Experimental investigation of breakdown voltage of CO2, N2 and SF6 gases, and CO2-SF6 and N2–SF6 mixtures under different voltage waveforms

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***Abstract*—In this paper, we present the results of a comparative study of breakdown voltage of CO2, N2 and SF6 gases, and CO2-SF6 and N2–SF6 mixtures under different types of voltage namely AC, DC and lightning impulse voltage in a sphere-to-sphere electrodes arrangement. The equivalencies between breakdown voltage of SF6 and those of mixtures with respect to pressure and percentage of SF6 in CO2 and N2 are presented and discussed.**

Keywords— Breakdown, DC, AC, Lightning impulse voltage, gas mixtures, SF6 content in mixtures, gas pressure.

I. Introduction

Due to its excellent and outstanding properties in both electrical insulation and current interruption performances, sulfur hexafluoride gas, SF_6, is the most used gas in high voltage power equipment such as circuit breakers (GCB), switchgears (GIS), and transmission lines (GIL) since 1960s. ; SF_6 is one of the best insulators gas known to date. However, by its excessive size, radiative effect and atmospheric lifetime (several centuries or even thousands of years), the SF_6 molecule is an agent aggravating the greenhouse effect; its global warming potential (GWP) is 23900 times that of CO_2.

In 1997, the Kyoto Protocol (COP 3) labeled SF_6 as one of the global warming gases and began to control its use and emission into the atmosphere. Thus, the international recommendations tend to heavily restrict or even prohibit in the future its use for preserving the environment. Since then, important researches have been undertaken to find substitutes for SF_6 that have less impact on the environment, compatible dielectric and current interrupting capabilities. Various gases have been considered. Unfortunately all these gases present a high liquefaction temperature as well as a high price. To increase the liquefaction temperature, these gases can be mixed with N_2 and CO_2. Among these gases, c-C_4F_8 has a dielectric strength 1.25 to 1.31 times higher than that of SF_6 and its global warming potentia1 (GWP) is 36 % 1ower than that of SF_6 [1-4]. However its liquefaction temperature is too high. The breakdown voltage of c-C_4F_8-N_2 mixture increases with pressure reaching an asymptote. Other mixtures that have been investigated include c-C_4F_8-CO_2, C_3F_8-CO_2, C_3F_8-N_2, C_2F_6-CO_2 and C_2F_6-N_2. Among these mixtures, 20% C_3F_8 - 80% N_2 shows the best performance. This mixture enables the GWP to be reduced and to have dielectric properties close to those of 20 %SF_6 - 80%N_2 at 0.79 MPa [5].

These last years, some new promising mixtures of complex fluids with natural gases (N2, CO2, dry air) have been developed and investigations to validate their use, are in progress [6-11]. These mixtures could constitute good compromise between dielectric performance and minimum operating temperature of the apparatus whilst providing a considerable reduction in the environment impact.

This paper is aimed at a comparison of breakdown voltage of CO_2, N_2 and SF_6 gases, and CO_2-SF_6 and N_2–SF_6 mixtures under different types of voltage in a sphere-to-sphere electrodes arrangement. The influence of pressure and percentage of SF_6 in CO_2 and N_2 are investigated and equivalencies between breakdown voltage of SF_6 and those of mixtures discussed.

II. Experimental Setup

The tests were performed in sphere-to-sphere electrodes arrangement whose axis is vertical. The spheres have a diameter of 10 mm and the inter-electrode distance is set at 10 mm (Fig. 1).

Three types of voltage sources are used: (1) a Marx generator (200 kV - 2 kJ) providing a standard lightning impulse voltage (1.2/50 µs); (2) a DC generator providing a positive voltage (200 kV - 400 W - 2 mA); and (3) a 200 kV – 60 kVA – 50 Hz high voltage test transformer.

