AC BREAKDOWN CHARACTERISTICS OF GAS MIXTURES CONTAINING A SMALL AMOUNT OF SF_6 IN NON-UNIFORM FIELD

Emel Önal
Electrical- Electronics Faculty
Istanbul Technical University
34469 Maslak, Istanbul, Turkey
e-mail: onal@elk.itu.edu.tr

Özcan Kalenderli
Electrical- Electronics Faculty
Istanbul Technical University
34469 Maslak, Istanbul, Turkey
e-mail: ozcan@elk.itu.edu.tr

Abstract: 50 Hz AC breakdown characteristics of CO_2, N_2, SF_6, air and mixtures of SF_6 + CO_2, SF_6 + N_2 and SF_6 + air containing 0.125% of SF_6 in non-uniform field of a rod-plane electrode system were experimentally investigated. The electrode gap spacing and the relative gas pressure were varied within the range of 5-25 mm and of 100-500 kPa, respectively. The experimental results showed that in non-uniform field gaps the AC breakdown strength of N_2 and CO_2 in the practical range of pressure (100 to 400 kPa) may be increased by adding a small amount of SF_6. As an example at about pressures of 300 kPa and 25 mm rod-plane gap spacing breakdown voltage of SF_6+CO_2 mixture were obtained 15% and 54% higher than that of pure SF_6 and CO_2 respectively but the breakdown voltages of SF_6+N_2 mixtures obtained lower than those of pure SF_6 at all defined pressures. At above 350 kPa the breakdown voltages of mixtures drop below than those of pure N_2 and CO_2. In addition, in short gaps the breakdown voltages of the SF_6 + air mixture and air have approximately similar and these values are below the breakdown voltage of pure SF_6. The experimental results have shown that the AC breakdown voltages of SF_6+air mixtures are higher than those of pure SF_6 and air above the range of pressure 250 kPa for 20 and 25 mm gap spacing. At this gap spacing SF_6+air mixtures show less degree saturation at high pressures.

Keywords
SF_6 gas mixtures, breakdown characteristic

I. INTRODUCTION

Sulphur hexafluoride (SF_6) is the most commonly used as an insulating gas in electric power apparatus such as switchgears, due to its superior insulation strength. However, it is known that breakdown strength of SF_6 under non-uniform electric field like metallic particle condition is extremely susceptible leading to be lower breakdown voltage. Furthermore, from the view point of environmental protection, as SF_6 has strong greenhouse effect, the use of SF_6 will be strongly controlled. Besides, it is more expensive than other gases. Thus, it is needed to develop the alternative dielectric gas or gas mixtures having better insulating characteristics, inexpensive and no greenhouse effect. For these reasons, SF_6 gas and its mixtures with other less expensive gases such as air, nitrogen (N_2) and carbon dioxide (CO_2) etc. have been extensively studied [1-12]. Consequently, There are two basic reasons for carrying out such investigations. Firstly, the aims are to develop an insulating medium that is technically as well as economically attractive. The other reason is to obtain a better understanding of the breakdown mechanisms operating in SF_6, other compressed gases, and their gas mixtures.

The breakdown characteristics of SF_6 gas mixtures in non-uniform field under applications of direct and impulse voltages have been the subject of several studies [1-3]. Earlier studies have shown that under positive direct voltage at 500 kPa, the breakdown voltage of SF_6+N_2 mixtures having less than 30% SF_6 is below that of pure N_2. When the rod electrode is negative, the breakdown voltage of a mixture containing 0.1% SF_6 is about half that of pure SF_6. Further increase in SF_6 content causes a slower increase in the breakdown strength of the mixtures [4]. At pressures below 200 kPa as the content of SF_6 is reduced below 5% the breakdown strength increases rapidly and reaches a maximum value for a mixture composed of about 99.8% of N_2 and 0.2% of SF_6. At high pressures, SF_6+CO_2 mixtures had breakdown voltages higher than the corresponding values for SF_6+N_2 mixtures for direct and impulse voltages. As mentioned earlier, in the low pressure range, for SF_6+CO_2 mixtures the breakdown voltages of negative and positive direct voltages have similar values. However, at higher pressures, negative breakdown voltages are significantly higher than the positive ones. Most of the SF_6+CO_2 mixtures investigated exhibited breakdown voltages which were similar to or even slightly higher than those observed for pure SF_6 for impulse voltages. Under negative impulse conditions, SF_6+CO_2 mixtures with less than 1% of SF_6 content have breakdown levels slightly lower than the corresponding values in pure CO_2 at gas pressures in excess of 300 kPa.

