SSRG International Journal of Electrical and Electronics Engineering
ISSN: 2348 – 8379 /doi:10.14445/23488379/IJEEE-V7I11P104
Volume 7 Issue 11, 22-30, November 2020

Breakdown Performance of N_2/O_2 Gas Mixtures in Quasi-Homogeneous Electric Field

Elysée OBAME NDONG[#1], Adoum TRAORE NDAMA[*2]

[#]*Masuku Electrical Engineering Laboratory, Département Génie Electrique, Ecole Polytechnique de Masuku, Université des Sciences et Techniques de Masuku, Mbaya, route nationale, BP 941, Franceville Gabon,*

Abstract *— AC and lightning impulse breakdown evaluations of 5%, 10%, 21%, 30%, and 40% O_2 rate in N_2/O_2 gas mixtures is performed with different electrode configurations. Measurements are carried out for different inter-electrode distances and gas pressures in a real Schneider Electric WI busbar tank. The aim here is to characterize the mixture's best composition as a possible candidate for the gas part in hybrid insulation systems of SF_6–free GIS. The computational breakdown voltage results performed using streamer inception and propagation criteria are also presented compared to experiments for prediction purposes. We observed that breakdown voltage is nonlinear versus oxygen content for the quasi-homogeneous electric field given in this paper. However, the mixtures with 5% O_2 and 30% O_2 present the higher AC breakdown voltage for relatively low (1 bar) and high (>1 bar) gas pressure, respectively. For lightning impulse breakdown measurement, the mixtures with 5% O_2 and 10% O_2 show the best dielectric strength for longest (>1 cm) and shortest (1 cm) inter-electrode distance, respectively, regardless of the gas pressure. A good prediction of breakdown voltage using our computational model remains strongly dependent on factor B related to the gas mixture for the case of a quasi-homogeneous electric field.*

Keywords — *Breakdown voltage, ionization coefficient, modeling, nitrogen-oxygen gas mixtures, sphere gaps.*

I. INTRODUCTION

SF_6 has been widely used in high-voltage insulation equipment [1, 2] because of its excellent insulation and current interruption performance. In particular, gas-insulated switchgear (GIS) has been made more compact by using SF_6 gas [3]. Global environmental problems such as global warming are of great concern, and SF_6 is known as a greenhouse gas with a long atmospheric lifetime. Its global warming potential (GWP) is 23900 [2]. 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 a gas part in a hybrid insulation system for SF_6–free GIS.

In general, environmentally friendly gases' insulation performance is significantly lower than that of SF_6 [4]. The dielectric strength of dry air and N_2 is higher than that of other environmentally friendly gases, but it is significantly lower than that of greenhouse gases.

Moreover, the dielectric strength of dry air is considered higher than that of N_2 gas due to oxygen O_2. This suggests that the dielectric strength of the N_2/O_2 gas mixture can be made higher than that of dry air by varying the rate of O_2. Thus a gas with insulation characteristics even better than air can be created. 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 has been selected as reference gas, and performances of N_2/O_2 gas mixtures at different fractions of oxygen have been analyzed. Further, when considering GIS, the pressure at which liquefaction starts when the temperature is –20 °C for the selected alternative gas is higher than for SF6 gas. So the rated pressure for equipment can be set higher. This possible increase in gas pressure could lead to insulation performance improvements; however, the equipment's design will likely be unchanged concerning safety.

The typical pressure level for the present medium voltage GIS is 1.5 bar. In this study, the investigations are conducted at 1, 1.5, and 2.5 bar, since the lowest pressure is considered 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. This study's main purpose is to characterize the optimum composition of our "green" gas using N_2/O_2 gas mixtures.

Our gases' breakdown characterization is performed with different electrode configurations to investigate the mixtures with various electric field inhomogeneities as encountered in high voltage devices. The experimental breakdown voltage data obtained in our measurements are compared with those given by a computational model described in this paper for prediction purposes. However, only the 15 cm diameter sphere electrode configuration (quasi-homogeneous field) is shown in the present paper. The cases involving inhomogeneous electric fields will be presented in other communication.

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

The computational program used here for our different N_2/O_2 gas mixtures has already been successfully used in [5] for breakdown calculation in open-air conditions. It investigates the conditions under which a tiny ionization seed like a single electron grows into a streamer and leads to a breakdown. We extended this model to all gas mixtures and pressure used in the present paper for prediction purposes.

It is commonly accepted that in gases at a higher or equal pressure to 1 bar and inter-electrode distance more than a few centimeters, the breakdown is primarily caused by the streamer mechanism. The theoretical analysis in this computation program utilizes an engineering approach in which the streamer inception criterion and propagation criteria are calculated based on provided electrostatic field distribution between electrodes.

