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Breakdown Characteristics of N_2/O_2 Gas Mixtures Using 2 cm Diameter Sphere Electrodes

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Abstract — *Flashover voltage of N_2/O_2 gas mixtures with successively 5%, 10%, 21%, 30%, and 40% O_2 rate is measured using 2 cm diameter sphere electrodes configuration. Measurements are carried out in a real Schneider Electric WI busbar tank using different inter-electrode distances and gas pressures. The aim is the characterization of the best composition of the mixture in these electric field conditions as a possible candidate for the gas part in hybrid insulation systems of SF_6–free GIS. The results obtained show that breakdown voltage increases logically with the increase of inter-electrode gap distance and gas pressure. But it is nonlinear versus oxygen content. However, the mixtures with 5% O_2 shows the higher AC breakdown voltage among the gases tested. For lightning impulse breakdown measurement, the mixtures with 10% O_2 and 30% O_2 show the best dielectric strength for shortest (>1 cm) and relatively longest (3 and 5 cm) inter-electrode distances respectively, regardless to the gas pressure and the voltage polarity.*

Keywords — *AC and lightning impulse breakdown voltages, sphere electrodes, nitrogen-oxygen gas mixtures, GIS.*

I. INTRODUCTION

Global environmental problems such as global warming caused by the use of greenhouse gases in high voltage engineering are of great concern. To cope with these environmental problems, we examined the fundamental insulation properties of nitrogen-oxygen (N_2/O_2) gas mixtures as possible candidates for the gas part in a hybrid insulation system for SF_6–free GIS.

It is well known that insulation performance of environmentally friendly gases is significantly lower than that of SF_6 [1]. The dielectric strength of dry air and N_2 is stronger than that of other green gases because of the presence of oxygen.

This assumes that under certain conditions the dielectric strength of N_2/O_2 gas mixture can be made higher than that of dry air by varying the rate of O_2, Applying this principle as shown in [2], the mixture with 40% O_2 seemed to provide the highest dielectric strength at 5 bar in point to plan electrode configuration. Thus in the present study, dry air (21% O_2) has been selected as reference gas and performances of N_2/O_2 gas mixtures with different fractions of oxygen has been analyzed.

The typical pressure level for the present medium voltage GIS is 1.5 bar. Our study is conducted at 1, 1.5 and 2.5 bar since the lowest pressure considered as ambient pressure. This pressure level is of special interest as it is the lowest level when considering leakage.

In our experiences, gas pressure is measured with a manometer of type WIKA®118.10 with a working range extending from 0 to 4 bar over the atmospheric pressure with a scale division of 0.02 bar according to EN 837–1.

Table 1 lists the composition of the N_2/O_2 gas mixtures investigated. AGA Gas AB ® Company provides these gas mixtures. So, the main purpose of this study is the investigation of the optimum composition of our "green" gas using N_2/O_2 gas mixtures in the condition of electric field imposed by 2 cm diameter sphere electrode configuration. To simplify, gas mixtures used in the present paper are named as Mj, where M stands for gas mixture and j the oxygen concentration (e;g; the mixture with 5% O_2 is named M5, that with 30% O_2, is noted M30).

TABLE 1. Gas Insulating (N_2/O_2) composition

Items	N_2/O_2	Uncertainty [%]
O_2 rate [mol.%]	5/10/21/30/40	2
Humidity [ppm]	10	-

II. EXPERIMENTATION AND METHODS

A. *Configuration of electrodes*

The experiments in the present study were conducted in a test vessel using a stainless steel sphere electrodes with 2 cm in diameter [3]. The spherical electrode connected to the HV bushing was fixed on stainless steel shank with 2.5 cm in diameter, and 26 cm length ended with a sharp rod of 5 cm length and 0.8 cm in diameter to reduce the protruding edge of the shank. The grounded electrode was mounted on a similar shank of 2.5 cm in diameter; however, its length was 16 cm for a total length of 21 cm when introducing the ended rod of 0.8 cm diameter. Fig. 1 shows the configuration of electrodes inside the test vessel.

