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in the insulation breakdown strength is in the range of quantities normally considered *contamination*. In this sense, a double contamination effect is said to develop, i.e., contamination by particles and by 2% of a gas, SF_6. In uniform field conditions, the addition of 2% SF_6 to N_2 raises the breakdown strength slightly [24].

4. Conclusions

Strongly attaching gases have the disadvantages of high cost and low liquefying pressures. If a small quantity of electronegative gas is added to a gas such as nitrogen or air, there results a very large increase in dielectric strength. SF_6 and its mixtures with other less expensive gases such as air, N_2, and CO_2 have been investigated aiming at developing an insulating medium which is technically and economically attractive. Such mixtures with 40% to 50% of SF_6 content exhibit 80% to 90% of the insulation strength available from SF_6 alone. These mixtures offer a cost advantage and can be used at lower ambient temperatures than pure SF_6.

From the technical point of view, the use of SF_6/N_2 mixtures as possible replacements for SF_6 appears to be most promising and feasible for conditions where the gas is used primarily as an insulating medium. In general, the SF_6/N_2 mixture has many of the properties that make SF_6 a desirable dielectric, e.g., it is nontoxic, it is thermally and chemically stable, and it has relatively good heat transfer characteristics. The acceptability of using SF_6/N_2 mixtures in practical insulation will be influenced by the additional costs associated with preparation, maintenance, recycling, and disposal of mixtures [11].

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A number of mixtures of gases are of interest as their behavior, in the presence of metallic particles, assists in understanding various particle phenomena and because some mixtures show promise of being less susceptible to breakdown initiated by particles than does SF_6 alone [1, 3, 12, 24]. SF_6 with helium and SF_6 with air in particular have strengths in the presence of particle contamination which are greater than those for either gas alone at the same gas pressure. Mixtures of SF_6 and air show a similar behavior to SF_6 and helium mixtures (with contaminating particle of 6.4 mm long x 0.45 mm diameter in a uniform field gap with spacing 76 mm) in that the breakdown strength for a given mixture exhibits a maximum as the pressure is increased [24]. The maximum breakdown voltage observed for mixtures is also greater than for either of the component gas alone at the same pressure. The maximum breakdown strength is observed with a similar partial pressure of SF_6 in the two mixtures.

Mixtures of SF_6 and N_2 in the presence of 6.4 mm long wire particles behaved in a similar way to SF_6/CO_2 mixtures in that none of the mixtures tested showed a breakdown strength higher than that for each gas alone at any pressure in the range explored [23, 24]. In addition, some mixtures (e.g., 2% SF_6 + 98% N_2) exhibited a breakdown voltage at high pressure as much as 40% less than that for N_2 alone, Fig. 2. This result may be very important and is particularly useful to counteract the tendency to believe that adding a little SF_6 cannot do any harm. The small amount of SF_6 (2%) which has to be added to N_2 to produce a 40% reduction

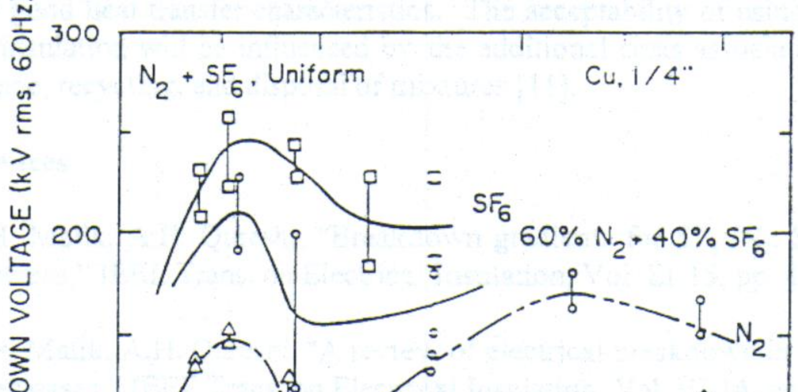

Fig. 2 Breakdown voltage in N_2/SF_6 mixtures with 6.4 mm long x 0.45 mm diameter copper particles in 76 mm parallel-plane gap [24].

than those observed for pure SF_6. At high pressures, mixtures with 10% to 20% SF_6 showed the highest impulse breakdown voltages. Furthermore, among the three types of mixtures investigated, SF_6/CO_2 mixtures have the highest breakdown voltages for negative rod-plane gaps [12]. A comparison of the results for negative rod-plane gaps with those of positive rod-plane gaps indicate that for all these gases and gas-mixtures, negative impulse breakdown voltages are substantially higher than the positive ones and therefore are less significant from a practical viewpoint.

In positive rod-plane gaps under direct applied voltages, breakdown of SF_6 and SF_6/N_2 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 discharge stabilizes the field at and near the rod tip and thus enhances the threshold voltage level for complete breakdown of the gap. However, above a certain pressure known as the *critical pressure*, stable corona cannot occur and the discharge onset leads to a *direct* breakdown. Several authors have examined such breakdown characteristics for SF_6 and its mixtures with other gases under various types of applied voltages [1-12].

