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"ELECTRODE SURFACE ROUGHNESS EFFECT ON THE BREAKDOWN CHARACTERISTICS OF COMPRESSED GAS CABLE"

By

M.B. Eteiba,
Faculty of Engineering,
Qatar University, Doha,
Qatar, Arabian Gulf.

ABSTRACT

The influence of electrode surface roughness on the breakdown field strength in SF_6 gas and mixtures is investigated. A coaxial electrode configuration is used to represent a practical gas insulated cable.

With the use of an approximate formula for the effective ionization coefficient and the streamer discharge criterion, it is possible to calculate the breakdown field strength both in SF_6 and in mixtures. The factors influencing the deterioration of the dielectric strength of SF_6 gas and mixtures with air, CO_2 and N_2 are discussed. A comparison between results obtained for SF_6 gas is presented. The results confirm that increased electrode surface roughness leads to reduced breakdown voltages of compressed gas insulated systems.

1. INTRODUCTION

Sulphur hexaflouride gas (SF_6) is commonly used as an insulating medium for gas-insulated cables and compact substation components because of its high dielectric strength and good heat transfer properties (1). For these high voltage equipments, knowledge of the breakdown voltage is of central importance.

In the determination of the breakdown voltage of SF_6, it has been observed that the correlation between measured results and theoretically calculated values is sufficiently accurate only at low gas pressures and with very smooth electrode surface (2). If these conditions are not satisfied, the breakdown voltage no longer attains the expected theoretically determined value. This deviation depends mainly upon gas pressure and the condition of the electrode surface. The roughness of the electrode surface leads to the existence of microscopic field regions with field strengths larger than the microscopic average field in the gas region near the electrode surface. Depending on the gas pressure, such a region of enhanced field strength can result in a large reduction of the dielectric strength and the immediate failure of the high voltage equipment.

The present study is an attempt to present a mathematical model that enables the calculation of the influence of electrode surface roughness on discharge thresholds in SF_6 and in mixtures with air, CO_2 and N_2 at different pressures in a coaxial cable system.

2. BREAKDOWN CRITERION IN GASEOUS DIELECTRICS

Electric discharge in a gas starts by an electron avalanche. This electron multiplication process by collision takes place in the region where the first ionization coefficient exceeds the attachment coefficient . The average total number of electrons in the avalanche N is given for a coaxial electrode configuration by the relation 3 .

$$\int_{r_i}^{r_c} [\alpha(r)-\eta(r)]\,dr = \int_{r_i}^{r_c} \bar{\alpha}(r)\,dr = 1n\ N \qquad (1)$$

Here, r_i is the radius of the high voltage electrode and r_c corresponds to a critical point in the gap where the effective coefficient equals zero, $\alpha(r) - \eta(r)$ is the effective coefficient of ionization. There is some controversy over the value of 1n N, the discharge constant. This may vary between gases; a value of 10.5 is the most frequently used for SF_6, but values up to 20 are also used for both SF_6 and other gas in some analyses.

For gas mixtures, the streamer equation, Equation (1), can also be used for SF_6-gas mixtures, if the effective ionization coefficient $\bar{\alpha}$ m is known for the mixture.

Equation (1), therefore reads:

$$\int_{r_i}^{r_c} \bar{\alpha}_m dr = \ln N \qquad (2)$$

3. DISCHARGE PARAMETERS IN SF_6 AND MIXTURES

In the previous section, it has been shown that the quantity of great influence upon the breakdown field strength is the effective ionization coefficient. In pure SF_6, this coefficient has been measured over a wide range of values of E/P, the ratio of field strength to pressure, and can be expressed as (3).

$$\bar{\alpha}/P = K\,[\,(E/P) - (E/P)_c\,] \qquad (3)$$

with

$$K = 27 \quad (KV)^{-1}$$
$$(E/P)_c = 88.4 \quad KV/cm\ bar$$
$$60 \leqslant (E/P) \leqslant 150 \quad KV/cm\ bar$$

The measurements of the effective ionization coefficient $\bar{\alpha}$ for pure CO_2, N_2 and Air gases reported in the literature (4-6) have been fitted to the following formula:

$$\bar{\alpha}/P = A\,EXP\,[-B/(E/P)\,] \qquad (4)$$

For pure CO_2,
A = 3375 1/cm bar, B = 137 kV/cm bar $30 \leqslant (E/P) \leqslant 120$ kV/cm bar
For pure N_2,
A = 6600 1/cm bar, B = 215 kV/cm bar $30 \leqslant (E/P) \leqslant 200$ kV/cm bar
For air,
A = 7148 1/cm bar, B = 196 kV/cm bar $30 \leqslant (E/P) \leqslant 100$ kV/cm bar

