_6$, as the main fluorine–sulfur compound generated during PD (SF$_4$ and SF$_3$ are unstable and easily recombine into SF$_6$ or SF$_4$ with the F atom), has a lower combination efficiency with H$_2$O outside of the ionization area compared with that with O in the ionization area. However, the amount of combination with H$_2$O is more sufficient than that with O when the H$_2$O content is high; then the $R_{RMS}$ of SOF$_4$ is the most significant and the $R_{RMS}$ of SO$_2$ is the lowest. In addition, when the H$_2$O content is 23 ppmv, the gas mixture can be seen as dry and SOF$_2$ hydrolysis is inefficient. Thus, the production rate of SOF$_4$ is higher than that of SOF$_2$. At the same time, the effective production rate of SOF$_2$ will decrease when the H$_2$O content increases because the hydrolysis reaction conditions are gradually satisfied. However, the production of SOF$_4$ still cannot exceed that of SOF$_2$.

If we ignore the influence of trace H$_2$O on the production rate of DC PD, $R_{RMS}$ will cause misjudgment on discharge fault diagnosis and severity evaluation. Hence, it is essential to reveal the intrinsic relationship between H$_2$O contents and the effective production rate of SF$_6$ decomposition components. By data fitting, the effective production rates of SOF$_2$, SOF$_2F_2$, and SOF$_4$ are

Figure 4. Production of SOF$_2$ varying with trace H$_2$O contents at different times.

Figure 5. Production of SO$_2$ varying with trace H$_2$O contents at different times.
SOF2 and SO2 under different H2O contents are expressed as follows

\[ f_{\text{SOF2}}(x) = 1.148 + 6.595 \times 10^{-4}x - 1.7 \times 10^{-7}x^2 + 2.652 \times 10^{-11}x^3, \quad R^2 = 0.980 \]

\[ f_{\text{SO2}}(x) = 0.86258 - 1.264 \times 10^{-4}x, \quad R^2 = 0.912 \]

\[ f_{\text{SOF2}}(x) = 0.73965 + 5.209 \times 10^{-4}x - 2.5 \times 10^{-7}x^2 + 3.862 \times 10^{-11}x^3, \quad R^2 = 0.983 \]

\[ f_{\text{SO2}}(x) = 0.088315 + 6.116 \times 10^{-5}x - 6.0 \times 10^{-9}x^2, \quad R^2 = 0.92 \]

where \( x \) is the H2O content, and, respectively, \( f_{\text{SOF2}}(x), f_{\text{SO2}}(x), f_{\text{SOF2}}(x), \) and \( f_{\text{SO2}}(x) \) are relevant effective production rates.

**2.4. Production Ratios of SF6 Decomposition Components.** The production rates of SF6 decomposition components with trace H2O under PD can effectively represent the severity of discharge faults.32 Because SOF2 and SOF4 as well as SO2 and SO2 have the same formation pathway during SF6 decomposition, the former (SOF2 and SOF2) and latter (SOF2 and SO2) two gases are considered as a group to analyze the severity of the insulation faults. Thus, the ratio \( (c(\text{SOF2}) + c(\text{SO2})) / (c(\text{SOF4}) + c(\text{SO2})) \) is determined in this paper. In most cases, a smaller volume fraction ratio \( (c(\text{SO2F2}) + c(\text{SO2})) / (c(\text{SO2F2}) + c(\text{SO2})) \) is worse for the PD.

The curves in Figure 7 reveal significant and corresponding relationship between H2O contents and characteristic ratios at different discharge times. One can find from this figure that regardless of the H2O content, the characteristic ratio does not change considerably as the discharge time increases, which means the ratio of SF6 decomposition components reaches an equilibrium state. Based on this finding, the mathematical relationship of average characteristic ratio in 10 h and the H2O content is plotted in Figure 8. When the H2O content is lower than 2900 ppmv, the characteristic ratio presents a decreasing trend from 1.27 to 0.58 with increasing the H2O content, and the ratio experiences a slight increase to 0.72 when the H2O content increases up to 5210 ppm.

As shown in Table 1, the total PD quantity and average PD quantity decrease when the H2O content increases from 23 to 2900 ppmv, which indicates the deficiency of dissociation capacity that average electrons exhibit toward H2O dissociation, leading to the low production of O. From this aspect, it would be much easier for SF6 to combine with H2O and generate SOF2 compared with its combination with O to generate SOF4. Thus, the influence of H2O on SOF2 is greater than that on SOF4. In addition, the production of SOF2 (SO2) is not as high as the hydrolysis reaction products, SOF4 (SOF2), which indicates the lower influence of H2O on the former species compared with the latter ones. Therefore, the total production of SOF4 and SOF2 is greater than that of SO3F2 and SO3, resulting in the decrease of the characteristic ratio \( r \) accordingly. As the H2O content increases from 2900 to 5120 ppmv, the average PD quantity increases and large-amplitude PD pulses are generated. In that case, SF6 and SF2 are more likely to react with H2O than to react with O.33 Since H2O can exert a greater effect on the content of SOF2 than SOF4, some part of SOF2 would turn to SOF4 and increase the content of SOF2. Therefore, the sum production of SOF4 and SOF2 would be greater than that of SOF2 and SO2, leading to the increase of the characteristic ratio \( r \).

