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Flashover Voltage Measurement of N_2/O_2 Gas Mixtures in 2–15 cm Diameter Sphere Electrodes: Determination of the Best Compromise for Different Field Factors

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Abstract — *Measurement of lightning impulse and AC breakdown voltages are carried out with different N_2/O_2 gas mixtures within a real Schneider Electric busbar tank for different inter-electrode distances and gas pressures. The electrodes are made of spheres having 2 cm and 15 cm in diameters. The objective is to yield more data at different field factors for deep analysis to determine the mixture with greater breakdown characteristics for gas part application in the hybrid insulation systems of SF_6–free GIS. As an achievement, it is observed that the mixture with 10% O_2 presents the best compromise regardless of the gas pressure, electrode configuration, and electric field inhomogeneity.*

Keywords — *Electric field inhomogeneity, Flashover voltage, Insulating gas, Nitrogen–oxygen gas mixtures, Sphere gaps.*

I. INTRODUCTION

The dielectric performance of SF_6 and its application in gas-insulated switchgear (GIS) is well known [1–7]. However, SF_6 is a greenhouse gas with a long atmospheric lifetime [4]. To cope with these environmental problems, we investigated 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.

Investigation of gas mixtures used in the present paper has already been achieved in [1] and [2] respectively for quasi-homogeneous and inhomogeneous electric fields. However, these studies did not identify the gas mixture with greater dielectric performance.

In the present study, we proposed identifying the gas mixture with the best compromise regardless of the electrode configuration, inter-electrode distance, and electric field inhomogeneity. The method includes breakdown test results using a new configuration of electrodes and the data given in [1] and [2].

II. EXPERIMENTAL MEASUREMENT AND METHODS

The breakdown voltage investigations for different N_2/O_2 gas mixtures are performed in a painted stainless steel test chamber [1, 2]. The electrode system is made with a large copper sphere electrode of 15 cm in diameter (HV electrode) and a small stainless steel sphere electrode of 2 cm in diameter (grounded electrode) to work with a diverging electric field.

The spherical electrodes were mounted on stainless steel shanks. The shank attached to the bigger electrode was 25 mm in diameter and that related to the small sphere was similar but ended by a 50 mm long tip with 8 mm in diameter to reduce the protruding edge of the rod [8]. The total length, including the sphere electrode shank tip, was 140 mm and 210 mm, respectively, for the bigger and the smaller electrode [8]. The bigger sphere constituting the HV electrode was connected to the bushing to conduct measurements, while the small sphere electrode and the test vessel were grounded. The voltage application and the measurement procedure are defined in [1] and [2].

For easier writing, our different gas mixtures are noted MX, where M stands for the mixture and X for the oxygen composition (e.g., gas mixtures with 10% O_2 and 30% O_2 are noted M10 and M30, respectively).

III. EXPERIMENTAL RESULTS

A. AC Breakdown measurements

Fig. 3–5 shows the average AC breakdown voltage results (AC BDV) for different N_2/O_2 gas mixtures. The electrode separated distance was successively fixed at 1, 3, and 5 cm according to the requirements [9] of our Schneider electric tank given by pre-breakdown tests.

At 1 cm inter-electrode distance (Fig. 1), the gas mixture M10 seems to show the higher AC BDV for all the gas pressure tested (1, 1..5 and 2.5 bar). This gas is following globally by M30 for 1 and 1.5 bar. The ranking of other gases remains difficult because of the nonlinearity. However, for relatively low pressure (1 and 1.5 bar), M21 shows the lower AC BDV.

For 3 cm inter-electrode distance (Fig. 2), the higher AC BDV is seen with M5, following by M10. While M21, M30, and M40 present almost the same breakdown level.

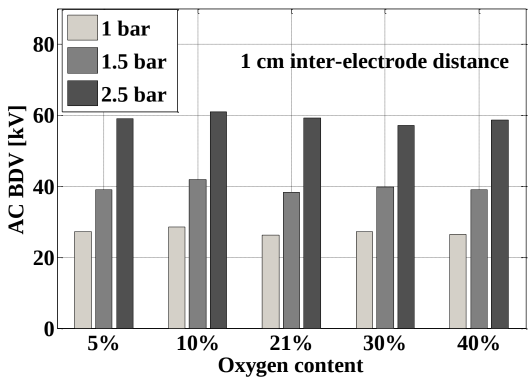

Fig. 1. AC breakdown voltages with 1 cm inter-electrode distance for different N_2/O_2 gas mixtures and pressures.

