ISTANBUL UNIVERSITY –
JOURNAL OF ELECTRICAL & ELECTRONICS ENGINEERING

YEAR : 2004 (1177-1182)
VOLUME : 4
NUMBER : 2

BREAKDOWN CHARACTERISTICS OF GASES IN NON-UNIFORM FIELDS

Emel ÖNAL

İstanbul Teknik Üniversitesi Elektrik-Elektronik Fakültesi
Elektrik Mühendisliği Bölümü Maslak-İstanbul

E-mail: onal@elk.itu.edu.tr

ABSTRACT

AC breakdown strengths of CO_2, N_2, SF_6 and air in non-uniform field were experimentally studied. The experimental results have shown that the breakdown voltages of SF_6 in the practical range of pressure (100-200 kPa) are always higher than those of other gases. Although at short gaps, the breakdown strength of SF_6 is superior at the pressure range from 100-500 kPa, at 25 mm electrode gap spacing and 300 kPa the breakdown voltage of air is %7.8 higher than that of SF_6. At above pressures of 400 kPa and 15 mm electrode gap spacing, there exists a critical field where the breakdown voltage of CO_2 has a maximum value.

Keywords: *Sulfur Hexafluoride, Breakdown Voltage, Non-uniform Field, Buffer gases*

1. INTRODUCTION

Gases are used as an insulating medium for compact substation components and gas insulated cables in recent years. The searches for even better gas insulation continues in order to develop gases and gas mixtures to satisfy specific requirements for various devices, provided such gases have dielectric properties comparable or superior to each other. There are two basic reasons for carrying out such investigations. Firstly, the aims are to develop an insulating medium, which is technically as well as economically attractive. The other reason is to obtain a better understanding of the breakdown mechanisms operating in compressed gases, and their gas mixtures. Most of the published data refer to uniform or nearly uniform field gaps for SF6, CO_2, (carbon dioxide) N_2 (nitrogen) and air[1-3]. However, there is still insufficient information regarding the alternating breakdown of these in non-uniform field gaps. In a typical industrial application the non-uniform field breakdown predominates. Earlier experimental results showed strong dependence of breakdown voltages upon applied voltage, voltage polarity, electrode spacing, pressure and the nature of the gas. It is recognized that Sulfur Hexafluoride (SF_6) gas has excellent dielectric and heat transfer properties and is increasingly being used in high-pressure gas insulated systems. However, in practice the electrical breakdown strength of compressed SF_6 is often governed by a local field enhancement due to the protrusions, surface roughness, and the presence of conducting

Received Date: 15.04.2001
Accepted Date: 15.06.2004

particles in the system. In addition the fact that SF_6 is a strong greenhouse gas has prompted interest in substitute gases with lower or no environmental impact. Therefore, there is an increasing interest in the possible application of mixtures of SF_6 and other gases to reduce insulation cost and to minimize the possible hazard of particle-initiated breakdown. Many researches have studied behavior of air, N_2 and CO_2 mixed with a small percentage of SF_6 as an additive. CO_2, weakly attaching gas has a special inhibiting property when used in gaseous mixtures. Hence it is useful to investigate the breakdown characteristics of CO_2 especially under various voltages. Air and N_2 have been suggested as environmentally uncritical insulation media for gas insulated electrical power equipment. This gases numerous applications, including use as insulation for high voltage equipment. From a practical point of view, only SF_6 mixtures with those common gases or buffer gases (air, N_2, CO_2) show an importance in most industrial applications. Several investigations have been reported in the literature on the breakdown behavior of SF_6, N_2 CO_2 and SF_6 mixtures [4-6]. The earlier measurements have shown that although the rod electrode is positive, the breakdown voltage-pressure characteristic has a maximum-minimum for SF_6, that phenomenon has not been seen in negative voltages [7]. This discontinuity is more distinct and seems at higher pressures in gaps with smaller diameter rods. Negative impulse breakdown voltage of SF_6 is about three times that of air, N_2 and CO_2 at a pressure of 50kPa. However, as the gas pressure is increased to about 500 kPa, the breakdown voltage of SF_6 is only marginally (about 10-20%) higher than those of air, N_2 and CO_2 [8]. For the electrode system used here, the negative impulse breakdown voltages of these gases are higher than their positive values. For a positive rod-plane gap, the electrons created of the avalanche by photo ionization travel towards the high field regions thereby creating more positive ion space charge at the avalanche head. In this fashion, the positive ion space charge is advanced towards the cathode maintaining the field at its tip and creating more electrons ahead of it to continue the advance. This not only results in a lower value of the breakdown voltage for a positive rod-plane gap but also results in a much lower value of the critical pressure in such gaps. For N_2 gas the ratio of the impulse breakdown voltage of negative gap to that of a similar positive gap is more or less independent of the gas pressure and has a value of about 2, in other gases, this ratio varies with pressure between 1 and 2 for air, 1.2 and 2.5 for CO_2, and 1.7 and 2.1 for SF_6 over the pressure range of 50 kPa to 500 kPa. The lowest values are generally recorded at atmospheric (100 kPa) or sub atmospheric pressures while the highest values are measured at pressures of 400 to 500 kPa. Thus, in all of these gases, positive impulse breakdown is the most critical factor for insulation of rod-plane gaps. For the positive impulse rod-plane systems, the breakdown voltage of N_2 increases with pressure. However, the characteristics appear to saturate above a pressure of 200 kPa. The negative polarity breakdown characteristics of N_2 exhibit a different trend. For N_2, the breakdown voltages are in general higher than the corresponding positive polarity breakdown voltages. There is a rapid increase in the negative polarity breakdown voltages of nitrogen beyond a pressure of about 200 kPa [9]. Mixtures with less than 1% of SF_6 content have breakdown levels slightly lower than the corresponding values in pure N_2, CO_2 and air at gas pressure in excess of 200-300kPa. This type of behavior is more pronounced when the field configuration is highly non-uniform and /or gas pressure is high. As is well known, there is an increasing interest in the possible applications of mixtures of SF_6 and other buffer gases [10]. For this reason the breakdown characteristics of the electronegative gas (SF_6) and common buffer gases, such as CO_2, N_2, air, have been investigated in our experiments.

