The Effect of Humidity on the AC Breakdown Strength of C_4-FN/CO_2 (5%/95%) and the Partial Discharge Behavior of Corona Under Different Operating Conditions

Veldhuizen, Ewout Van; Mier, Christian; Lathouwers, Andre; Rodrigo Mor, Armando; Ghaffarian Niasar, Mohamad

DOI
10.1109/TDEI.2024.3390649

Publication date
2024

Document Version
Final published version

Published in
IEEE Transactions on Dielectrics and Electrical Insulation

Citation (APA)
Veldhuizen, E. V., Mier, C., Lathouwers, A., Rodrigo Mor, A., & Ghaffarian Niasar, M. (2024). The Effect of Humidity on the AC Breakdown Strength of C_4-FN/CO_2 (5%/95%) and the Partial Discharge Behavior of Corona Under Different Operating Conditions. *IEEE Transactions on Dielectrics and Electrical Insulation*, *31*(5), 2503-2510. https://doi.org/10.1109/TDEI.2024.3390649

The Effect of Humidity on the AC Breakdown Strength of C_4-FN/CO_2 (5%/95%) and the Partial Discharge Behavior of Corona Under Different Operating Conditions

Ewout van Veldhuizen, Christian Mier, André Lathouwers, Armando Rodrigo Mor, and Mohamad Ghaffarian Niasar, *Member, IEEE*

***Abstract*—SF_6 is being phased out of the electrical grid as it is a strong greenhouse gas. A "green" alternative to SF_6 is fluoronitrile (C_4-FN). The dutch transmission system operator (TSO) TenneT wanted to investigate the electrical behavior of this "green" alternative as a pilot-gas insulated line (GIL) filled with C_4-FN/CO_2 (5%/95%) experienced multiple electrical breakdowns during the site acceptance tests (SATs). TenneT hypothesized that the breakdown was caused by the effect of (too much) humidity in the gas. Therefore, the ac breakdown behavior of the gas mixture has been researched under different amounts of humidity and operating pressures. This article also makes a small introduction on how humidity affects partial discharge (PD) behavior of corona, which is often a breakdown indicator. The results of this research conclude that humidity affects the ac breakdown strength. An increase in humidity in the gas results in a decrease in the ac breakdown strength. Moreover, the field configuration determines the amplitude of the impact. The impact of humidity on the ac breakdown strength in a homogenous field is substantially more compared to an inhomogeneous field, where the impact can almost be ignored. Yet, the effect of humidity decreases as the operating pressure increases. The phase-resolved PD pattern and PD characteristics of corona in a C_4-FN gas mixture also differ with humidity. On the other hand, the PD inception voltage did not change with the humidity content. As a result of the findings in this research, further research is proposed toward the affected breakdown mechanism and more various PD behavior.**

***Index Terms*—AC breakdown strength, fluoronitrile (C_4-FN), humidity, partial discharge (PD), SF_6 alternative gas.**

Manuscript received 17 December 2023; revised 17 March 2024; accepted 8 April 2024. Date of publication 17 April 2024; date of current version 14 October 2024. *(Corresponding author: Ewout van Veldhuizen.)*

Ewout van Veldhuizen, Christian Mier, André Lathouwers, and Mohamad Ghaffarian Niasar are with High Voltage Technology Group, TU Delft, 2628 CD Delft, The Netherlands (e-mail: ewout.vanveldhuizen@kema.com; C.MierEscurra@tudelft.nl; A.G.A. Lathouwers@tudelft.nl; M.GhaffarianNiasar@tudelft.nl).

Armando Rodrigo Mor is with the Instituto de Tecnología Eléctrica, Universitat Politècnica de València, 46022 València, Spain (e-mail: arrodmor@ite.upv.es).

Color versions of one or more figures in this article are available at https://doi.org/10.1109/TDEI.2024.3390649.

Digital Object Identifier 10.1109/TDEI.2024.3390649

I. Introduction

A LOT of research has been done to find a green alternative for SF_6. Fluoronitrile (C_4-FN) shows the most promise as a replacement for SF_6, especially for high-voltage (HV) applications [1]. However, pure C_4-FN is unsuited to use as insulation gas due to its high boiling point temperature, i.e., ca. −5 °C. IEC 62271-1 declares that the minimum operating temperature of a GIS can reach −25 °C and, for special conditions, even as low as −50 °C [2]. Therefore, C_4-FN is mixed with other gases, such as CO_2 or N_2, to decrease the boiling point temperature, thereby increasing the application range. A mixture of $5\%_{mol}$ C_4-FN and $95\%_{mol}$ CO_2, abbreviated as C_4-FN/CO_2 (5%/95%), has a boiling point of circa −53 °C at 1 bar_{abs} [3]. Manufacturers mostly use a mixture of CO_2 as it has a better extinguish performance compared to N_2.

TenneT has a pilot gas-insulated line (GIL) filled with a C_4-FN/CO_2 (5%/95%). The pilot experienced multiple electrical breakdowns during a site acceptance test (SAT) and the hypothesis of TenneT was that too much humidity affects the ac breakdown strength of C_4-FN. The existing research articles on this topic do not give a fully detailed and adequate explanation for these electrical breakdowns. Therefore, an investigation toward this problem was performed in the HV laboratory of TU delft.

Based on our literature review, there are currently two articles which researched some elements concerning the effect of humidity on the ac breakdown behavior. One article only examines the ac breakdown strength at one operating condition, i.e., 0.5 MPa in a nonuniform field configuration [4]. The other article has done research with a C_4-FN gas mixture of C_4-FN/CO_2 (9%/91%) in only nonuniform field configurations, though with multiple operating pressures [5].

Both articles provide not enough data to fully understand the effect of humidity on the ac breakdown behavior of C_4-FN/CO_2 (5%/95%). The reason is twofold.

The first reason is that the mixing ratios of gas differ. It is known that the mixing ratio can have a tremendous effect on the ac breakdown strength behavior but it is unknown how humidity affects the ac breakdown strength behavior for different mixing ratios [1]. The second reason is that the research of both articles was only performed in one field configuration. This concludes that there is an absence of data for completely understanding the effect of humidity in C_4-FN/CO_2 (5%/95%) on the ac breakdown behavior for different operating conditions, e.g., different field configurations and corresponding pressures.