A. Streamer inception and propagation criteria

The condition of streamer inception so-called Raether-Meek criterion states that the number of electrons inactive region of electron avalanche, namely in its head, must reach a critical value that would create a local field comparable with the externally applied field [5]. This condition is numerically evaluated by integrating the effective ionization coefficient in the active region along a critical path x. The field strength is highest between electrodes. Hence, the strongest ionization of the gas occurs.

The reduced ionization coefficient α/p and the reduced attachment coefficient η/p used in our calculation program are calculated from Bolsig+ software [6, 7], where p stands for gas pressure. Fig 1 exhibits Bolsig+ reduced effective ionization coefficient $(\alpha-\eta)/p$ of synthetic air (79% N_2/21% O_2) as a function of reduced electric field E(x)/p compared with the experimental data of air taken in [8–11]. As one can see, $(\alpha-\eta)/p$ of synthetic air is lower than those presented by reference data, and the shift between these data and those from Bolsig+ is about 11% at 100 V/cm/Torr (i.e., 75 kV/cm/bar). Above 150 V/cm/Torr (i.e., 112.5 kV/cm/bar), though the Sanders data [11] show a good agreement with synthetic air's computational data. The shift between the literature data of $(\alpha-\eta)/p$ and the calculation data from Bolsig+ could be attributed to the fact that Bolsig+ uses the so-called 'two-term approximation" theory, which can be inaccurate because it underestimates the electron distribution for a small fraction of electrons having high energies [12].

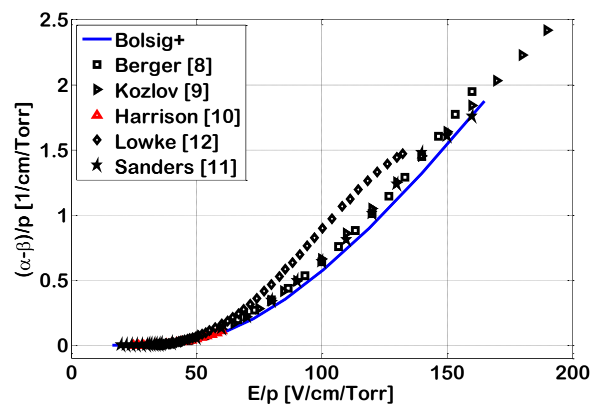


Fig. 1. Reduced effective ionization coefficient from bolsig+ software versus reduced electric field in synthetic air (79% N_2/21% O_2) compared with literature data (1 Torr=1.333 mbar)

However, the effective ionization coefficient could also be calculated as the sum of the partial-pressure-weighted coefficients in the gas mixture (1) according to [13]. However, the reliability of that method and the difficulty to find reliable data for oxygen and nitrogen have led us to prioritize Bolsig+ data.

For equation (1), F stands for oxygen fraction in the mixture.

$$\alpha'(N_2/O_2) = F\alpha'(O_2)+(1 - F)\,\alpha'(N_2) \tag{1}$$

The estimation of the shift between the literature and Bolsig+ data in other gas mixtures used in the present work was not possible owing to their unavailability. However, the shift observed between Bolsig+ and literature data at least 21% O_2/79% N_2 could impact breakdown calculations. We introduced a corrected constant B in breakdown evaluation equation (2) to guarantee a good agreement between the theoretical and experimental breakdown results.

Once the streamer ionization value integral reaches the critical number of electrons noted K, the avalanche can be transformed into a streamer. The coefficient K of the integral is usually estimated to be 9 to 18 [14]. However, it has been shown that it varies depending upon gas nature, pressure, and field conditions. In pure nitrogen N_2 and carbon dioxide CO_2, it was assigned to the values 5 and 27, respectively [15], and in sphere-gaps in air, it was found to be 9.15 [16]. The streamer inception condition defines the voltage necessary to be applied to the electrodes to transform an electron's avalanche to a streamer. The propagation of streamer into the gap for relatively long distances requires some energy input [5] from the external field that requires that the background field in which the streamer propagates exceeds a threshold value, referred to as the stability or propagation field Ep. For example, in the air at normal atmospheric conditions, Ep is found to be 5 to 7 kV/cm for positive streamers [12] and is 8 to 12 kV/cm for negatives ones. In gaps with uniform and slightly non-uniform fields, this condition is normally fulfilled, while in strongly non-uniform fields, streamer propagation is controlled by the field criterion [5]. In our calculation, we used 9.15 for K and 7 and 12 kV/cm for Ep, respectively, in positive and negative streamers for all the gases investigated. The constants K and Ep being known only at 1 bar gas pressure (p_0), the breakdown calculation for 1.5 and 2.5 bar is performed by using equation (2). In that equation, p stands for the gas pressure, q accounts for a constant taking the value of 1 for the homogeneous field and 0.75 for the inhomogeneous field. B is a factor introduced to guarantee a good agreement between the theoretical and the experimental breakdown data.