A systematic and extensive study of breakdown characteristics of SF_6+air mixtures is still lacking. Earlier measurements have shown that the positive direct breakdown voltages of SF_6+air mixtures exhibit corona stabilization over a pressure range, which depends upon SF_6 content of these mixtures, and is higher than the corresponding values for SF_6+N_2 and SF_6+CO_2 mixtures. Over the pressure range of 300 to 500 kPa, SF_6+air mixtures exhibited breakdown voltages, which were generally higher than those for SF_6 alone or its mixtures with N_2 and CO_2. In the low pressure range, the breakdown voltages of positive and negative gaps have similar [5]. The negative impulse breakdown characteristics of SF_6+N_2 and SF_6+air mixtures are somewhat similar. In this case, an addition of SF_6 impurity to air causes an improvement in the negative impulse breakdown level for gas pressures of up to 300 kPa and lowers this level when pressure is increased above that value [6].

From the existing information it appears that SF_6+air mixtures show relatively less degree of saturation as compared to SF_6+N_2 mixtures. This is probably due to the presence of electronegative O_2 in the air. Because of the presence of chemically active oxygen in air, SF_6+air mixtures are technically less important as compared to SF_6+N_2.

The objective of the present paper is to investigate breakdown voltages of compressed N_2, CO_2 and air mixtures containing small amount of SF_6 and the effect of field non-uniformity with and without presence of electrode surface roughness experimentally under alternating voltage.

II. EXPERIMENTAL SET-UP

In the experiments, rod-plane and rod-plane with protrusion electrode configurations were used to simulate and study the effect of field non-uniformities in practical systems (Fig.1). Experiments in the air were only carried out using a rod-plane electrode. Tip radius of the rod electrode with hemispherical tip was 1 mm. The plane electrode was disc shape of 75 mm diameter.

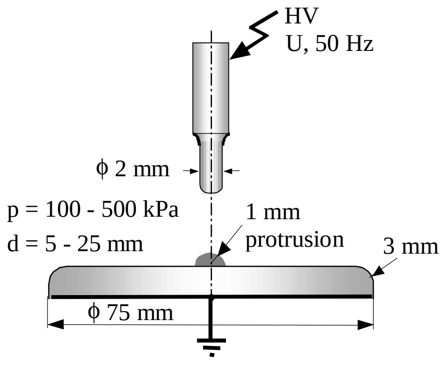

Figure 1. The electrode system used in the experiments.

All experiments were used over a pressure range extending from 100 kPa to 500 kPa and gap spacing ranging from 5 mm to 25 mm. In order to simulate a distortion of the highly inhomogeneous field between rod-plane electrode a metallic hemispherical protrusion with 1 mm radius was fixed to the center of the plane electrode. 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 (Fig. 2). 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 2 hours before test, for the purpose of obtaining a uniform mixture.

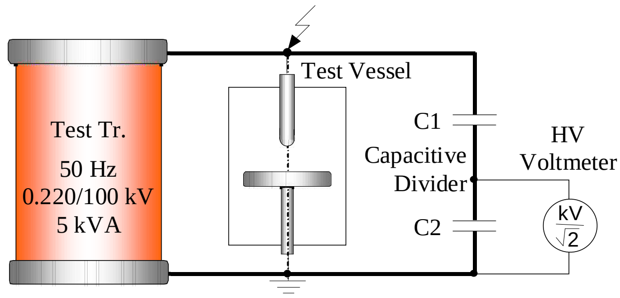

Figure 2. Test setup.

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.

III. TEST RESULTS FOR CO_2, N_2, SF_6 AND THEIR MIXTURES WITH SF_6

The breakdown voltages of CO_2, N_2, SF_6 and the mixtures of SF_6+CO_2 and SF_6+N_2 with 0.125% of SF_6 were measured up to a pressure of 500 kPa for rod-plane and rod-plane with protrusion electrode.

