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Experimental Investigation of the Breakdown Voltage of CO_2, N_2, and SF_6 Gases, and CO_2–SF_6 and N_2–SF_6 Mixtures under Different Voltage Waveforms

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Received: 13 February 2018; Accepted: 9 April 2018; Published: 12 April 2018

Abstract: This paper is devoted to a comparison study of the breakdown voltage of CO_2, N_2, and SF_6 gases, and CO_2–SF_6 and N_2–SF_6 mixtures under different voltage waveforms, namely AC, DC, and lightning impulse voltages, in point–plane and sphere–sphere electrode arrangements. The influence of pressure, voltage polarity, and percentage of SF_6 in CO_2 and N_2 were studied, and equivalencies between the breakdown voltage of SF_6 and those of the considered mixtures were analyzed. It is shown that the breakdown voltage of SF_6 is the highest, whatever the applied voltage waveforms. Similarly, for a given voltage waveform, the breakdown voltage of SF_6 is the highest. The AC breakdown voltage is the lowest for all gases. The addition of small amounts of SF_6 to CO_2 and N_2 significantly improved the breakdown voltages of both natural gases. For a given breakdown voltage, the ratio between the pressure of CO_2 to that of SF_6 was generally lower than the pressure of N_2 to SF_6, whatever the voltage waveforms.

Keywords: nitrogen; carbon dioxide; sulfur hexafluoride; SF_6 gas mixtures; breakdown voltage; DC; AC; lightning impulse voltage; gas pressure; polarity

1. Introduction

SF_6 possesses excellent insulating properties, it can interrupt the current of electric arcs and interfere with their performance, has good heat transfer capacity, and chemical stability. These factors mean that sulfur hexafluoride gas is the most widely used gas in high-voltage (HV) components integrated in the transmission and distribution of electric power (HV circuit breakers (GCB), gas insulated switchgears (GIS), transmission lines (GIL), etc.) for more than half a century. SF_6 is one of the best insulating gases known to date. However, despite its outstanding properties, SF_6 gas is an aggravating agent of the greenhouse effect, and has a global warming potential (GWP) 23,900 times that of CO_2. It is for this reason that since the Kyoto Protocol (COP3, 1997), SF_6 use and emission into the atmosphere started to be controlled, and intense research has been undertaken to find substitutes for SF_6 that have a lesser impact on the environment, as well as comparable dielectric and current interrupting capabilities. Unfortunately, all considered gases present a high liquefaction temperature [1–5], in addition to certain gases having excessive prices. To overcome this problem, and to decrease the liquefaction temperature, these gases are mixed with N_2 and CO_2; both of these natural gases are used as buffers. Thus, promising new mixtures of complex fluids using natural gases (N_2, CO_2, dry air) as buffers have been developed these last years, and some have been introduced in mean and high voltage apparatus [2–7].

Another solution would be to dilute small amounts of SF_6 in N_2 or CO_2; as these natural gases (N_2 and CO_2) are freely available in the atmosphere. Their impact on the environment is weak; their ozone depletion potential (ODP) is low compared to SF_6. With a suitable choice of parameters such as SF_6 concentration, pressure, and electrode gap, it would be possible to get mixtures that had a reduced impact on the environment (i.e., a low greenhouse effect) and would present a good compromise between insulating properties and minimum operating temperature. Many investigations have been conducted on SF_6–N_2 mixtures [7,8].

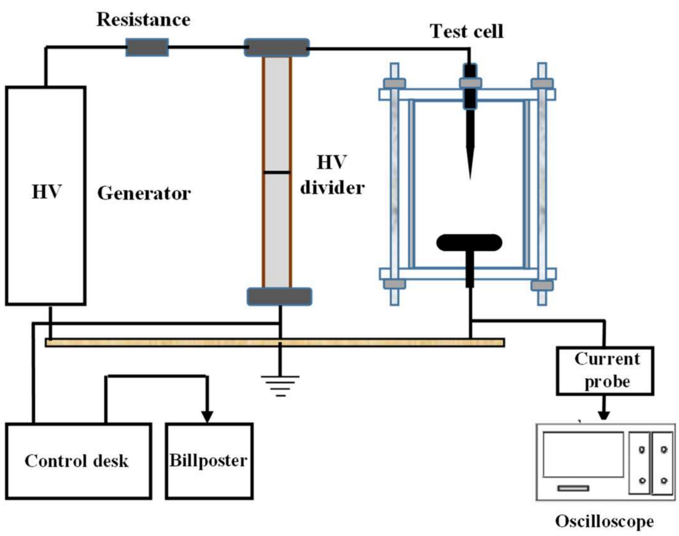
This paper is devoted to a comparison between the breakdown voltage (BDV) of CO_2, N_2, and SF_6 gases, and CO_2–SF_6 and N_2–SF_6 mixtures under three types of voltage waveforms, namely AC, DC, and lightning impulse voltages, in two different electrode geometries, namely point–plane and sphere–sphere electrode arrangements, at different pressures. The influence of pressure, voltage polarity, and percentage of SF_6 in CO_2 and N_2 are investigated, and equivalencies between the breakdown voltage of SF_6 and those of mixtures are discussed.