The main purpose of this work is therefore to investigate the effect of field non-uniformity and pressure on breakdown voltages of compressed SF_6, CO_2, N_2, and air in rod-plane electrode system for 50 Hz AC voltages.

2. EXPERIMENTAL SET-UP

Experiments were carried out using a rod plane electrode with a rod tip radius of 1 mm and plane disc diameter of 75 mm (Fig. 1). All experiments were used over a pressure range extending from 100 kPa to 500 kPa and gap lengths ranging from 5 mm to 25 mm. Electrodes were mounted in a pressure vessel of 120 mm diameter and 600 mm length. In rod-plane arrangement, the rod was connected to the high voltage supply while the plane was earthed. Before each series of tests, the electrodes were polished and cleaned thoroughly. The test vessel was first evacuated for at least two hours and then filled with the desired gas up to a relative pressure of 500 kPa. The gas mixture was left for at least thirty minutes before test, for the purpose of obtaining a uniform gas distribution. For the 50 Hz AC tests with voltages up to 100 kVrms a high voltage transformer was employed. AC breakdown voltage was measured by means of a capacitive divider. The mean value of breakdown voltage and standard deviation were calculated by means of ten voltage applications.

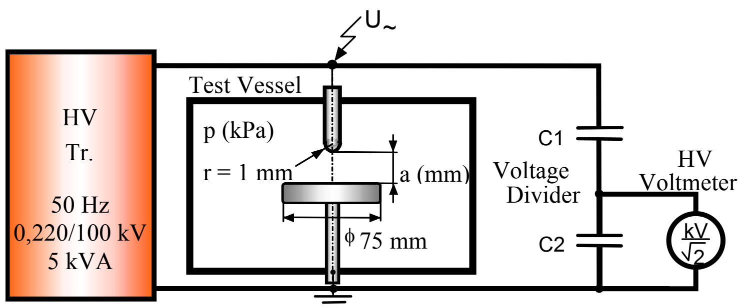

Figure 1. Experimental Set-up

3. TEST RESULTS

The present paper describes a study of the breakdown voltage-pressure characteristics of SF_6, CO_2, N_2 and air in rod plane gaps under alternating voltages. All results are given for 5, 10, 15, 20, 25 mm electrode gap spacing separately (Fig 2-6). The relative gas pressure is varied within the range of 100-500 kPa. As seen in experimental results, the breakdown voltages of gases are increased approximately linear with pressure for 5 mm gap spacing (Fig. 2). Because for short rod-plane gaps, the electrodes is similar to uniform field, there is no discontinuity in the breakdown voltage-pressure characteristics for short electrode gap. In this figure, the breakdown voltage of SF_6 is about two times that of air, N_2 and CO_2. The high breakdown strength of electronegative gases such as SF_6 depends mainly on their capability of taking up free electrons, thereby forming heavy negative ions. These gases generally have significantly higher electric strengths than other gases because of their attachment; their ionization coefficients are not very different from those of other gases.

