Breakdown and Corona Inception Voltages in Non-Uniform Fields with Compressed SF_6, N_2 and $SF_6 + N_2$ Gas Mixtures

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ABSTRACT: In this paper, breakdown and corona inception voltages of rod-plane and sphere-plane electrode configuration in compressed SF_6, N_2 and SF_6+N_2 gas mixtures under 50 Hz, AC voltages and DC voltages with different polarities were studied. In sphere-plane electrode configuration for pressures smaller than 2.5 bar breakdown voltages for %40 SF_6 + %60 N_2 mixture are higher than those for the %80 SF_6 + %20 N_2 mixture. For positive polarity DC voltages with increasing non-uniformity of the field, breakdown voltages of different percent mixtures approximately remain constant for gas pressures greater than 2 bar. For AC voltages with decreasing non-uniformity of the field inside gaps, breakdown voltages of different percent gas mixtures approximately remain constant for gas pressures greater than 2 bar. For negative polarity DC voltages, with increasing non-uniformity of the field, for pressures greater than 2 bar, breakdown voltage of mixtures with low percent of SF_6 are higher than those for the high percent of SF_6. In general, for gas pressures between 0.5-4 bar, DC breakdown voltages for positive polarity occur at a lower voltages than those for negative polarity.

Keywords: Breakdown voltages, Corona inception voltages, Electronegative gases.

I. INTRODUCTION

Sulfur hexafluoride has good dielectric and heat transfer properties and it is extensively being used in power apparatus as a dielectric medium. Besides being expensive, it has relatively high boiling temperature. It is very sensitive to strong localized fields often encountered in practical systems due to electrode surface imperfections and the presence of free particles. Therefore in practical systems, the ideal Paschen's law breakdown strength is not achieved. Furthermore, long non-uniform field gaps insulated with compressed SF_6 show surprisingly low breakdown strength under the applications of impulse voltages [1].

Measurement of uniform, quasi-uniform and non-uniform field breakdown voltages have shown that the addition of small amounts, a few percent of SF_6 to common gases like air and nitrogen, etc., results in an appreciable increase in the breakdown strength of this gases. From the existing information, it appears that SF_6 + air mixtures shows relatively less degree of saturation as compared to SF_6 + nitrogen 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 + nitrogen mixtures.

Although the excellent insulation and arc interruption properties of SF_6 have lead to its widespread use in circuit breakers, recent studies have shown the possibility of further enhancing these properties by using SF_6 mixed with lighter gases such as N_2. Garzon [2] have studied the comparative interruption properties of $SF_6 + N_2$ mixtures. By measuring the rate of rise of recovery of voltage (RRRV) for a synchronous interrupter, Garzon has shown that the performance of $SF_6 + N_2$ mixtures having %50, SF_6 by volume at the pressures 1300 to 1900 kPa is approximately 1.39 times better than that of pure SF_6. He also found that the recovery capability of a non-synchronous breaker using this gas mixture was at least as good as when pure SF_6 was used. Other advantages such as shorter times for pneumatic operations and the use of higher total pressures without liquefaction make mixtures of SF_6 more attractive and useful for further applications in circuit breakers. Synchronous breakers using SF_6+N_2 mixtures are already in operation.

Recent studies of $SF_6 + N_2$ mixtures have revealed that such mixtures are less sensitive to the presence of contamination and electrode surface roughness as compared to pure SF_6 [3], [4]. Furthermore, $SF_6 + N_2$ mixtures have the advantages of lower boiling points and are less expensive. The lower boiling point of the mixtures is rather important in colder climates.

The widespread use of SF_6 by the electric power and other industries has led to increased concentration of SF_6 in the atmosphere. This causes concern as to possible effect on global warming, because SF_6 is a potent greenhouse gas.

Among the gas mixtures that have been seriously considered as a possible short – term substitute for pure SF_6 is the mixtures of SF_6 with N_2 [5]. Even with very low SF_6 content, this mixtures exhibits many of the desirable properties of SF_6 as a gaseous dielectric. In many respects, it constitutes an ideal synergistic combination in which the buffer gas (N_2)

scatters 'energetic' electrons into the low -energy region where the electronegative gas (SF_6) captures them with highest efficiency and thereby inhibits the buildup of electrons that could produce ionization leading to electrical breakdown [6] - [8].