2. Experimental Section

The tested gases and gas mixtures were SF_6, N_2, and CO_2, and SF_6–N_2 and SF_6–CO_2, respectively. The breakdown voltage was measured for three voltage waveforms: AC, positive, DC negative, and positive lightning impulse voltages using two different electrode arrangements.

We first compared the three gases (CO_2, N_2, and SF_6) in point–plane electrode arrangement for three different electrode gaps (5, 10, and 20 mm). Then, we compared the breakdown voltages of those gases and their mixtures in a sphere–sphere electrode arrangement.

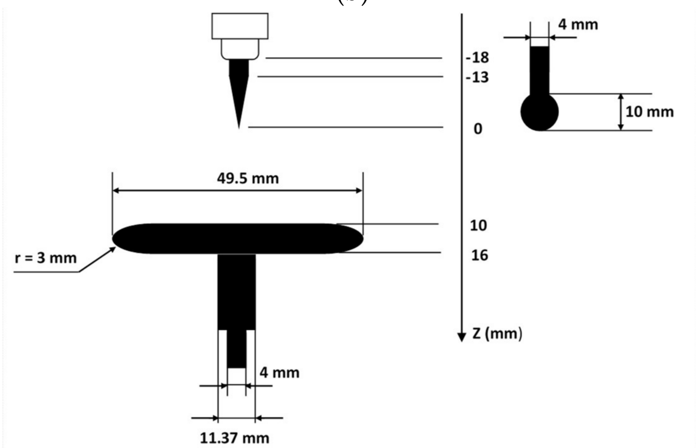
The point was made of tungsten and its radius of curvature was 10.0 ± 0.5 µm. This value may have varied slightly with the succession of tests due to tip erosion, the tip was replaced as soon as its profile became different from the original; its height was 18 mm. As for the plane electrode, it had the shape of a plane disk of which the edges were profiled according to Rogowski. The disc had a diameter of 49.5 mm, a thickness of 6 mm, and a periphery of radius curvature of 3 mm. The sphere electrode had the same height as the tip electrode and a radius of 5 mm. Note that the surface state of the electrodes were controlled, and that the electrodes were changed/replaced as soon as a defect was detected. In both configurations, the two opposite electrodes were axisymmetric and their axis was vertical. Figure 1 shows a diagram of the experimental setup, a general view of the test cell, and details on the dimensions of the electrodes.



(**a**)

Figure 1. *Cont.*

(**b**)



(**c**)

Figure 1. Experimental setup: (**a**) diagram of electrical circuit; (**b**) general view of the test cell containing point-plane electrodes geometry; and (**c**) details on the dimensions of electrodes.

Note that we limited our measurements to 0.4 MPa (4 bar). This pressure is generally the operating gas pressure in high voltage apparatus filled with pure SF_6 (gas insulated switchgear (GIS), for instance).

2.1. High Voltage Supplies

The AC high-voltage supply was a 200 kV, 50 Hz, 60 kVA transformer (Hipotronics type). A voltage regulator enabled the operator to increase voltage at a chosen rate. The maximum and effective values of the output voltages of the test transformer were measured using a 60 MHz Maxtron 60 MHz oscilloscope connected to a capacitive voltage divider 1:10,000 (BER 1423/1212-A314, 0.01 µF/100 pF—200 kV).

Two direct high-voltage supplies were used: A 200 kV, 400 W, 2 mA DC generator of positive polarity (Spellman type), and a 150 kV, 225 W, 1.5 mA DC generator (SAMES type) of negative polarity connected to a resistive divider.

The lightning impulse (LI) voltage was supplied either by a 200 kV–2 kJ Marx generator or a 1 MV–50 kJ Marx generator (both generators are Haefely type) each generator was connected to a dedicated capacitive divider; the ratio of dividers was 1:10,000 for the first generator and 1:11,000 for the second generator. The waveform of LI voltage used had a 1.2 µs ± 30% front time and a 50 µs ± 20% tail time. The lightning impulse voltage breakdown was measured using the up-and-down method according to International Electrotechnical Commission (IEC 60060-1:2010).

2.2. Filling the Test Cell and Breakdown Voltage Measurement Procedures

Before each series of breakdown tests, we emptied the test cell using a vacuum pump in order to attain a minimum pressure of approximately 10 mbar, which meant we could proceed to completely flush the test cell in accordance with the American Standards for Testing and Materials (ASTM-D-2477-2005); filling the test cell with the gas to be tested, followed by emptying of the test chamber. The gas was then introduced into the cell before applying the voltage. For a given electrode gap, the measurements were performed from high to low pressure. The pressure was decreased in steps of 0.5 bar. Regarding the realization of gas mixtures, we used Dalton method that takes into account the coefficient of compressibility of gases [9].

After a number of measurement series the cell was completely disassembled and cleaned, and the electrodes were treated (cleaning and sharpening/changing the tip if necessary). Throughout the study, a halogen gas detector allowed us to prevent and/or remedy any gas leaks. Control of the intake/emptying pressure was ensured by a system of taps, equipped with a pressure gauge, connected to the gas bottles using polyurethane pipes.

For the 50 Hz AC tests, the applied voltage was raised to breakdown at a rate of 0.5 kV/s $\pm$ 20%, according to ASTM-D-2477-2005. The time interval (waiting time) between two successive applied voltages was approximately 2 min. At least ten voltage applications were considered to estimate the mean breakdown value for each series of measurements. Each breakdown point plotted on a figure is the average of five sets of measurements; this was done to ensure their reproducibility.