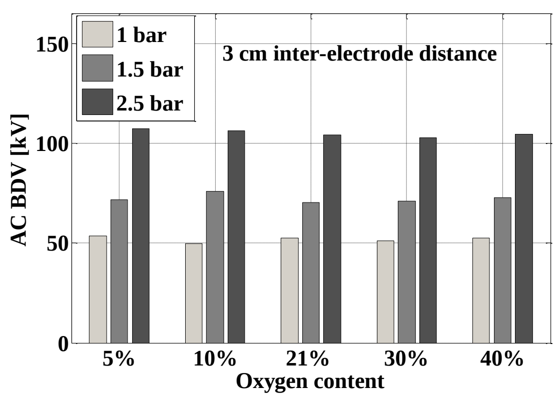

Fig. 2. AC breakdown voltages with 3 cm inter-electrode distance for different N_2/O_2 gas mixtures and pressures

For 5 cm inter-electrode distance (Fig. 3), the higher AC BDV is measured with M21, generally following by M5 and M10, which show almost the same breakdown level for 1.5 bar. And the lower AC BDV is given by M30 and M40 at 1.5 bar. However, for 1 bar, M5, M21, M30, and M40 show almost the same breakdown level. The lower breakdown value is measured with M10 at this gas pressure.

The minimum flashover voltage data of different gas mixtures are presented in TABLES I–III for different inter-electrode distances and gas pressures. So, TABLE IV exhibits these gases' ranking according to these minimum AC breakdown levels according to inter-electrode distances and gas pressures for a better comparison of tested insulating gases.

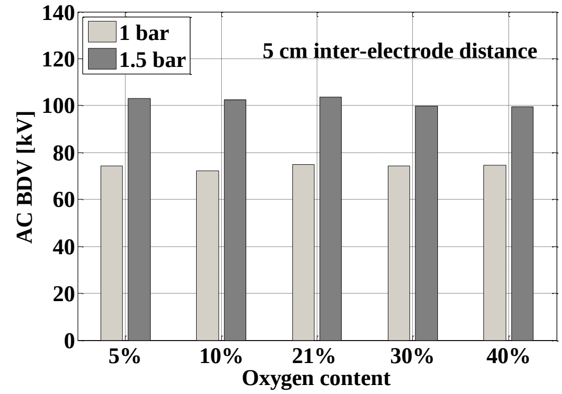

Fig. 3. AC breakdown voltages with 5 cm inter-electrode distance for different N_2/O_2 gas mixtures and pressures.

TABLE I. Minimum AC breakdown voltage of different gas mixtures tested at a different inter-electrode distance for 1 bar gas pressure

Gas mixture	Minimum AC breakdown voltage (AC BDV)		
	1 cm gap	3 cm gap	5 cm gap
M5	27.3	52.2	72.5
M10	25.9	48.3	68.6
M21	25.7	50.8	72.3
M30	26.7	50.5	73.7
M40	25.6	52.8	72.4

TABLE II. Minimum AC breakdown voltage of different gas mixtures tested at a different inter-electrode distance for 1.5 bar gas pressure

Gas mixture	Minimum AC breakdown voltage (AC BDV)		
	1 cm gap	3 cm gap	5 cm gap
M5	37.9	69.9	101.7
M10	38.4	74	99.4
M21	37.1	67.7	101.6
M30	39.1	70	97.6
M40	38.5	70.8	96.9

TABLE III. Minimum AC breakdown voltage of different gas mixtures tested at a different inter-electrode distance for 2.5 bar gas pressure

Gas mixture	Minimum AC breakdown voltage (AC BDV)	
	1 cm gap	3 cm gap
M5	57.3	105.6
M10	59.5	102.2
M21	58.3	102.3
M30	56.3	102.5
M40	57.7	103.2

TABLE IV. N_2/O_2 gas mixtures were ranked according to their minimum AC breakdown level.

Inter electrode distance [cm]	Gas pressure [bar]	Gas ranking according to their AC breakdown level
1	1	M5 > M30 > M10 > M21 > M40
	1.5	M30 > M40 > M10 > M5 > M21
	2.5	M10 > M21 > M40 > M5 > M30
3	1	M40 > M5 > M21 > M30 > M10
	1.5	M10 > M40 > M30 > M5 > M21
	2.5	M5 > M40 > M30 > M21 > M10
5	1	M30 > M5 > M40 > M21 > M10
	1.5	M5 > M21 > M10 > M30 > M40

TABLE IV shows that our insulating gas mixtures' ranking according to their minimum breakdown level does not give a coherence tendency. However, it highlights the nonlinear effect of oxygen in the breakdown behavior, as seen in [1] and [2]. So the measurement results obtained in the present work and those given in [1, 2] did not allow a clear identification of the best AC dielectric gas mixture among all the gases tested.