This research examined multiple different field configurations at different operating conditions, i.e., variation in humidity [ppmv] and pressure [bar_{abs}]. This makes it possible to draw multiple conclusions and to completely understand the behavior of humidity in C_4-FN/CO_2 (5%/95%) on the ac breakdown strength for different operating conditions. Furthermore, this article gives a detailed physical explanation, explaining the change in the ac breakdown behavior as a result of the humidity. Furthermore, this research has measured the humidity in the recommended unit, i.e., ppmv. This combined with the results of the different field configurations makes it possible to compare and assess the effect of humidity in live HV equipment in the grid.

This article consists of multiple sections. Section II describes the test cells, procedures, and setups used in the experiments. Section III contains the results of the experiments. Section IV discusses the results and gives an explanation on the physical interaction of the water molecules with C_4-FN molecules. The gas mixture C_4-FN/CO_2 (5%/95%) is from now on abbreviated to "C_4-FN" to ease the reading of this article.

II. Description of the Test Setups

This section consists of three parts. Section II-A discusses the different electric field configurations and test cells, in which the gas was tested. Section II-B discusses the different methods that were used during this research. Section II-C presents the different circuits used in the breakdown and partial discharge (PD) experiments.

A. Electric Field Configurations and Test Cells

Three electric field configurations have been designed based on CIGRE brochure 849 D1 [1, Sec. V.2]. The CIGRE brochure has designed and performed test for SF_6 alternatives like C_4-FN, including recommendations for field configurations for further testing. Each electric field configuration has its own specific field utilization factor η, which can be calculated with (1). The gap distance between the electrodes is for every experiment 5.0 mm. The different electric field configurations have been simulated in COMSOL to calculate the maximum field ($E_{\max}$), thereby confirming the required η-factor. The details of the different electric field configurations are summarized in Table I. The dimensions of the sphere and needle are listed in Fig. 1 and Table I, respectively

$$\eta = \frac{E_{\text{avg}}}{E_{\max}}. \tag{1}$$

1) Test Cells to Examine the AC Breakdown Behavior: A small test cell, Fig. 2(a), was used to examine the correlation between the ac breakdown strength of C_4-FN and the amount of humidity up to 15 000 ppmv. The small test cell has an external ac breakdown strength of ca. 90 kV_{peak}. A second larger test cell, Fig. 2(b), was created to examine the correlation between ac breakdown strength of C_4-FN with a specific humidity and different operating pressures up to 7 bar_{abs}. The small test cell was not sufficient anymore to examine higher pressures of C_4-FN, as the small test cell would have an external breakdown before the C_4-FN would break down. By extending the height of the small test cell, the external breakdown strength was increased, making it possible to examine higher pressures. The large test cell has an external ac breakdown strength of ca. 190 kV_{peak}.

TABLE I
Summarized Details of the Electrode Configurations. η—Factor Is Calculated With E_{AVG} = 1 kV/mm

Electric field configuration	Electrode configuration and dimensions		η - factor
Uniform	Rogowski	r = 20 mm	$\eta = 1$
	Rogowski	r = 20 mm	
Quasi uniform	Sphere	r = 2 mm	$\eta \approx 0.6$
	Plate	r = 20 mm	
Non-uniform	Needle	(see Figure 1)	$\eta \approx 0.08$
	Plate	r = 20mm	

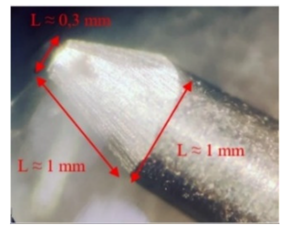

Fig. 1. Dimensions of the tungsten needle.

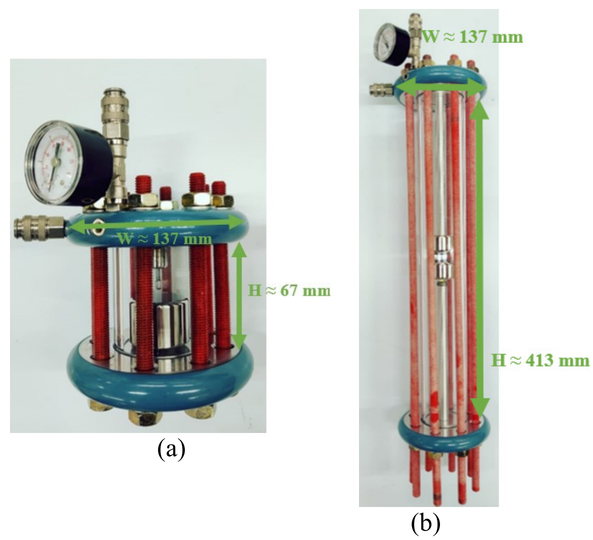

Fig. 2. Photograph of the two test cells used during this research. (a) Small test cell with a total length of ca. 12 cm. (b) Large test cell with a total length of ca. 47 cm. Radius of blue top and bottom electrode is 12 mm.

Fig. 3. Photograph of the test cell to examine the PD behavior of corona. The test cell is PD free up to 40 kV_{peak} and is of the same size as Fig. 2(b).

2) Test Cell to Examine the PD Behavior of Corona: The test cell to examine the PD behavior, Fig. 3, is similar to the small test cell of Fig. 2(a), except that the bottom electrode of the test cell has a guard electrode, in which the center electrode (connected to the needle) has a BNC connector with a characteristic impedance of 50 Ω. A short transmission line of 50 Ω connects the 50-Ω characteristic impedance with a 50-Ω input of the oscilloscope. Important is that the impedances of this chain match in order to limit the reflection of the PD's resulting in a high waveform time resolution [6].

B. Methods

Three methods have been used during this research. The methods are explained in the following sections.

1) A method to create C_4-FN with a specific humidity.
2) A method to measure the ac breakdown strength of C_4-FN.
3) A method to measure the PD behavior of corona in C_4-FN.