For SF_6-gas mixture, however, the effective ionization coefficient can be estimated from the pure gas coefficients. Provided that there are no gas interaction effects, it has been shown that, for a mixture of SF_6 at partial pressure P_1 with a non-attaching gas at partial pressure P_2, the effective ionization coefficient for the mixture can be given by (7):

$$(\bar{\alpha}_m/P) = [\,(\bar{\alpha}/P)_1 + K_1\,(\bar{\alpha}/P)_2]/\,(1+K_1) \qquad (5)$$

where $K_1 = P_2/P_1$ and $P = P_1 + P_2 =$ total pressure

$(\bar{\alpha}/P)_1 = F_1\,(E/P)$ and $(\bar{\alpha}/P)_2 = F_2\,(E/P)$

are the pure gas values for component gases as given in Equations (3) & (4).

The relation between $(\bar{\alpha}_m/P)$ and (E/P) in the neighbourhood of $(E/P)_c$ for SF_6-gas mixtures is expected to be straight lines for higher values of SF_6 in the mixture. For smaller values of SF_6 a slight deviation will be expected. However, this effect can be ignored and the effective ionization coefficient of SF_6-gas mixture can be expressed as:

$$(\bar{\alpha}_m/P) = K_m\,[\,(E/P) - (E/P)_{cm}] \tag{6}$$

where the values of K_m and $(E/P)_{cm}$ will depend upon the concentration of SF_6 in the mixtures. Figures 1 through 3 illustrate the variation of the calculated effective ionization coefficient as a function of (E/P) for SF_6-CO_2, SF_6-N_2 and SF_6-Air mixtures respectively. It should be noted that the calculated values shown are in fair agreement with the measured values, recently reported for SF_6-CO_2 (8), SF_6-N_2 (9) and SF_6-Air (10) mixtures.

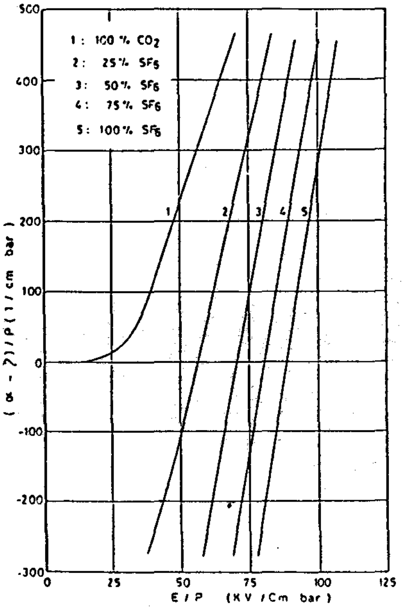

Figure (1)

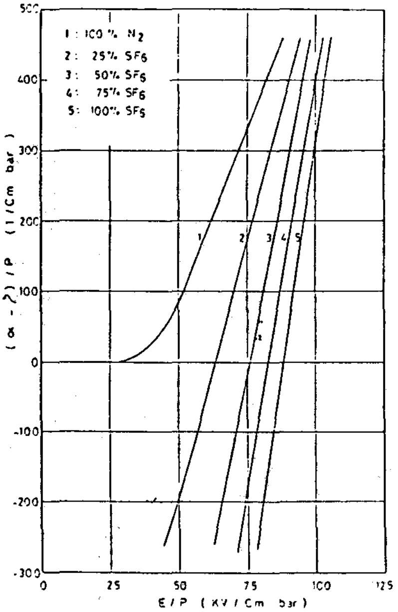

Figure (2)

Fig. 1: Effective ionization coefficient for SF_6- CO_2 mixtures.

Fig. 2: Effective ionization coefficient for SF_6- N_2 mixtures.