The tested gases are CO_2, N_2 and SF_6 gases, and CO_2-SF_6 and N_2–SF_6 mixtures. As concern mixtures, the amount of SF6 was limited to 20%. Beyond this percentage, the amount of SF6 is quite large, which may jeopardize the economic gain obtained with nitrogen and/or CO_2 as well as the ecological factor. The test are achieved according to standards (ASTM-D-2477-2005 and CEI-60-1-1989 and CEI-60660-1999).

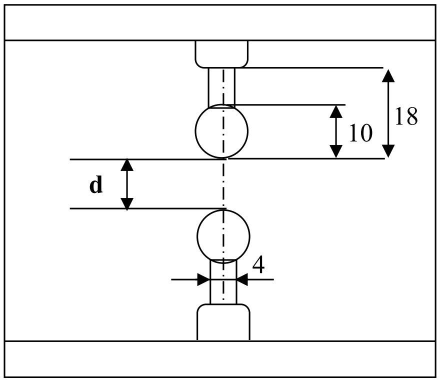

Fig. 1. Scheme of electrodes geometry; the dimensions are in mm.

III. Experimental Results

Figure 2 depicts the breakdown voltage (BDV) of CO2, N2 and SF_6 for the three types of voltage waveforms. It is observed that for a given gas, BDV is the lowest under AC voltage. For CO2 and N2, the LI BDV is first higher than DC BDVs and then one observes an inversion between 1.5 and 2.0 MPa in N2, and between 2.0 to 2.5 MPa in CO2; this inversion is more marked in N2. Note such inversion has been reported for SF6 under lightning impulse voltage when changing polarity [12].

The breakdown voltage of SF_6 is the highest whatever the type of voltage waveform confirming a well-known result (Fig. 3). BDV of CO_2 and N_2 are too close especially under lightning impulse voltage.

As concern N2-SF_6 and CO_2-SF_6 mixtures, the improvement of breakdown voltage increases with the percentage of SF6; it also depends on the type of applied voltage. Figure 4 gives BDV *vs*. the percentage (*c*) of SF6 for the three types of voltage waveforms at 0.2 MPa; *c* varies between 5 and 20 %.

Under lightning impulse voltage, BDV is improved by a factor of 44% for N_2-SF_6 mixture with 5% of SF_6 (from 58 to 103.74 kV) and 46% with 10% of SF_6 (58 to 107.97 kV) at 0.20 MPa. Note that for pure SF_6, the breakdown voltage is of 125.9 kV; such a value is obtained for a mixture with about 20% of SF6. For CO_2-SF_6 mixture, one has an improvement of 25% with 5% of SF6 (from 73 to 97.27 kV) and 20% with 10% of SF_6 (73 to 91.69 kV). At first sight, this result seems absurd. This phenomenon could be due to the stabilization effect of corona discharges which is more important in the case of mixtures under impulse voltage. Similar result is also observed in pure gases under LI where in N2, for instance, the breakdown voltage at 0.15 MPa is higher than that at 0.20 MPa. Thus it is difficult to draw a definite conclusion for lightning impulse voltage, especially in the case of nitrogen and its mixtures.

Under AC voltage, the addition of 5% of SF_6 to N_2 enables to increase the breakdown voltage of about 12% (48 to 54.33 kV); and with 10% of SF_6, this improvement of mixture reaches about 18% (48 to 58.5 kV). For SF_6-CO_2 mixture, the breakdown voltage increases by about 15% (42.4 to 50.33 kV) with 5% of SF_6 and 25% (42.4 to 56.66 kV) with 10% of SF_6. While for pure SF_6, the breakdown voltage is of 94.25 kV.

