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Green Gas for a Grid as An Eco-Friendly Alternative Insulation Gas to SF_6: From the Perspective of Partial Discharge Under AC

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Featured Application: Insulation design of gas-insulated electrical apparatus using eco-friendly green gas for a grid (g3) to replace SF_6 that causes environmental concerns.

Abstract: This paper deals with the characteristics of partial discharge (PD) in green gas for a grid (g3), which is thought to be a promising eco-friendly alternative to substitute SF_6 used in electrical power facilities and to reduce the greenhouse effect. g3 gas with 4% NOVEC^{TM} 4710/96% CO_2 was used and electrode systems including a protrusion on conductor (POC) and a protrusion on enclosure (POE) were fabricated to simulate PD in a gas-insulated structure. PD characteristics in terms of partial discharge inception voltage (PDIV), pulse parameters in time and frequency, and the phase-resolved partial discharge (PRPD) pattern in SF_6 and g3 were compared. From the results, the PDIVs of g3 were 76%–81% of that of SF_6 in the POC and were 78%–84% of that of SF_6 in the POE, depending on the gas pressure. Rising time, pulse width, and relative amplitude in the frequency domain of PD pulses in g3 gas were greater than those in SF_6. In addition, the PRPD patterns indicated that both the average apparent charge and pulse count of PD in g3 were higher compared with those in SF_6. The results from this paper are expected to provide fundamental material for the green manufacturing of gas-insulated power apparatus.

Keywords: green gas for grid; eco-friendly insulation gas; SF_6 alternative; partial discharge; discharge characteristics

1. Introduction

Insulation gases are used in electrical power apparatus such as gas-insulated switchgears (GIS), circuit breakers, and transmission lines to provide a high dielectric strength and to avoid electrical breakdown. Sulfur hexafluoride (SF_6) has been used as the most popular insulation gas since the 1960s owing to its excellent dielectric strength (approximately three times greater than air) and remarkable arc-quenching ability, making the gas-insulated facilities available at a compact size with a high reliability. In addition, SF_6 has general features of gas for high voltage insulation applications, including high heat dissipation, a low condensation temperature, low toxicity, non-flammability, and chemical stability [1–4]. However, SF_6 has significant environmental impacts owing to its high global warming potential (GWP) that is 23,500 times of that of carbon dioxide (CO_2) and its long lifetime of 3200 years in the atmosphere, whereas the lifetime of CO_2 is about 30–95 years [5]. It was reported that 1kg of SF_6 released into the atmosphere has the equivalent global warming impact as

23.5 tons of CO_2 [6]. As a result, the Kyoto Protocol designated SF_6 as one of the six greenhouse gases whose emission should be limited and must be gradually reduced by the year of 2020 [7]. It is therefore necessary to find an alternative insulation gas for green manufacturing and the application of gas-insulated power facilities.

Researchers and manufactures have carried out studies to investigate an alternative gas or gas mixture for substituting SF_6. The desirable gas or mixture is one that has the required properties for electrical insulation applications as advantages of SF_6, while having little impact on the environment. Natural gases such as dry air, CO_2, and Nitrogen have a low GWP, but a very limited dielectric strength that is only 40% of that of SF_6. The use of such gases results in a significant increase of the pressure and size of electrical facilities [8,9]. Trifluoroiodomethane (CF_3I) has been introduced as an emerging candidate that combines a high dielectric strength and lower environmental concerns. It was verified that 30% CF_3I/70% CO_2 has the best performance to replace SF_6 for GIS [10,11]. However, CF_3I is classified as a carcinogenic and mutagenic gas and is therefore not suitable for industrial applications [12]. Hydrofluoroolefins (HFOs), whose molecular formula is $C_n(H,F)_{2n}$, has a GWP lower than 9 and a good insulation performance; however, its dielectric strength is highly dependent on the gas pressure. In addition, the liquefaction temperature of HFOs is so low that gas liquefies at 0.42 MPa at room temperature. When a flashover occurs in HFOs, a carbon deposit may appear in the equipment [13,14]. Perfluorinated ketones, such as $C_5F_{10}O$, have a low GWP of 1 and a high dielectric strength. However, the boiling point of $C_5F_{10}O$ is as high as 24 °C at 0.1 MPa and it has a higher minimum operating temperature compared with SF_6 [15].

