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RESEARCH ARTICLE

Breakdown Characteristics of a Fluoronitrile Mixture Gas According to Mixing Ratio and Oxygen Content for High-Voltage Power Equipment Application

JIN YONG NA[1], RYUL HWANG[1], SUNG JOO CHO[2], TAE HUN SONG[2], AND BANG WOOK LEE[1], (Senior Member, IEEE)

[1]Department of Electrical Engineering, Hanyang University, ERICA Campus, Ansan 15588, South Korea
[2]Electric Power Machinery Research Department, HD Hyundai Electric Company Ltd., Seongnam 13553, South Korea

Corresponding author: Bang Wook Lee (bangwook@hanyang.ac.kr)

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ABSTRACT Fluoronitrile (C_4F_7N) has many advantages, such as high dielectric strength, low global warming potential (GWP), and short atmospheric lifetime compared to sulfur hexafluoride (SF_6). C_4F_7N is mixed with carbon dioxide (CO_2) to prevent liquefaction at the operating pressure of high-voltage power equipment. Therefore, it is essential to investigate the dielectric characteristics of the C_4F_7N/CO_2 mixture gas for the development of environmentally friendly power equipment. The dielectric characteristics of C_4F_7N/CO_2 at lower pressures have been previously reported. However, research into the breakdown characteristics of C_4F_7N/CO_2 under high pressure environments is insufficient. Furthermore, the effect of oxygen (O_2) content contributing to suppression of carbon soot formation by arc on breakdown characteristics of C_4F_7N/CO_2 has rarely been investigated. Therefore, in this paper, the breakdown characteristics of C_4F_7N/CO_2 according to the mixing ratio and O_2 content were investigated while considering a high–pressure environment. The electrode arrangements were determined based on the field utilization factor in order to consider two types of electric field distribution. Alternating current (AC) and negative lightning impulse (-LI) breakdown tests were performed. From these experiments, under an extremely non-uniform electric field, it was confirmed that the dielectric strength of C_4F_7N 5%/CO_2 95% at high pressure was about 75% of the strength of SF_6. In a weakly non-uniform electric field, increasing the C_4F_7N content contributed to the improvement of dielectric strength by 31-77% relative to pure CO_2 at the high pressure. Furthermore, it was investigated that the presence of O_2 had no significant influence on improving the insulation performance.

INDEX TERMS Fluoronitrile mixture gas, mixing ratio, oxygen content, extremely and weakly non-uniform electric fields, breakdown, high-voltage power equipment.

I. INTRODUCTION

SF_6, which is chemically and thermally stable, has the advantages of being non-toxic, non-flammable. The excellent insulation performance of SF_6 also enables it to inhibit electrical discharge at high voltages. Therefore, SF_6 has been widely used as an insulation medium for high-voltage power equipment, such as circuit breakers, gas-insulated switchgears (GISs), and transformers [1], [2].

Despite the advantages of SF_6, its environmental impact has recently emerged as a major issue. The GWP of SF_6 is 23500 times higher than that of CO_2, and its

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atmospheric lifetime is 3200 years. SF_6 was identified as a greenhouse gas by the Kyoto Protocol in 1997 due to its environmental impact. In addition, the Intergovernmental Panel on Climate Change (IPCC) reported that SF_6 is the most harmful gas to the global environment. Recently, the emission of greenhouse gases has been regulated to try and slow serious climate change. Countries around the world need to reduce the emission of greenhouse gases by at least 45% between 2019 and 2030 and reach "net zero" by 2050. With regulations placed on SF_6, research and development into materials to replace it are being actively carried out in the electric power industry [3], [4], [5], [6].

Alternative gas candidates for replacement of SF_6 can be divided into two broad types. One is natural gases, such as CO_2, nitrogen (N_2), and dry air. These natural gases have the advantages of being environmentally friendly and easy to handle, but the dielectric strength of natural gases is 40-45% of that of SF_6. Technologies such as insulation coating and surface treatment on conductors have been suggested in order to supplement the low dielectric strength of natural gases. However, there are many difficulties using natural gasses in applications involving high-voltage power equipment because these technologies are complex and expensive [7], [8], [9].

The other type of alternative gas candidate is fluorine gases, such as C_4F_7N and $C_5F_{10}O$. The liquefaction points of C_4F_7N and $C_5F_{10}O$ are –4.7 and 26.9 celsius at atmospheric pressure, respectively. These mean that C_4F_7N and $C_5F_{10}O$ are liquefied at the operating pressure of high-voltage power equipment. CO_2 is mixed with fluorine gases in order to artificially decrease the liquefaction temperature of C_4F_7N and $C_5F_{10}O$ at high pressure. C_4F_7N/CO_2 is most suitable as an SF_6 alternative gas in high-voltage power equipment because it has a lower liquefaction temperature than that of $C_5F_{10}O/CO_2$. The dielectric strength of pure C_4F_7N is about 2.2 times higher than that of SF_6. Additionally, pure C_4F_7N has a GWP of 2210 and atmospheric lifetime of 35 years, which are one tenth and one hundredth of those of SF_6, respectively. Therefore, it is essential to investigate the dielectric characteristics of C_4F_7N/CO_2 for development of high-voltage power equipment that is more environmentally friendly [10], [11], [12], [13].

The effect of C_4F_7N content on the AC dielectric characteristics considering the electric field enhancement factor at lower pressure has been previously studied [14]. Moreover, the LI breakdown tests of C_4F_7N 20%/CO_2 80% at low pressure were performed in order to compare the dielectric strength to those of SF_6, and the polarity effects were investigated [15]. However, research into the breakdown characteristics of C_4F_7N/CO_2 at high pressure for application of high-voltage power equipment is insufficient. Furthermore, the influence of O_2 content contributing to suppression of carbon soot formation by current interruption on dielectric characteristics of C_4F_7N/CO_2 has rarely been investigated. When carbon soot attaches to the surface of conductors and insulators, it may influence the insulation performance in the power equipment [16].

Therefore, in this study, the breakdown characteristics of C_4F_7N/CO_2 according to mixing ratio and O_2 content were investigated considering a high–pressure environment. The electrode arrangements were determined by field utilization factor in order to consider two types of electric field distributions. Based on AC and -LI breakdown tests, the dielectric strengths of SF_6 and C_4F_7N 5%/CO_2 95% under an extremely non-uniform electric field were compared. Under a weakly non-uniform electric field, the variation of dielectric characteristics by mixing ratio of C_4F_7N 2-7%/CO_2 93-98% was investigated. Furthermore, the effect of O_2 content on the breakdown characteristics was investigated under C_4F_7N 5%/CO_2.