Regarding the DC breakdown voltage measurements, the tests were carried out by progressively increasing the voltage stepwise until breakdown occurred. Each level of applied voltage was sustained for 1 min; each point plotted on a figure is the average of at least twenty measurements.

For the impulse voltage tests, we first performed preliminary tests to roughly determine the voltage at which breakdown occurs. We then started a series of measurements using the up-and-down method, according to the International Electrotechnical Commission (IEC 60060-1:2010). The intermediate stand time between a shot and the following shot was 90 s. The number of shot series we applied to establish the $U_{50\%}$ breakdown voltage was 40. This voltage is visualized by means of a display screen (Haefely Digital Impulse Analysis System (DIAS) 730) connected to the output of a capacitive divider. An oscilloscope was also used to record these breakdown voltages, and to check the concordance of the results with those of the display screen.

3. Experimental Results

3.1. Influence of Voltage Waveform and Polarity on Breakdown Voltage of Gases in a Point-Plane Electrode Arrangement

Figures 2–5 depict the BDV voltages of SF_6, N_2, and CO_2 gases as a function of the gas pressure and the inter-electrode gap, respectively, for a point–plane electrode arrangement under different voltage waveforms. These characteristics show that the breakdown voltage increases with the pressure and/or the inter-electrode distance *d*. By drawing straight lines of tendency, we noted that some experimental data deviates from the linear tendency. Note that for comparison purposes, AC breakdown voltages in all figures are peak values.

Under AC, CO_2 BDV is clearly higher than that of N_2. While the BDV of SF_6 is more than three times higher than that of both CO_2 and N_2 for the three investigated electrode gaps (5, 10, and 20 mm). In contrast, under a positive LI voltage, the BDV of N_2 was somewhat higher than that of CO_2. However, as expected, the SF_6 breakdown voltage was always the highest when compared to that of N_2 and CO_2, because of its well-documented superior insulation performance. Note that for an inter-electrode gap of 5 and 10 mm, the visible differences observed in N_2 at low pressures decreased when pressure was increased. If the slope of growth is maintained, the breakdown voltage at 10 mm, 4 bar would be approximately 20 kV, while on Figure 2 it is approximately 17 kV, representing a difference of 15%, which is not negligible. This could be due to the dispersion of measurements in N_2. The dispersion of the measurements of breakdown voltages in N_2 has also been reported by others [10].

Note that a linear variation in the breakdown voltage of N_2 and CO_2 has been observed by E. Onal [11] using a rod–plane electrode system with an electrode gap of 25 mm and a pressure between 1 to 5 bar; the tip radius of the rod was 1 mm.

Under DC, the BDV of N_2 and CO_2 were higher at negative polarity for the three electrode gaps. Similar to the trend observed for SF_6 with an electrode gap of 10 mm, we first observed, at 0.5 bar, that the positive DC BDV was higher than the negative DC BDV, and then we observed the inverse: that the negative DC BDV became higher (Figure 6). Such a variation has been reported in previous work in SF_6 under LI voltages [12]. This inversion phenomenon has also been observed with a 3.7% Fluoronitriles–96.3% CO_2 mixture [4]. This is likely due to space charges.

Note that the point–plane electrode geometry is generally investigated to simulate defects or triple points in high-voltage equipment (GIS for instance).

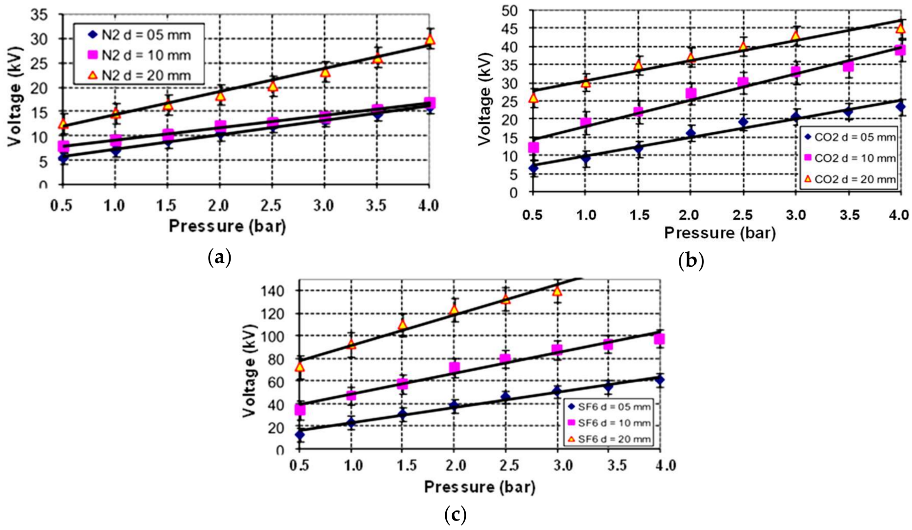


Figure 2. AC breakdown voltage of N_2 (**a**), CO_2 (**b**) and SF_6 (**c**) gases in the point–plane electrode arrangement.