The green gas employed for a grid (g3) is an SF_6-free gas mixture introduced by Alstom and GE in the last three years as a promising candidate to replace SF_6 for high voltage applications. Its insulation performances have been investigated by analyzing the breakdown voltage under AC power frequency and lightning impulse voltage [6,14]. However, few studies have been carried out to investigate the partial discharge (PD) characteristics in g3 gas, whereas PD is at an early stage and an indicator of insulation breakdown [3,16–18].

This paper studied the insulation performance of the g3 gas mixture from the perspective of PD. Characteristics in terms of partial discharge inception voltage (PDIV), discharge pulse in the time and frequency domain, and phase-resolved partial discharge (PRPD) in g3 were compared with those in SF_6.

2. A Review of g3 Gas

g3 is a gas mixture that is composed of NOVEC^{TM} 4710 commercialized by 3M company and CO_2. Physical and chemical properties of SF_6, NOVEC^{TM} 4710, and CO_2 are shown in Table 1 [19–22]. NOVEC^{TM} 4710 cannot be used alone owing to its high liquefaction temperature, and therefore, CO_2 that has a superior arc-quenching capability is selected to make the gas mixture [23]. g3 is a promising alternative that compromises between the dielectric performance and minimum operating temperature of the electrical facility. The ratio of NOVEC^{TM} 4710 in g3 is typically from 4% to 10%.

Table 1. Physical and chemical properties of gases.

Gas	Sulfur Hexafluoride	NOVEC^{TM} 4710	Carbon Dioxide
Chemical formula	SF_6	$(CF_3)_2CFCN$	CO_2
Number of electrons	77	48	16
Relative dielectric strength to SF_6	1	>2	<0.4
Liquefaction pressure at −30°C (MPa)	0.52	0.0311	1.43
Freezing point (°C)	−51	−118	−78.5
Boiling point at 0.1 MPa (°C)	−63	−4.7	−79
Ozone depletion potential	0	0	0
Global warming potential (GWP)	23,500	2100	1
Atmospheric lifetime (year)	3200	30	5–200
Toxicity (LC 50 (rat))	>500,000	10,000–15,000	>300,000
Flammability	No	No	No
Corrosion	No	No	No

The dielectric performances of g3 were investigated by the AC breakdown test and lightning impulse breakdown test [6,14,19,24]. The AC breakdown voltage was studied in a sphere-to-sphere electrode arrangement and in a 145 kV GIS at atmospheric pressure. It was verified that the dielectric strength of pure CO_2 was lower than 40% of that of SF_6, whereas adding a small amount of NOVEC^{TM} 4710 to CO_2 resulted in a significant increase in the breakdown voltage. The lightning impulse breakdown voltage was determined by the up and down method by applying a 1.2/50 μs standard lightning impulse voltage. The dielectric performance of gas mixtures at pressures of 0.88 MPa and 1.04 MPa was equivalent to that of SF_6 at 0.55 MPa and 0.65 MPa, respectively.

As to the environmental impact, the GWP of a gas mixture can be calculated according to the Intergovernmental Panel on Climate Change and the Regulation No 842/2006 of the European Parliament and of the Council of 17 May 2006 on Certain Fluorinated Greenhouse Gases [5,25]. The 4% NOVEC^{TM} 4710/96% CO_2 has a GWP of 378, which is only 1.6% of that of SF_6 [14]. As shown in Table 1, the NOVEC^{TM} 4710/CO_2 gas mixture has an ozone depletion potential of zero. The atmospheric lifetime of NOVEC^{TM} 4710 is much shorter than that of SF_6, but much longer than some of the other alternatives, such as $C_5F_{10}O$ or CF_3I.

In addition, g3 is classified as nontoxic, non-flammable, and non-corrosive, and is not a carcinogenic and mutagenic gas [6,15]. The temperature test was conducted on the main components of GIS, such as busbar conductors, enclosures, and disconnectors, when a 3150A current flowed. It was indicated that a temperature rise difference of 5 K to 6 K was observed with respect to SF_6, which can be compensated for by adequate design improvement. The switching bus-transfer current capability test showed that the arcing time was stable over 100 close/open operations and the average arcing time in the gas mixture was about 12 ms compared with a typical value of 15 ms for SF_6 [23,24]. Therefore, g3 is an effective technique that optimizes the insulation capability and advantageous features of SF_6.