To identify the gas with greater AC performance, we used another criterion based upon the fact that the high voltage equipment structure often leads to different electric field inhomogeneity in the GIS medium. Thus we calculated a quantity Q for a given gas mixture defined at a given pressure by relation (1) in which all the normalized AC BDV values of one of the gas based on the maximum breakdown level obtained among the tested gases in the same conditions (electrode system, inter-electrode distance) is multiplied by others for the same gas pressure regardless to the electrode configuration and inter-electrode distance.

$$Q_{AC} = \prod_k \left\{ \prod_j \frac{AC\ BDV_j(MX)}{MAX[AC\ BDV_j(M5),\dots,AC\ BDV_j(M40)]} \right\}_k \quad (1)$$

AC BDV is the AC breakdown voltage of a given gas mixture MX at a given inter-electrode distance j and electrode configuration k.

The quantity Q of a given gas indicates the gas's capability to be used in different electric field inhomogeneity. Thus it will be higher for the best performance and low for the weaker capability.

Fig. 4 shows the quantity Q of different gas mixtures versus the gas pressure. One can see that M5 gives the best AC dielectric performance for 1 bar, whereas the weaker AC BDV is obtained with M30 for the same pressure.

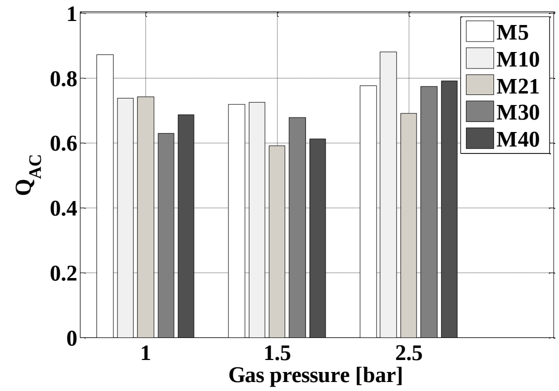

Fig. 4. Quantity Q_{AC} against gas pressure for different N_2/O_2 gas mixtures

For 1.5 and 2.5 bar, the greater AC BDV is seen with M10, whereas the lower insulation characteristic is given with M21.

M10 presents the higher dielectric performance for relatively high pressure, and for 1 bar, it roughly shows the same AC BDV as that measured with M21, which seconds that of M5 showing the best AC BDV. Therefore M10 can be seen globally as the best AC insulating gas among the gases tested.

B. Lightning impulse breakdown measurements

Lightning impulse breakdown test results of our gas mixtures are shown in Fig. 5 as average breakdown voltage U_{AV} versus inter-electrode distance for different gas pressure [10]. In that figure, error bars stand for the minimum, and the maximum applied voltage levels at which breakdown has been measured. A gas mixture with 40% O_2 for a reason given in [1] and [2]. One observes that U_{AV} normally increases with both gas pressure and inter-electrode distance for all the gases tested.

One can see that our gas mixtures show different levels of breakdown voltage. To define the best insulating gas, the comparison of flashover voltage is made by confronting the minimum breakdown level of different gases tested for a given inter-electrode distance and gas pressure.

TABLE V highlights the ranking of tested gases according to their minimum flashover voltage for different inter-electrode distances, voltage polarity, and gas pressure. One can observe the nonlinearity of the oxygen effect in flashover voltage. So the determination of the stronger dielectric gas mixture remains complex; however, some tendencies seem to appear (TABLE V).