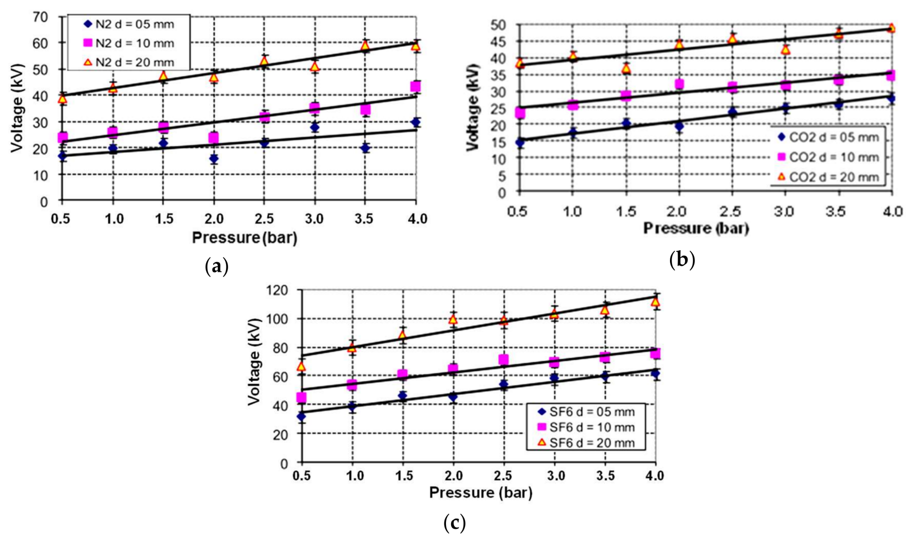


Figure 3. Lightning impulse (LI) breakdown voltage of N_2 (**a**), CO_2 (**b**) and SF_6 (**c**) gases in the point–plane electrode arrangement.

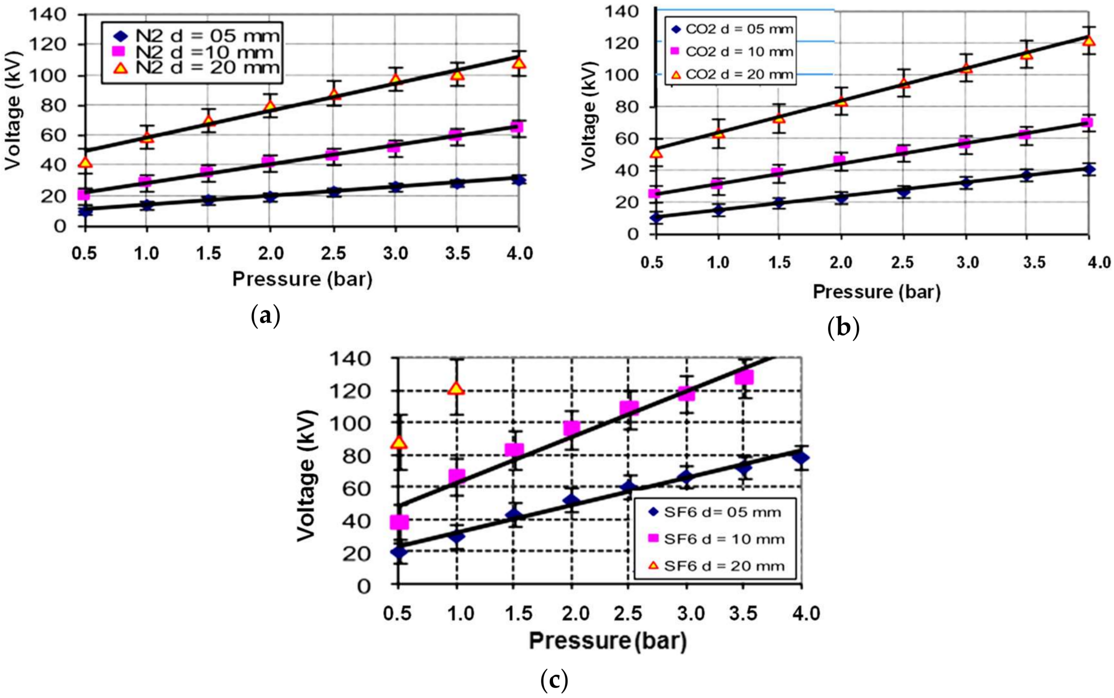


Figure 4. Negative DC breakdown voltage of N_2 (**a**), CO_2 (**b**) and SF_6 (**c**) gases in the point–plane electrode arrangement.