$$U(p) = U(p_0)\times(Bp/p_0)^q \qquad (2)$$

B. Electric field distribution

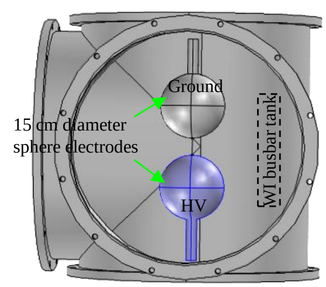
The unavoidable parameter to be known on each step of this study is the electric field distribution along the critical line, which is, in our case, the shortest distance between the two electrode spheres. It was calculated for each inter-electrode separated distance using finite-elements based on Comsol Multiphysics® software in three dimensions (3D). The geometry CAD–files of the test chamber in which electrodes are mounted, was supplied by Schneider Electric. The test chamber and the electrode arrangement are described in section III. The fig. 2a exhibits the simulated geometry for our 15 cm diameter sphere electrodes.

For calculations, the test vessel and one of the electrodes were grounded, the HV electrode was supplied with 1V, and the "extra fine" mashing size type was implemented.
The field distributions in the whole vessel are highlighted in fig. 2b and that of the critical path is seen in fig. 2c. So, the electric field is distributed in a nearly parabolic shape and presents its minima in the middle of the gap (fig. 2c). The field magnitude normally decreases by increasing the inter-electrode distance. However, the electric field curves show segments due to the meshing size used with Comsol Multiphysics software. Though the influence of that meshing size is weak and does not introduce a significant error in the breakdown calculations.

C. Breakdown voltage calculation

When the conditions of streamer inception and propagation are fulfilled at a certain magnitude of the applied voltage U, this voltage is taken as an estimate of the breakdown voltage [5].

The algorithm used for the calculations of the breakdown voltages is summarized in fig 3, where E(x) stands for the field distribution, (α–η) the net ionization coefficient, the integral of the net ionization coefficient gives the streamer inception criterion, and the relation $E(x_C)=Ep$ the propagation criterion where x_C is the length of the critical path and L_x accounts for the difference between the gap distance and x_C. After all, conditions have been fulfilled, the integral of the field allows the calculation of the theoretical breakdown value. This algorithm has been implemented on Matlab® software. The results obtained from these calculations are shown in comparison with the lightning impulse breakdown measurements.



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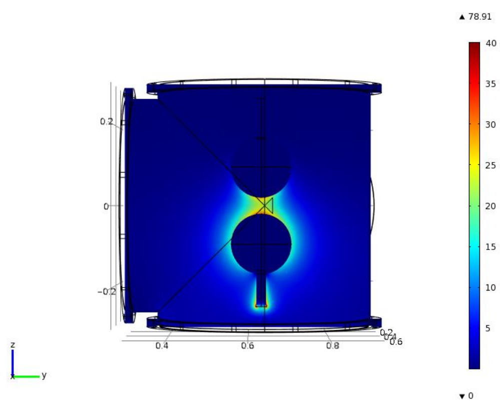

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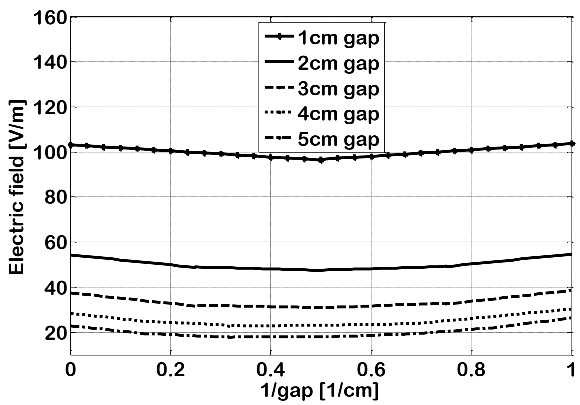


c)

Fig. 2. Electric field distribution in inter-electrode gap distance, (a) simulated geometry with 15 cm diameter sphere electrodes (b) field distribution in a slice containing the critical path, (c) field distribution on the critical path separating sphere electrodes.