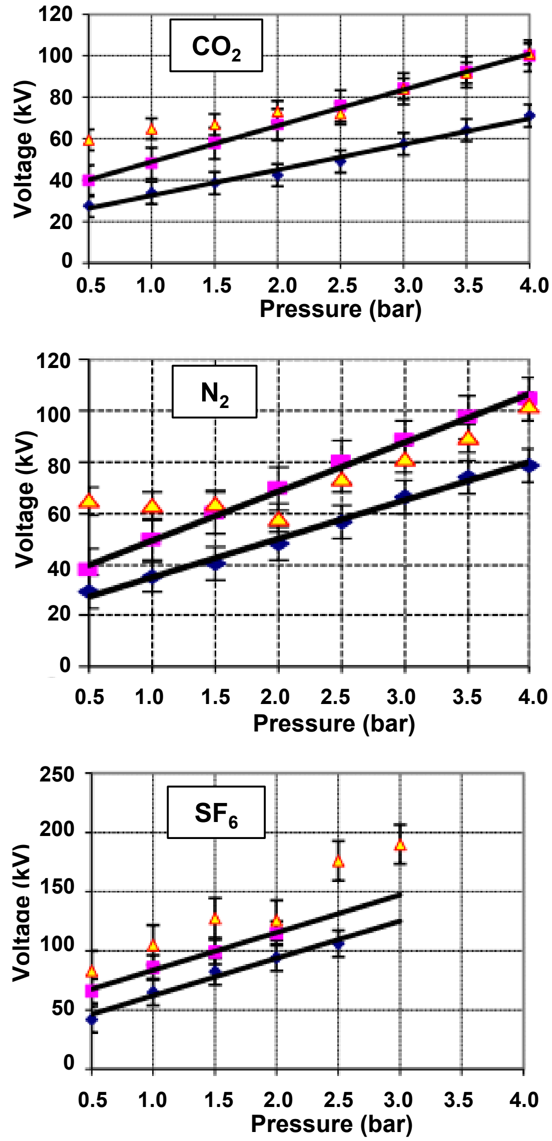

Fig. 2. Breakdown voltage of CO_2, N_2 and SF_6 in a sphere - sphere electrodes arrangement for different types of voltage. The voltage indicated for lightning impulse voltage is U50 and for AC in rms. (◆) AC; (■) DC; and (▲) LI+.

Under DC voltage, the addition of SF_6 to N_2 allows us also to improve the dielectric strength of mixture. One has an increase of 18% (69.5 to 85.16 kV) with 5% of SF_6 and 22% (69.5 to 89.15 kV) with 10% of SF_6. For CO_2, the improvement is of 20% (66.75 to 83.03 kV) with 5% of SF_6 against 29% (66. 75 to 94.42 kV) with 10% of SF_6. The breakdown voltage of pure SF_6 is of 114.77 kV.

Figure 5 gives the variation of DC BDV of N2-SF6 mixtures vs. the percentage of SF6, for three pressures namely 0.2, 0.3 and 0.4 MPa. One observes that the growth rate is the highest at 0.3 MPa. At this pressure, BDV of pure SF6 is of about 125 kV. Such a value is obtained with about 18% SF6 – 72% N2. This amount of additives remains in the acceptable limit (<20%).