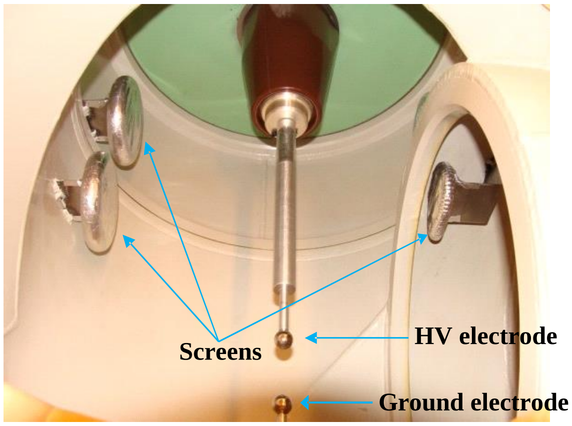

Fig. 1. Configuration of sphere electrodes inside the test vessel

B. Test vessel

The investigations of breakdown voltage for different N_2/O_2 gas mixtures are performed in a painted stainless steel test chamber. This test vessel is made based on WI-busbar tank (Schneider Electric product) and contains four flanges (Fig 1). The complete description of the chamber is given in [3].

The performance of the test vessel has been evaluated to reduce possible parasitic discharges by preliminary breakdown tests and pre-breakdown observations under DC voltage in atmospheric open-air conditions [3].

To fill the test vessel with the gas to be analyzed, the chamber and electrodes were firstly cleaned with alcohol and then the tank was exhausted at 90 mbar. Then it was filled with the investigated gas mixture up to 1 bar and evacuated again at 90 mbar and finally filled up to 2.5 bar with the same gas. Experiments in the test vessel were conducted for inter-electrode distances of 1, 3, and 5 cm.

C. Voltage applications and measurement procedure

The applied voltages in the present investigation are 50 Hz AC and standard lightning impulse voltages. AC voltage was provided by a Phenix Technologies® Model NO 6TD150–20 generator. For the AC breakdown evaluation, the voltage was applied three times at a given inter-electrode gap distance, and the reported breakdown voltage was taken as the average of these measurements.

For lightning impulse breakdown tests, the voltage was derived from a 5–stages 500 kV impulse generator having approximately 1.2/50 µs wave shape.

Since the breakdown is a stochastic phenomenon [4], the "up-and-down" method [5] was used for a statistical evaluation of breakdown voltages. However, in our case, we saw that each voltage shot in a series of measurements influenced the subsequent ones due to the possible effect of discharge plasma byproducts, presumably ozone and nitrogen oxides. Therefore, instead of investigating the 50% breakdown voltage $U_{50\%}$ that is not relevant here, our findings are exhibited as the average breakdown voltage U_{AV} [6], and we used a series of 20 shots according to the IEC standard [7]. All measurements were performed at an ambient temperature of about 19 °C.

To limit the effect of repetitive breakdowns on flashover characteristics, we adopted a method using a time between a series of measurements of 10 minutes and a time between shots of 3 minutes for one voltage polarity. The measurements with another voltage polarity were performed a day after [3].

III. EXPERIMENTAL RESULTS

A. AC breakdown measurements

AC breakdown results (AC BDV) are shown in Fig. 2–4 respectively for 1, 3 and 5 cm inter-electrode distances limited by the chamber pre–breakdown conditions.

The results of AC BDV show that breakdown voltage increases naturally with the increase in gas pressure and electrode gap distance for all the gas mixtures tested.

At a shortest inter-electrode distance (Fig 2), one can see that for gas pressure of 2.5 bar breakdown voltage is higher for M10 following by that measured with M21 which exhibits almost the same breakdown level as those measured with M5 and M40. The lower breakdown level in the present case is seen with M30. Then at 1.5 bar, AC BDV is higher with M5, seconded by M10, which shows almost the same breakdown level as that measured with M40. The breakdown voltage carried out with this latter is higher than that seen with M30, and the weaker breakdown level is measured with M21. For low pressure (1 bar), the higher AC breakdown strength is seen for M5 following by M10, which shows the same breakdown level as that performed with M21. AC BDV for this gas is higher than that measured with M40, and the lower breakdown value is given for M30.

For 3 cm inter-electrode distance (Fig 3), the higher breakdown is still observed with M10 at 2.5 bar, following by that of M40, which shows almost the same breakdown level as M5. The lower breakdown level is seen with M30, and M21 which show almost the same breakdown level. For 1.5 bar, the higher breakdown level is given with M5, this latter being equal to those measured with M21 and M40. The lower breakdown voltage is seen with M10, this one being also equal to that of M30. However, the higher breakdown voltage for 1 bar is observed simultaneously with M21, M5 and M10 gases following by that measured with M40 and the lower breakdown value is seen with M30.