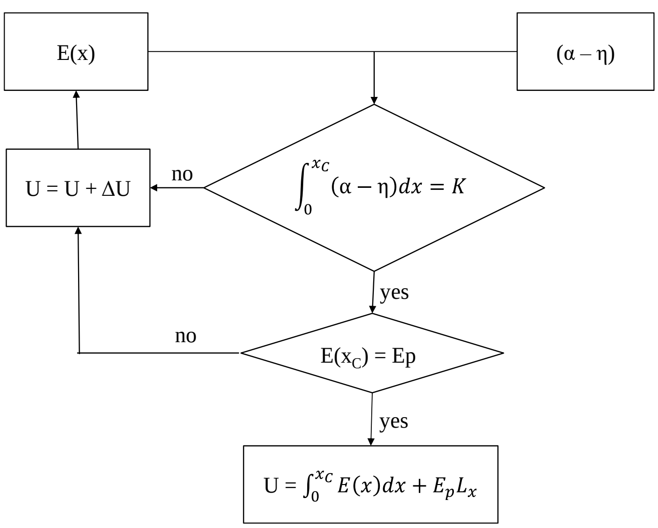


Fig. 3. Flowchart of the procedure for the calculations of breakdown voltages (α–η is the effective ionization coefficient)

III. EXPERIMENTATION AND METHODS

A. Electrode configuration

The present study experiments were conducted in a test vessel using a copper sphere electrodes 15 cm in diameter. The spherical electrodes are fixed on stainless steel shanks with 2.5 cm in diameter. The lengths, including the tip of the sphere electrode shanks, are 14 cm and 12 cm for the electrode connected to the HV bushing and the grounded electrode, respectively [17].

B. Test vessel

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 the WI-busbar tank (Schneider Electric product) and contains four flanges. The complete description of the chamber is given in [17].

The test vessel's performance has been evaluated to reduce possible parasitic discharges by preliminary breakdown tests and pre-breakdown observations under DC voltage in atmospheric open-air conditions [17].

The test vessel being grounded during experimental tests; it is well known that nearby earthed objects surrounding the sphere electrode gap can influence the breakdown voltage [18]. The radial clearance separating the sparking point and the grounded floor is 1.5 times the sphere electrode's diameter. Thus, a possible influence might appear in our measurements.

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 with inter-electrode distances of 1, 3, and 5 cm.
1, 3, and 5 cm.

C. Voltage application 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 distance, and the reported breakdown voltage was taken as the average of these measurements.

The voltage was derived from a 5–stages 500 kV impulse generator with approximately 1.2/50 µs wave shape for lightning impulse breakdown tests.

Since the breakdown is a stochastic phenomenon [19], the "up-and-down" method [20] 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} [21]. We used a series of 20 shots according to the IEC standard [22]. 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 time between a series 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 [17].

IV. EXPERIMENTAL AND MODELING RESULTS

A. AC breakdown measurement

AC breakdown results (AC BDV) are shown in fig. 5–7 respectively for 1, 3, and 5 cm inter-electrode distances. For this measurement, the error bars are lower than ± 1 kV.

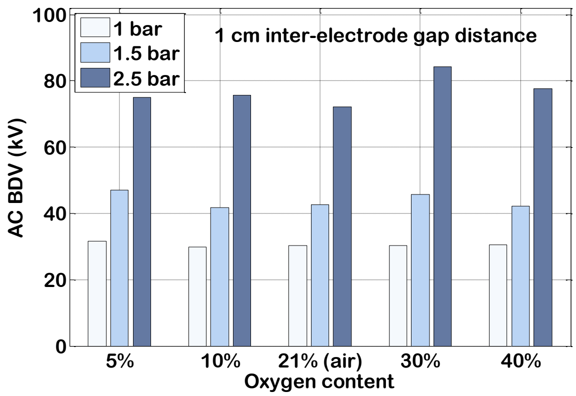


Fig. 4. AC breakdown voltages in 1 cm inter-electrode distance for different N_2/O_2 gas mixtures and pressures.

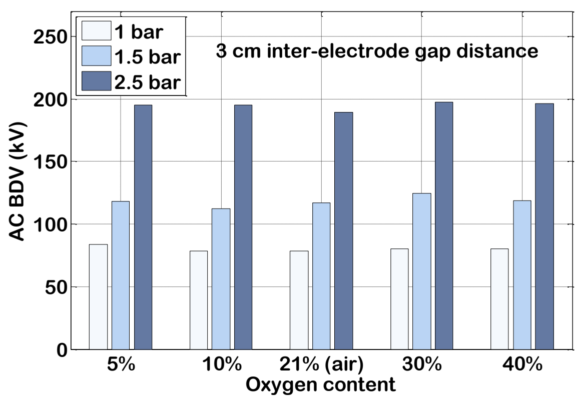


Fig. 5. AC breakdown voltages in 3 cm inter-electrode distance for different N_2/O_2 gas mixtures and pressures.