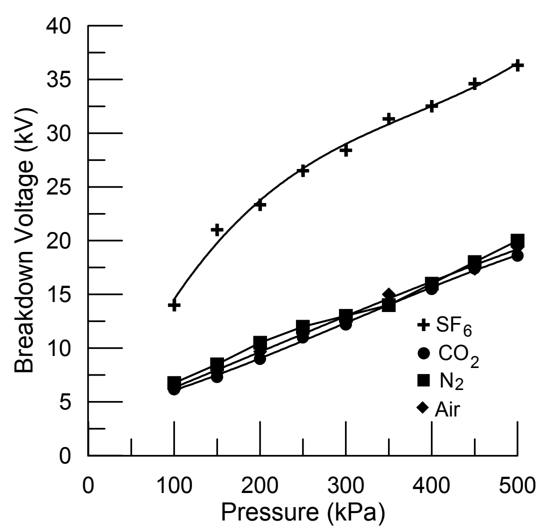

Figure 2. Variation of breakdown voltage with pressure in SF_6, CO_2, N_2, Air, for 5 mm gap spacing.

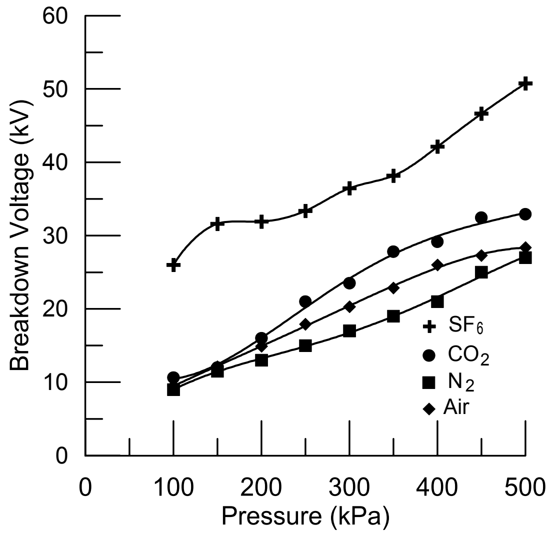

Figure 3. Variation of breakdown voltage with pressure in SF_6, CO_2, N_2, Air, for 10 mm gap spacing.

For 10 mm gap spacing, although the breakdown voltages of all buffer gases have similar values at low pressure, they have different breakdown strength at higher-pressure range (Fig. 3). Similar type characteristic of buffer gases were observed by I. D. Chalmers et al [11]. In that study, also noticed was that above 200 kPa, the minimum positive impulse breakdown voltage for pure SF_6 changes very little in the highly non-uniform field. The breakdown voltage–pressure characteristics for SF_6 have maximum-minimum behavior especially larger than 10 mm gap spacing. From optical observations it has been found that near the maximum breakdown voltage of SF_6 against pressure characteristics, the breakdown channel is always curved. This effect depends on polarity of voltage and field non-uniformity.

As seen in experimental results, the breakdown voltage of CO_2 is increased approximately linear with pressure in the range of 5-20 mm gap spacing especially at above pressures of 400 kPa and 15 mm gap spacing, the breakdown voltage has a maximum value (Fig.4). The earlier experiments about the positive impulse breakdown characteristics of CO_2 in non-uniform field have shown that there exists a "critical field" where the breakdown voltage will be a maximum over the entire range of pressures investigated [12-14]. At present work, that phenomenon has been seen. This could be due to the pronounced corona stabilization effect at this "critical field" caused by the neutralization of positive space charge by the negative space charge. A physical explanation for the presence of the "critical field" is rather complicated. Nevertheless, a qualitative postulation is possible considering space charge effects. The critical field conditions are created when the resultant electric field in the gap is such that the influence of positive space charges is nullified by the negative space charge; in the present investigation for CO_2 such a condition is created when the gap is 15 mm. In this case the breakdown value of CO_2 is only about 17% less than that of SF_6 (Fig.4). It is shown that CO_2 for 20 mm gap spacing can have breakdown voltages lower than the corresponding values in air at above the pressure of 200 kPa (Fig. 5).