1) C_4-FN Humidification: Humid C_4-FN was made by first creating gaseous water, i.e., humidity, and then adding dry C_4-FN. The humidity can be calculated with (2)–(4) [7]. By controlling the amount of water [relative humidity (RH)], the dew point temperature (T_d) can be controlled and thereby the water vapor partial pressure (e), which ultimately determines the humidity (ppmv). It is also possible to control T_d by altering the gas temperature (T), but controlling the humidity through the temperature creates unnecessary complications and was thus avoided. It is also possible to control the humidity with the gas pressure (p), but the gas pressure is kept constant just like in live HV equipment. The ambient and gas temperature (T) was constant during all the experiment at ca. 20 °C

$$\text{ppmv} = \frac{e}{p-e} \cdot 10^6 \tag{2}$$

$$e = 611.2 \exp\left(\frac{17.62 \cdot T_d}{243.12 + T_d}\right) \tag{3}$$

$$T_d = \frac{237.7 \cdot \gamma(T, \text{RH})}{7.27 - \gamma(T, \text{RH})} \text{ where}$$
$$\gamma(T, \text{RH}) = \frac{17.27 \cdot T}{237.7 + T} + \ln(\text{RH}/100). \tag{4}$$

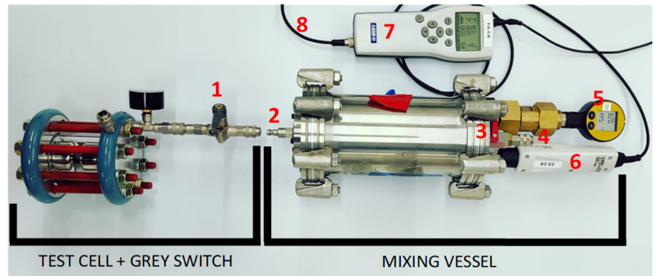

Fig. 4. Test setup used to create a humid C_4-FN gas mixture. 1 = removable gray switch; 2 = male DILO outlet of the mixing vessel; 3 = red switch to give more control over the inlet of the mixing vessel; 4 = female DILO inlet of the mixing vessel; 5 = digital pressure sensor (up to two decimals); 6 = humidity probe DMP74B; 7 = handheld dewpoint meter DM70; and 8 = data connection between probe and meter.

C_4-FN was given a specific humidity with the test setup from Fig. 4. Before injecting water and the C_4-FN, the setup was flushed with N_2 to remove any remaining humidity. Afterward, the setup was vacuumed, which would allow the injected water to be vaporized. After the water vapor settled down (ca. 20 min), the C_4-FN was introduced. The gray switch prevents a random amount of gas from flowing out of the test cell during the decoupling procedure. The gas pressure can be read from the digital pressure sensor as the pressure inside the test cell and mixing vessel is in equilibrium.

The temperature and the dewpoint of the C_4-FN were closely monitored on the DM70 meter. The humidity, i.e., the water vapor, in the gas will condensate if the gas temperature drops below the dewpoint temperature as the gas cannot contain any more humidity at that temperature. This means that the test cell would contain moisture as well as humidity. Since only the effect of humidity on C_4-FN is examined during this research, it is of the utmost importance that $T_{C4-FN} > T_d$.

2) AC Breakdown Strength Measurement: The ac breakdown strength is measured using the ramp method described in ASTM D2477-07(2012) [8]. The ac breakdown strength is measured in all three electric field configurations through multiple experiments. One experiment consists of ten breakdown repetitions. The estimated average breakdown voltage was measured before the start of the experiment. This was achieved by performing three consecutive breakdowns by applying a ramp of 2 kV_{peak}/s until a breakdown occurred. The applied voltage for the ten breakdown repetitions was increased up to 80% of the estimated breakdown voltage with a ramp of 1–5 kV_{peak}/s. The last 20% was increased with a ramp of 0.5 kV_{peak}/s. Each breakdown was followed by a waiting time of 3 min.

It was observed during the testing that the spread of the measured breakdown voltages with the Rogowski electrodes kept increasing after each experiment. The increasing spread was caused by the increase of the surface roughness due to the energy released during a breakdown. An increase in surface roughness will create localized electric field enhancement(s), which results in an earlier arrival to the critical electric field strength and thus a lower breakdown voltage [9]. The Rogowski electrodes were polished with sanding paper P1200

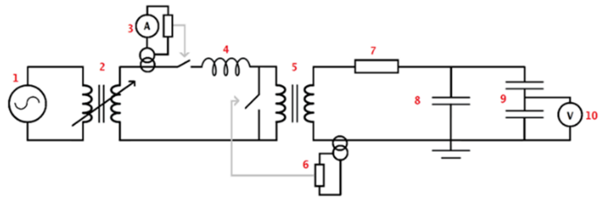

Fig. 5. Test setup for examining the ac breakdown behavior of the C_4-FN gas mixture. 1 = fixed power source 19 kVA and 50 Hz; 2 = variac; 3 = overcurrent protection; 4 = 64-mH inductor; 5 = step up transformer; 6 = fast tripping circuit; 7 = 1-kΩ resistor; 8 = test cell; 9 = 400-pF capacitive voltage divider; and 10 = DMI of voltage.

after each experiment to mitigate the increasing spread. P1200 ensured a surface roughness of ca. 15 μm, which is typical for HV electrodes [1]. This spread was not observed for the quasi-uniform and nonuniform field, i.e., the sphere and needle.

3) Corona Behavior Measurement: The PD inception voltage (PDIV), the phase resolved PD (PRPD) pattern, and the waveform of the corona PDs were measured to examine the PD behavior in C_4-FN. The effect of humidity on the PD behavior is examined by measuring and comparing these three characteristics in humid C_4-FN against dry C_4-FN, both at 1.00 bar_{abs}.

The PDIV and PRPD pattern were measured according to the IEC60270 [10]. The PDIV was measured by increasing the applied voltage with a steady rate rise of 0.5 kV_{peak}/s. The waveform was measured 10% above the PDIV. The 100 PD waveforms were measured and analyzed with MATLAB, where various characteristics were calculated, e.g., rise/fall time, PD rate, and so on.