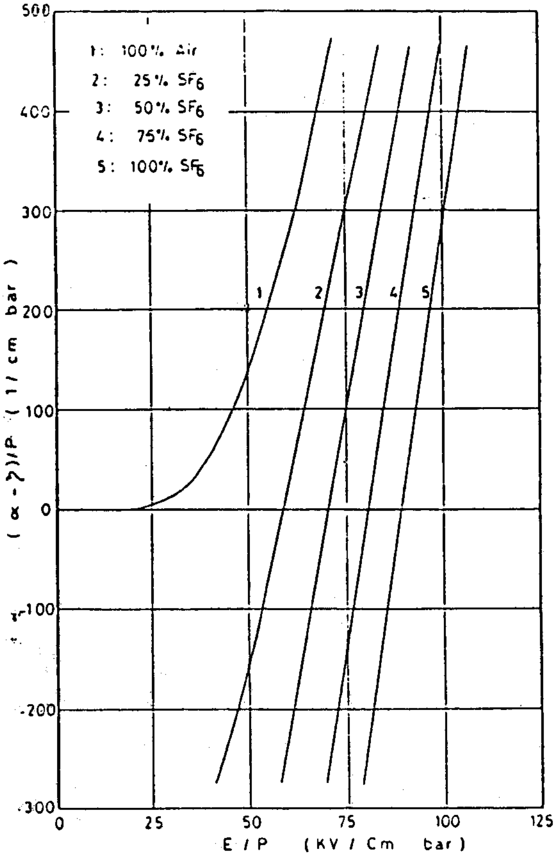

Fig. 3: Effective ionization coefficient for SF_6– Air mixtures.

4. MATHEMATICAL MODEL SIMULATING THE EFFECT OF ELECTRODE SURFACE ROUGHNESS

It has been shown by Baumgartner (11) that it is useful to represent the localized field enhancement due to naturally formed surface roughness in terms of that created by a single idealized protrusion in the form of a prolate semi-elliposid mounted on a perfectly smooth conductor. The influence of electrode protrusion on dielectric strength may be represented by a roughness factor ξ $(0 \leq \xi \leq 1)$ which is a function of PR, where P is the gas pressure and R is the protrusion tip radius. With coaxial cylinders having a semi-ellipsoidal protrusion of tip radius R, the field along the line of force from the apex of the semi-ellipsoid will be (12):

$$E(z) = E_a \left\{ 1 + \frac{1}{(1/2)\ln[(Y+1)/(Y-1)] - (1/Y)} \times [[1/(z/c) - (c/z)] - (1/2)\ln[(z/c+1)/(z/c-1)]] \right\} \tag{7}$$

Where E_a is the macroscopic field at the high voltage electrode surface and $Y = a/c$ while $c = (a^2-b^2)^{1/2}$
where a is the protrusion height or the larger semiaxis, b is the small semiaxias.

An electron avalanche developing along this line of force may lead to breakdown. The streamer criterion may be expressed as

$$\int_{a}^{a+z_o} \overline{\alpha}_m dz = \ln N \tag{8}$$

Where z_o is the critical avalanche length. At $z = a + z_o$, $\bar{\alpha} m = 0$ and $E(z)/P = (E/P)_{cm}$. In electronegative gases, the value of z_o is found to be very small. Therefore, it can be assumed that the macroscopic field remains constant for $a \leqslant z \leqslant a + z_o$. Thus the value of E/P at breakdown is approximately given by (13):

$$E/p = \zeta (E/P)_{cm} \tag{9}$$

Substituting Equations (6) and (7) in Equation (8) and performing the integral yields:

$$K_m \Big\{ z_o (E_a - P\grave{E}_{cm}) + (E_a/2G) \Big[c \ln\frac{(a+z_o)^2 - c^2}{a^2 - c^2} + (a-c)\ln\frac{a+z_o-c}{a-c} + (a+c)\ln\frac{a+c}{a+z_o+c} + z_o \ln\frac{a+z_o-c}{a+z_o+c} \Big] \Big\} = \ln N \tag{10}$$

$$\text{where}: G = \frac{1}{2}\ln\frac{a+C}{a-c} - \frac{c}{a}$$

$$E'_{cm} = (E/P)_{cm}$$

At a distance z_o from the protrusion tip, the net ionization is equal to zero, therefore, the following expression may be obtained:

$$E_a \left\{ 1 + \frac{c(a+z_o)}{G[(a+z_o)^2 - c^2]} - \frac{1}{2G}\ln\frac{a+z_o+c}{a+z_o-c} \right\} - P\grave{E}_{cm} = 0 \tag{11}$$

The system of Equations (10) and (11) can be solved by an iterative technique on a computer to determine z_o and E_a.