TABLE 1. Configurations of electric field distribution according to values of field utilization factor.

Classification	Degree of uniformity
Uniform field	$\eta = 1$
Weakly non-uniform field	$0.25 < \eta < 1$
Extremely Non-uniform field	$0.25 \geq \eta$

II. EXPERIMENTS

A. ELECTRODE ARRANGEMENTS

The configuration of electric field distribution has a dominant effect on dielectric breakdown, and it is formed depending on the arrangement of electrodes. The configuration of the electric field is numerically expressed by the field utilization factor, which indicates the uniformity of an electric field. The field utilization factor is defined as in (1).

$$\eta = \frac{E_{mean}}{E_{max}} = \frac{U}{d} \cdot \frac{1}{E_{max}} \tag{1}$$

Here, E_{mean} and E_{max} are the mean and maximum electric field intensities, respectively. U is the voltage applied to the electrodes, and d is the distance between the two electrodes. The types of electric field distribution are determined by the value of the field utilization factor, as shown in Table 1. The value of the field utilization factor lies between 1.0 and 0, with a uniform electric field distribution between the electrodes when the field utilization factor is equal to one. If the field utilization factor is less than one, a non-uniform electric field distribution is formed in the electrode gap. It can be assumed that a non-uniform electric field is distinguished as a weakly or extremely non-uniform field according to the value of the field utilization factor. The value of the field utilization factor for a weakly non-uniform electric field is greater than 0.25 and less than 1.0. An extremely non-uniform electric field has a field utilization factor below 0.25 [17].

In this study, extremely and weakly non-uniform electric fields were considered using two electrode arrangements for the breakdown tests. The electrode configuration along with the electric field simulation results for the extremely

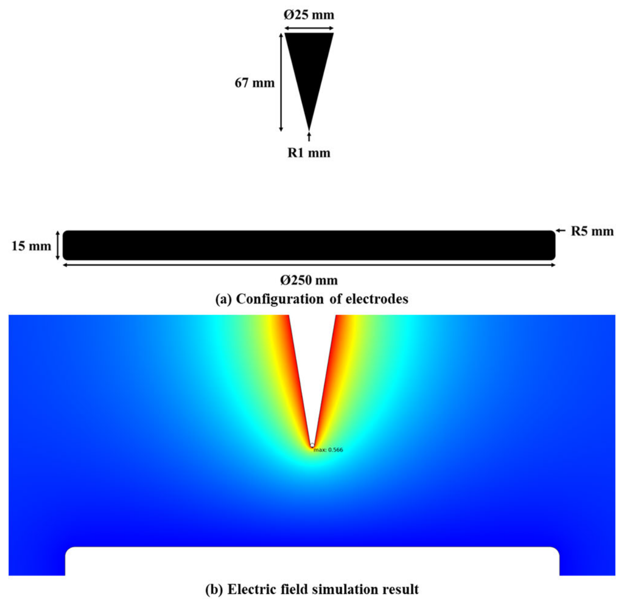

FIGURE 1. Electrode arrangement and electric field simulation results for an extremely non-uniform electric field.

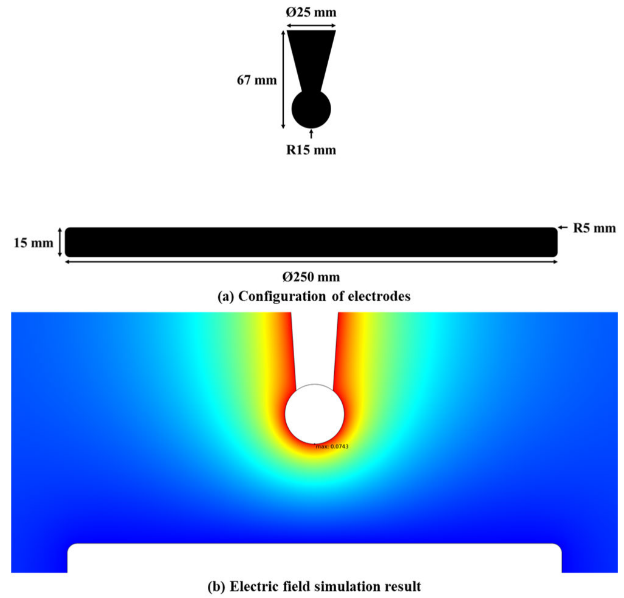

FIGURE 2. Electrode arrangement and electric field simulation results for a weakly non-uniform electric field.

non-uniform electric field can be seen in Fig. 1. The point-plane electrode arrangement using stainless steel as the electrode material was considered. The radius of the point electrode was 1 mm. The plane electrode had a diameter of 250 mm and a curvature of 5 mm. The distance between the two electrodes was set at 50 mm. The maximum electric field and field utilization factor of the point-plane electrode arrangement calculated by COMSOL Multiphysics were 0.566 kV/mm (at the applied voltage of 1 kV) and 0.035, respectively. Additionally, the electrode configuration profile and electric field simulation results of the weakly non-uniform electric field are illustrated in Fig. 2. The configuration of the top electrode was spherical with a radius of 15 mm. The specifications of the lower electrode and gap for the weakly non-uniform electric field were the same as for the extremely non-uniform field. The field utilization factor of the sphere-plane electrode with a maximum electric field of 0.074 kV/mm (at the applied voltage of 1 kV) was 0.269.

B. EXPERIMENTAL SETUPS

Schematic views of the AC and LI breakdown experimental circuit are presented in Fig. 3. The AC and LI test system produced by HIGHVOLT Prüftechnik Dresden GmbH were used for the breakdown tests. The AC voltage was supplied by a 400 kV metal tank transformer (type WP) and recorded by an AC capacitor voltage divider (type WM). For generation and measurement of -LI, a 1600 kV lightning impulse test system composed of an impulse voltage generator (type IP) and damped capacitive voltage divider (type SMC) was employed.

The test vessel for the breakdown tests was composed of the polymer wall bushing and single-phase epoxy spacer. The single-phase epoxy spacer is responsible for separating

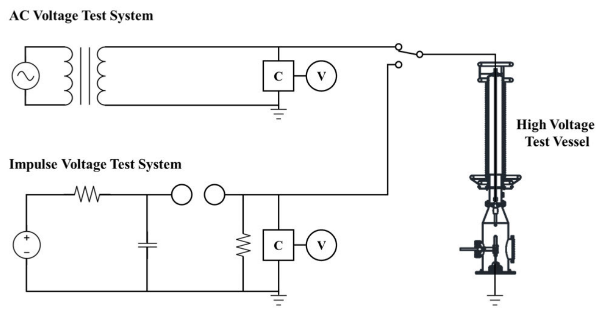

FIGURE 3. Schematic view of the AC and LI breakdown experimental circuit.

the bushing section from the compartment where the experimental gas is injected.