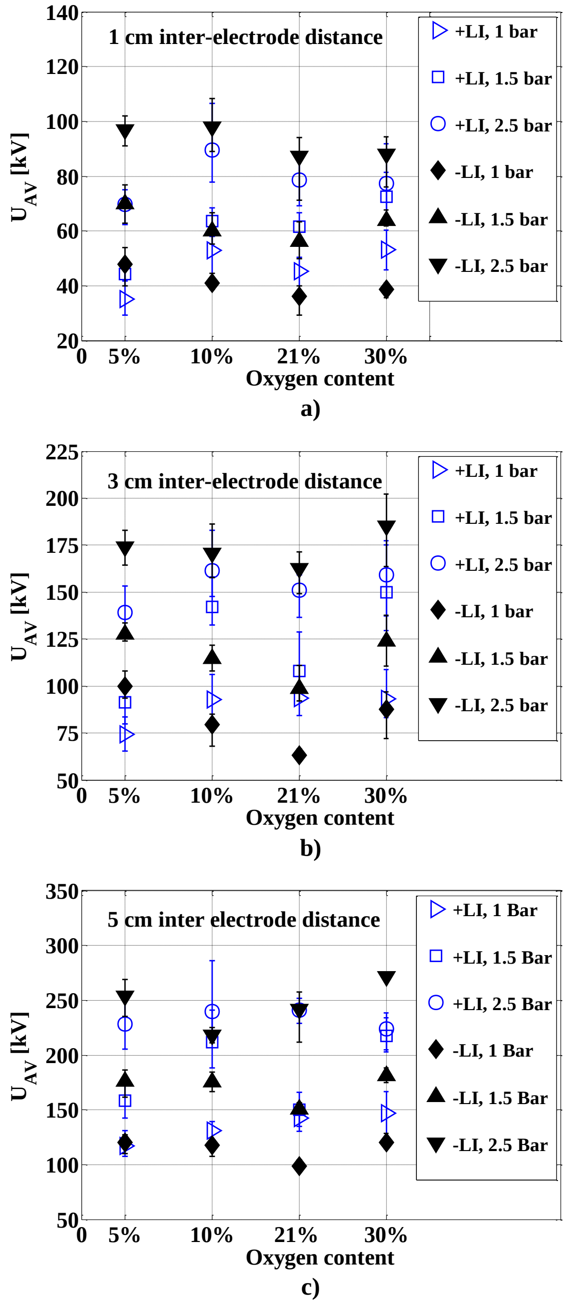

Fig. 5. Impulse breakdown voltage in different N_2/O_2 gas mixtures. Measured with 1 cm inter-electrode distance (a); measurement with 3 cm inter-electrode distance (b), and measurement with 5 cm inter-electrode distance (c). The error bars in the figures stand for the minimum and the maximum breakdown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

Thus for 1 and 3 cm, inter-electrode distance M5 shows the greater and the lower flashover voltage for negative and positive lightning impulse voltage, regardless of the gas pressure. The higher breakdown voltage is seen globally with M30 for 1 cm inter-electrode in positive polarity. And for all the gases tested, the weaker breakdown voltage in negative polarity is obtained with M21.

The tendencies given by the ranking of gas mixtures in TABLE V do not allow a clear identification of the best dielectric gas mixture. This was globally the case for measurements carried out in [1] and [2].

TABLE V. N_2/O_2 gas mixtures are ranking according to their lightning impulse breakdown level.

inter-electrode distance	Gas pressure	Voltage polarity	Gas ranking
1 cm	1 bar	+	30% > 10% > 21% > 5%
		-	5% > 10% > 30% > 21%
	1.5 bar	+	30% > 10% > 21% > 5%
		-	5% > 30% > 10% > 21%
	2.5 bar	+	10% > 21% > 30% > 5%
		-	5% > 10% > 30% > 21%
3 cm	1 bar	+	21% > 30% > 10% > 5%
		-	5% > 30% > 10% > 21%
	1.5 bar	+	30% > 10% > 21% > 5%
		-	5% > 30% > 10% > 21%
	2.5 bar	+	10% > 30% > 21% > 5%
		-	5% > 30% > 10% > 21%
5 cm	1 bar	+	21% > 10% > 30% > 5%
		-	30% > 5% > 10% > 21%
	1.5 bar	+	30% > 10% > 5% > 21%
		-	30% > 10% > 5% > 21%
	2.5 bar	+	21% > 10% > 5% > 30%
		-	30% > 5% > 21% > 10%

To highlight the gas mixture with stronger dielectric strength, we used the parameter Q_{LI} defined in (2) distinctly for positive and negative voltage polarities. The evaluation of the quantity Q_{LI} is performed, including the data from [1] and [2].

$$Q_{LI} = \prod_k \left\{ \prod_j \frac{U_j(MX)}{MAX[U_j(M5),\ldots,U_j(M30)]} \right\}_k \qquad (2)$$

U is the minimum breakdown voltage level of a given gas mixture MX at a given inter-electrode distance j and electrode configuration k.