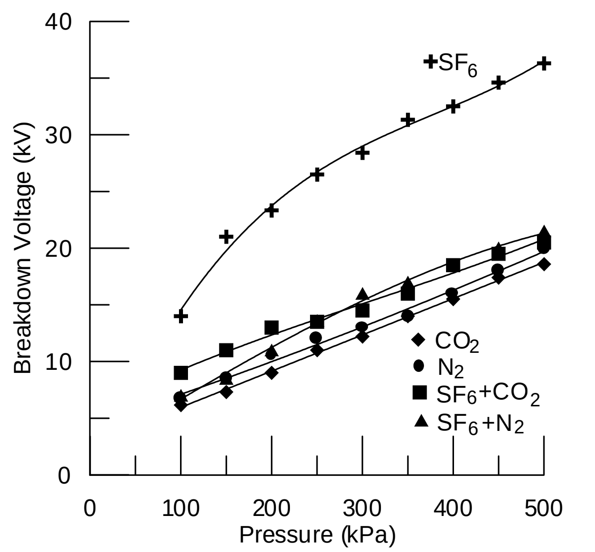

Figure 3. Variation of breakdown voltage with pressure in CO_2, N_2, SF_6, 0.125%SF_6+CO_2 and 0.125%SF_6+N_2 for 5 mm rod-plane gap spacing.

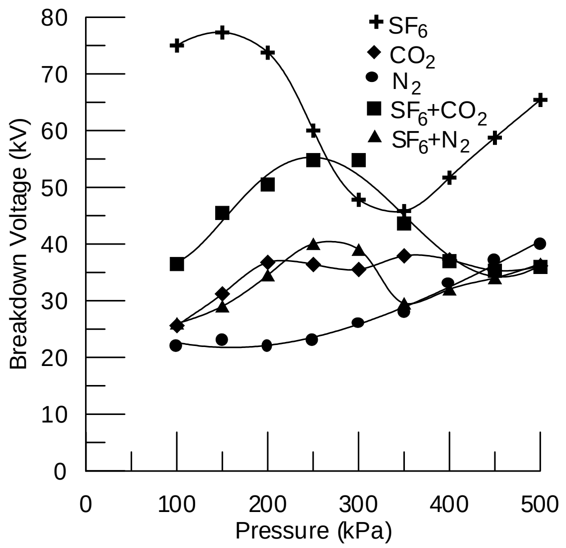

Figure 4. Variation of breakdown voltage with pressure in CO_2, N_2, SF_6, 0.125%SF_6+CO_2 and 0.125%SF_6+N_2 for 25 mm rod-plane gap spacing.

Figures 3-6 show the AC breakdown voltages as a function of gas pressure in CO_2, N_2, SF_6 and SF_6 mixtures for 5 and 25 mm gap spacing. Figures show the effect of gap length on the breakdown voltage pressure characteristics for alternating voltages. As the gap length is reduced the breakdown voltage peak is lowered and for a 5 mm gap no pronounced peak is observed. This effect was present at 25 mm gap. Under alternating voltages, the addition of few percent of SF_6 to N_2 and CO_2 causes a large increase in the breakdown of mixture voltage.

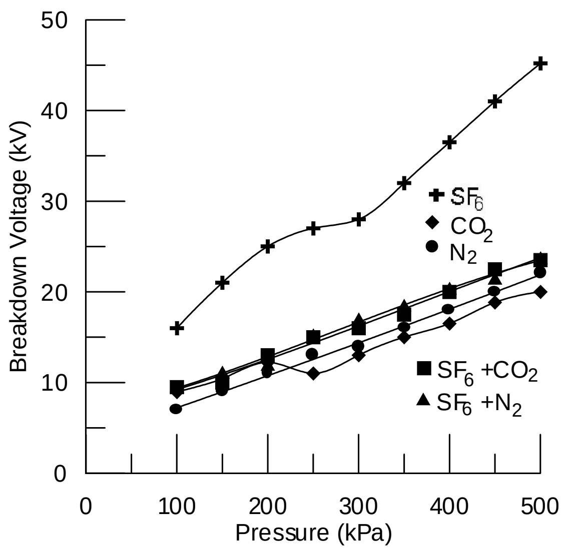

Figure 5. Variation of breakdown voltage with pressure in CO_2, N_2, SF_6, 0.125%SF_6+CO_2 and 0.125%SF_6+N_2 for 5 mm rod-plane with protrusion gap spacing.