3. Experiment and Method

The configuration of the experimental setup is shown in Figure 1. The applied voltage was supplied by a dry-type transformer with a maximum output of 50 kV and 30 mA, and was measured using a high-voltage divider with a ratio of 10,000:1. The transformer was controlled by an alternative current (AC) regulator. Two types of electrode systems were fabricated to simulate typical insulation defects in a gas-insulated structure, including a protrusion on conductor (POC) and a protrusion on enclosure (POE). A high voltage was applied to the upper electrode and the lower electrode was grounded through a 50 Ω non-inductive resistor. The electrode systems were filled with SF_6 gas or g3 gas with 4% NOVEC^{TM} 4710/96% CO_2. Before each experiment, the electrode systems were vacuumed for 30 minutes by a vacuum pump with a pumping speed of 120 L/min, and were then filled with CO_2 with purity over 99.9% and vacuumed again. This procedure was repeated three times in order to prevent any pollution of gas [20]. PD pulses were measured using the detection resistor, and were acquired using a digital oscilloscope (DSO, YOKOGAWA, 5 GS/s, Tokyo, Japan) and a peripheral component interconnect eXtensions for instrumentation (PXI, National Instrument, 250 MS/s, Austin, TX, USA). PD detection was carried out in a shielding box to reduce external interference [26].

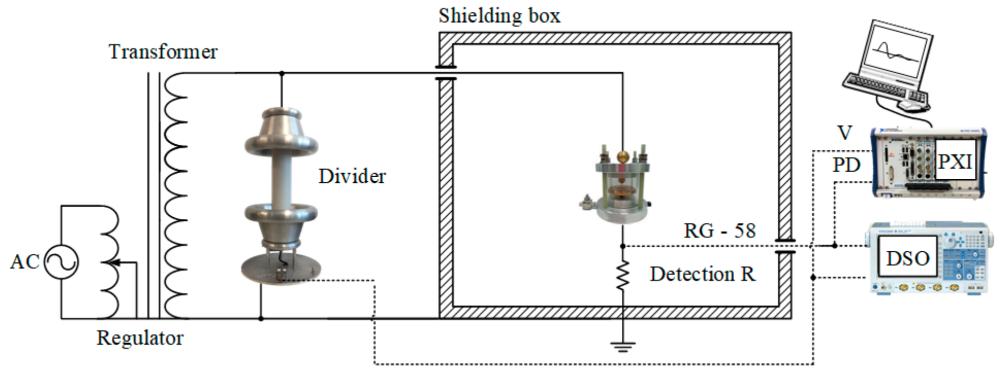


Figure 1. Configuration of experimental setup. PD: partial discharge; DSO: digital oscilloscope; PXI: peripheral component interconnect eXtensions for instrumentation.

Figure 2 illustrates the electrode systems. The POC mainly consisted of a needle electrode with a curvature radius of 10 μm and a plane electrode that was made of a tungsten–copper alloy with a diameter of 80 mm and a thickness of 20 mm. In the POE arrangement, the same needle electrode was attached to the plane electrode and a rod electrode with a curvature radius of 10 mm was used. The distance between electrodes was 5 mm and the permissible maximum gas pressure was 0.55 MPa. Before each test, the electrodes were conditioned with metal polishing paste and were cleaned carefully with isopropyl alcohol.

(**a**) (**b**)

Figure 2. Electrode system. (**a**) Protrusion on conductor (POC); (**b**) Protrusion on enclosure (POE).

In this paper, the background noise level was measured as 2.37 picocoulomb (pC). The PDIV was defined as the voltage at which discharges with a magnitude over 10 pC occurred clearly and repeatedly. The PDIV under the same condition was measured 10 times for calculating its mean value. Since discharge is a complicated process, PRPD patterns were acquired for 2 s for analyzing the average discharge magnitude, pulse count, and discharge phase.

4. Results and Discussions

4.1. Partial Discharge Inception Voltage

The PDIVs of SF_6 and g3 with 4% NOVEC^{TM} 4710 in the POC and the POE at different pressures are shown in Figure 3. It can be observed that PDIVs almost increased linearly with the gas pressure in both gases in two types of electrode systems. In addition, SF_6 had a steep increase in PDIV with gas pressure compared with g3. At the same gas pressure, the PDIVs of g3 were about 76%–81% of that of SF_6 in the POC, and were about 78%–84% of that of SF_6 in the POE. In two types of electrode systems, the PDIVs in g3 gas at 0.5 MPa were equivalent to SF_6 at 0.3 MPa. To be specific, the PDIV of 0.5 MPa g3 was 12.8 kV in the POC, whereas it was 12.7 kV in 0.3 MPa SF_6. In the POE, the PDIVs of 0.5 MPa g3 and 0.3 MPa SF_6 were 12.1 kV and 11.8 kV, respectively. Therefore, the use of g3 with 4% NOVEC^{TM} 4710 as an alternative gas to SF_6 requires an increase in gas pressure in regards to PDIV.