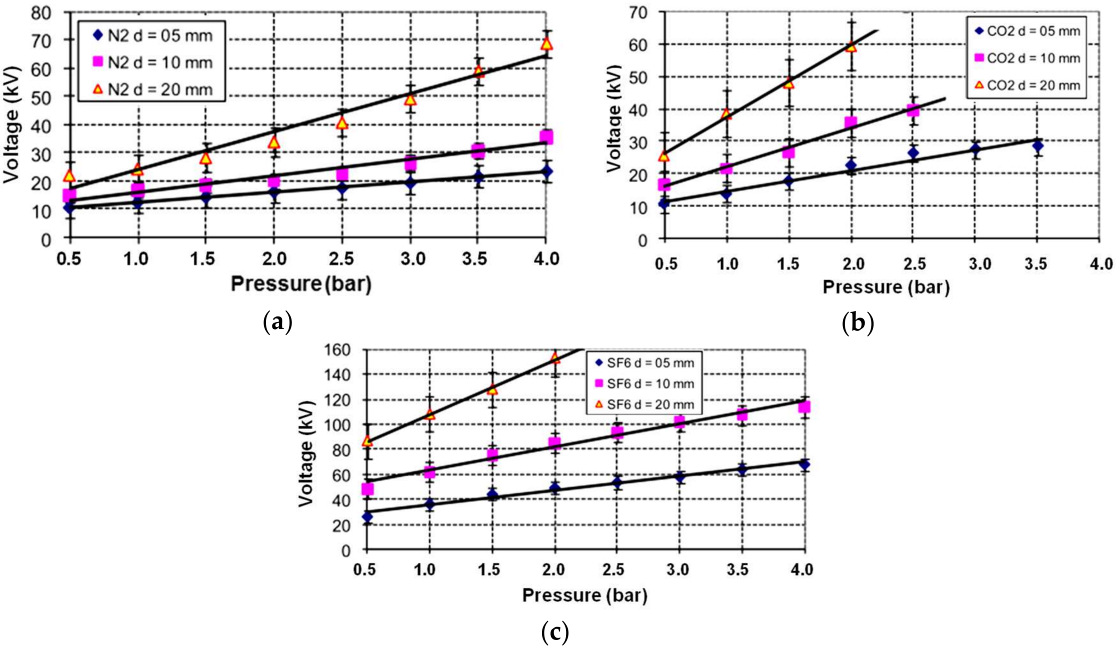


Figure 5. Positive DC breakdown voltage of N_2 (**a**), CO_2 (**b**) and SF_6 (**c**) gases in the point–plane electrode arrangement.

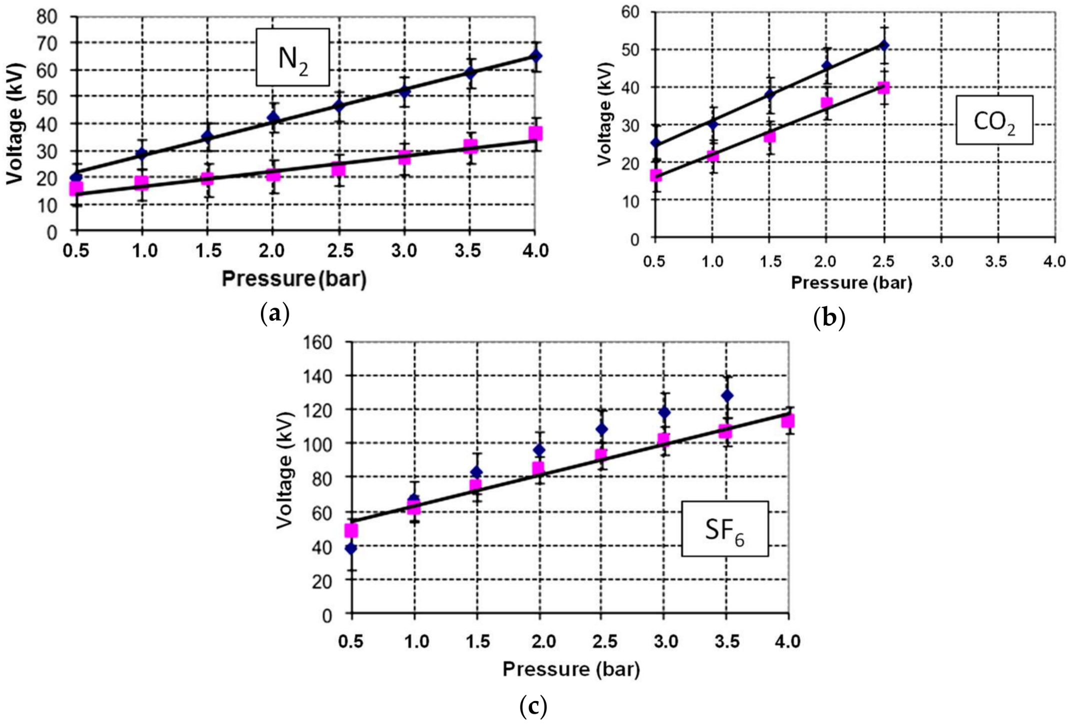


Figure 6. Comparison of breakdown voltages of N_2 (**a**), CO_2 (**b**) and SF_6 (**c**) gases in positive (■) and negative (◆) DC in point–plane electrode arrangement; electrode gap = 10 mm.

3.2. Influence of Voltage Waveform on the Breakdown Voltage of Gases and Mixtures in Sphere–Sphere Electrode Arrangement

Generally, in order to investigate the dielectric strength of a given material (gas here) one uses an electrode geometry that provides a uniform or quasi-uniform electric field. In this study, we consider a sphere–sphere electrode arrangement whose axis is vertical. The spheres have a radius of 5 mm and the inter-electrode distance was set to 10 mm (Figure 7). This geometry provides an electrode utility factor η of 0.42 (η being the Schwaiger form factor [13]).

