Calculation Of Sparking Potentials Of SF_6 And SF_6-Gas Mixtures In Uniform And Non-Uniform Electric Fields

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ABSTRACT

A simple formula is developed to predict the sparking potentials of SF_6 and SF_6-gas mixture in uniform and non-uniform fields. The formula has been shown to be valid over a very wide range from 1 to 1800 kPa·cm of pressure and electrode gap separation for mixtures containing 5 to 100% SF_6. The calculated values are found to be in good agreement with the previously reported measurements in the literature. The formula should aid design engineers in estimating electrode-spacings and clearances in power apparatus and systems.

INTRODUCTION

Out of a variety of insulating gases available, SF_6 has been accepted as one of the best for the insulation of electrical equipment. The cost of SF_6 being high, binary mixtures of SF_6 with inexpensive gases like air, N_2, CO_2, and N_2O have been under continuous investigation in order to arrive at efficient and economical mixtures useful in power systems. Such mixtures have a dielectric strength comparable to that of pure SF_6 and at the same time can improve arc quenching characteristics of pure SF_6 giving it better overall electrical properties. A number of measurements of the sparking potentials of these mixtures are available [1-7, 9-13, 17-19] and it would be useful to put this data in a handy form so that it can be used conveniently in practical problems of engineering interest.

There is a definite indication from the published data [5-7] that the sparking potential of a mixture is related to the sparking potential of pure SF_6, but so far no correlation effort has been made. In this paper we have demonstrated that the sparking potential and percentage of SF_6 in a binary mixture can be formulated into a quantitative relationship. Furthermore, we have shown that the relationship obtained from data at a particular *pd* (pressure × electrode gap) is true for other *pd* values also. It is well known that in non-uniform field gaps the degree of non-uniformity can be calculated in many cases where electrode shape and size are well defined. Based on the degree of non-uniformity so calculated, it is shown that sparking potentials in non-uniform field conditions can be predicted by incorporating a certain multiplier in the formula for sparking potentials of uniform field gaps. A good agreement is found between our calculated values and the measurements reported in the literature.

UNIFORM FIELD BREAKDOWN IN SF_6

Uniform field breakdown data are of great significance since they provide important information regarding relative dielectric behavior of single and mixed gases. In this analysis, we have used the sparking potentials of SF_6 in uniform fields from the data compiled by CIGRE and published in Electra [8] for obtaining the Paschen curve shown in Fig. 1. The most useful part of this curve for application in insulation technology is in the range of 1 to about 2000 kPa·cm. A simple mathematical expression has been fitted to this data in order to compute the sparking potentials of SF_6 and is:

$$V_{SF_6} = 1321\ (pd)^{0.915} \qquad (1)$$

which gives V_{SF_6} in volts when the product *pd* is in kPa·cm.

A comparison of the calculated values by Eq. (1) shows (Fig. 1) that in the most useful range of $50 \le pd \le 1200$ kPa·cm, V_{SF_6} lies within ±3.5% of the values reported in [8]. For $1 \le pd \le 50$ kPa·cm i.e. in the low *pd* range, predicted values are within ±15% of CIGRE values. At higher $pd > 1200$ kPa·cm, only extrapolated breakdown data are available and therefore no comparison is made with the values from Eq. (1) but the expression has been used up to 1800 kPa·cm in this analysis successfully for data available in non-uniform fields.

UNIFORM FIELD BREAKDOWN IN MIXTURES OF SF_6

Extensive study of sparking potentials of SF_6-air is still not available, perhaps because SF_6-air mixtures are thought to be technically less important due to the presence of chemically active oxygen in air. Breakdown