The needle was visually checked for degradation as a consequence of the constant discharges. There was no degradation found during the examination of the corona behavior.

C. Circuits

There are two circuits used during this research: a circuit to examine the ac breakdown strength and a circuit to examine the PD behavior of corona.

1) Circuit to Measure AC Breakdown Strength: Fig. 5 shows the circuit used to examine the ac breakdown strength. The circuit contains a few elements to optimize the experiments.

1) A series resonance inductor, as prescribed in IEC 60060-1 [11].
2) A fast-tripping circuit as a mitigating measure to prevent the spread in the breakdown voltages. This was used to decrease the breakdown duration, effectively limiting the energy released during an electrical breakdown.
3) A 1-kΩ resistor to create a low-pass filter with the capacitance of the circuit to protect the transformer from transient overvoltages.

2) Circuit to Measure Corona PD Behavior: Fig. 6 shows the circuit used to examine the PD behavior. The metal plates at the bottom and top of the test cell mimic the coupling capacitor.

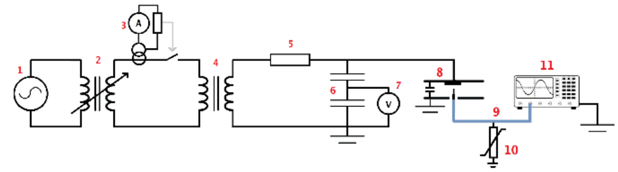

Fig. 6. Test setup for examining the corona PD behavior in the C_4-FN gas mixture. 1 = power socket; 2 = variac; 3 = overcurrent protection; 4 = step up transformer; 5 = 50-kΩ current limiting resistor; 6 = ac/dc voltage probe; 7 = multimeter; 8 = test cell; 9 = 50-Ω coaxial cable; 10 = overvoltage protection; and 11 = oscilloscope.

III. Results

This section consists of three parts. Section III-A shows the correlation between the ac breakdown strength of C_4-FN and the amount of humidity up to 15 000 ppmv. Section III-B shows the correlation between ac breakdown strength of C_4-FN with a specific humidity and different operating pressures up to 7 bar_{abs}. Section III-C shows the effect of humidity on the PD behavior of corona in C_4-FN.

A. Effect of Humidity on the AC Breakdown Strength of C_4-FN

Figs. 7–9 show the correlation between the ac breakdown strength and the amount of humidity present in C_4-FN in a uniform, quasi-uniform, and nonuniform field, respectively. The low pressures allowed a high humidity of up to 15 000 ppmv. It would have been necessary to alter the temperature of the gas to reach high(er) humidities at higher pressures. As explained before, altering the temperature is avoided as it creates unnecessary hardships.

About the graphs/experiments.

1) Each dot represents an experiment and is the average value of the ten breakdown repetitions.
2) The scattering shows the breakdown voltages of the ten breakdown repetitions of each experiment.
3) The red vertical error bars are the 95% (2σ) confidence bounds (normal distribution).
4) The horizontal error bars show a possible 5% deviation in the measured humidity, as the humidity measurements would sometimes change after transferring the humid C_4-FN gas mixture to the test cell.
5) The gas pressure of the experiments for each electric field configuration was identical up to two decimals.
6) The ambient room and gas temperature were constant during all the experiments at ca. 20 °C.
7) The preferred pressure for all fields is 1 bar_{abs}, so that also the degree of variation that the humidity causes through a variation in the electric field, i.e., field configurations, could be compared and examined. However, the voltage measuring device could not measure continuously up to its rated value but instead measured in various "ranges." During the switching between ranges, it would not show the measured voltages but a blank screen (i.e., no voltage was measured for circa a second). This resulted in an unknown breakdown voltage if the breakdown occurred at a voltage between two ranges. Therefore, it was necessary to deviate from the preferred pressure for the uniform and nonuniform fields.

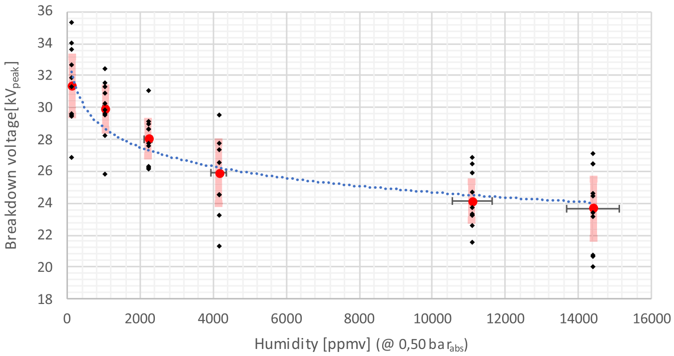

Fig. 7. U_{50} of C_4-FN in a uniform electric field.

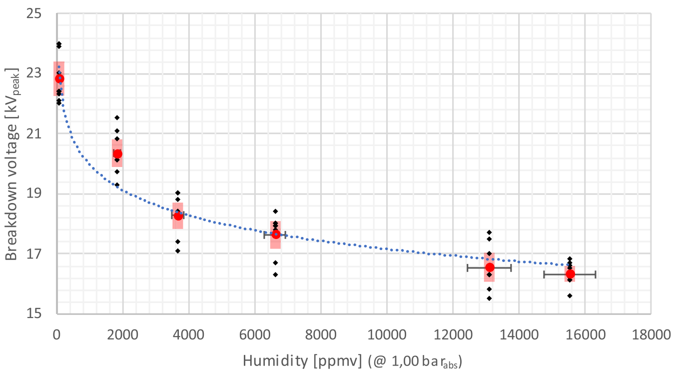

Fig. 8. U_{50} of C_4-FN in a quasi-uniform electric field.