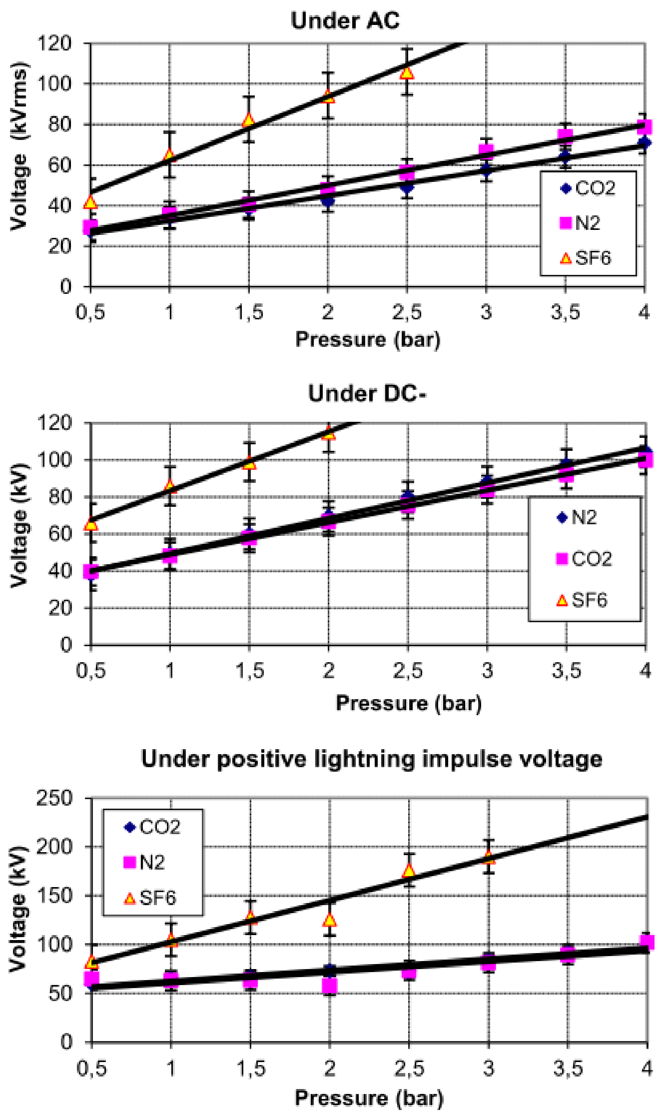

Fig. 3. Comparison of breakdown voltage of CO_2, N_2 and SF_6 in a sphere - sphere electrodes arrangement for different types of voltage. The voltage indicated for lightning impulse voltage is U50.

IV. Discussion

The comparison between the three gases (N_2, CO_2 and SF6) and their mixtures (N_2-SF_6 and CO_2-SF_6) can be done either for a given common breakdown voltage (U_{BDV}) for the three waveform voltages or for a fixed common pressure. For a given breakdown voltage, the ratio of pressure between CO2 and N2 to SF6 is the highest under lightning impulse. For instance, for U_{BDV} = 100 kV, this ratio is of about 4 while with DC is between 2.4 and 2.8.

It appears from the above results that one can use either N2 or CO2 as basic gas for mixtures (Fig. 2); the breakdown voltage of these gases being close too. The choice will mainly depends on the reproducibility of results with the one or the other. The question is: what is the optimum amount of SF6 that gives the best compromise? The appropriate choice must take into account the pressure which must be lower than a given value to ensure the safety and the admissible concentration of SF6 with respect to the environment and its price.