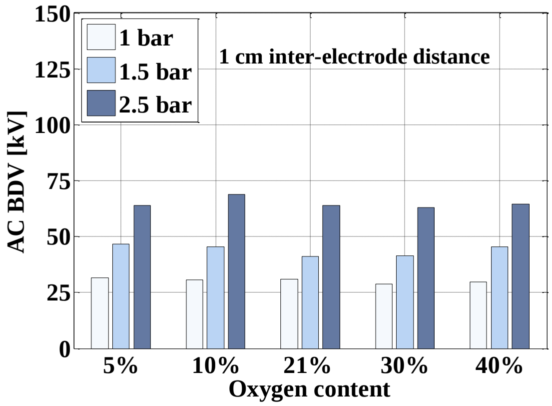

Fig. 2. AC breakdown voltages (AC BDV) measured with 1 cm inter-electrode distance for different N_2/O_2 gas mixtures and pressures.

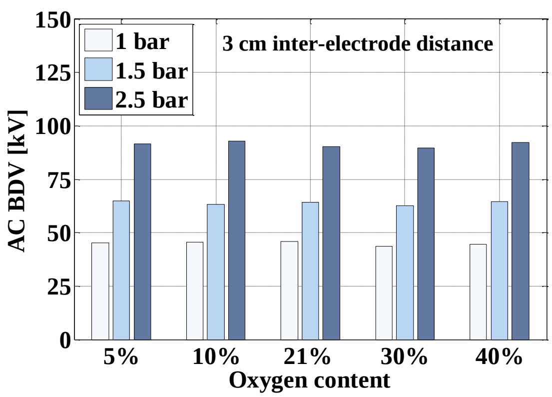

Fig. 3. AC breakdown voltage (AC BDV) measured with 3 cm inter-electrode distance for different N_2/O_2 gas mixtures and pressures.

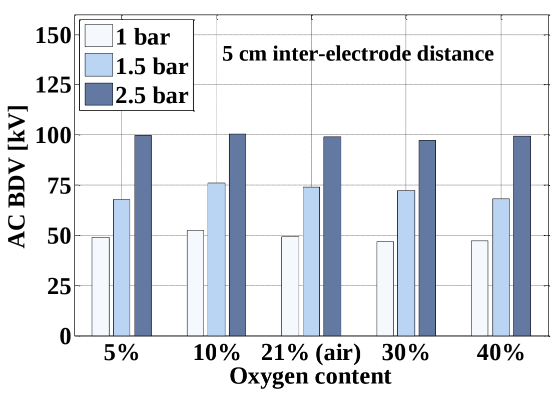

Fig. 4. AC breakdown voltage (AC BDV) measured with 5 cm inter-electrode distance for different N_2/O_2 gas mixtures and pressures.

As seen generally in Fig 3, the higher AC BDV level at 5 cm inter-electrode distance (Fig 4) is given with M10 for all pressures tested, following, at 2.5 bar, by that measured with M5 which is equal to that obtained with M4. This latter is slightly higher than the AC BDV given by M21, and the lower AC BDV value is seen with M30. For 1.5 bar (Fig. 4), AC BDV of M10 is seconded by that measured with M21 and then that of M30. The lower breakdown voltage is given with M5, this latter being equal to that measured with the M40. Finally, for 1 bar, M21 and M5 show almost the same breakdown level seconded by what is measured with M10. That of M40 follows the breakdown voltage measured with these gases. The mixture exhibits a lower breakdown value with 30% O_2.

To classify more rigorously our gas mixtures according to their AC breakdown characteristic, we considered the minimum level at which breakdown was occurred instead of the average AC breakdown voltage. Table 2–4 show the minimum level at which the AC breakdown has occurred for each gas mixture at different pressure.

TABLE 2. Comparison of a minimum level of AC breakdown voltage in different gas mixtures for 1 bar gas pressure.

N_2/O_2 gas composition	AC Minimum Breakdown level (kV)		
	1 cm gap	3 cm gap	5 cm gap
5 % O_2	30.97	44.4	48.8
10 % O_2	29.13	44.41	49.1
21 % O_2	29.45	44.83	47.94
30 % O_2	27.43	43.13	45.11
40 % O_2	28	43.56	45.68

TABLE 3. Comparison of a minimum level of AC breakdown voltage in different gas mixtures for 1.5 bar gas pressure.

N_2/O_2 gas composition	AC Minimum Breakdown level (kV)		
	1 cm gap	3 cm gap	5 cm gap
5 % O_2	46.24	63.07	66.89
10 % O_2	42.14	60	69.44
21 % O_2	39.17	62.37	68.16
30 % O_2	41.3	62.37	69.86
40 % O_2	44.26	62.65	66.89

TABLE 4. Comparison of the minimum level of AC breakdown voltage in different gas mixtures for 2.5 bar gas pressure.