As seen in Fig. 3 and 5 for 5 mm gap spacing the breakdown voltage of pure SF_6 is higher than that of other gases. At 5 mm gap spacing, the rod-plane with protrusion electrode system is similar to uniform field

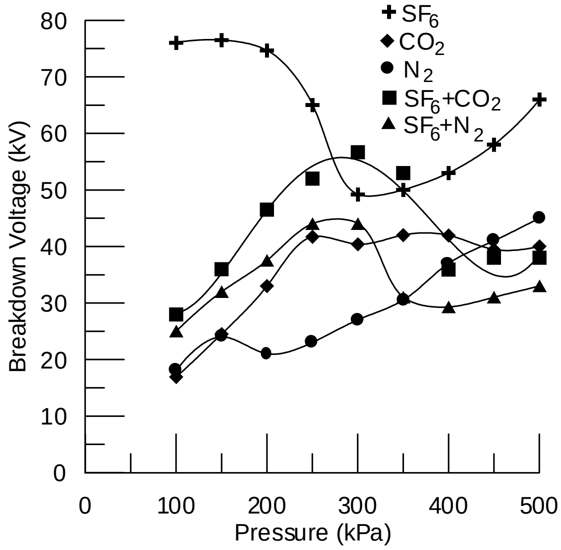

Figure 6. Variation of breakdown voltage with pressure in CO_2, N_2, SF_6, 0.125%SF_6+CO_2 and 0.125%SF_6+N_2 for 25 mm rod-plane with protrusion gap spacing.

so the breakdown voltages for rod-plane with protrusion gap spacing are higher than that of rod-plane gap spacing at all defined pressures. The breakdown voltages of rod-plane gap are higher than other electrode system up to the pressure at that the breakdown voltage is maximum. After that pressure, the breakdown voltages of rod-plane with protrusion electrode system are higher. This effect increases with pressure probably because of increasing space charge density and reduced diffusion at higher pressure. the result is that at high pressure, the breakdown streamers are more curved.

Previous investigations in SF_6 with small single electrode surface protrusions showed that at pressures up to 200-500 kPa, the breakdown strength may be influenced by generating initial electrons. At higher pressures this time lag effect decreases. From observations it has been found out that SF_6 and its mixtures, the spark channels were affected by the total gas pressure and electrode geometry. These experiments have shown that in the pressure range pressure $p< p_m$ at which the breakdown voltage is maximum, there is a uniform corona discharge at rod tip with a few millimeters length. The spark followed the shortest distance between electrodes. By increasing the pressure to p_m the streamer discharge are developed into different directions from the rod tip. This means that space charge increases the radial field strength and introduces a spark in that direction. In the region around p_m, the spark discharge does not follows the shortest path between electrodes, but advances along a curved path to the cathode and the designation curved spark [6].

Furthermore the movement of space charge due to ion drift and diffusion process will also be affected by the total pressure, field configuration and waveform of the applied voltage. As it has been seen from our experiments, for 25 mm gap spacing the breakdown voltages of rod-plane with protrusion are higher than those of other electrode system for high pressures (200-500 kPa). Because of curved path, the electrode gap spacing is higher than that of rod-plane electrode system. At above 350 kPa the breakdown voltages of mixtures drop below than those of pure N_2 and CO_2. Earlier experiments show that, at mixtures with less than 1% SF_6, similar observations have been reported for direct voltage, lightning and switching impulses Earlier authors reported that for SF_6+N_2 mixtures, the corona onset levels of SF_6+N_2 mixtures are higher than those of nitrogen but since at such high pressures the corona stabilization is more effective in nitrogen than in SF_6, the breakdown voltages of mixtures containing low SF_6 content drop below that of nitrogen [7-9]. The breakdown voltages of SF_6+CO_2 mixtures were obtained higher than those of pure SF_6 at the pressure range of 250-350 kPa for 25 mm gap spacing but the breakdown voltages of SF_6+N_2 mixtures obtained lower than those of pure SF_6 at all defined pressures.