From the fitting curve shown in Figure 8, the mathematical expression is given as

\[ f(x) = 1.2793 - 0.4146 \times 10^{-3}x + 5.967 \times 10^{-8}x^2 \]

where \( x \) is the H2O content, \( f(x) \) represents the equilibrium characteristic ratio of component production, and \( R^2 \) is 0.98.

The curve can clearly and directly reflect the influence of trace H2O on the characteristic ratio \( (c(\text{SO2F2}) + c(\text{SOF4})) / (c(\text{SO2F2}) + c(\text{SO2})) \). More accurate results and references can be deduced for PD fault diagnosis in DC SF6 gas-insulated equipment if the characteristic ratio is used.

**3. CONCLUSIONS**

The investigation to evaluate the operation status of DC SF6-insulated equipment by analyzing the SF6 decomposition components is quite important. The conclusions obtained in this work are listed as follows:

(1) Owing to the new production pathway of initial electrons influenced by H2O, the total discharge quantity and discharge repetition rate averaged for 1 s of DC PD decrease slightly when the H2O content is below 970 ppm.
ppmv, and they increase gradually as the H₂O content increases up to 5120 ppmv. However, the discharge number of pulses with large discharge quantity higher than 100 pC keeps increasing with the H₂O content.

(2) The productions of SOF₂, SO₂F₂, and SO₂ increase because of H₂O and the positive effect of H₂O on SF₆ O₃ and OH production and reactions with the increasing content under DC PD, whereas the production of SOF₄ decreases because of the gradual fulfillment of the hydrolysis reaction conditions for SOF₄ to react with H₂O.

(3) The RMS of SOF₂, SO₂F₂, and SO₂ keeps a sustained and approximate linear growth trend with the H₂O content, whereas the RMS of SOF₄ decreases. The results indicate that the order of the effective production rate is SOF₂ > SO₂F₂ > SOF₄ > SO₂ when the H₂O content exceeds 23 ppmv.

(4) The characteristic ratio \((\frac{c(SOF₂) + c(SO₂F₂)}{c(SOF₄) + c(SO₂)})\) presents a decreasing trend with the H₂O content first and presents a slight increase when the H₂O content increases up to 5210 ppm; it reflects clearly and directly positive DC PD fault severity, and more accurate results and references will be achieved for PD fault diagnosis in DC SF₆ gas-insulated equipment using the characteristic ratio.

4. EXPERIMENTAL SYSTEM AND METHODS

4.1. Experimental Platform. The experimental platform for decomposing SF₆ under DC PD is shown in Figure 9, with a chamber volume of 15 L, needle electrode diameter of 4 mm, needle tip curvature radius of 0.3 mm, closed cone angle of 30°, ground electrode diameter of 120 mm, ground electrode thickness of 10 mm, and a needle−plate gap of 8 mm. The needle-plate electrodes are made of stainless steel.

When the DC voltage is applied on the needle−plate electrode in the gas chamber, the PD pulse current signals pass through the coupling capacitance (C₁) and are acquired by the electrode in the gas chamber, the PD pulse current signals are displayed and stored on a digital oscilloscope (LeCroy WavePro 7100A). Then, they are displayed and stored on a digital oscilloscope (LeCroy WavePro 7100A). The pulse current amplitudes are used to calculate the pulse discharge quantity by the impulse correction generator. Meanwhile, the contents of SF₆ decomposition components are detected by a Varian CP-3800 gas chromatograph (GC) and a QP2010 ultra gas chromatography mass spectrometer (GC/MS). The H₂O content is detected by a mirror dew point instrument (GE600), and the O₂ content is detected by an oxygen gas analyzer (HF-YF).

4.2. Experimental Methods and Scheme. To determine the influence of the H₂O content on SF₆ decomposition, six grades are defined including 0, 1000, 2000, 3000, 4000, and 5000 ppmv to simulate the real environment of SF₆ insulation devices in a long run, and the detected H₂O contents in our experiment are 23, 970, 2023, 2900, 3815, and 5120 ppmv, respectively. Other experimental parameters are kept constant: DC voltage at 30 kV (PD inception voltage: 21 kV), gas pressure at 2.0 atm, gas temperature at 25 ± 3 °C, and SF₆ purity at 99.999%. The O₂ impurity of the SF₆/H₂O mixture is controlled under 1000 ppmv (according to IEC60480). To avoid mis-discharge and possible damage to the equipment, the test voltage is boosted gradually in our experiment. That is, the test voltage will slowly and continuously rise to the vicinity of \(U₀\), which is the start of DC partial discharge, and then, the voltage will increase by 1 kV per 1 min until it rises to the test voltage. The experiment will last for 10 h because the positive DC PD is generated steadily, continuously, and time independently. The main experimental procedures are illustrated as follows, which are similar to those reported by Zeng:

(a) Clean the chamber inner wall and needle−plate electrodes with ethanol carefully before the experiment to avoid the influence of impurities. 
(b) Vacuum the chamber to eliminate the impurity; then fill it with fresh SF₆ gas. Repeat these two steps for three times to thoroughly eliminate gaseous impurities. 
(c) Inject required trace H₂O to the chamber and fill it with fresh SF₆. Detect and ensure that the contents of H₂O and O₂ satisfy the experimental requirements, or do the steps above again.
(d) Supply the DC voltage; detect PD signals and decomposition components for every hour. Each sampling time for PD is determined as 1 s.

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Notes
The author declares no competing financial interest.

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