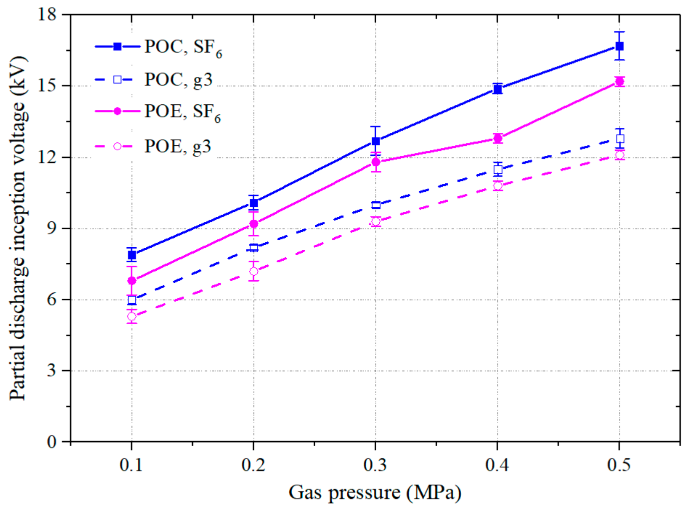
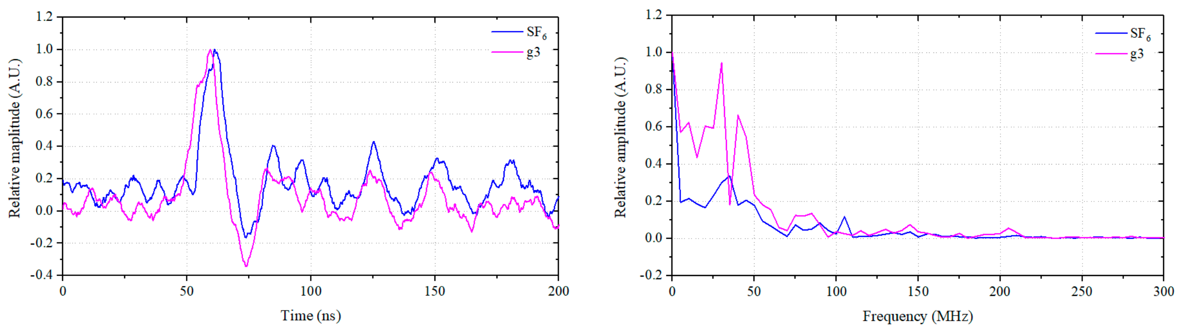


Figure 3. Partial discharge inception voltages (PDIVs) of SF_6 and g3 in the POC and POE at different pressures.