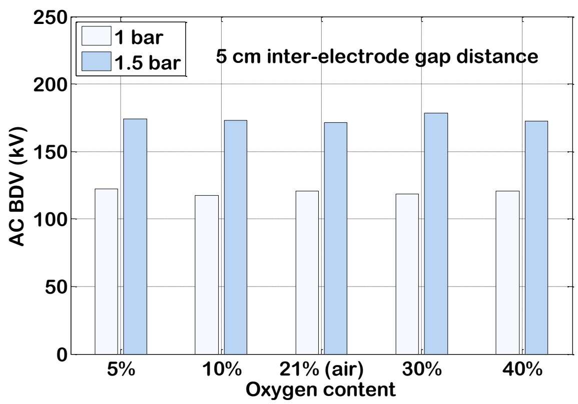


Fig. 6. AC breakdown voltages in 5 cm inter-electrode distance for different N_2/O_2 gas mixtures and pressures.

Table 2 exhibits the ranking of tested gases according to their AC breakdown level for different inter-electrode distances and gas pressures. It is shown that N_2/O_2 gas mixtures with 5% O_2 and 30% O_2 exhibit a higher dielectric strength among the tested gases under AC voltage. The mixture with 30% O2 shows the strongest dielectric strength for gas pressure above 1 bar, whereas the gas with 5% O2 exhibits the highest breakdown at 1 bar gas pressure regardless of the distance between electrodes. The mixtures with 10% O_2 and 21% O_2 show the lower flashover voltage in general. One could expect that breakdown voltage would increase with the concentration of oxygen molecule in N_2/O_2 gas mixture since oxygen is a negative gas. However, as seen in [23], the breakdown voltage in N_2/O_2 shows nonlinearity versus gas pressure and O_2 concentration. This is exactly the tendency observed in our AC measurements.

TABLE 2. . N_2/O_2 gas mixtures ranking according to their AC breakdown level (air stands for the 20% O_2 content gas)

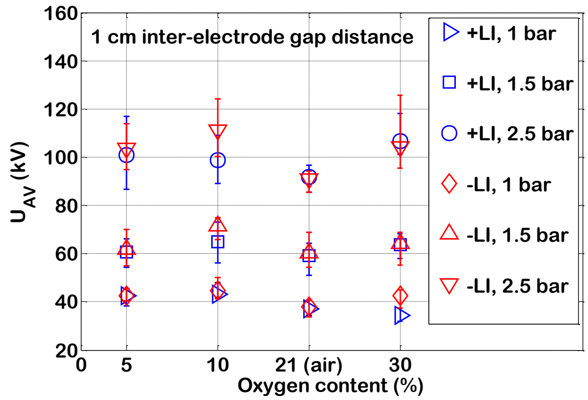
Gap distance [cm]	Gas pressure [bar]	Gas ranking according to their AC breakdown level
1	2.5	30% > 40% > 10% > 5% > air
	1.5	5% > 30% > air > 40% > 10%
	1	5% > 30%= air = 40% = 10%
3	2.5	30% > 40% > 10% > 5% > air
	1.5	30% > 40% > air > 5% > 10%
	1	5% > 30% > 40% = 10% = air
5	1.5	30% > 5% > 10% = 40%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

B. Lightning impulse breakdown measurements

The positive and negative lightning impulse breakdown test results are shown in fig. 7 as average breakdown voltage versus inter-electrode distance for different tested gases. In that figure, error bars stand for the minimum, and the maximum applied voltage levels at which breakdown has been measured. The gas mixture with 40% O_2 has been excluded in these measurements to limit the possible influence of O_2, such as oxidation.

According to their flashover voltage, the comparison of tested gases is made by confronting their minimum breakdown level for a given inter-electrode distance and gas pressure.

Table 3 highlights the ranking of tested gases according to their breakdown level for different inter-electrode distances, voltage polarity, and gas pressure obtained from fig. 7. One can observe that the mixture with 10% O_2 shows, in general, the greater breakdown voltage for 1 cm inter-electrode distance (fig. 7a) among the gases investigated, and those with 5% O_2 and 30% O_2 share the second place. The lower breakdown voltage for 1 cm inter-electrode distance is observed for the gas with 21 % O_2 for both positive and negative polarities.