If a = b = R, the semi-ellipsoid degenerates into a hemisphere and the field distribution will be

$$E(z) = E_a[1 + 2(R/z)^3] \tag{12}$$

The critical avalanche length z_o can be calculated from Equations (9) and (12)

$$z_o = R\left[\frac{1}{\left[\frac{1}{2}\left(\frac{1}{\xi} - 1\right)\right]^{1/3}} - 1\right] \tag{13}$$

It is of interest to note that, according to Equations (10), (11) and (13), the critical avalanche length is a function of the protrusion radius and gas pressure as well as the

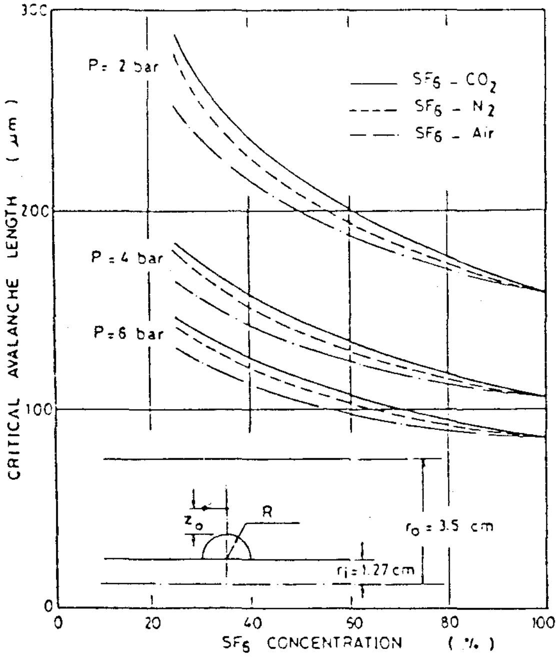

Fig. 4: Critical avalanche length for a 500 μm radius hemispherical protrusion in SF_6– gas mixtures.

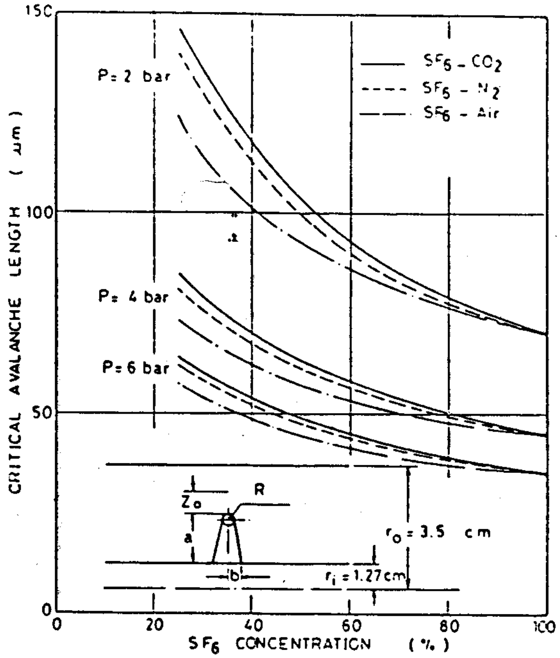

Fig. 5: Critical avalanche length for a 75 μm tip radius, 300 μm height semi-ellipsoid protrusion in SF_6– gas mixtures.

type of gas employed. Typical variations of this length for mixtures of SF_6 and CO_2, N_2 as well as air at pressures of 2, 4 and 6 bar, calculated for a 2.54/7.0 cm coaxial-cylinder electrodes with a 500 μm radius hemispherical protrusion are illustrated in Figure 4. Similar results are obtained with a prolate semi-ellipsoid protrusion of height 300μm and tip radius of 75μm as shown in Figure 5. It should be pointed out that this coaxial electrode configuration will be adapted throughout the present investigation to calculate the effect of electrode surface roughness on the breakdown of SF_6 and mixtures. This is due to the availability of measured breakdown field strength data for SF_6 gas(14).

With $\bar{\alpha}$ m expressed in terms of Equation (6), the integration leads to the general relation between ξ and PR for a hemispherical protrusion:

$$\int_{R}^{R+z_o} PK_m \{ \xi (E/P)_{cm}[1+2(R/z)^3]-(E/P)_{cm} \} = \ln N \qquad (14)$$

Integration of Equation (14) yields,

$$PR = \frac{\ln N}{K_m(E/P)_{cm}\left\{1-3\left[\frac{1}{4}\xi(1-\xi)^2\right]^{1/3}\right\}} \qquad (15)$$

5. RESULTS AND DISCUSSION

Figure 6 presents the calculated breakdown field of different radius as a function of SF_6 gas pressure. Also included in the figure are the measured values for different electrode surface conditions as reported by Trinh (14), which clearly indicate the fair agreement at low gas pressure.