IV. TEST RESULTS FOR AIR, SF_6 AND SF_6 + AIR MIXTURE

The breakdown voltages of SF_6, air and a mixture of 0.125%SF_6+air were measured up to a pressure of 500 kPa in rod plane gaps. All results were given in the range of 5-25 mm gap spacing separately in Fig. 7-12.

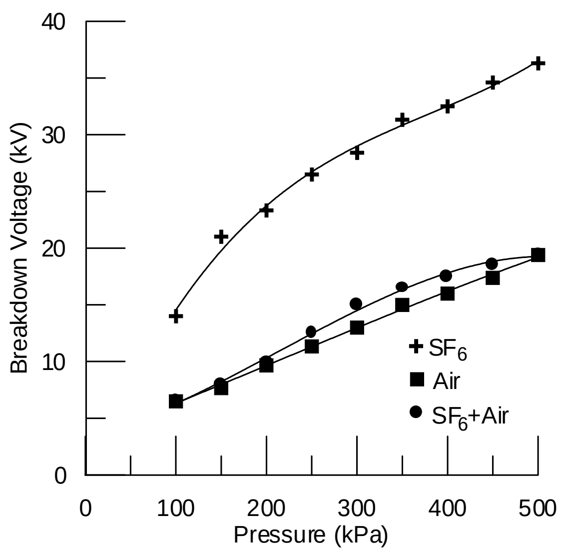

Figure 7. Variation of breakdown voltage with pressure in air, SF_6, 0.125%SF_6+air for 5 mm gap spacing.

Our results indicate that the AC breakdown voltages of 0.125%SF_6+air mixture increase linearly with pressure for 5, 10 and 15 mm gap spacing. For 20 and 25 mm gap spacing the breakdown voltage of mixture exhibit a saturation tendency above 400 kPa. At this pressure the breakdown voltage of air has same character that of mixture. As seen in figures 7-9 for 5, 10 and 15 mm gap spacing, the breakdown voltages of the mixture and air have approximately similar values.

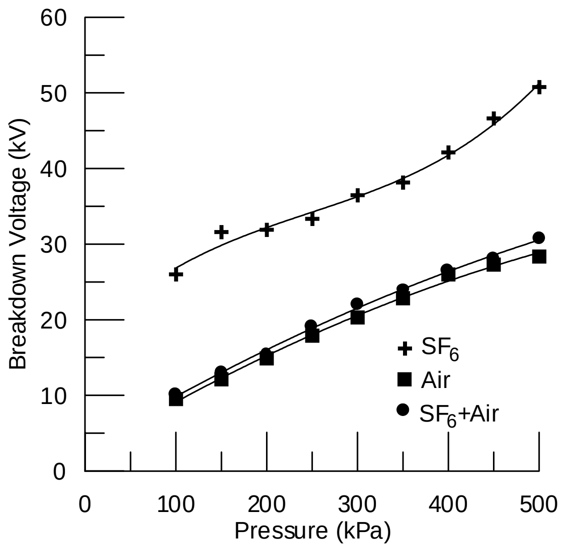

Figure 8. Variation of breakdown voltage with pressure in air, SF_6, 0.125%SF_6+air for 10 mm gap spacing.

In these gaps, breakdown voltages of mixture were less than that of pure SF_6 at defined pressure range. Whereas in 20 and 25 mm gap spacing the breakdown voltage of the mixture is higher than that of pure SF_6 at above 250 kPa. For example, in short gaps the breakdown voltage of SF_6 is about 2 times that of air and mixture at a pressure of 400 kPa, however at that pressure the breakdown voltages of mixture for 20 mm and 25 mm gap spacing were obtained 33% and 50% higher than that of pure SF_6 respectively. Even at the pressure range of 300-400 kPa the breakdown voltage of air is higher than that of pure SF_6 for 25 mm gap spacing.