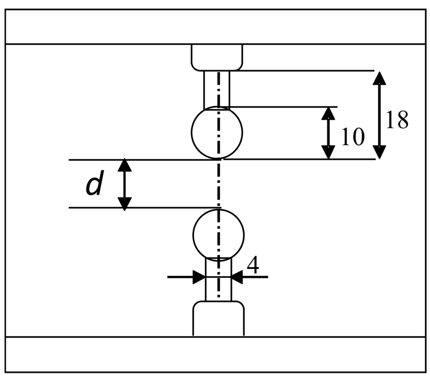


Figure 7. Scheme of the electrode geometry; the dimensions are in mm; d = 10 mm.

Regarding the mixtures, the amounts of SF_6 diluted in N_2 or CO_2 were limited to 20%. Because of what we stated earlier, beyond this value mixtures with SF_6 become less interesting, both ecologically and economically. The tests were conducted according to standards IEC 60060-1:2010.

3.2.1. Comparison of Breakdown Voltages of N_2, CO_2, and SF_6

The BDV is clearly dependent on the voltage waveform whatever the considered gas, as shown in Figure 8. It is noted that the AC and DC breakdown voltages of N_2 and CO_2 vary quasi-linearly with pressure, which is not the case with LI BDV, where the variation is clearly non-linear. On the other hand, the DC and LI BDVs were always higher than the AC BDVs. The LI BDVs of CO_2 and N_2 were at first higher than the negative DC BDVs, however, following an inversion, they were lower. This inversion is sharper in N_2; occurring between 1.5 and 2.0 bar, and in CO_2 between 2.0 and 2.5 bar. Beyond 2.0 bar, the LI and negative DC voltages were very similar for CO_2. While in N_2, DC BDV remained higher than LI BDV. In SF_6, LI BDV was always the highest. This result makes it possible to envisage the replacement of SF_6 by nitrogen, especially in medium HV equipment, at a moderate pressure.

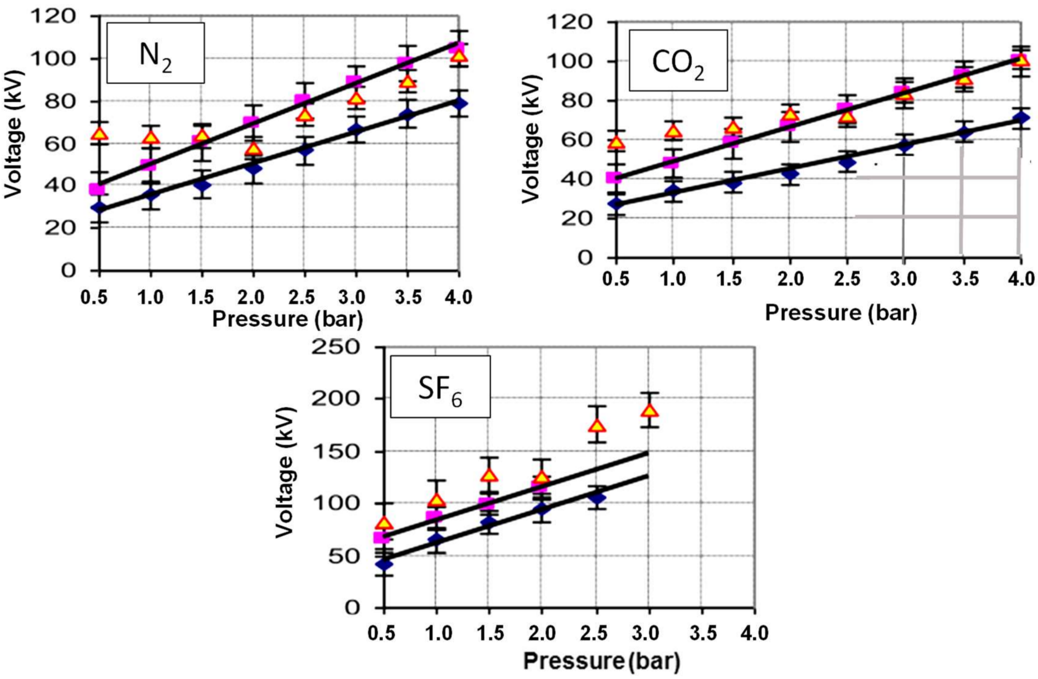


Figure 8. Comparison of the breakdown voltages of each of the investigated gases in the sphere–sphere electrode arrangement for AC (♦), negative (■) and LI (Λ) voltages; electrode gap d = 10 mm.

Figure 9 shows a comparison of the BDVs of each of the three investigated gases for a given voltage waveform. It is noted that the BDV of SF_6 is always higher than that of N_2 and CO_2, whatever the voltage type. The lowest breakdown voltage of the three gases was observed when using AC. Under AC, the BDV of CO_2 was lower than that of N_2, while under DC and LI voltages, the BDVs of both gases were very similar.