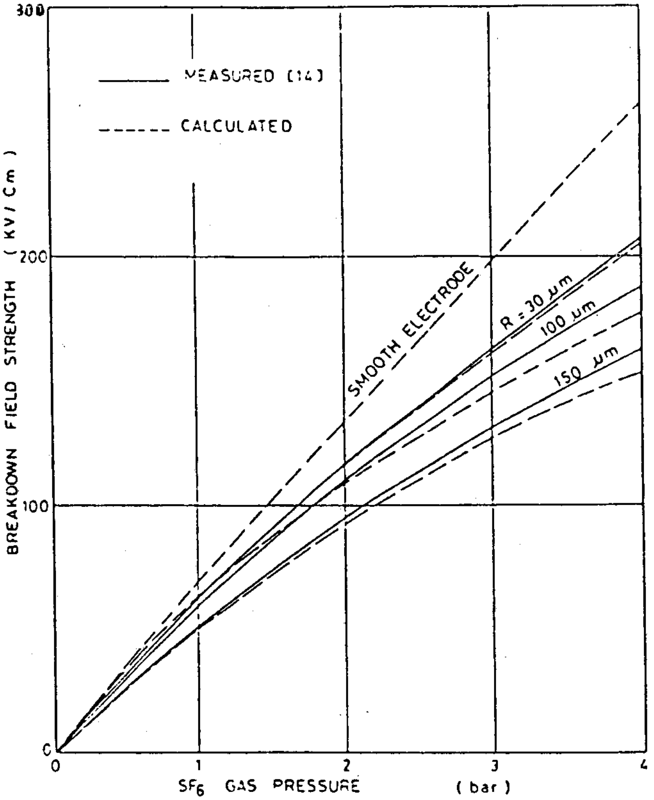

Fig. 6: Variations of the breakdown field strength with SF_6– gas pressure for different electrode surface conditions.

At high gas pressure, however, the effect of electrode surface roughness is more pronounced and the difference between calculated and measured values is noticeable.

In view of the increasing interest in the insulating properties of mixtures of SF_6 with other gases, it is interesting to consider whether they are subjected to the same electrode surface roughness constraints as SF_6. For this purpose, the breakdown field strength has been calculated for SF_6-CO_2, SF_6-N_2 and SF_6-Air gas mixtures with different SF_6 concentration in the mixture using both the prolate semi-ellipsoid and the hemispherical protrusion models. The calculated results for 50% SF_6 — 50% gas mixture for the three gases as a function of the pressure x protrusio radius, PR, using the hemispherical protrusion shape model is illustrated in Figure 7. These results indicate that the field necessary to initiate a breakdown is lowered as the value PR increases. Moreover, the addition of CO_2, N_2 or Air to SF_6 reduces sensitivity to electrode surface condition.

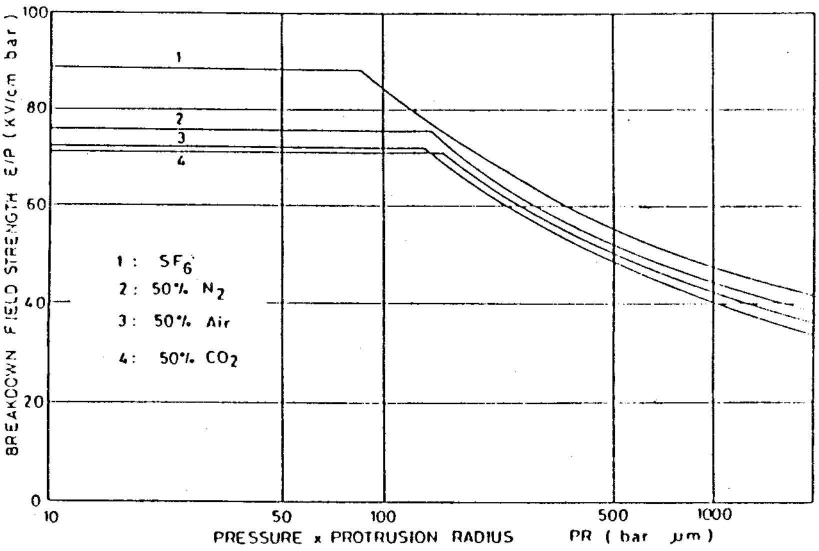

Fig. 7: Reduction of the breakdown field strength, in presence of a hemispherical protrusion, as a function of product PR in SF_6– gas mixtures.