Before the experimental gas was injected into the test vessel, pre-treatments on the test electrodes and chamber were carried out. The test electrodes were cleaned by ethyl alcohol to eliminate impurities from the surfaces. The vacuum evacuation of the test vessel was carried out in order to minimize residues that might affect the purity of experimental gases [18].

C. EXPERIMENTAL METHODS AND TREATMENT OF TEST RESULTS

The AC and –LI breakdown tests were performed using a stepwise method corresponding to IEC 60060-1, as shown in Fig. 4. The AC voltage with an increment rate of 3 kV/s was applied until reaching 50% of the expected AC breakdown voltage. Then, the AC voltage was increased step by step (by 10 kV) and maintained for one minute. The stepwise increase was continued until AC breakdown occurred. The –LI voltage was increased in 10 kV steps from the initial voltage with 50% of the expected breakdown voltage to the occurrence of

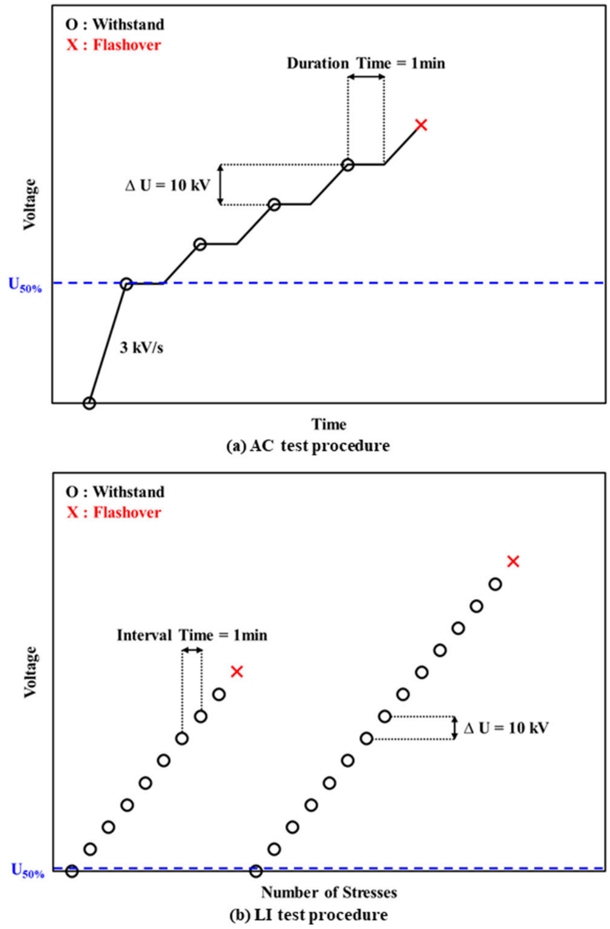

FIGURE 4. AC and LI breakdown test procedures.

–LI breakdown. Time intervals of one minute between the steps were used to allow dissipation of the space charge. The AC and –LI breakdown voltages were measured 10 times each. The arithmetic mean (U_{50}) and standard deviation (s) were derived as the experimental results of the AC and –LI breakdown tests [19], [20].

The breakdown electric field was derived for comparative analysis of the experimental results. The breakdown electric field is defined as in (2).

$$E_b = \frac{U_{50}}{\eta \cdot d} = E_{max,1\ kV} \cdot U_{50} \tag{2}$$

Here, U_{50} is the average value of the breakdown voltage. η and d are the field utilization factor and distance between electrodes, respectively, and $E_{max,1\ kV}$ is the maximum electric field intensity at the applied voltage of 1 kV.

III. EXPERIMENTAL RESULTS

A. BREAKDOWN CHARCATERISTICS OF SF_6 AND C_4F_7 N 5%/CO_2 95% UNDER AN EXTREMELY NON-UNIFORM ELECTRIC FIELD

The AC and –LI breakdown voltages of SF_6 according to pressure under an extremely non-uniform electric field are depicted in Fig. 5. The AC breakdown voltage decreased until the pressure was 5 bar, but -LI breakdown voltage increased. The AC breakdown voltage at 5 bar was 56% compared to the one at 3 bar. The AC breakdown voltage at 7 bar increased by 31% compared to the one at 5 bar. The -LI breakdown voltage at 5 bar increased by 8% compared to the one at 3 bar. The breakdown voltage at 7 bar was almost the same as that at 5 bar.

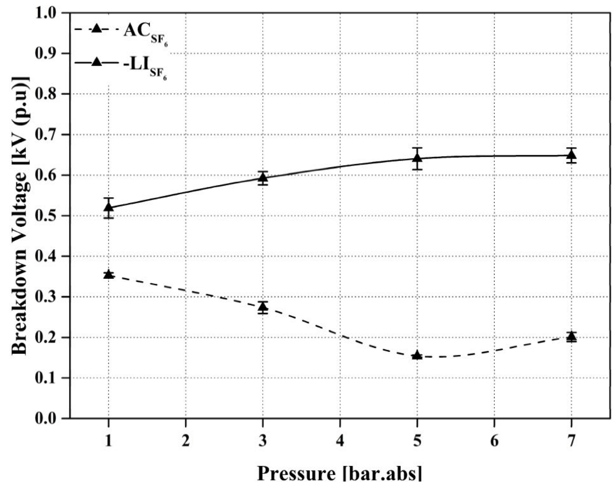

FIGURE 5. AC and –LI breakdown voltages of SF_6 according to pressure under an extremely non-uniform electric field.

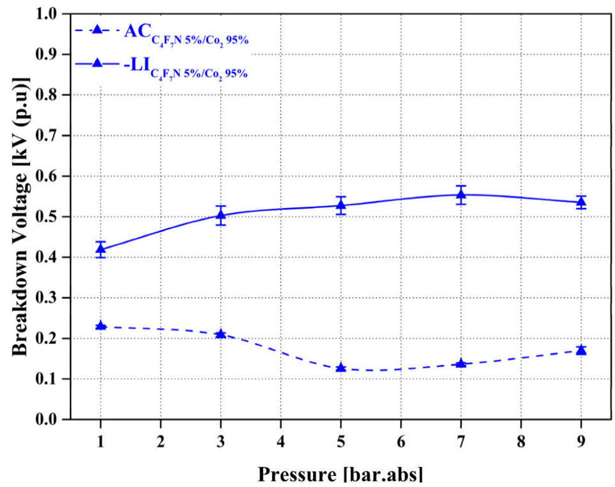

FIGURE 6. AC and –LI breakdown voltages of C_4F_7N 5%/CO_2 95% according to pressure under an extremely non-uniform electric field.