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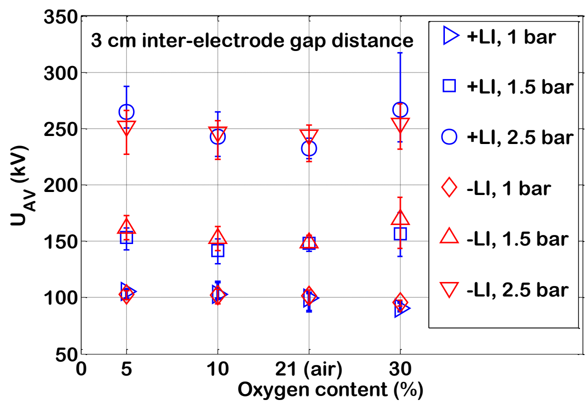

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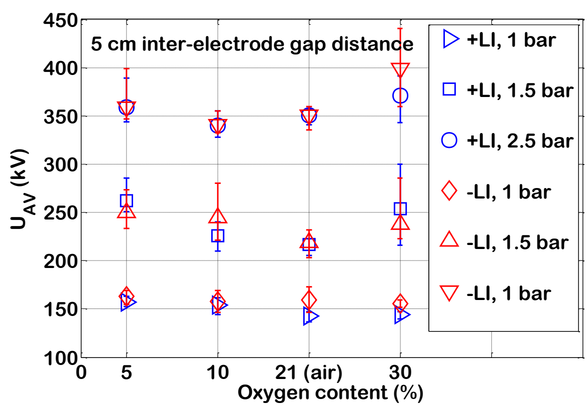


c)

Fig. 7. Impulse breakdown voltage in different N_2/O_2 gas mixtures, including dry air (21% O_2). 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.

For 3 cm (fig. 7b) and 5 cm (fig. 7c) inter-electrode distances, the higher breakdown voltage is given for the mixture with 5% O_2. This gas is seconded roughly by those having 21% O_2 and 30% O_2 for 3 cm inter-electrode distance, and the weaker breakdown level is seen with 10% O_2 in general. At 5 cm inter-electrode distance (fig. 7c), the gas with 5% O_2 is seconded by that with 30% O_2. The lowest breakdown level is seen, with the mixture having 10% O_2.

In summary, the lightning impulse breakdown voltage measurements performed here show non–linearity versus the oxygen content also. The gas mixtures with 5% O_2 and 10% O_2 seem to show the best dielectric performance regardless of the gas pressure. For 1 cm inter-electrode distance (fig. 7a), the high dielectric strength is seen with the gas having 10% $O_{2.}$ For 3 cm (fig. 7b) and 5 cm (fig. 7c), inter-electrode distances are observed with the best dielectric characteristic, with the mixture containing 5% O_2 in general.

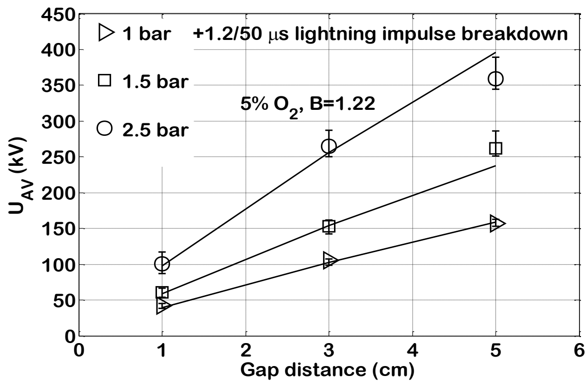
TABLE 3. N_2/O_2 gas mixtures are ranking according to their lightning impulse breakdown level (air stands for 21% O_2 content gas).

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

The fig. 8–11 exhibit the comparison between impulse breakdown voltage measurements performed with different N_2/O_2 gas mixtures and the corresponding theoretical results. The figures in the figures stand for experimental data, whereas solids lines represent the theoretical curves computed using relation (2). The constant ionization K was set at 9.15, whereas the propagation field Ep was fixed to 7 kV/cm and 12 kV/cm for positive and negative voltage polarities.

Fig. 8 shows the results for the gas mixture with 5% O_2. One can observe that the theoretical results agree with experimental data with a factor B of 1.22. Thus, the calculated impulse breakdown is 22% higher than that given by the basic theory given in [5, 17] for both positive and negative voltage polarities.

Figure 9 shows that measurements with the gas mixture having 10% O_2, and the theory are in good agreement with a coefficient B of 1.1.