According to above facts, the main objective of the present paper is to investigate the effect of polarity, field non-uniformity, on breakdown and corona inception voltages of compressed SF_6, N_2 and SF_6+N_2 gas mixtures.

II. EXPERIMENTAL ARRANGEMENTS AND PROCEDURES

Experiments are carried out with 50 Hz AC and DC voltages up to the peak value of 280 kV in both polarities, using rod-plane, sphere-plane electrode systems. To obtain various degrees of non-uniformity, radius of 1 mm rod electrode and radius of 2 mm sphere electrode are mounted on the plane electrode for each configuration. The electrodes are mounted in a pressure vessel. All electrodes are made of brass covered with chromium. The lower electrode in both arrangements is a plane electrode with an overall diameter of 75 mm and its edges are rounded with a radius of curvature of 3 mm. A 20 mm gap was used for all these measurements. The gases used were of commercial purity and were always filtered and dried prior to their admission in to the pressure vessel. No external irradiation was used in any of these measurements.

Several measurements of the breakdown and corona inception voltages were made at each pressure, and for each case the lowest recorded value was used for the plots given in this paper. The lowest rather than the average breakdown value was used because it provides a better indication of the withstand level and is therefore of considerable interest from a practical point of view [9]. Before starting any experiments, electrodes are treated with a metal polish and clean washed carefully with ethyl alcohol.

III. RESULTS AND DISCUSSION

(a) Positive Rod-Plane and Sphere-Plane Gaps

In positive rod-plane and sphere-plane gaps under direct applied voltages, breakdown of SF_6 and SF_6 + N_2 gas mixtures is characterized by the existence of a pressure region where breakdown occurs in the presence of sustained corona discharges and the breakdown voltage is higher than the corona threshold. In this pressure region, breakdown is said to be "corona stabilized" since it is believed that the space charge produced by corona discharges stabilizes the field at and near the rod or sphere tip and thus enhances the threshold voltage level for complete breakdown of the gap [9]. However, above a certain pressure known as the "critical pressure", stable corona cannot occur and the discharge onset leads to a direct breakdown.

The results of the present measurements indicate that SF_6 + N_2 gas mixtures exhibit a general breakdown behavior which is similar to that for SF_6. The major difference is the extent of corona stabilization in the mixtures compared to case of SF_6. Fig. 1 and 2 show the breakdown and corona inception voltages for SF_6, N_2 and SF_6 + N_2 gas mixtures for rod-plane and sphere-plane gaps with a 2 mm diameter rod and 4 mm diameter sphere as the anode. In these and the subsequent figures, the breakdown voltages are shown by solid curves while the corona onset voltages are represented by broken curves.

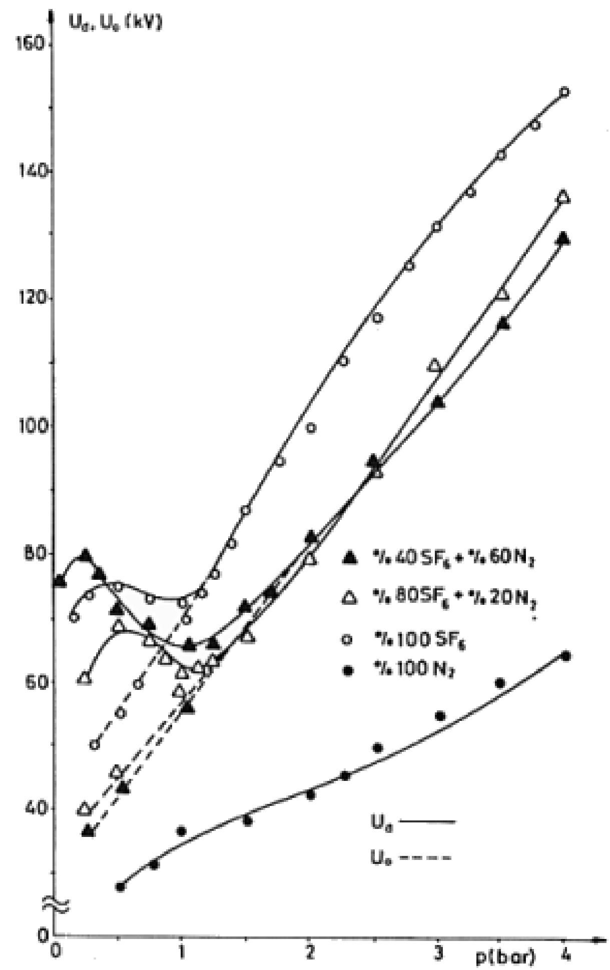

Figure 1. Positive polarity breakdown and corona inception voltages (sphere-plane gap)