The AC and –LI breakdown voltages of C_4F_7N 5%/CO_2 95 % according to pressure under an extremely non-uniform electric field are depicted in Fig. 6. The AC breakdown voltage decreased until the pressure was 5 bar. The breakdown voltage at 5 bar was 60% compared to 3 bar. The breakdown voltage at 9 bar increased by 25% compared to that at 7 bar. The -LI breakdown voltage increased until the pressure was 5 bar. The breakdown voltage at 5 bar was increased by 5% compared to that at 3 bar. The breakdown voltage above 7 bar was almost the same as that at 5 bar.

The breakdown characteristics of SF_6 and C_4F_7N 5%/CO_2 95% depending on pressure were similar under an extremely non-uniform electric field. The AC breakdown voltages of

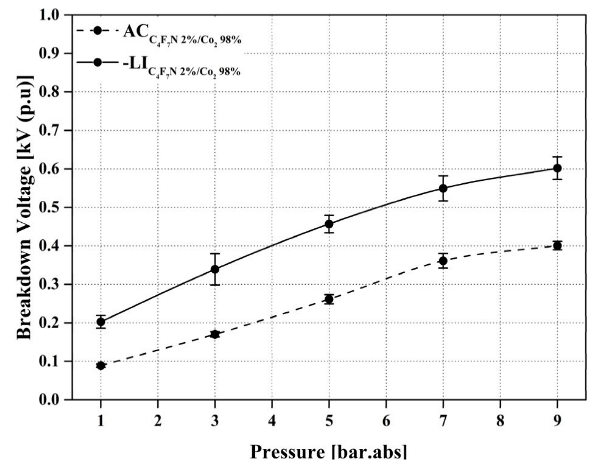

FIGURE 7. AC and –LI breakdown voltages of C_4F_7N 2%/CO_2 98% according to pressure under a weakly non-uniform electric field.

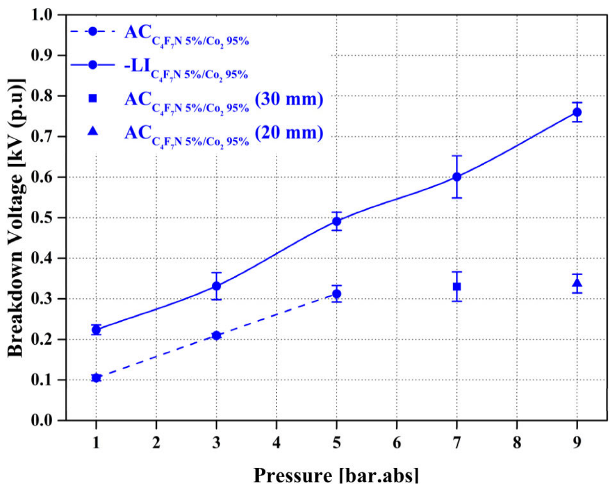

FIGURE 8. AC and –LI breakdown voltages of C_4F_7N 5%/CO_2 95% according to pressure under a weakly non-uniform electric field.

SF_6 and C_4F_7N 5%/CO_2 95% decreased with increasing pressure. The pressure with the lowest AC breakdown voltage was 5 bar for both SF_6 and C_4F_7N 5%/CO_2 95%. The AC breakdown voltage increased when the pressure was above 5 bar. The –LI breakdown voltages of SF_6 and C_4F_7N 5%/CO_2 95% increased with an increase in pressure but saturated at 5 bar. The –LI breakdown voltage of SF_6 and C_4F_7N 5%/CO_2 95% was about 1.5-4.2 times higher than that of AC according to pressure.

B. BREAKDOWN CHARACTERISTICS OF C_4F_7N/CO_2 WITH DIFFERENT MIXING RATIOS UNDER A WEAKLY NON-UNIFORM ELECTRIC FIELD

The AC and –LI breakdown voltages of C_4F_7N 2%/CO_2 98% according to pressure under a weakly non-uniform electric field are depicted in Fig. 7. The AC and -LI breakdown voltage was non-linearly increased with an increase in pressure. The AC and –LI breakdown voltages at 5 bar increased by 54% and 35% compared to those at 3 bar, respectively. The AC and –LI breakdown voltages at 9 bar increased by 11% and 10% compared to those at 7 bar, respectively.

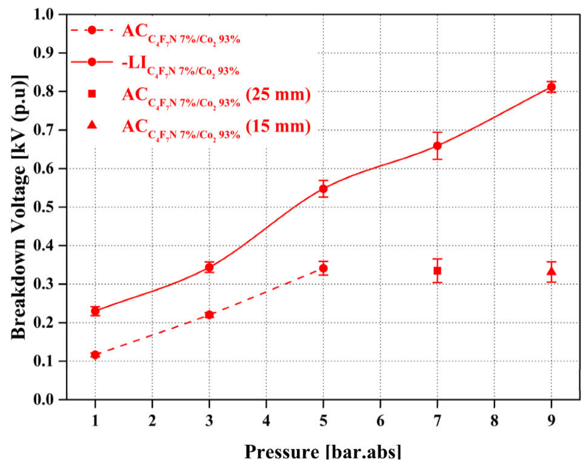

FIGURE 9. AC and –LI breakdown voltages of C_4F_7N 7%/CO_2 93% at different pressures in a weakly non-uniform electric field.

The AC and –LI breakdown voltages of C_4F_7N 5%/CO_2 95 % according to pressure under a weakly non-uniform electric field are depicted in Fig. 8. The AC and -LI breakdown voltage increased non-linearly with increasing pressure. The AC breakdown voltage at 5 bar increased by 49% compared to that at 3 bar. The improvement rate of -LI breakdown voltage due to an increase in pressure was stable at 48% at pressure less than 5 bar, but it decreased to 25% above 7 bar.

The AC and –LI breakdown voltages of C_4F_7N 7%/CO_2 93 % according to pressure in a weakly non-uniform electric field are depicted in Fig. 9. The AC and -LI breakdown voltage increased non-linearly with increasing pressure. The AC breakdown voltage at 5 bar increased by 55% compared to that at 3 bar. The improvement rate of -LI breakdown voltage due to an increase in pressure was stable at 55% below 5 bar, but it reduced to 22% at pressure above 7 bar.