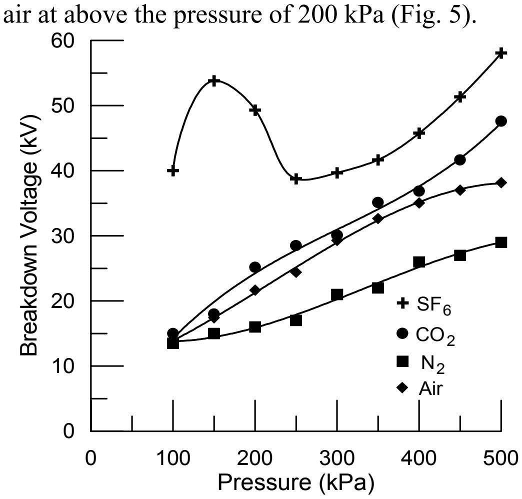

Figure 4. Variation of breakdown voltage with pressure in SF_6, CO_2, N_2, Air, for 15 mm gap spacing.

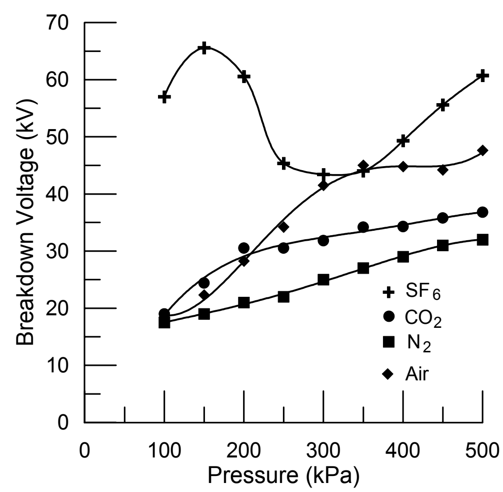

Figure 5. Variation of breakdown voltage with pressure in SF_6, CO_2, N_2, Air, for 20 mm gap spacing.

The breakdown voltage of air is approximately same as that of SF_6 at a pressure of 350 kPa. Several authors have examined that the breakdown voltage-pressure characteristics of compressed N_2, CO_2 for positive direct and impulse voltages, have maximum-minimum behavior in non-uniform field. This effect also can be observed above the pressure of 500 kPa. For this reason, similar effect was not reported in our experiments.

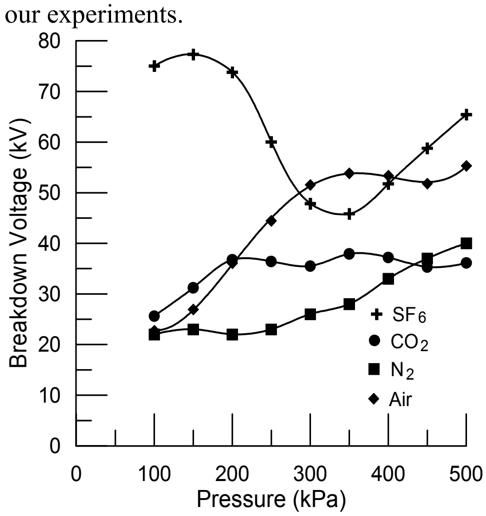

Figure 6. Variation of breakdown voltage with pressure in SF_6, CO_2, N_2, Air, for 25 mm gap spacing.

As seen in experimental results using 25 mm rod-plane gap, the breakdown voltage of SF_6 is about three times higher these of air, N_2, CO_2 at a pressure of 100 kPa (Fig.6). However as the gas pressure is increased to about 350 kPa, the breakdown voltage of SF_6 is 15% less than that of air. At a pressure of 500 kPa, SF_6 has 20% higher breakdown strength than air. The breakdown voltages of CO_2 and N_2 are always lower than these of SF_6. The breakdown of CO_2 drops below that of N_2 at a pressure of 500 kPa. In all electrode gaps the breakdown strength of N_2 increases with increasing pressure.