The results of figs. 1 and 2 also show that the critical pressure p_{cr} at which transition from corona stabilized to a direct breakdown is completed is also affected by the SF_6 content of the mixture. All of the SF_6 + N_2 gas mixtures had slightly higher value of the critical pressure than pure SF_6. Fig. 3 shows the change of critical pressure with respect to SF_6 content of the mixtures in rod-plane electrode configuration. In corona stabilized region, breakdown voltages are higher than corona inceptions. In this region, breakdown voltage-pressure curves have maximum and minimum values. Also in corona stabilized region, for pressures below 1 bar, with increasing non-uniformity of the field, breakdown voltages of all gases are increased.

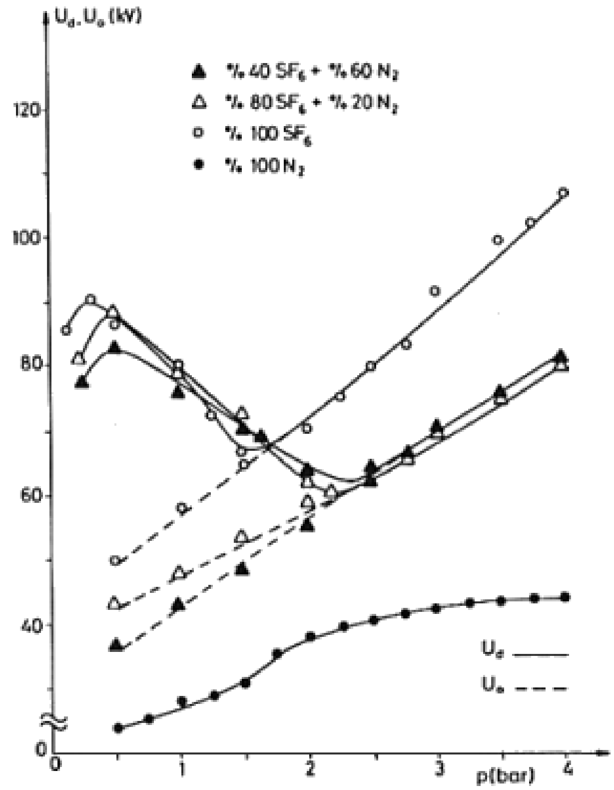

Figure 2. Positive polarity breakdown and corona inception voltages (rod-plane gap)

In all figures, U_d shows breakdown voltages and also U_o shows corona inception voltages of SF_6 and SF_6 + N_2 gas mixtures.

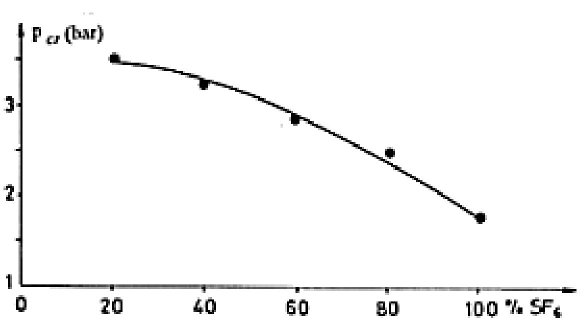

Figure 3. Critical pressure with respect to SF_6 content (rod-plane gap)

In general, for all gas pressures above critical values, breakdown and corona inception voltages are equal. The results further show that, p_{cr} in SF_6 + N_2 gas mixtures are higher than pure SF_6, for example in rod-plane gap, p_{cr} = 1.75 bar for pure SF_6 and p_{cr} = 2.50 bar for %80 SF_6 + %20 N_2. Also with increasing field non-uniformity, values of critical pressure for all gases are increased.