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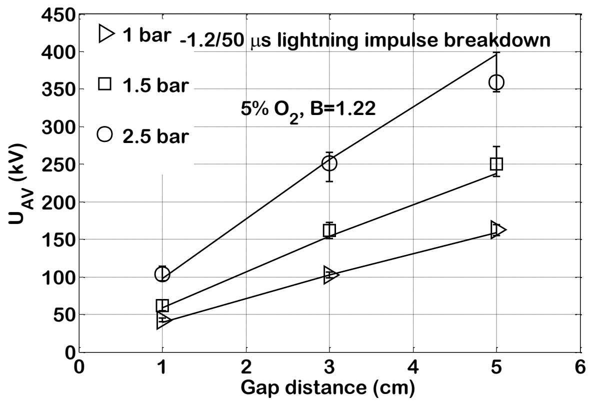
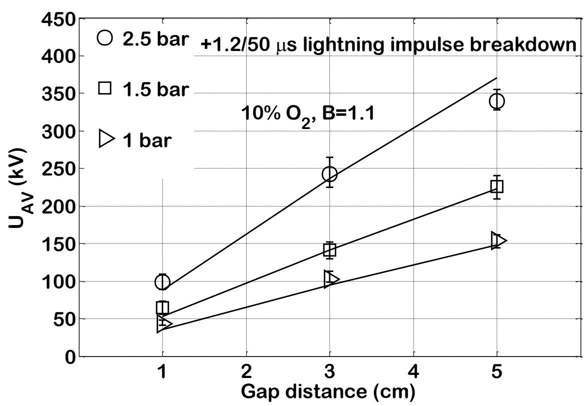


b)

Fig. 8. Lightning impulse (1.2/50 µs) breakdown for N_2/O_2 gas mixture with 5% O_2 content: Comparing our experimental data and the theoretical results for positive polarity a) and negative polarity b). The points in the figures stand for experimental data, and the dashed lines account for the theoretical results with a constant B of 1.22.



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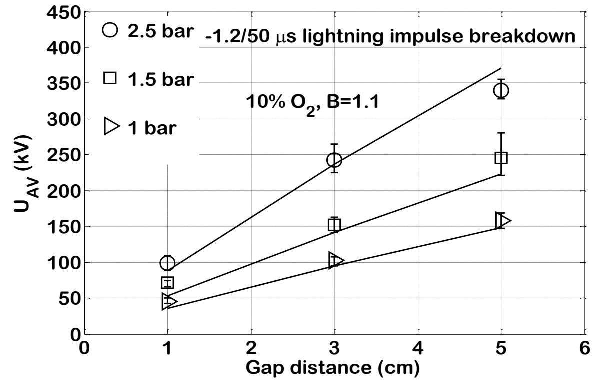
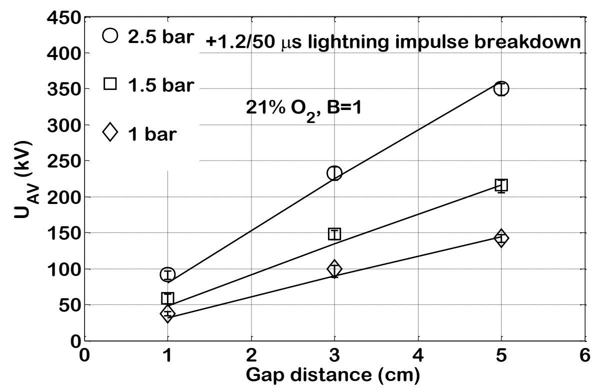


b)

Fig. 9. Lightning impulse (1.2/50 µs) breakdown for N_2/O_2 gas mixture with 10% O_2 content: comparison between our experimental data and the theoretical results for positive polarity a) and negative polarity b). The points in the figures stand for experimental data, and the dashed lines account for the theoretical results with a constant B of 1.1.

In fig. 10 (21% O_2), one can see a good measurement agreement between the theory and the experimental data for the two voltage polarities when factor B is 1. These results are consistent with those obtained by Yuriy Serdyuk [5].



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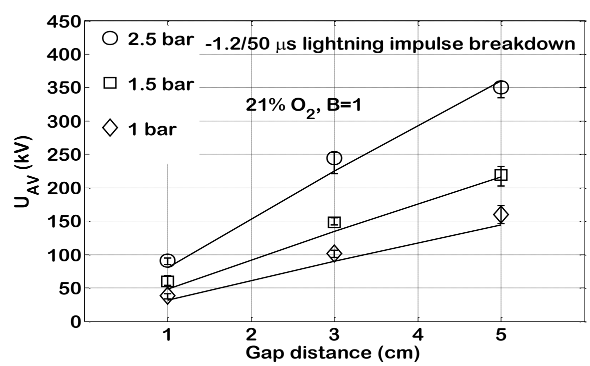
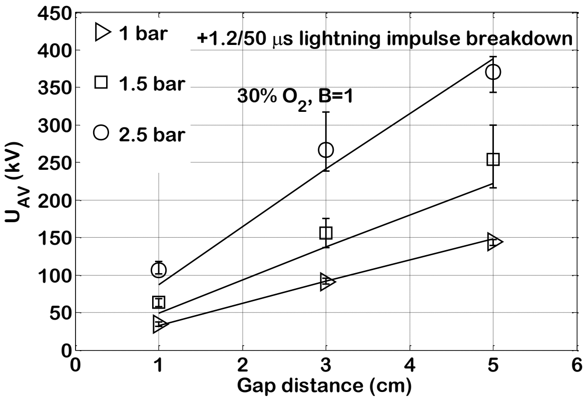


b)