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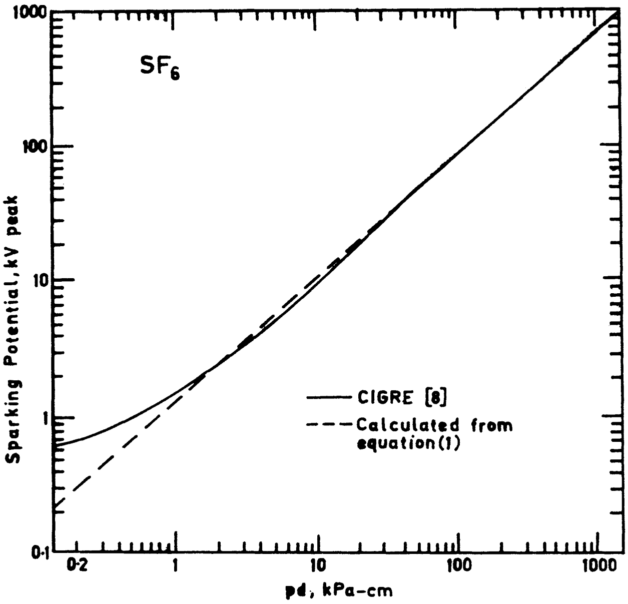

Fig. 1: Measured [8] and calculated sparking potentials of SF_6 in uniform field gaps

data at *pd* from 100 to 400 kPa·cm is available from the measurements of Malik and Qureshi [9]. Data of Gross [10] has been used for 64.413 kPa·cm. Breakdown data for SF_6-N_2 is available [11] in the range of 51 to 204 kPa·cm. A definite indication is available from measurements [5,9,19] that SF_6-CO_2 mixtures have sparking potentials similar to SF_6-air or SF_6-N_2. These measurements show that the sparking potential of a mixture containing SF_6 is a certain fixed percent of the sparking potential of SF_6 itself. It is also important to note that if the sparking potential of gases relative to SF_6 is approximately equal, the sparking potentials of the binary mixtures of such gases with SF_6 are also approximately equal under similar conditions of pressure, electrode gap, type of voltage and individual mixture ratio. On the basis of this information, the sparking potentials of mixtures of air or N_2 with SF_6 can be put into a formula such as

$$M = 38.03\ N^{0.21} \tag{2}$$

where M gives the sparking potential of the mixture as a percentage of sparking potential of SF_6 under similar conditions and N is the percentage of SF_6 in the mixture by volume. Thus if the relation is to be used for 153 kPa·cm, the sparking potential for SF_6 from Eq. (1) is obtained as 131.79 kV. In order to find the sparking potential of SF_6-air in which SF_6 is 60%, N is substituted as 60 in Eq. (2) and M is obtained as 89.85. Again 89.85% of the sparking potential 131.79 kV of SF_6 gives 118.41 kV as the sparking potential of the mixture which agrees very well with that published in the literature [3]. Calculated and measured [3,9,10] sparking potentials for SF_6-air and SF_6-N_2 are compared in Figs. 2 and 3 respectively for different *pd* values and the agreement between them is good considering that in some cases (Fig. 2, 400 kPa·cm) measured values of breakdown of SF_6 are significantly less than in [8]. On this basis the sparking potentials of SF_6-air and SF_6-N_2 mixtures can be combined into a single expression from Eqs. (1) and (2) as

$$V_{Mix} = 502.40\ (pd)^{0.915} N^{0.21} \tag{3}$$

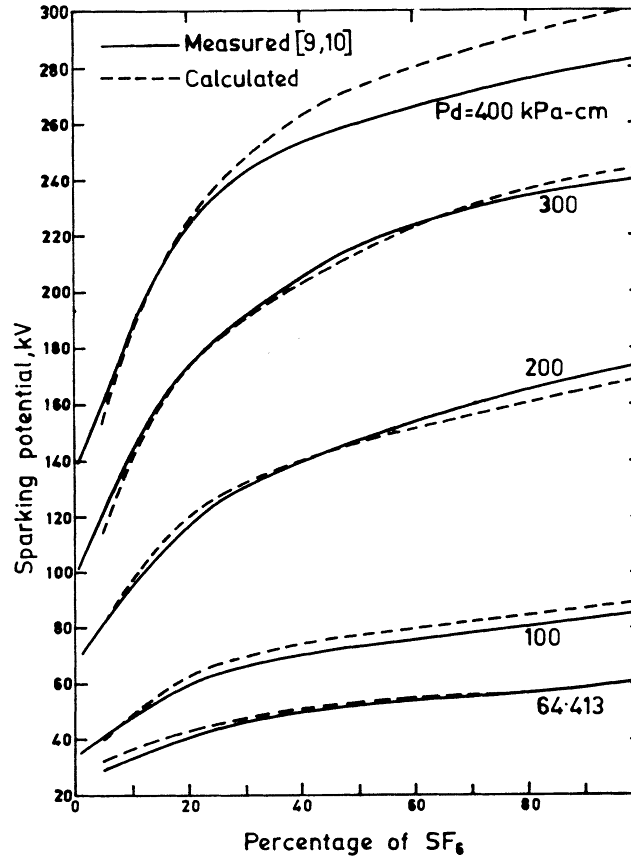

Fig. 2: Measured [9,10] and calculated values of uniform field sparking potentials in SF_6-air mixtures