Figs. 1 to 2 also show that corona inception voltages generally increase with an increase in the electronegativity (or SF_6 percentage). This is due to the fact that the net ionization coefficient α decreases with an increase in the SF_6 percentage thereby increasing the inherent dielectric strength of these mixtures. The corona inception voltages shown in Figs. 1 and 2 increase with pressure due to an increase in the gas number density. The most interesting feature of these inception curves is the fact that inception voltages for SF_6 and SF_6 + N_2 gas mixtures generally increase linearly with pressure over a wider pressure range. The results for negative polarity and 50 Hz AC voltages, to be discussed later also show a similar tendency. In positive rod-plane and sphere-plane gaps, with increasing non-uniformity of the field, breakdown voltages of %40 SF_6 + %60 N_2 and %80 SF_6 + %20 N_2 close up to each other.

(b) Negative Rod-Plane and Sphere-Plane Gaps

The previous results indicate that the corona stabilization processes are more effective when the road is cathode rather than when it is anode [10]. Generally the breakdown and corona inception voltage-pressure curves for both polarities show similar features. Fig. 4 shows negative polarity breakdown and corona inception voltages for rod-plane electrode configuration.

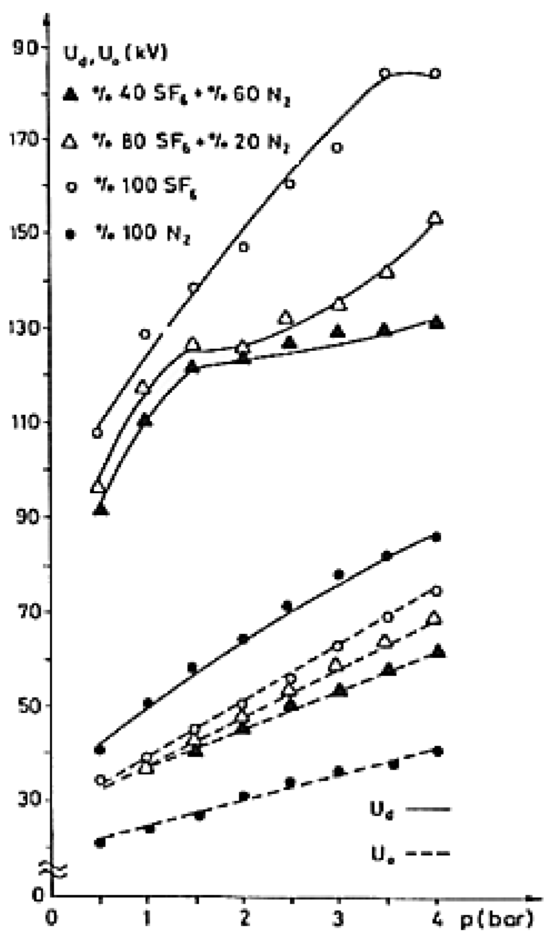

Figure 4. Negative polarity breakdown and corona inception voltages (rod-plane gap)

The values of critical pressures are higher for the negative rod than for the positive rod under dc and impulse voltages [10] - [13]. Malik, has been reported that, for a rod cathode of 1.59 mm in diameter, critical pressure in SF_6 is in excess of 5 bar [9]. Fig. 4 shows that, also For a rod cathode of 2 mm in diameter, critical pressures in SF_6 and $SF_6 + N_2$ gas mixtures excess of 5 bar. Thus in the present study, breakdown in SF_6 and its mixtures with nitrogen is corona stabilized over the entire pressure range of 0.5 to 5 bar as shown in Fig. 4. Generally the breakdown voltages increase linearly for low pressures and tend to saturate at higher pressures. This tendency was least evident in sphere-plane electrode configuration as shown in Fig. 5. Figs. 4 and 5 also show that at high pressures, SF_6 had breakdown voltages than the corresponding values for $SF_6 + N_2$ gas mixtures. Similar results was obtained by Malik, for SF_6 + air gas mixtures also [9].