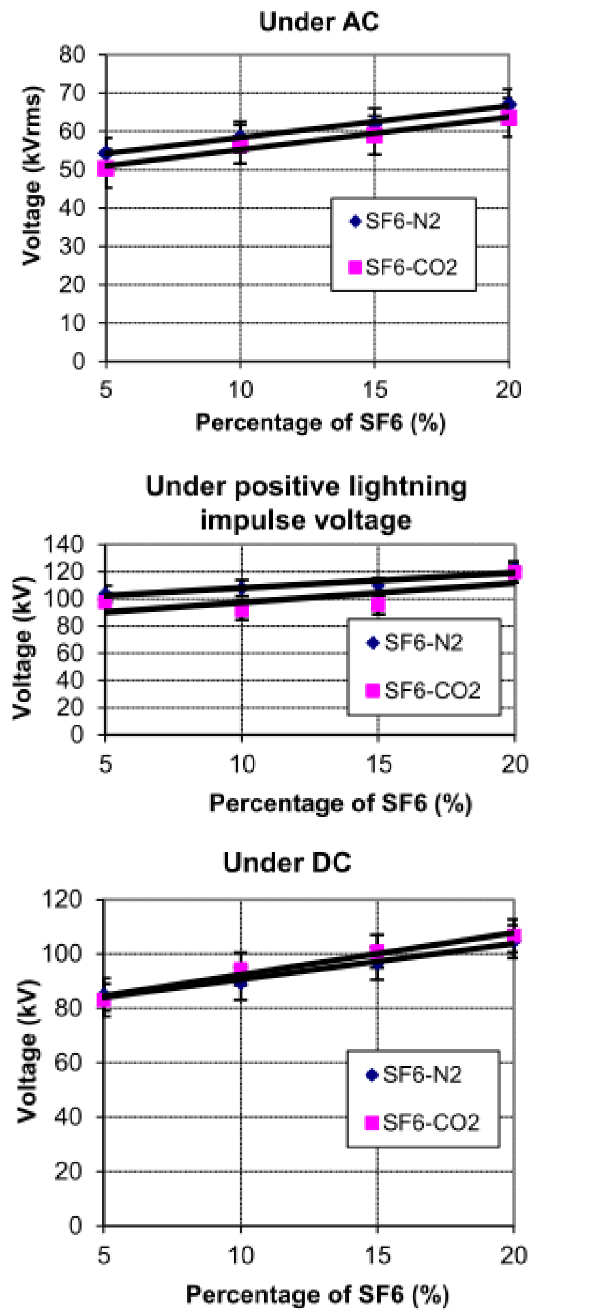

Fig. 4. Comparison of breakdown voltage of SF_6 - N_2 and SF_6 - CO_2 mixtures under different types of voltage wave forms, at P= 0.2 MPa (2 bars).

Note that the operating gas pressure in high voltage apparatus filled with pure SF6 (gas insulated switchgear – GIS, for instance) is generally 0.40 MPa. To compare the breakdown voltage of pure SF6 to the considered mixtures at such a pressure, one needs higher pressures (2.5 to 3 times more). Unfortunately, due the limit of our test cell, we were limited to 0.4 MPa in our measurements.

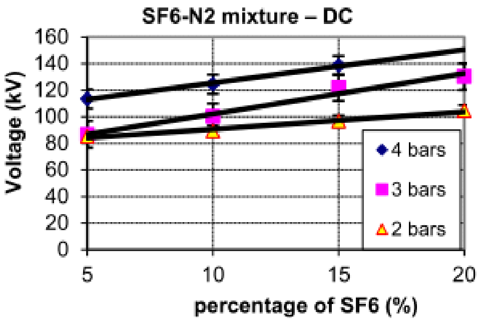

Fig. 5. Breakdown voltage of SF_6-N_2 mixture at 0.2, 0.3 and 0.4 MPa, under negative DC voltage.

On the other hand, for the three voltage wave-forms and for a given breakdown voltage, the ratio between the pressure of CO2 to that of SF6 is generally lower than that between the pressure of N2 to that of SF6. Also, previous studies showed that the breakdown measurements of N2 in other geometrical structures present some dispersion compared to CO2 [13]; there is a problem of reproducibility. The above arguments have led the researchers/industrials to focus their investigations on new mixtures using CO2 as a basic gas [14].

V. CONCLUSION

It appears from this work that the breakdown voltage of SF_6 is the highest whatever the type of voltage waveform. For a given gas, BDV is the lowest under AC voltage. BDV of CO_2 and N_2 are too close especially under lightning impulse voltage.

As concerns mixtures, for a given breakdown voltage, the ratio between the pressure of CO2 to that of SF6 is generally lower than that between the pressure of N2 to that of SF6 whatever the voltage wave-forms. Thus the use of CO2 would be preferable to that of N2 for mixtures. This confirms the fact that in the ongoing research on mixtures use CO2 as basic gas.

For mixtures, the optimum amount of SF6 (or any other new gas) that gives the best compromise must take into account the pressure which must remain lower than a given value to ensure the safety and the admissible concentration of SF6 with respect to the impact environment and its price.