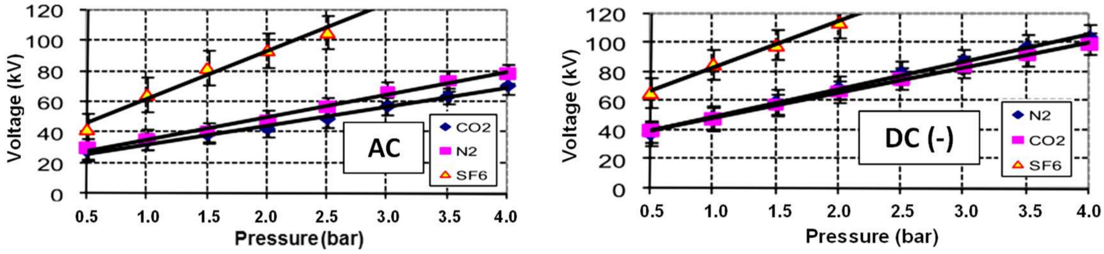


Figure 9. *Cont.*

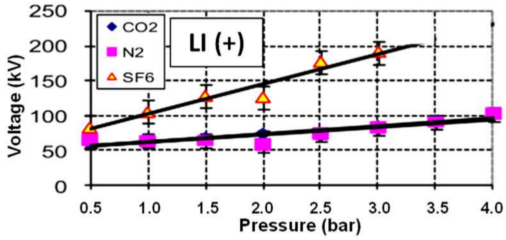


Figure 9. Comparison of breakdown voltages of the three investigated gases in sphere–sphere electrode arrangement for AC, negative DC, and positive LI voltages; electrode gap d = 10 mm.

3.2.2. Comparison of Breakdown Voltages of SF_6–N_2 and SF_6–CO_2 Mixtures for Different Voltage Waveforms in Sphere–Sphere Electrode Arrangement

The addition of SF_6 to CO_2 and N_2 improves the breakdown voltages of these natural gases. This improvement depends both on the concentration of SF_6 and the type of voltage waveforms. The comparison between the three gases (N_2, CO_2, and SF_6) and their mixtures (N_2–SF_6 and CO_2–SF_6) can either be carried out at a given common breakdown voltage (U_{BDV}) of the three waveform voltages, or at a fixed common pressure. In the following, we compared the BDVs of mixtures at a given pressure, namely 2 bar, with the BDVs of N_2, CO_2, and SF_6 for the three voltage waveforms at this pressure (Table 1).

Figure 10 depicts the variation in BDV versus the percentage of SF_6 for the three types of voltages at 2 bar. We observed that the AC BDV of CO_2 increased by 15% and 25% at 5% and 10% SF_6, respectively. The AC BDV of N_2 increased by 12% and 18% at 5% and 10% SF_6, respectively. For DC, the BDV of CO_2 increased by 20% and 29% at 5% and 10% SF_6, respectively. While for N_2, BDV increased by 18% and 22% at 5% and 10% SF_6, respectively.

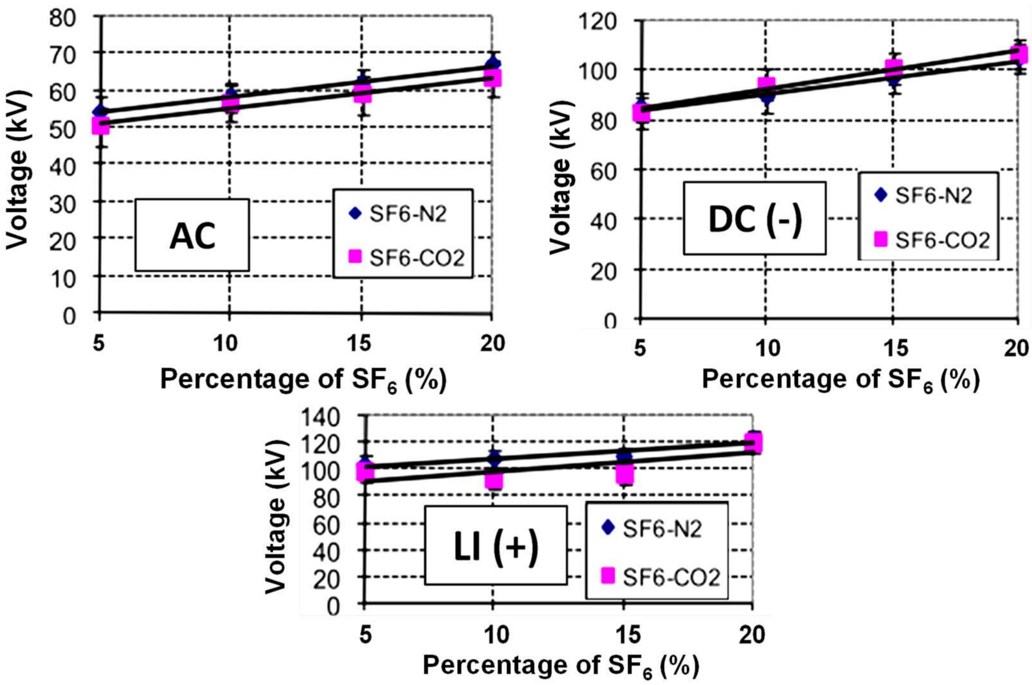


Figure 10. Comparison of the breakdown voltage of SF_6–N_2 and SF_6–CO_2 mixtures in sphere–sphere electrode arrangement under different types of voltage waveforms at p = 2 bar.

Table 1. Average breakdown voltage of N_2, CO_2, and SF_6 for the three voltage waveform voltages at 2 bar.