With C_4F_7N 5%/CO_2 95% and C_4F_7N 7%/CO_2 93%, the AC breakdown voltages over 7 bar was constant with increasing pressure because the gap distance decreased below 50 mm to observe breakdown below the limit supply voltage of the AC test system. The gap distances of C_4F_7N 5%/CO_2 95% were 30 mm and 20 mm at pressures of 7 bar and 9 bar, respectively. The distances between the two electrodes of C_4F_7N 7%/CO_2 93% at the same pressures were 25 mm and 15 mm, respectively.

The AC and –LI breakdown voltages of C_4F_7N/CO_2 with different mixing ratios under a weakly non-uniform electric field were improved with increasing pressure. The –LI breakdown voltage of C_4F_7N/CO_2 with different mixing ratios was about 1.5-2.3 times higher than that of AC.

C. BREAKDOWN CHARACTERISTICS OF C_4F_7N 5%/CO_2 BY O_2 CONTENT IN A WEAKLY NON-UNIFORM ELECTRIC FIELD

The AC and –LI breakdown voltages of C_4F_7N 5%/CO_2 90% with an O_2 content of 5% under a weakly non-uniform electric field are depicted in Fig. 10. The AC and -LI breakdown voltage increased non-linearly with an increase in pressure. The AC and –LI breakdown voltages at 5 bar

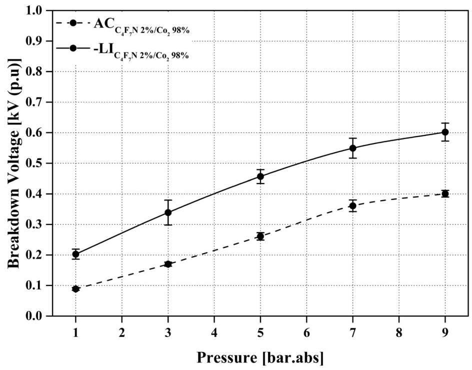

FIGURE 10. AC and –LI breakdown voltages of C_4F_7N 5%/CO_2 90% considering an O_2 content of 5% under a weakly non-uniform electric field.

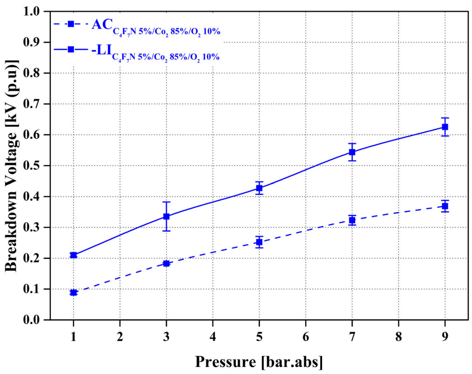

FIGURE 11. AC and –LI breakdown voltages of C_4F_7N 5%/CO_2 85% considering an O_2 content of 10% under a weakly non-uniform electric field.

increased by 43 % compared to those at 3 bar. The improvement rate of AC and -LI breakdown voltage due to an increase in pressure was less than 10% of that above 7 bar.

The AC and –LI breakdown voltages of C_4F_7N 5%/CO_2 85% at an O_2 content of 10% under a weakly non-uniform electric field are depicted in Fig. 11. The AC and -LI breakdown voltage increased non-linearly with an increase in pressure. The AC and –LI breakdown voltages at 5 bar increased by 38 % and 28% compared to those at 3 bar, respectively. The AC and –LI breakdown voltages at 9 bar increased by 15% compared to those at 7 bar.

The AC and –LI breakdown voltages of C_4F_7N 5%/CO_2 75% considering an O_2 content of 20% under a weakly non-uniform electric field are depicted in Fig. 12. The AC and -LI breakdown voltage increased non-linearly with an increase in pressure. The AC and –LI breakdown voltages at 5 bar increased by 46% and 35% compared to those at 3 bar, respectively. The AC and –LI breakdown voltages at 9 bar increased by 5% and 11% compared to those at 7 bar, respectively.

The AC breakdown voltages of C_4F_7N 5%/CO_2 with different O_2 contents under a weakly non-uniform electric field were improved by increasing the pressure. Similar to the AC case, the –LI breakdown voltages also increased with increasing pressure. With C_4F_7N 5%/CO_2 90% at an O_2 content of 5%, the AC breakdown voltage at 7 bar was similar

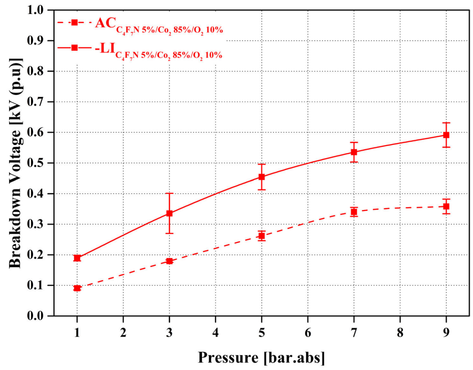

FIGURE 12. AC and –LI breakdown voltages of C_4F_7N 5%/CO_2 75% considering an O_2 content of 20% under a weakly non-uniform electric field.

to the one at 5 bar. The –LI breakdown voltage of C_4F_7N 5%/CO_2 with different O_2 contents was about 1.6-2.4 times higher than that of AC.

D. BREAKDOWN MECHANISM IN GASES ACCORDING TO ELECTRIC FIELD UNIFORMITY

Streamer theory is a representative breakdown mechanism for insulating gases in non-uniform electric fields. The major causes of streamer phenomenon are the enhancement electric field in the avalanche by space charge field and photoionization of gas molecules. The space charge field play an important role in the development of avalanches in a non-uniform field. When the number of charge carriers exceeds the threshold value, the streamer begins to initiate at the head of avalanche and quickly convert to the conductive channel for breakdown. The mathematical model of streamer criteria is defined as in (3).

$$\int_{x} \alpha dx = K \tag{3}$$

where, α and x are the effective ionization coefficient of gases and the coordinate on the critical path, respectively. K is the ionization content value, which is commonly 18 [17], [21].

From the experimental results, it was confirmed that the breakdown characteristics of an extremely non-uniform electric field according to increasing pressure were significantly different from those of a weakly non- uniform electric field. This phenomenon can be explained by the occurrence of partial breakdown (PB) according to electric field uniformity. PB, which causes the formation of space charges, occurs before breakdown in extremely non-uniform electric fields. Space charges influence the electric field characteristics for the occurrence of avalanche. Therefore, the effect of increasing pressure on the breakdown voltage is not significant because the space charge effect decreases as the pressure increases [17], [22], [23].