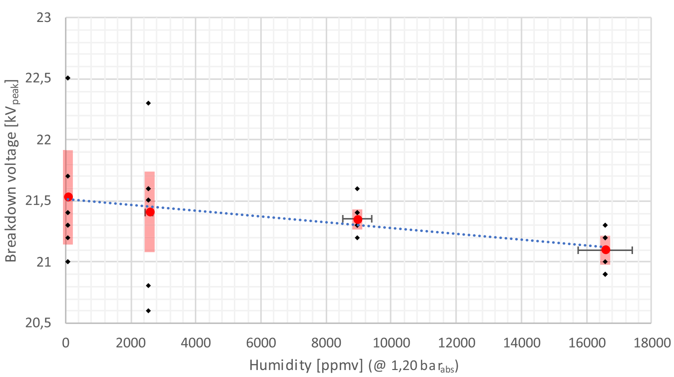

Fig. 9. U_{50} of C_4-FN in a nonuniform electric field.

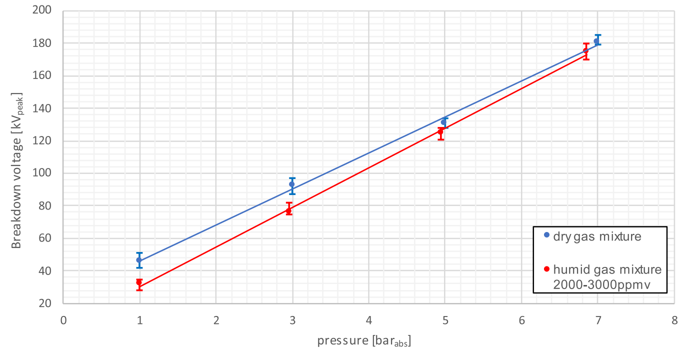

Fig. 10. Breakdown strength of C_4-FN with different humidities in a uniform electric field against increasing operating pressures.

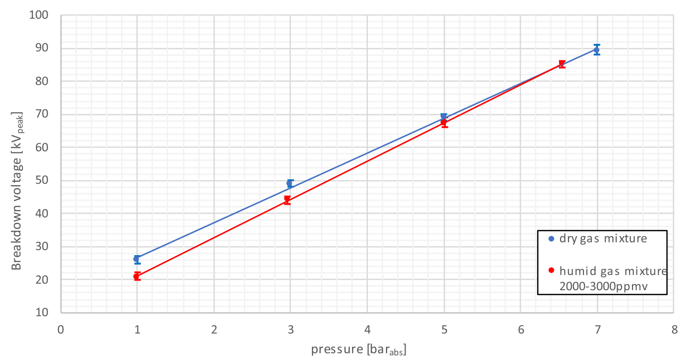

Fig. 11. Breakdown strength of C_4-FN with different humidities in a quasi-uniform electric field against increasing operating pressures.

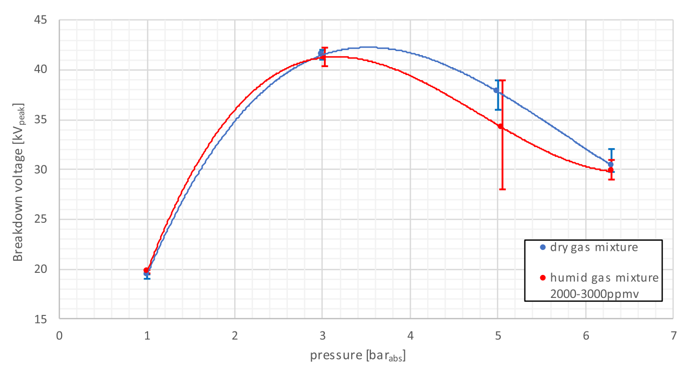

Fig. 12. Breakdown strength of C_4-FN with different humidities in a nonuniform electric field against increasing operating pressures.

Two observations can be made from Figs. 7–9.

1) An increase in humidity decreases the ac breakdown strength.
2) The effect of humidity is different for each of the three electric field configurations. The effect is the highest at a uniform field, i.e., a high field utilization factor of $\eta = 1$. The effect decreases as the electric field becomes less uniform.

B. Effect of Humidity on the AC Breakdown Strength of C_4-FN at Different Operating Pressures

Figs. 10–12 show the correlation between the ac breakdown strength of C_4-FN with a humidity of 2000–3000 ppmv and various operating pressures in a uniform, quasi-uniform, and nonuniform field, respectively. The ac breakdown strength of dry C_4-FN has also been added for comparison.

About the graphs/experiments.

1) Each dot represents an experiment and is the average value of the ten breakdown repetitions.
2) The (vertical) error bars show the range in which the ten breakdown repetitions are measured.
3) The humidity is chosen to be in a constant range as it is impossible with the used setup to create exactly the same humidity multiple times over. The humidity is therefore constant between 2000 and 3000 ppmv. The used setup was not able to create a humidity >2200 ppmv at 7 bar$_{abs}$ without altering the gas temperature.
4) The dry C_4-FN gas mixture has a T_d of ca. −55 °C (at 1 bar$_{abs}$), corresponding to a humidity of 35 ppmv at 1 bar$_{abs}$.

5) Not all the experiments are performed at 7.00 bar_{abs} as the C_4-FN gas mixture from the gas tank was exhausted to a point where it was unable to create high-pressure gas mixtures. A new gas tank was not used as it would not have the exact identical proportion of C_4-FN and CO_2.
6) The room and gas temperature were constant during all the experiment at ca. 20 °C.

The experiments in Fig. 12 show that the ac breakdown strength in a nonuniform field is not affected by humidity regardless of higher operating pressures. An anomaly can be seen at 5 bar_{abs}, where a huge spread of the measured breakdown voltages was measured. This experiment was repeated with clean electrodes and gas and showed exactly the same behavior, i.e., the huge spread.

Two observations can be made from Figs. 10–12.

1) The effect of humidity on the ac breakdown strength decreases as the operating pressure increases.
2) The effect of humidity on the ac breakdown strength continues to be different for each electric field configuration even at different operating pressures. It can be noted that the ac breakdown strength of dry and humid C_4-FN becomes equal at 6.55 bar_{abs} in a quasi-uniform electric field configuration, which is not true for a uniform electric field. Instead, the ac breakdown strength of humid and dry C_4-FN gas mixture in a uniform field will become equal around 8.00 bar_{abs} if it is assumed that the trendline continues linearly beyond 6.85 bar_{abs}.