Fig. 10. Lightning impulse (1.2/50 µs) breakdown for N_2/O_2 gas mixture with 21% O_2 content: comparison between our experimental data and the theoretical results for positive polarity a) and negative polarity b). The points in the figures stand for experimental data, and the dashed lines account for the theoretical results with a constant B of 1.



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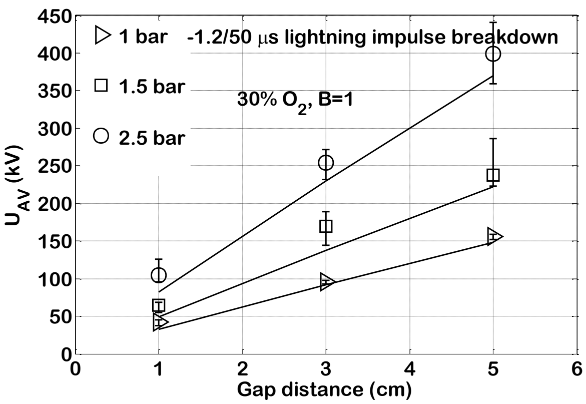

b)

Fig. 11. Lightning impulse (1.2/50 μs) breakdown for N_2/O_2 gas mixture with 30% O_2 content: Comparing our experimental data and the theoretical results for positive polarity a) and negative polarity b). The points in the figures stand for experimental data, and the dashed lines account for the theoretical results with a B of 1.

As in fig. 11, the experimental data obtained with the gas mixture having 30% O_2 agree with the theory for a coefficient B of 1.

TABLE 4. Factor B was used in the computational model for suitability between the theoretical and experimental breakdown data for different N_2/O_2 gas mixtures. B is independent of the voltage polarity.

Gas mixture	Voltage polarity	B
N_2/O_2 with 5% O_2	+	1.22
	-	1.22
N_2/O_2 with 10% O_2	+	1.1
	-	1.1
N_2/O_2 with 21% O_2	+	1
	-	1
N_2/O_2 with 20% O_2	+	1
	-	1

The coefficients B of different gases investigated here are given in table 4. This factor seems to decrease with the increase of oxygen concentration. It is greater (1.22) for the mixture with 5% O_2 and lower (unity) for 21% O_2 and 30% O_2 concentrations. A good prediction of breakdown voltage for the quasi-homogeneous electric field, using our computational model, remains tributary to factor B. This factor is only related to the gas mixture for the present field condition (quasi-homogeneous field).

V. CONCLUSION

AC and lightning impulse Breakdown voltage evaluation of 5%, 10%, 21%, 30%, and 40% oxygen content in N_2/O_2 gas mixtures have been performed with different inter-electrode distances and gas pressures within a real Schneider Electric WI–busbar tank. The sphere electrodes were the copper spheres with 15 cm in diameter. The aim was to characterize the mixture's best composition as a possible candidate for the gas part in hybrid insulation of SF_6–free GIS. The computational breakdown voltages using the field distribution in the inter-electrode distance and the streamer inception and propagation criteria were also presented compared to experimental data. Identifying the optimum mixture remains difficult according to the results because of non–linearity of the mixture's oxygen effect. However, the mixtures having 5% O_2 and 30% O_2 seem to present the higher AC breakdown voltage for relatively low (1 bar) and high gas pressure (> 1 bar), respectively, and regardless of the inter-electrode distance. For lightning impulse breakdown measurement, the mixtures with 5% O_2 and 10% O_2 show the best dielectric performance for longest (> 1 cm) and shortest (1 cm) inter-electrode distance, respectively, regardless of the gas pressure. For all the gas mixtures investigated in the present paper, a good prediction of breakdown voltage using our computational model remains strongly dependent on factor B related to the gas mixture.

ACKNOWLEDGMENT

The author thanks Pr Stanislaw GUBANSKI and Pr Yuriy SERDYUK for their substantial contribution and their availability for this work. He also expresses his gratitude to Raimund SUMMER and Uwe HAUK, our Schneider Electric partners without whom this work would not have taken place.

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