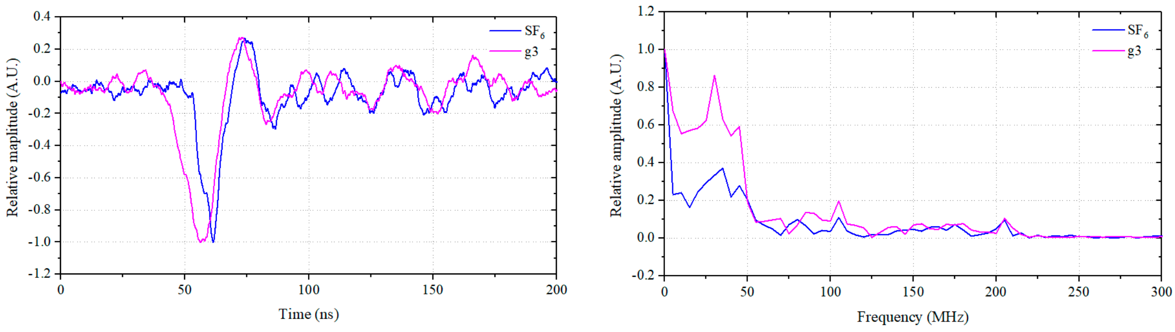
4.2. Pulse in Time and Frequency Domain

Figures 4 and 5 show a typical single PD pulse and its fast Fourier transform (FFT) in SF_6 and g3 in the POC and the POE, respectively. Parameters in terms of rising time (time period from 10% to 90% of peak magnitude), falling time (time period from 90% to 10% of peak magnitude), and pulse width (time interval between 50% of peak magnitude) in SF_6 and g3 were compared. A summary of the comparison of parameters is shown in Table 2, which were the average values extracted from 20 pulses for each case. It can be seen that pulses in the g3 gas had a relatively longer rising time and pulse width compared with the rapider rising time and shorter pulse width in SF_6. In addition, although the frequency ranges of pulses in both gases were similar, the relative amplitudes of FFT in g3 gas were much greater that those in SF_6. Possible reasons for this phenomenon were the remarkable corona stabilization effect due to the electronegativity of SF_6 and the great effective ionization coefficient of NOVEC^{TM} gas, in which discharge was suppressed and developed easily, respectively [20,27].



(**a**) (**b**)

Figure 4. PD pulse and its fast Fourier transform (FFT) in SF_6 and g3 in the POC. (**a**) In time domain; (**b**) In frequency domain.



(**a**) (**b**)

Figure 5. PD pulse and its FFT in SF_6 and g3 in the POE. (**a**) In time domain; (**b**) In frequency domain.

Table 2. Comparison of pulse parameters.

Electrode System	Gas	Rising Time [ns]	Falling Time [ns]	Pulse Width [ns]
POC	SF_6	7.81	6.46	10.24
	g3	10.50	6.04	11.21
POE	SF_6	7.04	6.06	9.10
	g3	11.90	6.66	14.12

4.3. Phase-Resolved Partial Discharge

The comparison of the average apparent charge and pulse count at different voltages in SF_6 and g3 in the POC is shown in Figure 6. Data in Figure 6 are average values extracted from the 10 PRPD patterns for each case at a gas pressure of 0.5 MPa. It was revealed that the average apparent charge and pulse count in two types of gases increased with the applied voltage. Both the average apparent charge and the pulse count in g3 were higher than those in SF_6, although PD occurred at a lower voltage level. This result can also be indicated from the PRPD patterns shown in Figure 7. Take the voltage of 17 kV as an example, where the average apparent charge and the pulse count in SF_6 were 7.15 pC and 323 N/s, respectively. However, in g3, the average apparent charge and the pulse count increased rapidly to 42.16 pC and 4378 N/s. Similar results were obtained in the POE, as shown in the figures in the Appendix A. Therefore, to achieve the same insulation ability with SF_6 for g3 from the perspective of PD, it is necessary to increase the gas pressure or increase the mixing ratio of NOVEC^{TM} 4710. From the PRPD patterns in Figures 7 and A2, the phase angle at which the discharge pulse occurred was 48°–140° in the POC and 230°–322° in the POE, regardless of gas type.

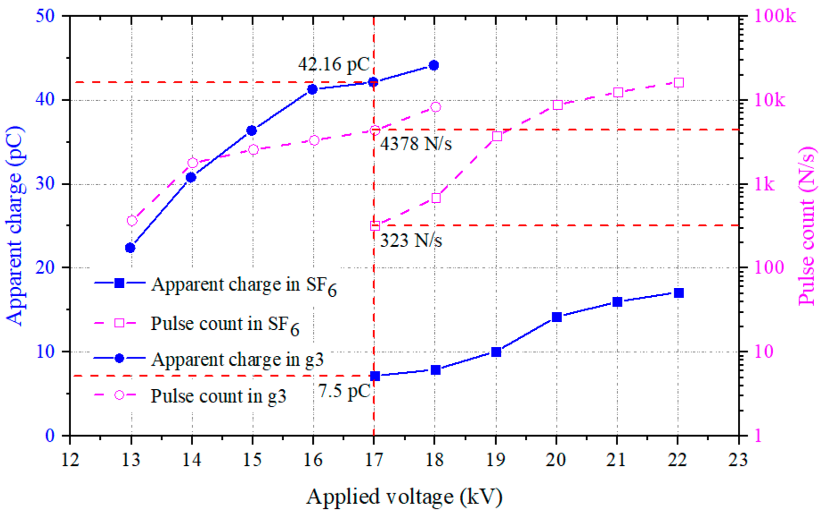


Figure 6. Average apparent charge and pulse count in SF_6 and g3 in the POC.