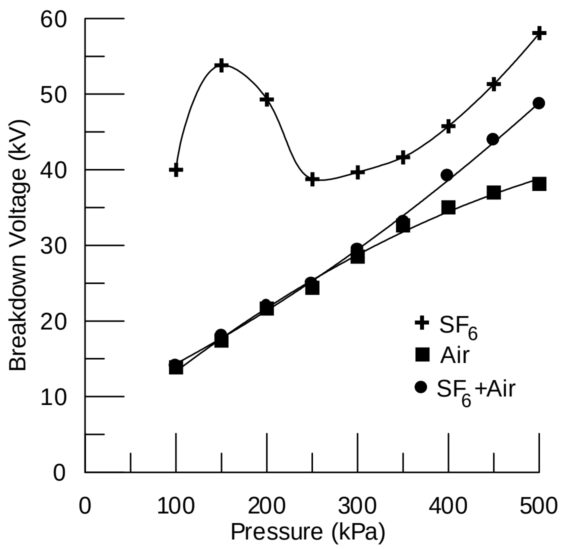

Figure 9. Variation of breakdown voltage with pressure in air, SF_6, 0.125%SF_6+air for 15 mm gap spacing.

SF_6+air mixtures show relatively less degree saturation at high pressure as compared to SF_6+N_2 and SF_6+CO_2 but at higher pressure the breakdown voltages of SF_6+air mixtures are better than that of others [10-12].

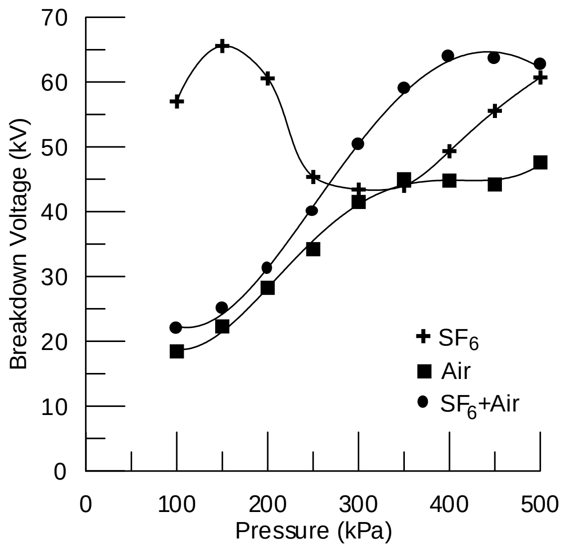

Figure 10. Variation of breakdown voltage with pressure in air, SF_6, 0.125%SF_6+air for 20 mm gap spacing.

As seen in figures 7 to 9, the pressure p_m where the peak occurs in the breakdown voltage-pressure curve is about 150 kPa for pure SF_6. However its value is in the range of 400 kPa for SF_6+air mixtures.

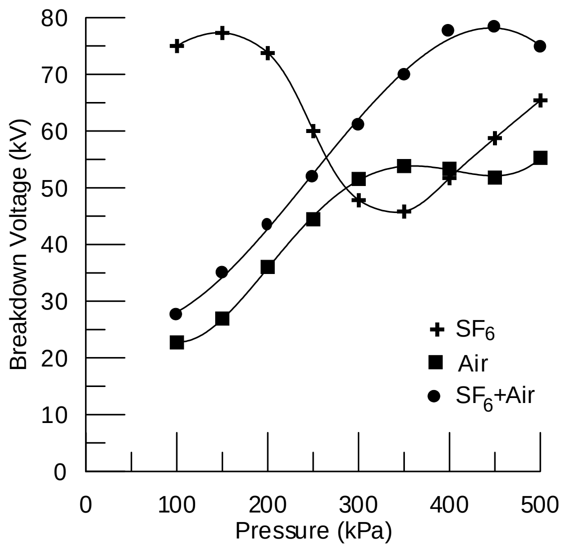

Figure 11. Variation of breakdown voltage with pressure in air, SF_6, 0.125%SF_6+air for 25 mm gap spacing.