C. Effect of Humidity on the PD Behavior of Corona in C_4-FN

This part consists of three topics. The first part shows the effect of humidity on the PDIV, the second part covers the PRPD pattern, and the third part dives into the wave shape of the PD. The experiments to examine these three topics were all measured under the same conditions.

1) The gap distance is increased from 5 to 10 mm as extra caution to prevent a breakdown, as the oscilloscope is directly connected to the needle.
2) The pressure of the dry and humid C_4-FN gas mixture is both 1.00 bar_{abs}.
3) The humidity of the dry gas mixture is 35 ppmv and ca 10 000 ppmv for the humid gas mixture.
4) The background noise is <1 pC.

1) PDIV: Fig. 13 shows the results of three PDIV experiments. The PDIV was always measured to be equal for both C_4-FN gas mixtures, i.e., ca. 9.4 kV_{peak}. The figure indicates that the PDs in humid C_4-FN contain more charge compared to the PDs in dry C_4-FN.

2) PRPD Pattern: The PRPD Pattern was measured at 10 and 14 kV_{peak}. These voltages were chosen based on the PD activity shown in Fig. 13. It was expected that the PRPD measurement of corona in dry C_4-FN would show a stable rate of Trichel pulses, which make up low-voltage corona PRPD pattern in other gases, e.g., air and SF_6 [12]. However, it can be seen from Fig. 14 that a lot of irregularities were measured. The irregularities ceased after 5 min and the rate of Trichel

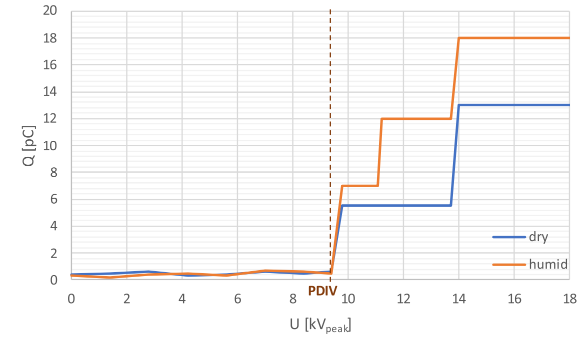

Fig. 13. Measured average charge at different voltages. Q[pC] is the averaged charge according to the IEC60270.

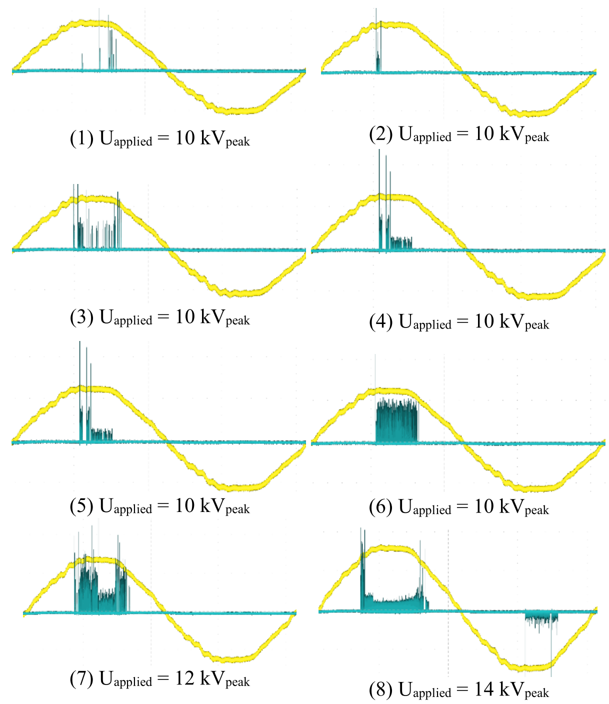

Fig. 14. Eight screenshots (interval of 60 s) of the oscilloscope PRPD pattern in dry C_4-FN. Yellow = applied voltage. Blue = corona PDs.

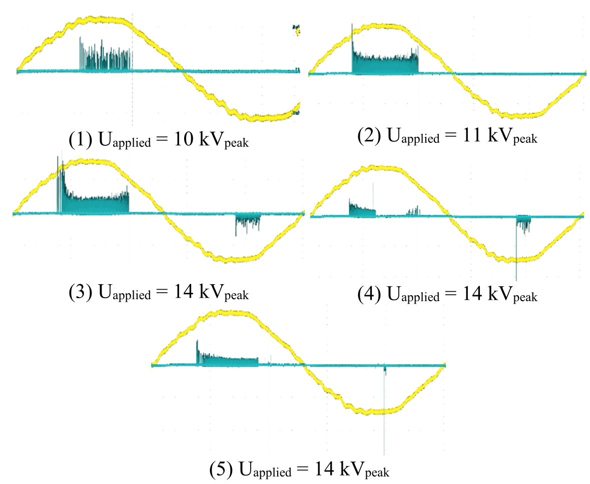

Fig. 15. Five screenshots (interval of 60 s) of the PRPD pattern in humid C_4-FN. Yellow = applied voltage. Blue = corona PDs.

TABLE II
AVERAGED CHARACTERISTICS OF 100 CORONA PD SAMPLES IN A DRY AND HUMID C_4-FNGAS MIXTURE

Characteristic	**Dry C_4-FN**	**Humid C_4-FN**
Rise time [ns]	2,55	1,58
Fall time [ns]	2,74	4,86
Bandwidth [MHz]	202	227
PD rate [n/s]	109	54
Apperent charge [pC]	1,02	5,57

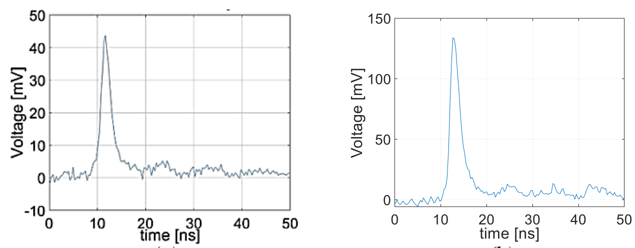

Fig. 16. (a) Waveform of a corona PD in dry C_4-FN. (b) Waveform of a corona PD in humid C_4-FN.