N_2/O_2 gas composition	AC Minimum Breakdown level (kV)		
	1 cm gap	3 cm gap	5 cm gap
5 % O_2	62.37	90.65	99
10 % O_2	67.18	89.24	99
21 % O_2	62.08	88.25	98
30 % O_2	61.09	89.34	97.16
40 % O_2	61.8	89.8	98

Table 5 exhibits the ranking of tested gases according to their minimum voltage at which breakdown has occurred for different inter-electrode distances and gas pressure.

TABLE 5. Ranking of gas mixtures tested according to their minimum AC breakdown level for 2 cm diameter sphere electrodes.

Gap distance [cm]	Gas pressure [bar]	Gas ranking according to their AC breakdown level
1	1	5% > 21% > 10% > 40% > 30%
	1.5	5% > 40% > 10% > 30% > 21%
	2.5	10% > 5% > 21% > 40% > 30%
3	1	21% > 10% > 5% > 40% > 30%
	1.5	5% > 40% > 21% = 30% > 10%
	2.5	5% > 40% > 30% > 10% > 21%
5	1	10% > 5% > 21% > 40% > 30%
	1.5	30% > 10% > 21% > 5% = 40%
	2.5	5% = 10% > 21% = 40% > 30%

AC BDV (Table 5) is nonlinear regarding oxygen concentration following the results of T. Ishida et *al.* [8].

The general tendency in our experimental results shows that the higher AC breakdown voltage is obtained essentially with a gas mixture with 5% O_2. And the weaker AC BDV seems to be given by the mixture with 30% O_2 regardless of the gas pressure and inter-electrode distance (Table 5). This behaviour is not observed in [8]. The difference between experimental conditions and electrode system used might explain the difference observed.

B. Lightning impulse breakdown measurement

Results from lightning impulse breakdown tests are shown in Fig. 5 as average breakdown voltage U_{AV} against inter-electrode distance for both positive and negative voltage polarities. Error bars stand for the minimum, and the maximum applied voltage levels at which breakdown were measured (Fig. 5). These measurements were performed approximately at 20°C. M40 has been excluded from these measurements to reduce the possible influence of O_2, such as oxidation.

The comparison of our gas mixtures according to their breakdown level is made by confronting the minimum flashover voltage obtained in each gas for a given inter-electrode distance.

The results of U_{AV} show that breakdown voltage also increases naturally with the increase in gas pressure and inter-electrode distance for all the gas mixtures tested regardless of the voltage polarity.

To better compare the characteristics of our gas mixtures, table 6 exhibits the ranking of tested gases according to their minimum voltage at which breakdown was occurred for different inter-electrode distance and gas pressure.

One can see that, at a shortest inter-electrode distance, M10 seems to provide a higher flashover voltage regardless of the gas pressure and the voltage polarity. M30 globally seconds this gas and then M21. The lowest breakdown voltage is seen with M5 (Table 6).

At 3 cm inter-electrode distance, M30 shows the greater flashover voltage among the tested gases. M10 globally seconds this gas and then M21. The lower breakdown voltage is measured with M5.