V. CONCLUSION

The results show that in non-uniform field which is inevitable and predominant in a practical system, SF_6+N_2, SF_6+CO_2 gas mixtures are at least as good as SF_6 in terms of their AC breakdown characteristics. The experimental results show that in non-uniform field the AC breakdown strength of N_2 and CO_2 in the practical range of pressure (100 to 400 kPa) may be increased by adding a small amount of SF_6. There are indications that

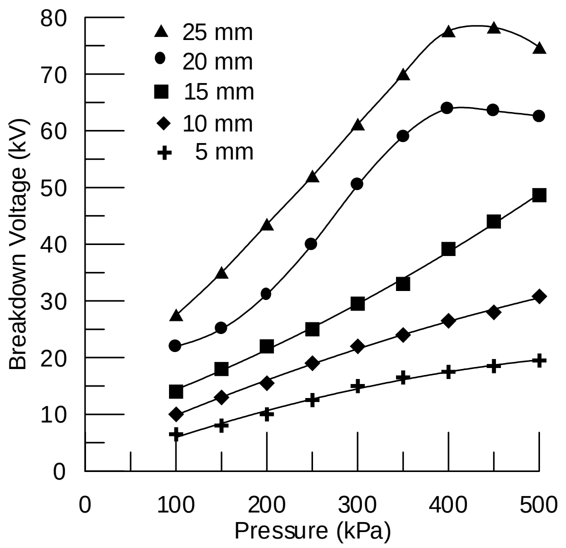

Figure 12. Variation of breakdown voltage with pressure in 0.125%SF_6+air for different gap spacing.

these mixtures are technically and economically attractive alternatives.

Mixtures of 0.125%SF_6+air appear technically very attractive since such mixtures can have dielectric strength superior to that of pure SF_6 and air especially for 20, 25 mm gap spacing above the pressure of 250 kPa. In short gaps, the breakdown voltages of pure SF_6 and air have similar values. However a complete evaluation of air due to sparking is essential before this mixture is considered for possible applications in high voltage devices. This phenomenon is probably due to the presence of oxygen in the air and leads us to think of the use of such mixtures in high voltage apparatus.

VI. REFERENCES

[1] I. D. Chalmers, X. Q. Qiu and P. Coventry, "The study of SF_6 mixtures with buffer gases", Gaseous Dielectrics VIII, New York, pp. 189-195, 1998.

[2] H. M. Ryan, W. L. Watson, S. J. Dale, D. J. Tedford and A. Kurimoto, "Factors affecting the insulation strength of SF_6 filled systems", International Conference on High Voltage Electrical Systems, Proceedings of the 26th Session (CIGRE), Vol. 1, 15.02, pp. 1-8, 1976.

[3] W. S. Zaengl and K. Petcharaks, "Application of streamer breakdown criterion for inhomogeneous fields in dry air and SF_6", The 7th International Symposium on Gaseous Dielectrics, Tennessee, pp. 153-159, 1994.

[4] A. H. Cookson and B. O. Pedersen, "Analysis of the high voltage breakdown results for mixtures of SF_6 with CO_2 and air", The 3rd International Symposium on High Voltage Engineering, Milan, Paper 31.10, 1979.

[5] N. H. Malik, A. H. Qureshi and Y. A. Safar, "DC voltage breakdown of SF_6+air and SF_6+CO_2 mixtures in rod-plane gaps", IEEE Transactions on Electrical Insulation, Vol. EI-18, No. 6, pp. 629-635, 1983.

[6] S. Sangkasaad, "Corona inception and breakdown voltages in non-uniform fields in SF_6", International High Voltage Symposium, Zurich, pp. 378-384, 1975.

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

[8] A. Yializis, N. H. Malik, A. H. Qureshi and E. Kuffel, "Impulse breakdown and corona characteristics for rod-plane gaps in mixtures of SF6 and nitrogen with less than 1% of SF_6 content", IEEE Trans. on Power Apparatus and Systems, Vol. PAS-98, No. 5, 1979.

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

[10] E. Onal, O. Kalenderli and K. Mardikyan, "Breakdown characteristics of CO_2 and N_2 containing SF_6", IEEE Budapest, PowerTech'99 Conference, Budapest, Hungary, Paper No.BPT99-441-30 in the Electronic (CD-ROM) Proceedings or Abstract Records, p. 279, 1999.

[11] E. Onal, O. Kalenderli and K. Mardikyan, "Breakdown characteristics of N_2 containing 0.125% of SF_6", The 11th International Symposium on High Voltage Engineering, Vol. 3 pp. 305-308, London, 1999.

[12] E. Onal, O. Kalenderli and K. Mardikyan, "Breakdown characteristics of CO_2 containing 0.125% of SF_6", The 11th International Symposium on High Voltage Engineering, Vol. 3 pp. 301-304, London, 1999.