As has been mentioned earlier in this paper, a practical way to take the conductor surface roughness into account in determining the breakdown field for compressed gas systems is the introduction of the surface roughness factor ξ. This factor has been calculated as a function of PR for 50% mixtures of SF_6 with CO_2, N_2 and Air using Equations (7) to (15). The results are presented in Figure 8 for different enhancement factor β, which is a function of the prolate semi-ellipsoid dimensions as well as the configuration of the electrode system used (12).

The characteristics of Figure 8 indicate that, as SF_6 is mixed with CO_2, N_2 or Air, there is an increase in the value of PR which can be tolerated before ξ falls below unity. The effect of increasing the enhancement factor β, however, results in a reduction in the calculated value of the surface roughness factor ξ and consequently a reduction in the breakdown voltage of the system. This may partly be due to the fact that with high values of β, more electrons are liberated from the protrusion tip due to field emission mechanisms, thus leading to lower breakdown voltages. Similar results are obtained if the value of PR is replaced by the value PH, the product of pressure and protrusion height as shown in Figure 9 for SF_6 and SF_6-gas mixture. These results are in good agreement with the results reported by other investigators (5, 12, 13, 15-17).

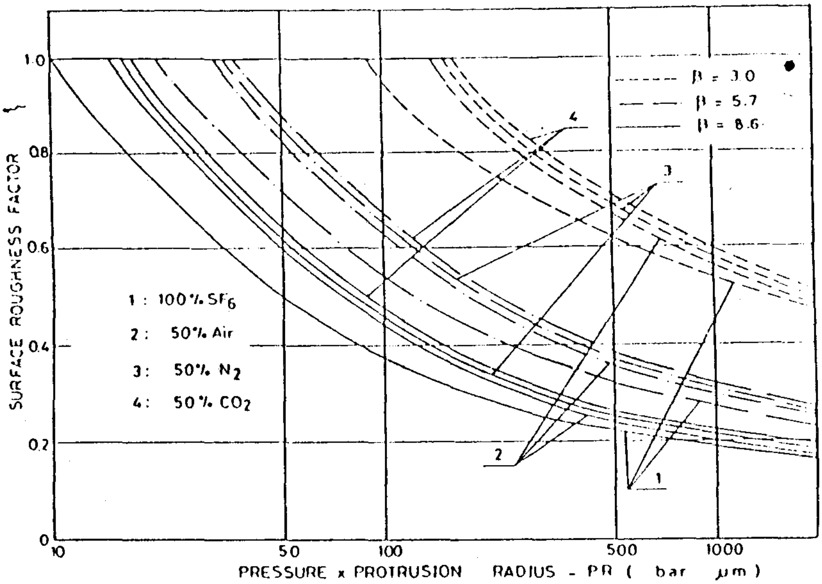

Fig. 8: Surface roughness factor, in presence of a semi-ellipsoid protrusion, as a function of product PR in SF_6– gas mixtures.

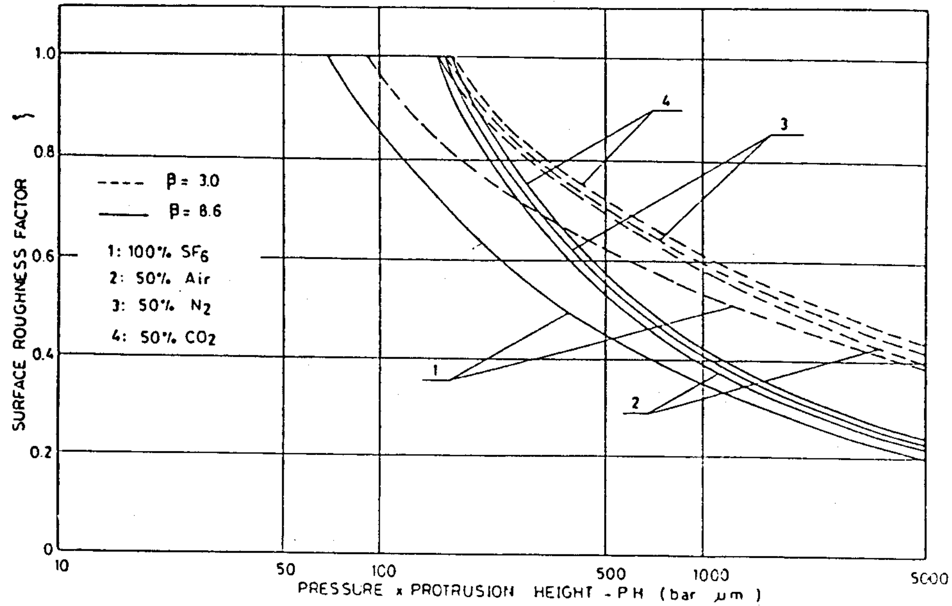

Fig. 9: Surface roughness factor, in presence of a semi-ellipsoid protrusion, as a function of product PH in SF_6– gas mixtures.