REFERENCES

[1] H. Toyota, S. Matsuoka and K. Hidaka, "Measurement of sparkover voltage time and Lag characteristics in CF_3I - N_2 and CF_3I - mixtures Air gas by using steep front-square voltage" IEEJ Trans. FM, Vol. 125, No.5, pp. 409-414, 2005.

[2] B. Wu, D. Xiao, S. Qin and D. Huang, "Research on lighting impulse breakdown characteristic of c-C_4F_8 and N_2 gas mixture in rod-plane gaps", XVI International Conference on Gas Discharge and their Applications, Xi'an, China, September 11-15, 2006.

[3] L. Zhang, D. Xiao, D. Zhang, "Applying c-C_4F_8 – CO_2 substituting SF_6 as an insulation medium at low E/N (<400Td)", XVI International Conference on Gas Discharge and their Applications, Xi'an, China, 11-15 September, 2006.

[4] H. Katagiri, H. Kasuya, S. Yanubu, "Investigation of the performance of CF3I gas as possible substitute for SF6", IEEE Trans. Dielectr. Electr. Insul., Vol. 15, No 5, pp. 1424-1429, 2008.

[5] M. S. Kamarudin, L. Chen, P. Widger, K. H. Elnaddab, M. Albano, H. Griffiths, and A. Haddad, "CF3I gas and its mixtures: Potential for electrical insulation", CIGRE, ,Session 45, D1-308, Paris, France, 2014.

[6] H. Okubo and A. Beroual, **"**Recent Trend and Future Perspectives in Electrical Insulation Techniques in Relation to SF6 Substitutes for High Voltage Electric Power Equipment", IEEE Electrical Insulation Magazine, March/April, Vol. 27, No. 2, pp. 34-42, 2011.

[7] J. D. Mantilla, N. Gariboldi, S. Grob and M. Claessens, "Investigation of the Insulation Performance of a New Gas Mixture with Extremely Low GWP", Electrical Insulation Conference (EIC), Philadelphia, Pennsylvania, USA, 8-11 June, 2014.

[8] Y. Kieffel, A. Girodet, Ph. Ponchon, J. Owens, M. Costello, M. Bulinski, R. Van San, K. Werner, "SF6 alternative development for high voltage switchgears", CIGRE, Session 45, D1-305, Paris, France, 2014.

[9] A. Hopf, M. Rossner, F. Berger and U. Prucker, "Dielectric strength of alternative insulation gases at high pressure in the homogeneous electric field", IEEE Electrical Insulation Conference (EIC), Seattle, USA, 7-10 June, 2015.

[10] L. Chen, P. Widger, C. Tateyama, A. Kumada, H. Griffiths, K. Hidaka and A. Haddad, "Breakdown Characteristics of CF3I/CO2 gas mixtures under fast impulse in rod-plane and GIS geometries", the 19th International Symposium on High Voltage Engineering, Pilsen, Czech Republic, 23-28 August, 2015.

[11] P. Simka and N. Ranjan, "Dielectric strength of C5 Perfluoroketone", the 19th International Symposium on High Voltage Engineering, Pilsen, Czech Republic, 23-28 August, 2015.

[12] F. Sadaoui and A. Beroual, "Influence of polarity on breakdown voltage of gases in divergent electric field under lightning impulse voltages", 2012 International Conference on High Voltage Engineering and Application, 17 - 20 September, 2012, Shanghai, China.

[13] T. Diarra, A. Beroual, F. Buret, V.D. Pham, "Correspondence between SF6, N2 and Air under pressure for a common surface flashover voltage", Ninth International Symposium on High Voltage Engineering (ISH'95), Graz (Austria), paper 2264, August 28 - September 1, 1995.

[14] H. E. Nechmi, A. Beroual, A. Girodet and P. Vinson, "Fluoronitriles / CO2 gas mixture as promising substitute to SF6 for insulation in high voltage applicationse, IEEE Trans. Dielectr. Electr. Insul., Vol. 23, Issue 5, pp. 2587-2593, 2016.