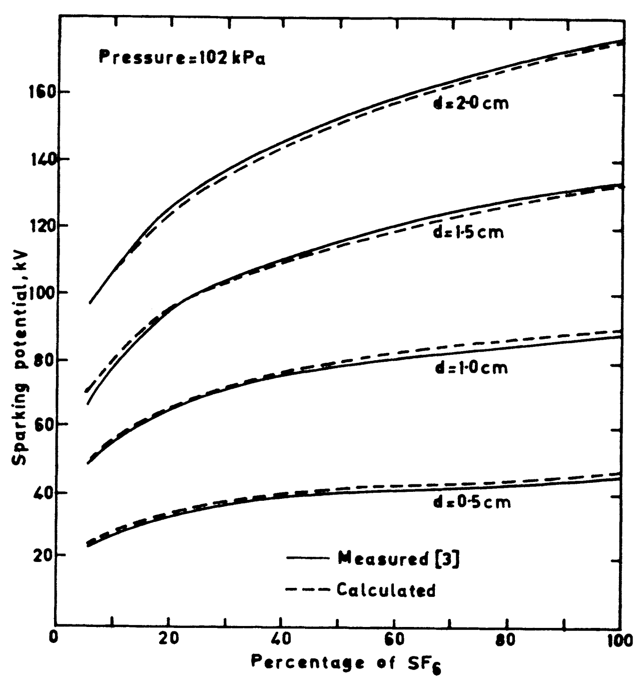

Fig. 3: Measured [3] and calculated values of uniform field sparking potentials in SF_6-N_2 mixtures.

which gives V_{Mix} in V when the product pd is in kPa·cm. This expression can be used for mixtures in which SF_6 is 10% or more by volume with 5% error. If the SF_6 content is less than 10% the error in determining V_{Mix} increases such that for a mixture containing 5% SF_6 the error is 10%. Hence, no attempt is made to use these equations below 5% SF_6 content in the mixture.

The relative sparking potential of N_2O is about 10% higher than that of air or N_2 and is about 50% that of SF_6. On the basis of data obtained by Dutton et al. [12], Eq. (2) is modified for N_2O as

$$M = 39.95\ N^{0.21} \tag{4}$$

and the sparking potential of SF_6-N_2O mixture is written as

$$V_{Mix} = 527.70(pd)^{0.915}N^{0.21} \tag{5}$$

Calculated and measured [12] values for SF_6-N_2O are shown in Fig. 4 and are in good agreement.

Sphere-Sphere gaps, up to a gap less than their radii, spark approximately at the same potentials as uniform field gaps. While this is true in air, measurements by Howard [13] and a comparison of his data with uniform field breakdown [8] show that this is also true in SF_6 but since SF_6 and SF_6-gas mixtures are strongly electronegative, their breakdown voltages are likely to be affected by field non-uniformities when sphere-sphere gaps are used. Data obtained by Howard [13] in SF_6-N_2 mixtures for spheres of 5.0 cm diameter and calculated values using Eq. (3), plotted in Fig. 5, show good agreement.

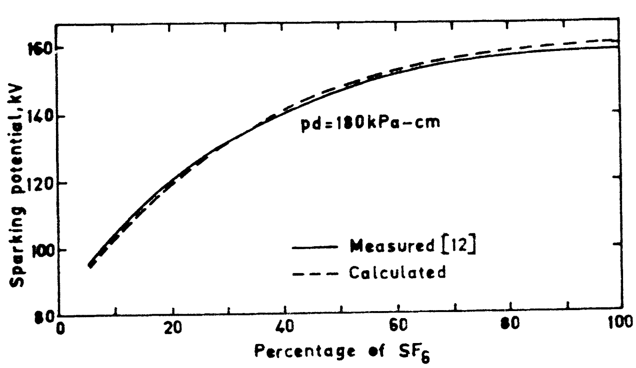

Fig. 4: Measured [12] and calculated values of uniform field sparking potentials in SF_6-N_2O mixtures.