Figure 10 illustrates the effect of surface roughness on the breakdown voltage — mixture characteristics for the coaxial configuration in SF_6-CO_2 mixture for different values of the enhancement factor β . For a given pressure and values of R for the hemispherical protrusion ($\beta = 3.0$) greater than the onset values, there is an optimum gas mixture for each surface condition. At 4 bar, for example, a 50% SF_6 mixture with CO_2 is the best choice for a 30 µm finish, however, with protrusions of 75 µm, a mixture containing only 8% SF_6 would be adequate. For higher values of β , however, and at different semi-ellipsoid tip radii, the breakdown voltage for all percentage of mixtures is considerably reduced. Similar results are obtained for SF_6-N_2 and SF_6-Air mixtures. These are presented, respectively, in Figures 11 and 12.

The critical value of the product value $(PR)_c$ where the dielectric strength of a gas insulated systems begins to considerably deteriorate, can be calculated using the equation (16):

$$\frac{PR\,(\text{mixture})_{max}}{PR\,(SF_6)_{max}} = \frac{(E/P)_c \cdot k}{(E/P)_{cm} \cdot k_m} \qquad (16)$$

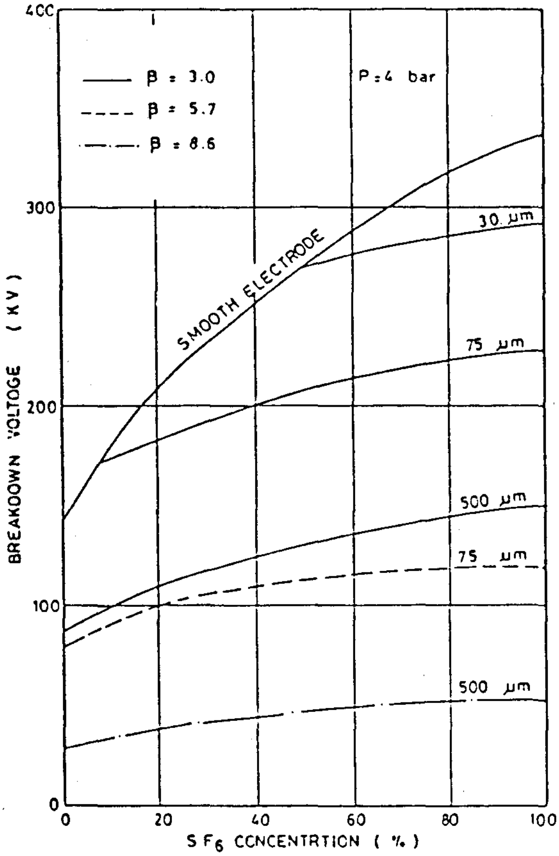

Fig. 10: Effect of electrode surface roughness on calculated breakdown voltage - mixture characteristics for coaxial configuration in SF_6–CO_2 mixtures.

This relationship is shown in Figure 13 as a function of SF_6 concentration for SF_6-CO_2, SF_6-N_2 and SF_6-Air mixtures. It should be noted that Equation (16) is independent of the protrusion shape selected to represent a surface defect. From the results in Figure 13 a slightly superior performance of SF_6-CO_2 mixture can be observed compared to SF_6-N_2 or SF_6-Air mixtures.

6. CONCLUSIONS

The effect of electrode surface roughness in reducing the breakdown field strength of SF_6 and mixtures has been quantitatively analysed for a coaxial cable system in which a semi-ellipsoidal or hemispherical protrusion is mounted at the inner electrode surface. Such models are considered to be representative of many practical situations. A fair agreement is obtained between the calculated and measured breakdown field strength in SF_6, particularly at low pressure values.