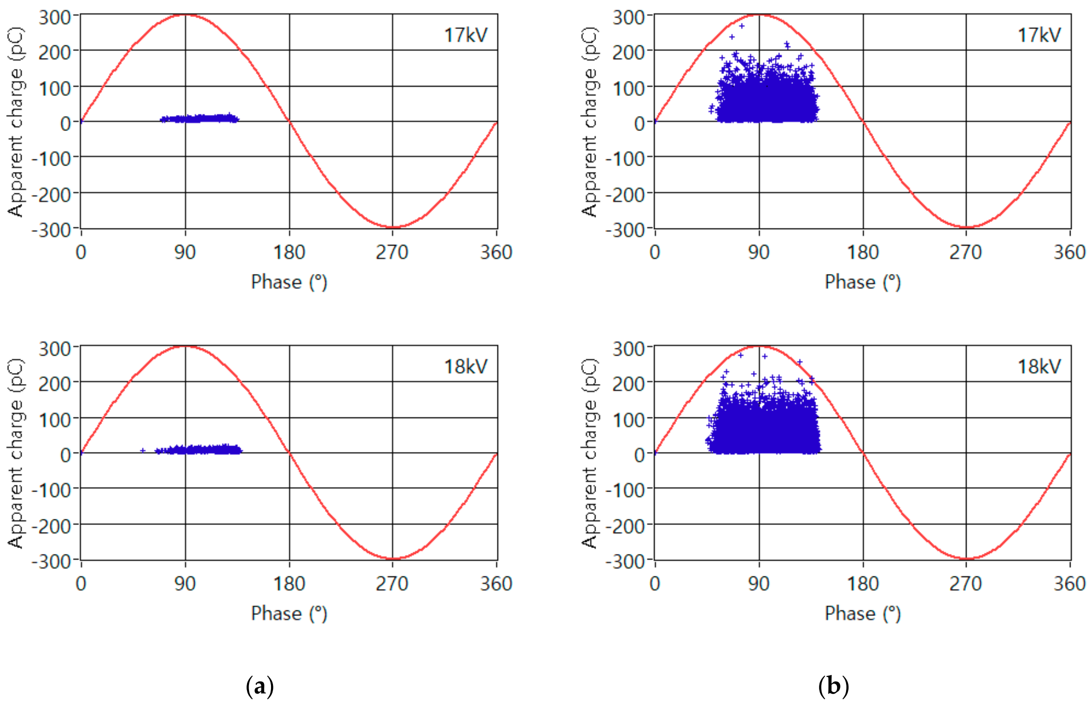


Figure 7. Phase-resolved partial discharge (PRPD) patterns in the POC. (**a**) In SF_6; (**b**) In g3.

5. Conclusions

The g3 with 4% NOVEC^{TM} 4710/96% CO_2 used in this paper has a GWP of 1.6% of that of SF_6 and has a much shorter lifetime than that of SF_6. Therefore, the greenhouse effect can be significantly reduced by replacing SF_6 with g3. The liquefaction temperature of this mixture ratio is about −30 °C, which meets the required minimum operating temperature for outdoor switchgear. By investigating PD characteristics in g3 and SF_6, it was shown that PDIVs of g3 were 76%–84% of that of SF_6, depending on the type of electrode system and gas pressure. Compared with SF_6, PD pulses in g3 gas had a longer rising time and pulse width, and relative amplitudes of FFT in g3 gas were much greater. Even at a lower applied voltage, the average apparent charge and pulse count in g3 were higher. From the perspective of PD, the use of g3 as a substitute for SF_6 requires an increase in gas pressure or a mixing ratio of NOVEC^{TM} 4710.

g3 gas mixtures are promising and emerging eco-friendly alternative insulation gases to SF_6, but investigations still need to be conducted before final industrial application. Results from this study are expected to be used as fundamental material for manufacturers to develop SF_6-free gas-insulated power apparatus. For future studies, much effort should be made to investigate the most appropriate compromise between insulation performance, liquefaction temperature, and environmental concerns.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Figure A1 shows the average apparent charge and pulse count in SF_6 and g3 in the POE. PRPD patterns in the POE are demonstrated in Figure A2.