In a weakly non-uniform electric field where PB does not occur, breakdown occurs simultaneously with the initiation of the streamer. Previous research observed that the streamer radius and length were decreased with increasing pressure in a non-uniform electric field [24], [25]. Based

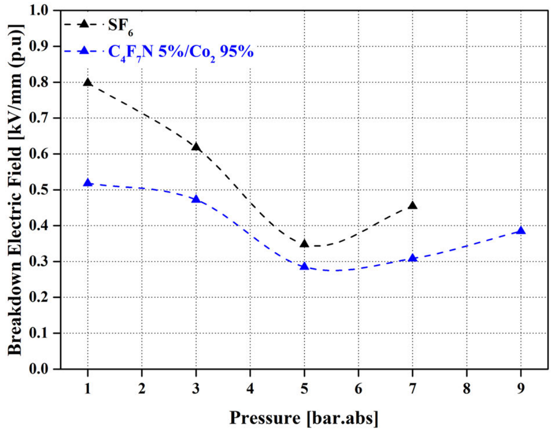

FIGURE 13. AC breakdown electric fields of SF_6 and C_4F_7N 5%/CO_2 95% according to pressure under an extremely non-uniform electric field.

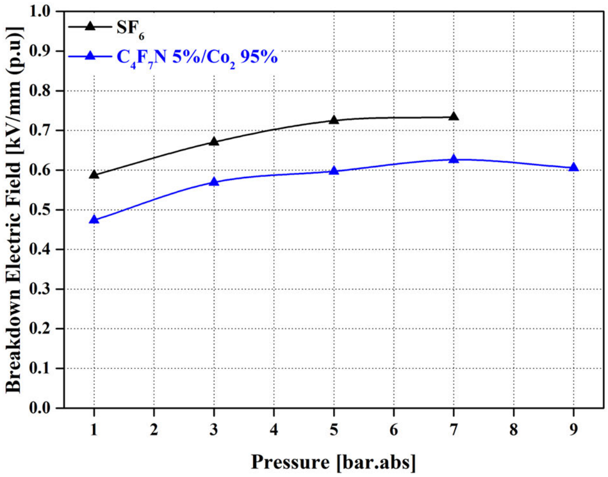

FIGURE 14. -LI breakdown electric fields of SF_6 and C_4F_7N 5%/CO_2 95% according to pressure under an extremely non-uniform electric field.

on the previous research, it can be assumed that the applied voltage for breakdown increases as the pressure increases in a non-uniform electric field.

IV. DISCUSSION

A. COMPARISON OF DIELECTRIC STRENGTH BETWEEN SF_6 AND C_4F_7N 5%/CO_2 95% WITH AN EXTREMELY NON-UNIFORM ELECTRIC FIELD

The AC breakdown electric fields of SF_6 and C_4F_7N 5%/CO_2 95% according to pressure under an extremely non-uniform electric field are depicted in Fig. 13. The dielectric strength of SF_6 and C_4F_7N 5%/CO_2 95% was decreased to the critical pressure with the lowest breakdown electric field. The breakdown electric fields of SF_6 and C_4F_7N 5%/CO_2 95% at the critical pressure were 43.6% and 55.0% of those at 1 bar, respectively. The breakdown electric field above the critical pressure was increased with an increase in pressure. These phenomena can be described by a change of breakdown mechanism by pressure under an extremely non-uniform electric field. The corona streamer caused by photoionization has a dominant effect on the breakdown when the pressure is below a critical value. Over the critical pressure, the field emission from the cathode is dominant [26]. The -LI breakdown electric fields of SF_6 and C_4F_7N 5%/CO_2 95% according to pressure under an extremely non-uniform electric field are depicted in Fig. 14. The breakdown electric fields of SF_6 and C_4F_7N 5%/CO_2 95% increased to the threshold pressures of 5 bar.

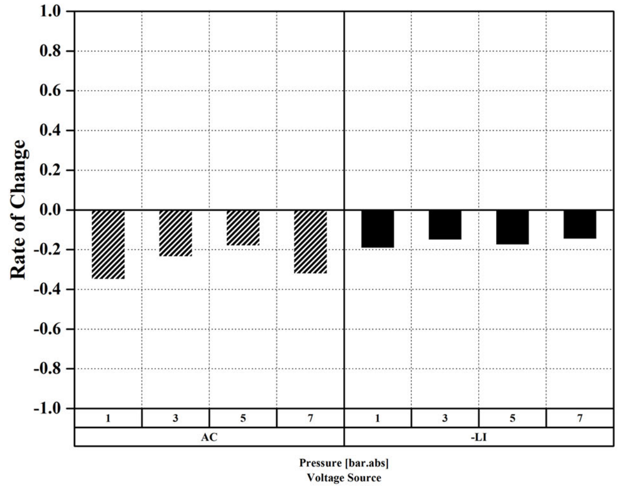

FIGURE 15. Rates of change for the AC and –LI breakdown electric fields of C_4F_7N 5%/CO_2 95% relative to those of SF_6.

The rates of change of the AC and –LI breakdown electric fields of C_4F_7N 5%/CO_2 95% relative to those of SF_6 are depicted in Fig. 15. The dielectric strengths of C_4F_7N 5%/CO_2 95% were 18-35% lower in the AC breakdown electric fields and 15-19% in the -LI breakdown electric fields compared to SF_6 when the same pressures were considered. It is assumed that C_4F_7N 5%/CO_2 95%, which has a higher effective ionization coefficient than SF_6 at the same density normalized electric field (E/N), requires less energy for propagation of the streamer by ionization [27].

These experimental results confirmed that the critical pressure could be considered for AC insulation design under an extremely non-uniform electric field. In addition, the dielectric strength of C_4F_7N 5%/CO_2 95% according to pressure was about 73-82% of the strength of SF_6.