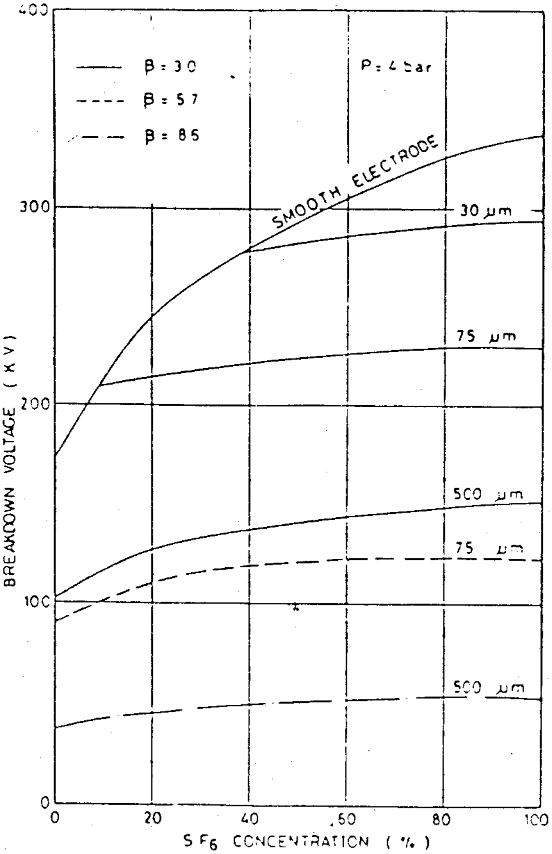

Fig. 11: Effect of electrode surface roughness on calculated breakdown voltage - mixture characteristics for coaxial configuration in SF_6–N_2 mixtures.

Moreover, the results indicate that the dielectric strengths of mixtures of SF_6 with CO_2 and Air are less sensitive to electrode surface roughness than that of pure SF_6.

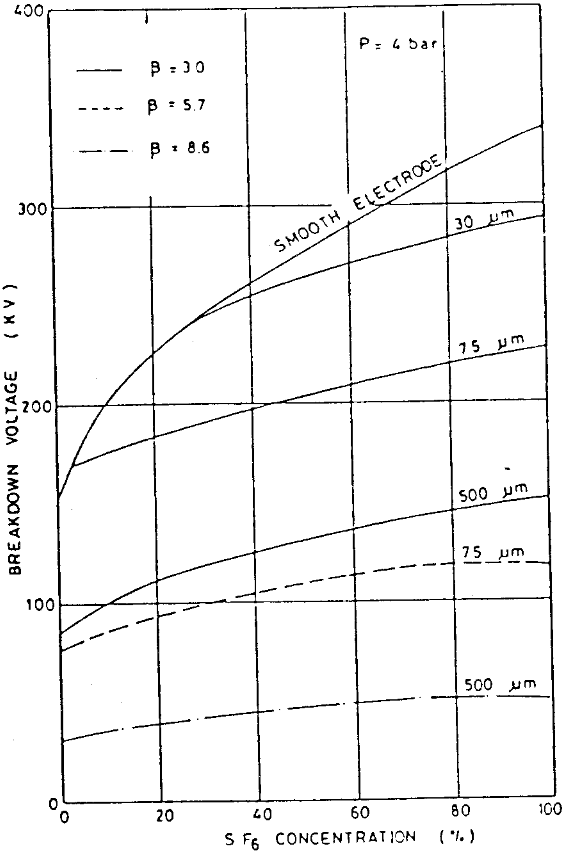

Fig. 12: Effect of electrode surface roughness on calculated breakdown voltage - mixture characteristics for coaxial configuration in SF_6–Air mixtures.

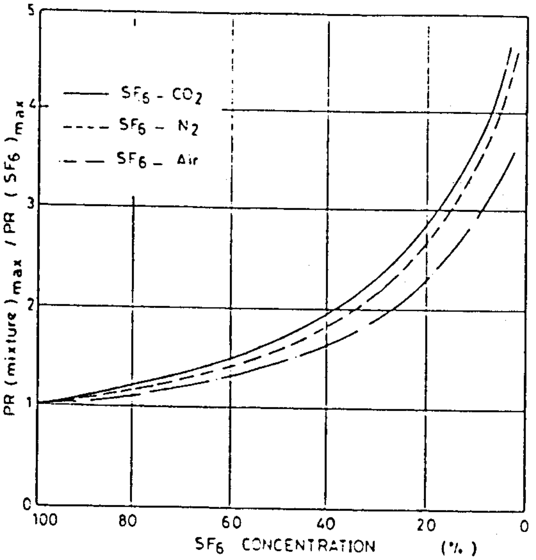

Fig. 13: Relative limits for threshold of surface protrusion effects in SF_6– gas mixtures.

For gas-insulated systems, and among the various mixtures investigated, SF_6-CO_2 mixtures appear to be promising because they exhibit the least reduction in the breakdown field strengths due to the electrode surface irregularities.

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