3. Gas-mixtures with conducting particle contamination

Many experimental results have been published involving particle contamination in uniform and coaxial fields. The particles studied in the published reports are of many different shapes and sizes such as spheres, filamentary (wire-shaped), and fine dust. It has been found that insulating particles have little effect on the insulation behavior of gases [13-17]. The withstand voltage of SF_6 may be drastically reduced due to the presence of conducting particles in a gas insulated gap [18-20]. The effect of metallic particles on the SF_6 breakdown voltage is more pronounced at high gas pressures. The loss of dielectric strength of SF_6 in the presence of 6.4 mm long x 0.45 mm diameter wire-shaped free conducting particles in a coaxial system subject to direct voltages is more than 80% compared with clean gap of the same conditions under gas pressures of more than 0.5 MPa [21]. So, it may be seen that practically no gain exists in the gas insulation at pressures above 0.5 MPa.

Several attempts have been made to determine the role of conducting particles in the breakdown process of compressed gas insulation. Cookson et al [22] found that elongated particles greatly reduce the SF_6 breakdown voltage and corona onset levels. In general, the gas breakdown voltage decreases with the wire particle length, while the breakdown voltage is not necessarily reduced by decreasing the wire diameter. Under the influence of the applied voltage, free conducting particles become charged and oscillate in the inter-electrode gap. The particle motion largely depends upon the type of applied voltage. Under AC voltages, for a wire particle of given radius, the activity increases with particle length since the particle charge-to-mass ratio at lifting increases with length. This ratio decreases with the spherical particle radius where the particle movement is reduced in this case [23].

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Effect of gas mixtures on breakdown characteristics of gas insulated systems

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1. Introduction

As practical insulation, strongly attaching gases have the disadvantages of high cost and low liquefying pressures. If a small quantity of electronegative gas is added to a gas such as nitrogen (N_2) or air, there results a very large increase in the dielectric strength and as a result, considerable advantages can be gained from the use of such mixtures.

Sulphur-hexafluoride (SF_6) gas and its mixtures with other less expensive gases such as air, N_2, and carbon dioxide (CO_2) have been investigated in recent years [1-9]. There are two basic reasons for carrying out such investigations. Firstly, the aims are to develop an insulating medium which is technically and economically attractive. The other reason is to obtain a better understanding of the breakdown mechanisms operating in SF_6 and other compressed gases and their mixtures.

SF_6 mixtures with air, N_2, and CO_2 have been investigated for applications in high-voltage equipment as insulating, arc quenching and cooling media. Uniform and quasi-uniform field breakdown characteristics of SF_6/N_2, SF_6/air and SF_6/CO_2 mixtures are nearly similar [1, 3]. Such mixtures with 40% to 50% of SF_6 content exhibit 80% to 90% of the insulation strength available from SF_6 alone [9]. However, these mixtures are somewhat less sensitive to the electrode surface defects and the presence of conducting particles [5, 9]. Mixtures of SF_6 with these gases may offer a cost advantage and can be used at lower ambient temperatures than pure SF_6. Therefore, they have been considered for possible applications in compressed gas-insulated transmission (CGIT) systems.

2. Breakdown of gas mixtures

The breakdown and prebreakdown characteristics of SF_6/N_2 mixtures in non-uniform field gaps under applications of direct and impulse voltages have been the subject of several studies [1, 3-5, 7, 10, 11]. The impulse breakdown and corona characteristics of SF_6/air and SF_6/CO_2 mixtures have also been investigated [1-3, 7, 12]. Malik et al [9] investigated the nonuniform field breakdown characteristics of SF_6/air and SF_6/CO_2 mixtures under direct applied voltages for positive and negative rod-plane gaps. The results for SF_6/CO_2 and SF_6/air mixtures are compared with those for SF_6/N_2 mixtures obtained under similar experimental conditions. At low gas pressures, the corona stabilization breakdown voltages are in reasonable agreement with the reported experimental measurements [9]. However, as the gas pressure is increased, the nonuniform field breakdown voltage no longer increases linearly with pressure and the discrepancy between the measured and the calculated values increases.

Figure 1 shows the 50% impulse breakdown voltage-mixture ratio characteristics for a negative rod-plane gap filled with SF_6/N_2 mixtures having SF_6 content up to 100%. Breakdown voltage levels for pure N_2 are included in the figure for comparison. However, actual data points for mixtures with 1% SF_6 are excluded for clarity. These results are for a 50 mm gap. As seen in Fig. 1, at atmospheric and subatmospheric pressure, the breakdown voltage of N_2 is the lowest while that of SF_6 is the highest. In between these limits, the breakdown voltages of mixtures increase with increasing SF_6 content in a manner similar to that reported earlier [4]. The breakdown voltage characteristics for SF_6/CO_2 gas mixtures are significantly different from those for SF_6/N_2 and SF_6/air mixtures. Most of the SF_6/CO_2 mixtures investigated exhibit breakdown voltages which were similar to or even slightly higher

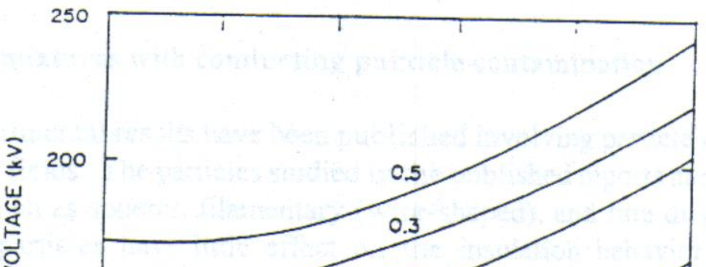

Fig. 1 Negative impulse breakdown voltage – mixture ratio relationship for a 50 mm rod-plane gap filled with SF_6/N_2 mixtures. Rod diameter = 1.59 mm [12]