B. INFLUENCE OF C_4F_7N CONTENT ON DIELECTRIC STRENGTH UNDER A WEAKLY NON-UNIFORM ELECTRIC FIELD

The AC breakdown electric fields with different C_4F_7N contents under a weakly non-uniform electric field are depicted in Fig. 16. The breakdown electric field of pure CO_2 with 0% C_4F_7N was from previous research [28]. The AC dielectric strength improved as the C_4F_7N content increased. Below 5 bar, the improvement of dielectric strength was not significant when C_4F_7N content was 2%. The -LI breakdown electric fields according to C_4F_7N content under a weakly non-uniform electric field are depicted in Fig. 17. The dielectric strength of –LI was improved with increasing C_4F_7N content. Especially, the increase of the dielectric strength with increasing C_4F_7N content was reinforced as the pressure increased. When the amount of C_4F_7N was increased from

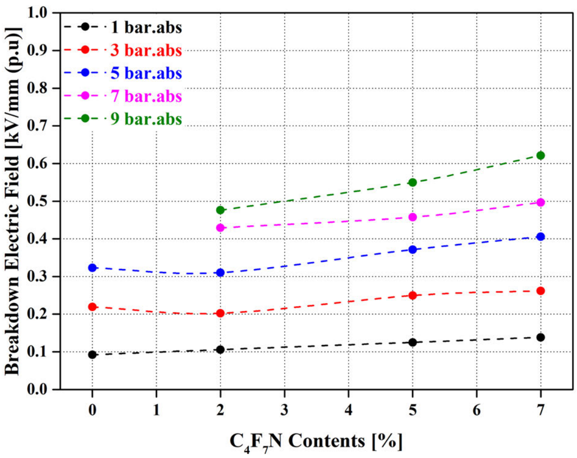

FIGURE 16. AC breakdown electric fields with different C_4F_7N contents under a weakly non-uniform electric field.

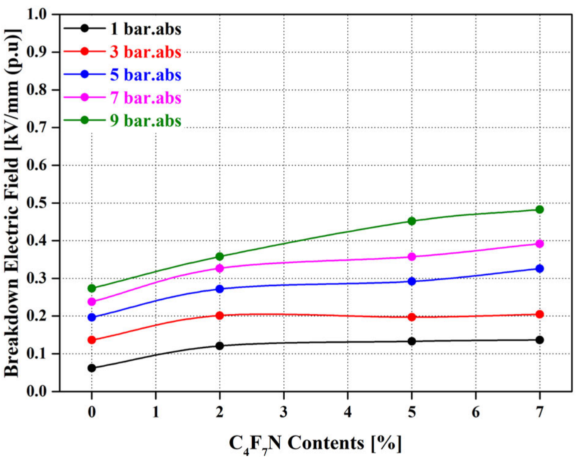

FIGURE 17. -LI breakdown electric fields with different C_4F_7N contents under a weakly non-uniform electric field.

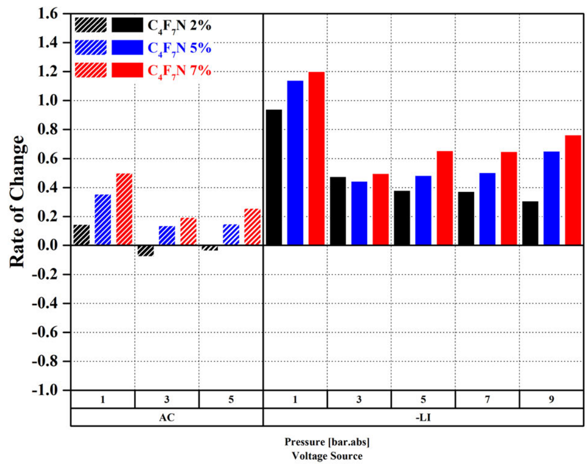

FIGURE 18. Change rates of AC and –LI breakdown electric fields with different C_4F_7N contents compared to that of pure CO_2.

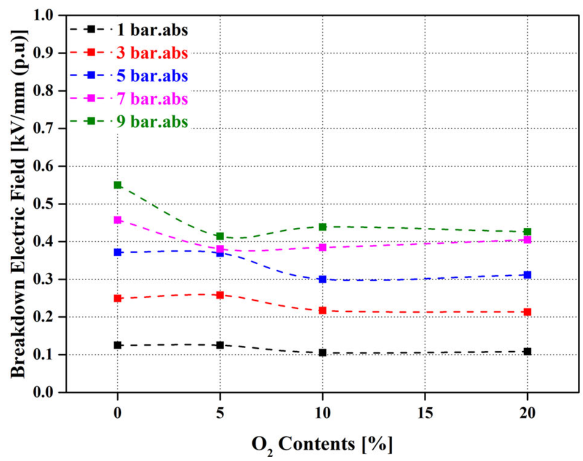

FIGURE 19. AC breakdown electric fields of C_4F_7N 5%/CO_2 with different O_2 contents under a weakly non-uniform electric field.

2% to 5%, the improvement of dielectric strength was not significant at low pressure below 3 bar.

The change rates of AC and –LI breakdown electric fields according to C_4F_7N content compared to that of pure CO_2 are depicted in Fig. 18. In most cases, the AC dielectric strength improved by 14-50% compared to that of pure CO_2due to increased C_4F_7N content. The AC dielectric strength at 3 bar and 5 bar decreased to 8% and 4%, although the C_4F_7N content was increased to 2%, respectively. The –LI dielectric strength at high pressure was increased to 31-77% with increasing C_4F_7N content. The improvement rate of dielectric strength was highest when the pressure was 1 bar. At 3 bar, increasing the C_4F_7N content had a non-significant effect on dielectric strength.

Consequently, it was verified that increasing the C_4F_7N content can have a significant effect on improving the dielectric strength of the mixture gas. The effective ionization coefficient of the mixture gas decreases with increasing the C_4F_7N content for the same E/N. A lower effective ionization coefficient makes the ionization processes more difficult. In addition, previous research about the thermodynamic and transport properties of fluorine gas mixed with CO_2 reported that the enthalpy decreased as the fluorine content increased. Low enthalpy means that the gas molecules remain stable even at high external energy. When the fluorine content of the mixture gas is high, decomposition and ionization are difficult because the molecules are more stable. Therefore, with increasing C_4F_7N content, a high electric field is necessary for the breakdown [27], [29], [30].

C. EFFECT OF O_2 ON DIELECTRIC STRENGTH UNDER A WEAKLY NON-UNIFORM ELECTRIC FIELD

The AC breakdown electric fields of C_4F_7N 5%/CO_2 with different O_2 contents under a weakly non-uniform electric field are depicted in Fig. 19. The O_2 content had a negative effect on the dielectric strength of mixture gas. At pressures below 5 bar, the dielectric strength was saturated when the O_2 content was 10%. At pressures above 7 bar, the dielectric strength was become constant when the O_2 content was 5%. The -LI breakdown electric fields of C_4F_7N 5%/CO_2 for different O_2 contents considering a weakly non-uniform electric field are depicted in Fig. 20. The –LI dielectric characteristics were similar to those of the case of AC when the pressure was

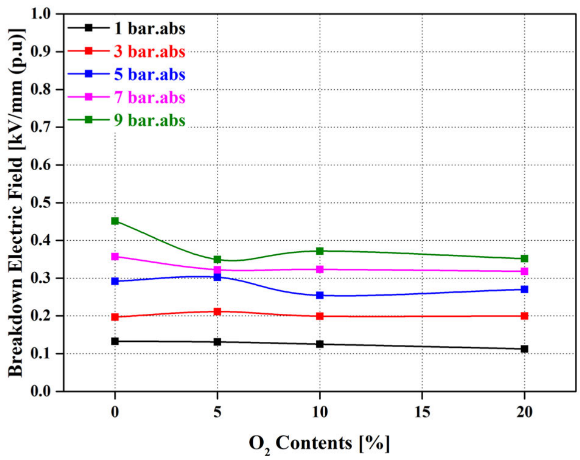

FIGURE 20. -LI breakdown electric fields of C_4F_7N 5%/CO_2 with different O_2 contents considering a weakly non-uniform electric field.