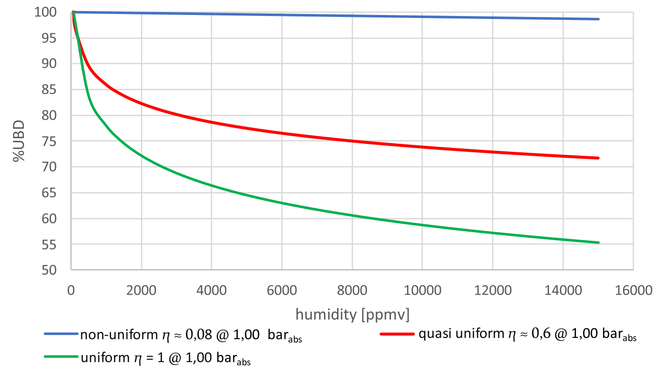

Fig. 17. Rough comparison between the relative ac breakdown strength of the three examined electric field configurations.

pulses became stable. The PRPD pattern took the shape of a half-crescent moon after increasing the voltage.

It was investigated if the same phenomenon was observed when measuring corona in humid C_4-FN. The results of those measurements can be seen in Fig. 15. The rate of Trichel pulses was measured to be stable after applying the voltage. After increasing the voltage to 14 kV_{peak}, the PRPD pattern of corona in humid C_4-FN also took the form of a crescent moon. At 14 kV_{peak}, the rate of Trichel pulses was still stable. However, a few seconds after increasing the voltage to 14 kV_{peak}, the rate of Trichel pulses became irregular. It became stable again after 60 s. Yet, the magnitude of the discharges became lower compared to the magnitude before the irregularities.

The Trichel pulses of corona have also been measured in pure CO_2 gas to further investigate the irregularities. It has also been measured in pure SF_6 and air. The Trichel pulses were measured to have a stable rate in air, SF_6, and CO_2. Which is opposite to the multiple repeated measurements in both dry and humid C_4-FN.

3) Wave Shape: Hundred corona PDs have been measured at 10% above their inception voltage and their characteristics have been averaged. Table II gives an overview of these averaged characteristics. Fig. 16(a) and (b) shows the averaged waveform of a corona PD in dry and humid C_4-FN, respectively.

IV. DISCUSSION

This research has thus far shown that the effect of humidity on the ac breakdown behavior is different for various field configurations and can variate depending on the pressure.

It was also desired to compare the degree of variation that humidity causes through a variation in the electric field, i.e., field configuration. However, this was not possible as it was necessary to deviate from the desired 1-bar_{abs} operating pressure. Nevertheless, it is interesting to investigate the extent of the effect that humidity has on the ac breakdown behavior in various field configurations. This means that only the electric field is allowed to variate. All other parameters must be constant. This was achieved by repeating some experiments in a limited fashion.

1) Three experiments in the uniform electric field were repeated at 1.00 bar_{abs}.
2) Fig. 12 shows that humidity affects the breakdown strength of C_4-FN in a nonuniform configuration at 1.00 bar_{abs} almost the same as at 1.20 bar_{abs} and that their breakdown strength only differs a few percentages. Therefore, the breakdown strength of 1.20 bar_{abs} is assumed to be equal to 1.00 bar_{abs}.

The results are processed in Fig. 17 and show the ac breakdown strength of each electric field configuration relative to their ac breakdown strength at dry conditions.

The measured ac breakdown behavior of the nonuniform field for various operating pressures (see Fig. 12) is similar to that of what already has been published [5], implying that humidity affects the breakdown behavior for different mixing ratios of the insulating gas commensurately.

Numerical studies have shown that α_{eff} of a gas can change with the presence of humidity, which will affect PD activity and the breakdown strength [13], [14], [15], [16]. Those studies calculated the reduced ionization and reduced attachment coefficients by solving the two-term Boltzmann equations. The reduced effective ionization coefficient (α_{eff}/N $[m^2]$) is expressed against the reduced electric field strength (E/N $[T_d]$) [13], [14]. E/N (T_d) can be calculated according to (5), where U_{BD} is the breakdown voltage $[V]$, d is the distance between the electrodes $[m]$, K_B is the Boltzmann constant, T is the temperature $[K]$, p is the pressure $[Pa]$, and N is the density of the gas

$$\frac{E}{N}(T_d) = \frac{U_{\text{BD}}}{d} \cdot \frac{k_B \cdot T}{p} \cdot 10^{21}. \quad (5)$$

Fig. 18 shows an example of air, where α_{eff} is affected by humidity. An increase in the humidity of air decreases the α_{eff} coefficient. This allows a higher breakdown voltage. The figure also shows that the effect of humidity at lower

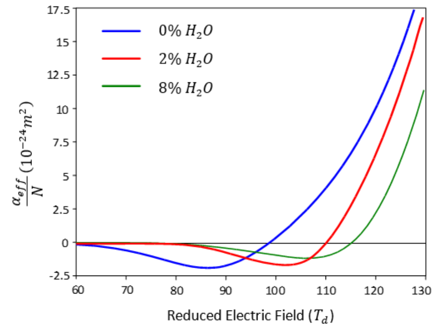

Fig. 18. α_{eff} for air mixed with humidity, reproduced from [12].

reduced electric field strength on α_{eff} is almost negligible. It is hypothesized that the opposite effect is true for C_4-FN. Furthermore, a smaller reduced electric field strength can, according to (5), correspond to a gas mixture with a higher breakdown strength at higher pressures. This can also be seen in Figs. 10 and 11, where the effect of humidity on the ac breakdown strength becomes smaller at higher pressures, i.e., the difference between dry and humid C_4-FN becomes smaller.