4. CONCLUSION

The results of the present measurements indicate that although the breakdown voltages of CO_2, N_2 and air are the same, they have half of breakdown strength of SF_6 for 5 mm electrode gap CO_2 has superior breakdown voltage to N_2 and air for 10-15 mm gap but at a pressure of 500 kPa and for 25 mm gap spacing dielectric strength is minimum. N_2 exhibits linear breakdown-pressure behavior for all gap spacing. As seen in experimental results using 25 mm rod-plane gap, the breakdown voltage of SF_6 is about three times higher these of air, N_2, CO_2 at a pressure of 100 kPa. However as the gas pressure is increased to about 350 kPa, the breakdown voltage of SF_6 is 15% less than that of air. At a pressure of 500 kPa, SF_6 has 20% higher breakdown strength than air. Consequently SF_6, air, N_2, CO_2 can offer suitable choice for applications in compressed gas insulated devices for certain pressure and certain electrode gap spacing. This effect depends upon the polarity of the voltage, the pressure, electrode gap spacing, field uniformity and the nature of the gas. The present work shows that these gases are technically and economically attractive alternatives. Therefore the gas mixtures with lower liquefied temperature, high chemical stability and no greenhouse effect is promising gas dielectrics applicable in future power apparatus.

5. REFERENCES

[1] Malik, N. H., Qureshi, A H., “A review of electrical breakdown in mixtures of SF_6 and other gases", *IEEE Trans. Electrical Insulation*, Vol. EI-14, No. 1, pp. 1-11, Feb 1979.

[2] Olivier, G., Gervais, Y., Mukhedkar, D., "A new approach to compute uniform field breakdown of gases", *IEEE Trans. on Power Apparatus and Systems,* Vol. PAS-97, pp. 969-976, 1978.

[3] Malik, N. H., Qureshi, A. H., "Breakdown gradients for SF_6+N_2, SF_6+CO_2 and SF_6+air mixtures", *IEEE Transactions on Electrical Insulation*, Vol. 15, No. 5, pp. 413-418, 1980.

[4] Malik, N. H., Qureshi, A. H., Theophilus, G. D., “Static field breakdown of SF_6-N_2 mixtures in rod-plane gaps", *IEEE Trans. Electrical Insulation*, Vol. EI-14, No. 2, , pp. 61-70, April 1979.

[5] Cookson, A. H., Pedersen, B. O., "High voltage performance of mixtures of SF_6 with N_2, air and CO_2 in compressed gas insulated equipment", *Proceedings Fifth Int. Conf. on Gas Discharges*, pp. 161-164, 1978.

[6] Qiu, Y., Xiao, D. M., "Dielectric strength of the SF_6+CO_2 gas mixture in different electric fields", *Ninth International Symposium on High Voltage Engineering*, Graz, Sept., Paper 2255-1-4, 1995.

[7] Kuffel, E., Yializis, A., "Impulse breakdown of positive and negative rod plane gaps in SF_6-N_2 mixtures", *IEEE Trans. on Power Apparatus and Systems*, Vol. PAS-97, No. 6, Nov-Dec, pp. 2359-2366, 1978.

[8] Safar, Y. A., Malik, N. H., Qureshi A. H., "Impulse breakdown behavior of negative rod plane gaps in SF_6+N_2, SF_6+air and SF_6+CO_2 mixtures", *IEEE Trans. on Electrical Insulation*, Vol. 17, No. 5, pp. 441-449, October 1982.

[9] Medeiros, P.T, Naidu, S.R., "Positive and negative lightning impulse breakdown of rod-plane gaps in nitrogen", *Conference of Electrical and Dielectric Phenomena, Annual Report*, New York, pp.48-53, 1983.

[10] Yializis, A., Malik, N. H., Qureshi A. H., Kuffel, E., "Impulse breakdown and corona characteristics for rod-plane gaps in mixtures of SF_6 and nitrogen with less than 1% of SF_6 content", *IEEE Trans. on Power Apparatus and Systems*, Vol. PAS-98, No. 5, pp. 1832-1839, Sep-Oct 1979.

[11] Chalmers, L. D., Qiu, X. Q., Coventry, P., "The Study of SF_6 Mixtures with Buffer Gases", *Gaseous Dielectrics VIII*, pp. 189-195, 1998.

[12] Rajendran, T. V., Lakshminarasimha, C. S., Naidu M. S., "Effect of electrode geometry on positive impulse breakdown in carbon dioxide", *IEEE Trans. on Electrical Insulation*, Vol. EI-18, No. 4, pp. 455-457, August 1983.

[13] Önal, E., Kalenderli, Ö., Mardikyan, K., "Breakdown Characteristics of CO_2 Containing 0.125% of SF_6", *Eleventh International Symposium on High Voltage Engineering*, London, 1999.

[14] Önal, E., Kalenderli, Ö., Mardikyan, K., "Breakdown Characteristics of CO_2 and N_2 Containing SF_6", *Budapest Power Tech 99*, Budapest 1999.