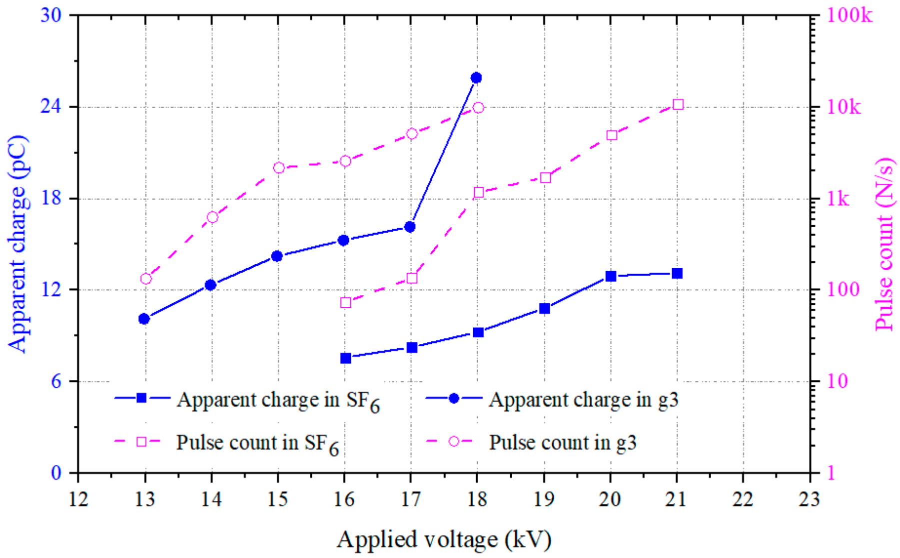


Figure A1. Average apparent charge and pulse count in SF_6 and g3 in the POE.

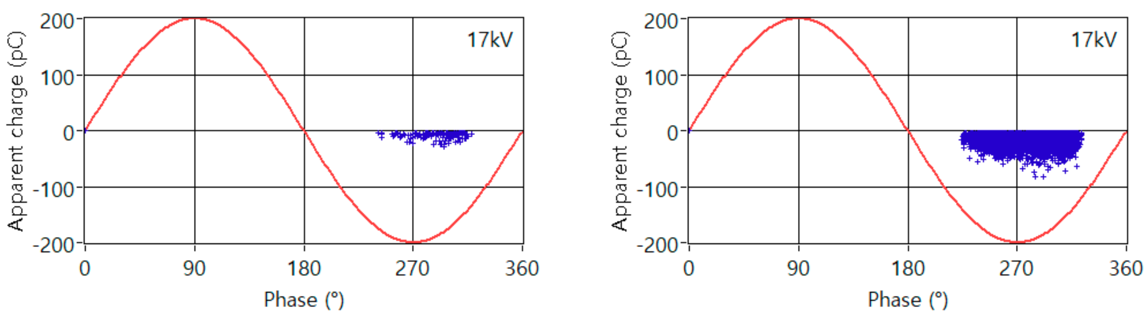
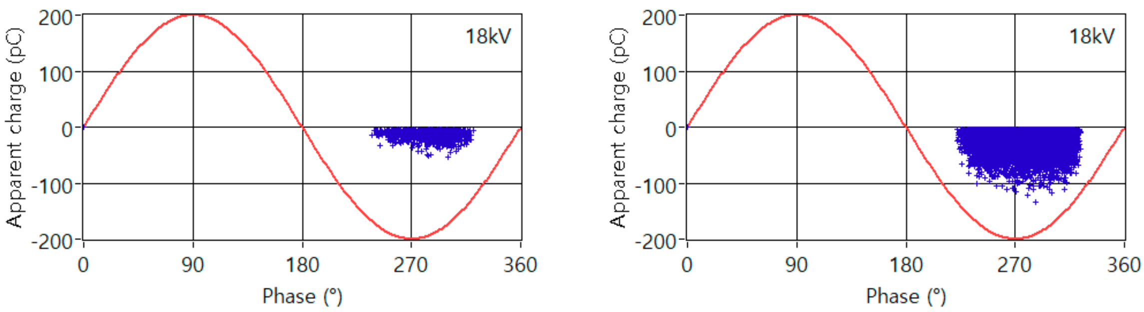


Figure A2. *Cont.*



(**a**) (**b**)

Figure A2. PRPD patterns in the POE. (**a**) In SF_6; (**b**) In g3.

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