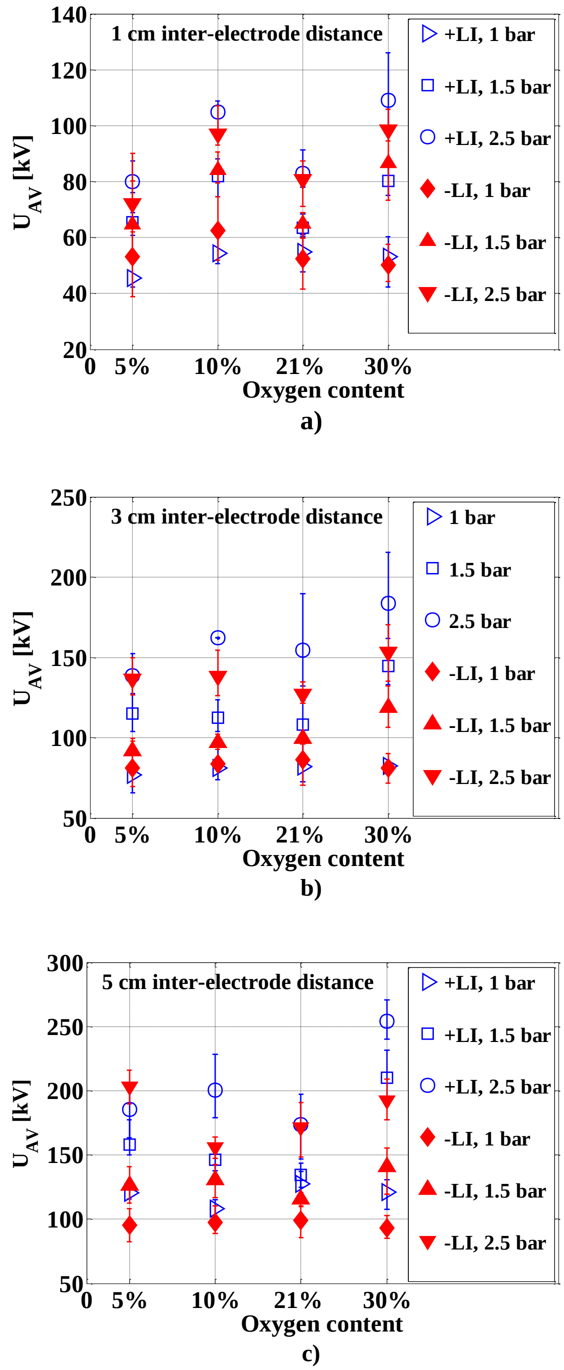

Fig. 5. Impulse breakdown voltage measurements in different N_2/O_2 gas mixtures and gas pressures, a) measurement with 1 cm inter-electrode distance, b); measurement with 3 cm inter-electrode distance, and c) measurement with 5 cm inter-electrode distance. The error bars in figures stand for the minimum and the maximum breakdown level during measurements.

For 5 cm inter-electrode distance, the greater flashover voltage is measured with M10 at 1 bar regardless of the voltage polarity. However, the ranking of other gas mixtures at this pressure is not obvious (Table 6). At relative higher pressure (1.5 and 2.5 bar) M30 presents the higher breakdown voltage independently to the voltage polarity. This gas is seconded globally by M10 and then M5. The lower breakdown voltage is generally seen with M21.

TABLE 6. Ranking of gas mixtures tested according to their minimum lightning impulse breakdown level for 2 cm diameter sphere electrodes.

Gap distance [cm]	Gas pressure [bar]	Voltage polarity	Gas ranking according to their AC breakdown level
1	1	+	10% > 21% > 30% > 5%
		-	10% > 30% > 21% > 5%
	1.5	+	10% > 21% > 30% > 5%
		-	10% > 30% > 5% > 21%
	2.5	+	30% > 10% > 21% > 5%
		-	10% = 30% > 21% > 5%
3	1	+	30% > 10% > 21% > 5%
		-	10% > 30% > 21% > 5%
	1.5	+	30% > 10% > 5% > 21%
		-	30% > 21% > 10% > 5%
	2.5	+	30% > 10% > 21% > 5%
		-	30% > 5% > 10% > 21%
5	1	+	10% > 5% > 30% > 21%
		-	10% > 21% > 30% > 5%
	1.5	+	30% > 5% > 10% > 21%
		-	30% > 10% > 5% > 21%
	2.5	+	30% > 10% > 5% > 21%
		-	5% > 30% > 21% > 10%

In short, the gas mixtures M10 and M30 seem to yield the higher flashover voltage at 1 bar and relatively greater pressure (1.5 and 2.5 bar) respectively for our electrode configuration. And the lower flashover voltage is seen generally with M5 at 1 and 3 cm inter-electrode distances. Low values of breakdown voltage are registered at 5 cm inter-electrode distance for M21.

M10 and M30 can be considered according to specific inter-electrode distance as the best dielectric gases among all the gases tested. Other criteria for specific application could favour the choice of one of these dielectric gases.

IV. CONCLUSION

AC and lightning impulse flashover voltage evaluation of 5%, 10%, 21%, 30%, and 40% oxygen content in N_2/O_2 gas mixtures have been carried out with different inter-electrode distances and gas pressures within a real Schneider Electric WI–busbar tank. The sphere electrodes were stainless steel spheres with 2 cm in diameter. The aim was the characterization of the optimum composition of the mixture as a possible candidate for a gas part in hybrid insulation of SF_6–free GIS. The measurements showed a non–linearity effect of oxygen on the breakdown voltage. However, the mixtures having 5% O_2 seems to provide the higher AC breakdown voltage among the gases tested. For lightning impulse breakdown measurement, the mixtures with 10% O_2 and 30% O_2 show globally the best dielectric performance for shortest (1 cm) and longest (> 1 cm) inter-electrode distance respectively, regardless to the gas pressure and the voltage polarity. Other criteria for a specific application might allow the selection of the relevant gas among these two latter.

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