However, these simulated effects of humidity on α_{eff} are not always present. The effect of humidity on the breakdown strength depends on the electric field configuration and phenomenon. The effect of humidity in air on the ac breakdown voltage in uniform fields is negligible, but more significant for quasi-uniform and nonuniform fields [15], [16]. Furthermore, the effect of humidity in SF_6 on the flashover voltage can vary for different voltage phenomena. The effect of humidity in SF_6 on the ac flashover voltage in a quasi-uniform field is significant but negligible for positive lightning impulses [17]. It is thus possible that humidity would affect C_4-FN differently for other phenomena as well and needs further investigation.

V. Conclusion

This research has shown that humidity affects the ac breakdown strength of C_4-FN/CO_2 (5%/95%). The degree of influence depends on multiple factors.

1) *Amount of Humidity*: An increase in the amount of humidity decreases the breakdown strength.
2) *Electric Field:* Similar test conditions, where only the electric field strength differed, i.e., field configuration, showed a different response of humidity toward the breakdown behavior. For the worst case tested scenario, i.e., 15 000 ppmv, the breakdown strength in the uniform field decreased 45%. The reduction in the quasi-uniform field was 28% and only 2% in the nonuniform field.
3) *Operating Pressure:* An increase in operating pressure decreases the effect of humidity on the breakdown strength. The breakdown strength of the tested humid gas (2000–3000 ppmv) in a uniform field reached the breakdown strength of the dry gas around 8 bar_{abs}. A lower pressure is sufficient toward a more nonuniform field for the effect of humidity to disappear.

The PRPD pattern and PD characteristics of corona in a C_4-FN also appear to differ with the presence of much humidity in the gas. The charge of the corona discharges around the inception voltage in a humid C_4-FN gas mixture is larger, around 50%–100%. The PDIV, however, did not change with the presence of much humidity in the gas. These results invite more specific research toward the effect of humidity on more PD behavior and conforming the hypothesis on the affected α_{eff}.

References

[1] *Technical Brochure 849: Electric Performance of New Non-SF6 Gases and Gas Mixtures for Gas-insulated Systems*, document D1.67, Cigré Work. Group, 2021.
[2] *High-voltage Switchgear and Controlgear—Part 1: Common Specifications for Alternating Current Switchgear and Controlgear*, Standard IEC 62271-1:2017, 2017.
[3] G.-C. Shin, S.-W. Kim, and G.-S. Kil, "Comparison between the PD characteristics of G^3 and dry air for gas-insulated switchgears," *Energies*, vol. 15, no. 19, p. 7043, Sep. 2022, doi: 10.3390/en15197043.
[4] J. Deschler and J. Kindersberger, "Influence of humidity on electric strength of CO_2 and C_4-FN/CO_2 gas mixtures," in *Proc. VDE High Voltage Technol. ; ETG-Symposium*, Nov. 2020, pp. 1–6.
[5] Y. Yang, K. Gao, J. Bi, L. Ding, S. Yuan, and G. Wang, "Influence of micro-water on AC breakdown characteristics of C_4F_7N/CO_2 gas mixture under non-uniform electric field," *High Voltage*, vol. 7, no. 6, pp. 1059–1068, Dec. 2022, doi: 10.1049/hve2.12215.
[6] A. J. Reid, M. D. Judd, B. G. Stewart, and R. A. Fouracre, "Partial discharge current pulses in SF_6 and the effect of superposition of their radiometric measurement," *J. Phys. D, Appl. Phys.*, vol. 39, no. 19, pp. 4167–4177, Oct. 2006, doi: 10.1088/0022-3727/39/19/008.
[7] *IEEE Guide for Moisture Measurement and Control in SF_6 Gas-Insulated Equipment*, Standard C37.122.5-2013, 2013.
[8] *Standard Test Method for Dielectric Breakdown Voltage and Dielectric Strength of Insulating Gases At Commercial Power Frequencies*, Standard ASTM D2477:2012, 2012.
[9] A. M. Mahdy, H. I. Anis, and S. A. Ward, "Electrode roughness effects on the breakdown of air-insulated apparatus," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 5, no. 4, pp. 612–617, Aug. 1998, doi: 10.1109/94.708280.
[10] *High Voltage Test Techniques—partial Discharges Measurement*, Standard IEC 60270:2000, 2000.
[11] *High-voltage Test Techniques—Part 1: General Definitions and Test Requirements*, Standard IEC 60060-1:2010, 2010.
[12] A. R. Mor, L. C. C. Heredia, D. A. Harmsen, and F. A. Muñoz, "A new design of a test platform for testing multiple partial discharge sources," *Int. J. Electr. Power Energy Syst.*, vol. 94, pp. 374–384, Jan. 2018, doi: 10.1016/j.ijepes.2017.07.013.
[13] B. Li, X. Li, M. Fu, R. Zhuo, and D. Wang, "Effect of humidity on dielectric breakdown properties of air considering ion kinetics," *J. Phys. D, Appl. Phys.*, vol. 51, no. 37, Sep. 2018, Art. no. 375201, doi: 10.1088/1361-6463/aad5b9.
[14] Q. Gao et al., "Effects of H_2O and O_2 impurities on the trichel pulses characteristics of the negative point-plane corona discharge in SF_6," *Plasma Chem. Plasma Process.*, vol. 41, no. 4, pp. 1101–1119, Jul. 2021, doi: 10.1007/s11090-021-10166-7.
[15] E. Hussian, M. R. Nandagopal, and B. R. Prabhakar, "Effect of humidity on breakdown voltages of gaps and insulators," *J. Indian Inst. Sci.*, vol. 56, no. 11 and 12, p. 481, 1974.
[16] D. Wu, G. Asplund, B. Jacobson, M. Li, and F. Sahlen, "Humidity influence on switching-impulse breakdown voltage of air gaps for indoor high-voltage installations," in *Proc. 14th Int. Symp. High Voltage Eng.*, 2005, pp. 1–4.
[17] A. P. Purnomoadi, A. Rodrigo Mor, and J. J. Smit, "Spacer flashover in gas insulated switchgear (GIS) with humid SF_6 under different electrical stresses," *Int. J. Electr. Power Energy Syst.*, vol. 116, Mar. 2020, Art. no. 105559.