Gas species	Breakdown Voltage (kV)		
	AC	DC	LI
N_2	48	70	58
CO_2	42	67	73
SF_6	95	115	126

The LI BDVs of CO_2 and N_2 increased by 25% and 44%, respectively, at 5% SF_6. While the LI BDVs of CO_2 and N_2 increased by 20% and 46%, respectively, at 10% SF_6. The fact that the BDV of a 95% $N_2$5% SF_6 mixture is higher than that of 90% N_2–10% SF_6 mixture seems illogical at first glance. This is also the case with N_2, where the LI BDV at 1.5 bar is higher than at 2 bar.

Note that the LI BDV of SF_6 at 2 bar (approximately 126 kV) is obtained with an 80% N_2–20% SF_6 mixture.

In the range of investigated SF_6 concentrations, the DC BDVs of N_2–SF_6 mixtures increase with the percentage of SF_6 and/or pressures, as depicted in Figure 11. We noticed an equivalency between pure SF_6 and 82% N_2–18% SF_6 at 3 bar; the BDV was approximately 125 kV. We observed a linear tendency when increasing the SF_6 concentration; this is not the case under LI. Indeed, beyond 5% SF_6, we even noted a decrease in BDV, evidencing a non-linearity, as shown in Figure 10.

This non-linearity could result from space charge and mechanisms involved in discharge phenomena. Juhre and Kynast [14] reported a similar observation when analyzing the BDV of SF_6–CF_4 in a non-homogeneous field. They attributed this phenomenon to the stabilization mechanism of corona discharges. Onal [10] also reported this non-linearity of SF_6–N_2 and SF_6–CO_2 mixtures in the rod-to-plane electrode system. According to this author, the non-linearity is due to the charge density and development of streamers.

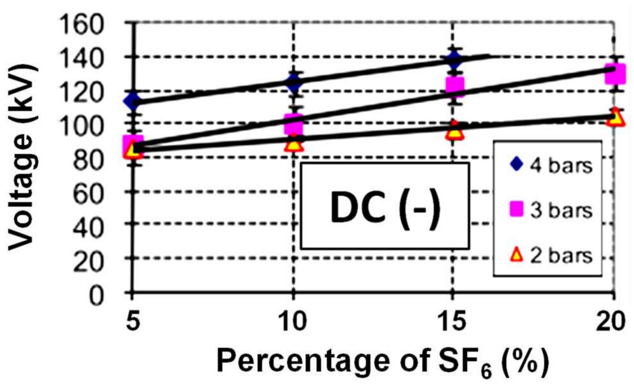


Figure 11. Breakdown voltage of a SF_6–N_2 mixture at 2, 3, and 4 bar, under negative DC voltage; electrode gap d = 10 mm.

The use of natural gases can be considered, particularly in medium voltage apparatus, when pressures remain moderate and do not present a great danger to people. Regarding breakdown, N_2 and CO_2 are more or less equivalent. However, the choice of which gas to use must integrate other parameters. CO_2 is usually preferred over N_2 because of its better repeatability of dielectric performance when compared to N_2 [15–17], and its better current interruption capabilities. These advantages justify the choice of CO_2 as a buffer gas in the development of mixtures with new gases that are potential candidates for the substitution of SF_6 in high-voltage apparatus [1,5,18].

4. Conclusions

This work shows that the breakdown voltage of SF_6 is the highest of the studied gases, whatever the applied voltage waveform. Similarly, for a given voltage waveform, the breakdown voltage of SF_6 is the highest. The AC breakdown voltage is the lowest voltage for all gases. Additionally, the dielectric strengths of natural gases (CO_2 and N_2) are very close, especially under lightning impulse voltage.

Thus, pure CO_2 and N_2 and their mixtures with SF_6 constitute potential gases for HV applications. Their insulating properties can be improved by increasing pressure and/or size of apparatus. With apparatus of the same size, the use of N_2 or CO_2 requires a working pressure about three times higher than that of SF_6. However, it should be emphasized, that if increasing the working pressure of GIS, a new dimensioning of the mechanical structure would be required to withstand the higher pressure; one must also be very careful to remain below the security pressure. Of course, economic aspects must also be considered. In case of surface imperfections and defects in equipment what is simulated by point-plane electrodes geometry, a significant decrease breakdown voltage was observed.

On the other hand, the addition of small amounts of SF_6 to CO_2 and N_2 significantly improved the breakdown voltages of both natural gases. However, the amount of SF_6 has to remain at a reasonable value so as to not compromise the benefits of such mixtures or negatively impact the environment; the economic aspect (especially the SF_6 price) must be taken into account as well. Also, the use of CO_2 would be preferable to N_2 in the creation of mixtures used in HV apparatus, because, (1) CO_2 better interrupts the electrical arc than N_2; (2) the fact that for a given breakdown voltage, the ratio between the pressure of CO_2 to that of SF_6 is generally lower than that between the pressure of N_2 to SF_6, whatever the voltage waveforms; and (3) compared to N_2, CO_2 shows less dispersion in experimental measurements of breakdown voltage.

Acknowledgments: The authors would like to thank the International Scientific Partnership Program (ISPP) at King Saud University for funding this research work through ISPP#0047.

Author Contributions: All authors contributed in the design and realization of experiments as well as in writing the paper.

Conflicts of Interest: The authors declare no conflicts of interest.

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