Fig. 6 highlights the quantity Q_{LI} of different gas mixtures as a function of gas pressure.

For positive lightning impulse voltage, at 1 bar (Fig. 6a), M10 gives the higher quantity Q_{LI}. It is seconded by M21 and then M30. The lower Q_{LI} is observed with M5 at this pressure. For 1.5 and 2.5 bar, the higher Q_{LI} is seen with M30 seconded by M10. These two gas are seconded at 1.5 bar by M5, and the lower Q_{LI} value is seen in M21. However, at 2.5 bar, M30 and M10 are followed by M21, and the lower Q_{LI} is seen with M5.

For negative lightning impulse voltage tests at 1 bar, the higher Q_{LI} is obtained with M10 seconded by that seen with M5 and then obtained using M30. The lower Q_{LI} is observed in M21. For 1.5 bar, the greater Q_{LI} is obtained with M30, seconded by M10 and then M5. The lower quantity Q_{LI} is measured with M21. And for 2.5 bar, the stronger Q_{LI} is seen with M30 followed by M5 and then M10. As for 1 and 1.5 bar, the lower Q_{LI} at 2.5 bar is observed in M21.

Owing to these results, it is seen for both positive and negative polarity that the greater Q_{LI} is seen with M10 for 1 bar gas pressure, whereas the stronger Q_{LI} is exhibited by M30 for 1.5 and 2.5 bars. M10 follows this gas except at 2.5 bar in negative lightning impulse voltage.

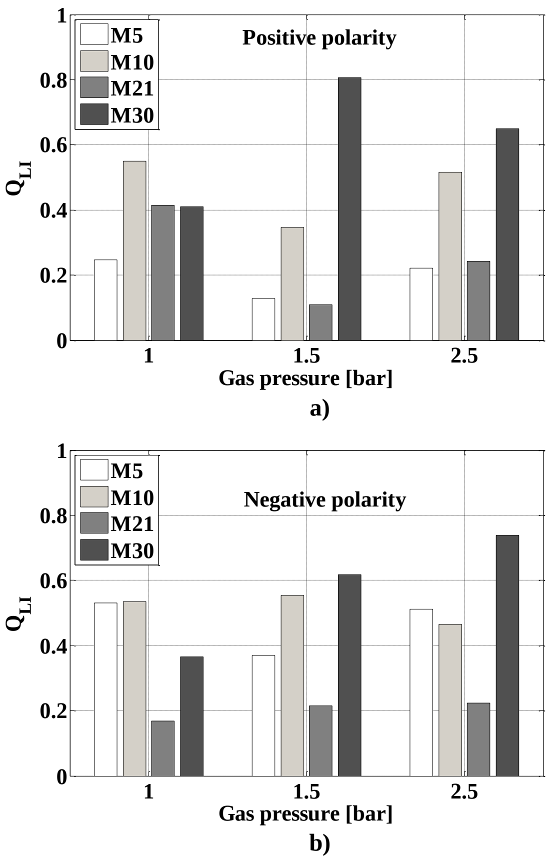

Fig. 6. Quantity Q_{LI} against gas pressure for different N_2/O_2 gas mixtures. Positive lightning impulse voltage (a), negative lightning impulse voltage (b)

M10 is seen as the best AC dielectric gas compared to other gases tested in the present paper. For impulse breakdown voltage measurements, this behavior is confirmed at 1 bar regardless of the voltage polarity. However, for relatively higher pressure (i.e., 1.5 and 2.5 bar) breakdown characteristic of M10 seconds globally that of M30, the stronger dielectric gas for these pressures, which the AC breakdown characteristic remains lower than that of M10. Therefore, M10 can be globally considered the best compromise for gas insulated power equipment among the tested gases.

IV. CONCLUSIONS

Investigation of flashover voltage characterization of different N_2/O_2 gas mixtures has been achieved for the inhomogeneous electric field. The measurements with 50 Hz AC and lightning impulse voltages were conducted within a real Schneider Electric WI–busbar tank. Sphere electrode systems used in this measurement were respectively 15 cm and 2 cm in diameter. The results show the non–linearity effect of oxygen on the breakdown voltage. However, because the structure of high voltage equipment in the GIS medium often leads to different electric field inhomogeneity, we defined the quantity Q_{AC} and Q_{LI}. These quantities show that the gas mixture with 10% O2 (M10) can be globally considered the best compromised for gas insulated power equipment among the tested gases.

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