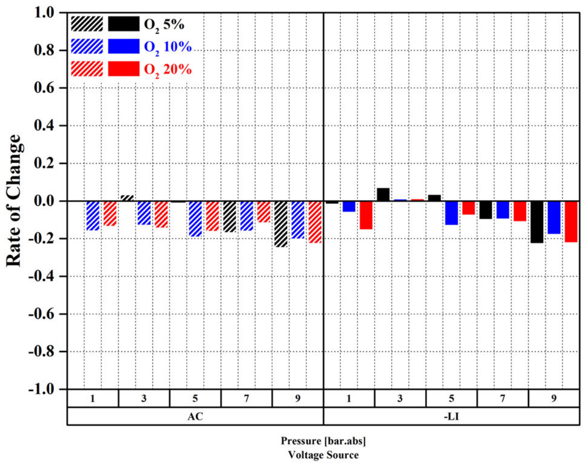

FIGURE 21. Rates of change for investigating variations of the dielectric strength with different O_2 contents compared to C_4F_7N 5%/CO_2 95%.

above 5 bar. The O_2 content had no influence on the change of dielectric strength when the pressures were below 3 bar.

The rates of change for investigating variations of dielectric strength by O_2 content compared to that of C_4F_7N 5%/CO_2 95 % are depicted in Fig. 21. The dielectric strength was decreased by the presence of O_2 in most conditions. The dielectric strengths were generally reduced by 0-23% for AC and 2-22% for –LI. The decrease in dielectric strength caused by O_2 was more significant at higher pressures than at lower pressures. At 3 bar and 5 bar, the dielectric strength was slightly improved when O_2 content was 5%.

In conclusion, the presence of O_2 had no significant influence on improving the dielectric strength. Research in the literature reported that the dielectric strength can be improved in the presence of O_2 with high electron attachment. Nevertheless, the dielectric characteristics of a mixture gas with O_2 can be changed by various factors, such as O_2 contents, pressures, and electrode arrangements. In addition, previous research reported that the dielectric strength of $C_4F_7N/CO_2/O_2$ gas mixture decreased when the O_2 content was above 6%. A high O_2 content accelerates the decomposition of gas mixture and generates by-products. The generated by-products have lower dielectric strength. Therefore, improvement of dielectric strength was not significant with an increase of O_2 content [28], [31], [32].

V. CONCLUSION

In this study, the dielectric characteristics of C_4F_7N/CO_2 were investigated under high-pressure conditions according to mixing ratio and O_2 content. The dielectric strengths of SF_6 and C_4F_7N 5%/CO_2 95% were compared under an extremely non-uniform electric field. Under a weakly non-uniform electric field, the variation of dielectric characteristics with different mixing ratios of C_4F_7N 2-7%/CO_2 93-98% was confirmed. Furthermore, the effect of O_2 content on the breakdown characteristics was investigated under C_4F_7N 5%/CO_2. The experimental results in this study can be summarized as follows.

- The critical pressure could be considered for AC insulation design under an extremely non-uniform electric field. In addition, the dielectric strength of C_4F_7N 5%/CO_2 95% according to pressure was about 73-82% of the strength of SF_6.
- The C_4F_7N content has a significant effect on dielectric strength. The AC dielectric strength was improved by 14-50% due to an increase in C_4F_7N content compared to that of pure CO_2. The –LI dielectric strength at high pressure was increased to 31-77% with increasing C_4F_7N content.
- The presence of O_2 had no significant influence on improving the dielectric strength. The dielectric strength was reduced by 0-23% for AC and 2-22% for –LI in most conditions. The decrease in dielectric strength due to O_2 was more significant at high pressures than at low pressures.

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JIN YONG NA received the B.S. degree in electrical engineering from Chungbuk National University, Chungju, South Korea, in 2016, and the M.S. degree in electrical engineering from Hanyang University, Ansan, South Korea, in 2019, where he is currently pursuing the Ph.D. degree in electrical engineering. His research interests include insulation material, high-voltage discharge, and insulation design.

RYUL HWANG received the B.S. degree in electrical engineering from Hoseo University, Asan, South Korea, in 2002. He is currently pursuing the Ph.D. degree in electrical engineering with Hanyang University, Ansan, South Korea. His research interests include insulation materials, high-voltage discharge, insulation design, high-voltage power equipment, and partial discharge.

SUNG JOO CHO received the B.S. and M.S. degrees in electrical engineering from Hanyang University, Ansan, South Korea, in 2011 and 2013, respectively, where he is currently pursuing the Ph.D. degree in electrical engineering. He is also a Senior Researcher with HD Hyundai Electric Company Ltd., South Korea. His research interests include the insulation design of gas insulated switchgear and the characteristics of alternative gases for high-voltage insulation.

TAE HUN SONG received the B.S., M.S., and Ph.D. degrees in mechanical engineering from Hanyang University, Seoul, South Korea, in 1996, 1998, and 2017, respectively. Currently, he is a Senior Researcher with HD Hyundai Electric Company Ltd., South Korea. His research interests include arc simulation and interrupting performance evaluation of high-voltage SF_6 and eco gas circuit breaker.

BANG WOOK LEE (Senior Member, IEEE) received the B.S., M.S., and Ph.D. degrees in electrical engineering from Hanyang University, Seoul, South Korea, in 1991, 1993, and 1998, respectively. He was a Senior Research Engineer with LS Industrial Systems Company Ltd., South Korea. In 2008, he joined the Department of Electronic System Engineering, Hanyang University, Ansan, South Korea, where he is currently a Professor. His research interests include HVDC protection systems, high-voltage insulation, renewable energies, and the development of electrical equipment, including transmission line structures for HVDC and HVAC power systems. He is a member of the HVDC Research Committee of the KIEE, the Power Cable Experts Committee of the Korean Agency for Technology and Standards, and CIGRE.