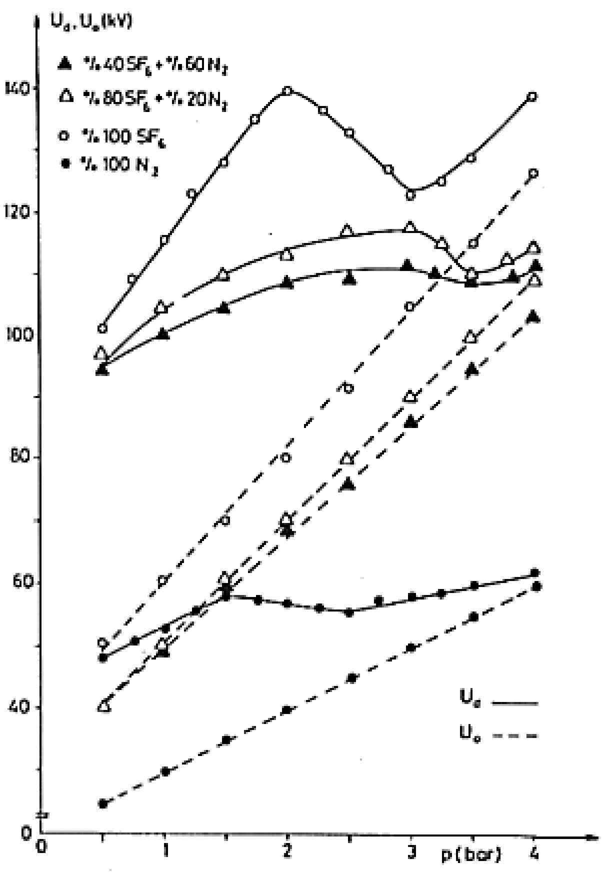

Figure 5. Negative polarity breakdown and corona inception voltages (sphere-plane gap)

At higher pressures, negative breakdown voltages are significantly higher than the positive ones as is clear from Figs. 1 to 5.

Similar to the case of positive polarity, the corona inception voltages for rod-plane and sphere-plane gaps increase with SF_6 percentage and the number density of the mixtures. However, the inception voltages for negative polarity are significantly lower than the corresponding values for positive polarity. This type of behavior is well documented in the literature [14], [15]. The reason for this difference of inception voltages under positive and negative polarity are related to the different mechanisms of corona inception and statistical time lag effects, as discussed in detail by Van Brunt and Misakian [14].

The results of Figs. 1 and 3 show that for rod-plane gap, critical pressures for mixtures is higher than that for SF_6. However since for negative gaps breakdown is corona stabilized for $p > 4$ bar, the influence of mixture ratio on critical pressure is not known. Some measurement using larger diameter cathodes indicate that, similar to the positive gaps, p_{cr} for $SF_6 + N_2$ gas mixtures is higher than p_{cr} in SF_6 [9].

(c) 50 Hz AC Voltages

Under 50 Hz ac, breakdown voltage-pressure and corona inception voltage-pressure curves for rod-plane and sphere-plane electrode configuration with compressed SF_6 and $SF_6 + N_2$ gas mixtures has been obtained.

Under 50 Hz ac voltages, corona pulses appeared at first on the negative half-cycle, perhaps conforming an earlier observation under dc voltages. When we increase ac voltages more than previous values corona pulses appeared over the positive half-cycle. At the end with increasing ac voltages further, corona pulses split in to two population on both sides of the peak of ac wave.

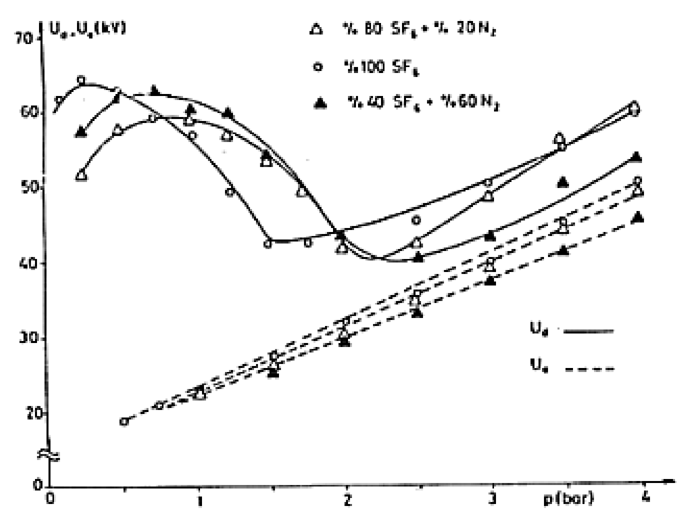

Figure 6. 50 Hz ac breakdown and corona inception voltages (rod-plane gap)

Figs. 6 and 7 show that in 50 Hz ac voltage, with decreasing non-uniformity of the field, in corona stabilization region, the difference between breakdown and corona inception voltages of SF_6 and $SF_6 + N_2$ gas mixtures has been reduced. Also in ac voltages between 0.5 and 4 bar gas pressures, with increasing voltages, corona inception voltages approximately increase linearly. The results further show that, corona stabilization region for rod-plane and sphere-plane gaps are greater than 4 bar (p_{cr} > 4 bar).

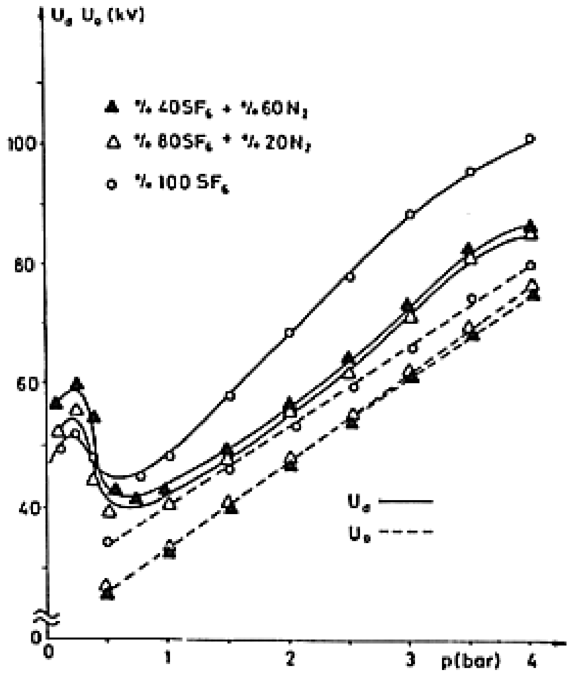

Figure 7. 50 Hz ac breakdown and corona inception voltages (sphere-plane gap)

In 50 Hz ac voltages, with increasing non-uniformity of the field and also with decreasing SF_6 percentage of the mixtures, minimum pressure are increased. For example in rod-plane gap, p_{min} = 1.5 bar for pure SF_6, and p_{min} = 2.25 bar for %80SF_6+%20N_2 gas mixture. In Figs. 7 and 6 p_{min} is the pressure that is obtained in minimum breakdown voltages. In decreasing region of the breakdown voltage-pressure curves, with decreasing non-uniformity of the field, the slope of the curves has been increased.

The results of Fig. 6 for 50 Hz ac voltage rod-plane gaps clearly show that over the pressure range of 3 to 4 bar, breakdown voltages of SF_6 and SF_6 + N_2 gas mixtures are approximately equal.

IV. CONCLUSION

Corona stabilized breakdown gradients are reported for SF_6, N_2 and SF_6 + N_2 gas mixtures using rod-plane and sphere-plane gaps under 50 Hz ac voltages and dc voltages with positive and negative polarities. In general, with increasing non-uniformity of the field inside gaps, the critical pressure is higher for the mixtures than for SF_6. In 50 Hz ac voltages, with decreasing non-uniformity of the field inside gaps, breakdown voltages of different percentage gas mixtures approximately remain constant for gas pressures greater than 2 bar. Under positive dc voltages are not observed corona inception for pure N_2 gas, but in negative rod-plane and sphere-plane gaps we also obtained corona inception voltages for pure N_2 gas. In positive polarity dc voltages with increasing non-uniformity of the field, breakdown voltages of different percentage gas mixtures, approximately remain constant for gas pressures greater than 2 bar. In general, with compressed SF_6, N_2 and SF_6 + N_2 gas mixtures, over the pressure range of 0.5 to 4 bar, dc breakdown voltages for positive polarity are obtained at lower voltages than those for negative polarity.

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