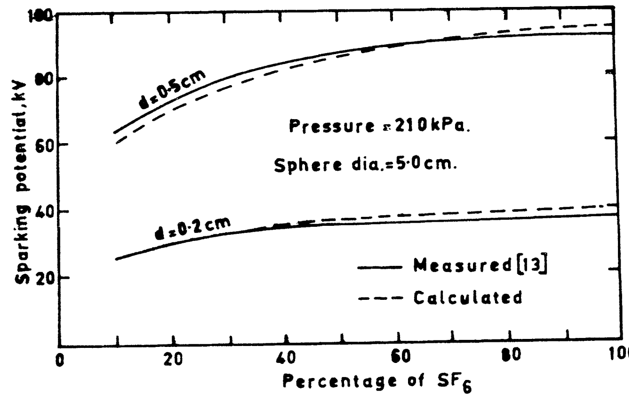

Fig. 5: Measured [13] and calculated values of sparking potentials for sphere-sphere gaps insulated with SF_6-N_2 mixtures.

NON-UNIFORM FIELD BREAKDOWN IN MIXTURES OF SF_6

Sphere-plane, hemispherically tipped rod-plane and coaxial cylindrical electrode systems are usually used to study the effect of field non-uniformities on the sparking potentials of gases and gas mixtures. They have been studied by Fiegel and Keen [14] and Russel [15]. Azer et al. [16] have given the field factors for highly non-uniform fields of rod-plane gaps which can be used to study the prebreakdown and breakdown characteristics of SF_6 and SF_6-gas mixtures. It is seen from their results that for practical use a field utilization factor U can be obtained as

$$U = [0.6162\ (d/R)^{0.9716} + 1.1377]^{-1} \tag{6}$$

where d is the electrode gap and R is the radius of rod. It gives satisfactory results when $0.8 \leq d/R \leq 40$.

In the case of a coaxial electrode system having inner and outer electrode radii of R_i and R_o respectively, the field utilization factor U is given [11] by

$$U = \frac{R_i}{R_o - R_i} \ln \frac{R_o}{R_i} \tag{7}$$

The effect of field utilization factor can be evaluated by measuring the sparking potentials in uniform and non-uniform fields under similar conditions. Our calculations show that for practical use in a non-uniform field in which the field utilization factor is U, the sparking potentials can be obtained as a fraction

$$f = U^{0.85} \tag{8}$$

of the uniform field sparking potential for the same gap under similar conditions of gas and pressure. Thus for SF_6-N_2 or SF_6-air mixtures under non-uniform field conditions Eq. (3) is modified as

$$V_{Mix} = 502.40(pd)^{0.915}N^{0.21}U^{0.85} \tag{9}$$

and for SF_6-N_2O Eq. (5) gives

$$V_{Mix} = 527.70(pd)^{0.915}N^{0.21}U^{0.85} \tag{10}$$

giving V_{Mix} in V when pd is in kPa·cm. It is obvious that Eqs. (9) and (10) are of a more general form than the previous equations and can be used for uniform fields in mixtures when $U=1$; and for SF_6 breakdown when $U=1$ and $N=100$. The application range of the above form of these equaitons is so wide and good that we are tempted to call it NKH formula (after Nema, Kulkarni and Husain). Eq. (9) will now be applied to illustrate its applicability in non-uniform field conditions.

(a) Sphere-Plane Gaps

Malik and Qureshi [11] have measured the sparking potentials in a 1.0 cm gap using a 5.1 cm diameter sphere and a 15.0 cm diameter plane electrode in SF_6-N_2 mixtures using static voltages of positive polarity applied to the sphere electrode. The measured [11] and calculated values from Eq. (9) agree well as shown in Fig. 6. The value of U for this purpose is calculated from Eq. (6). It has been suggested [11] that power frequency breakdown voltages will not be much different than static voltage breakdown.

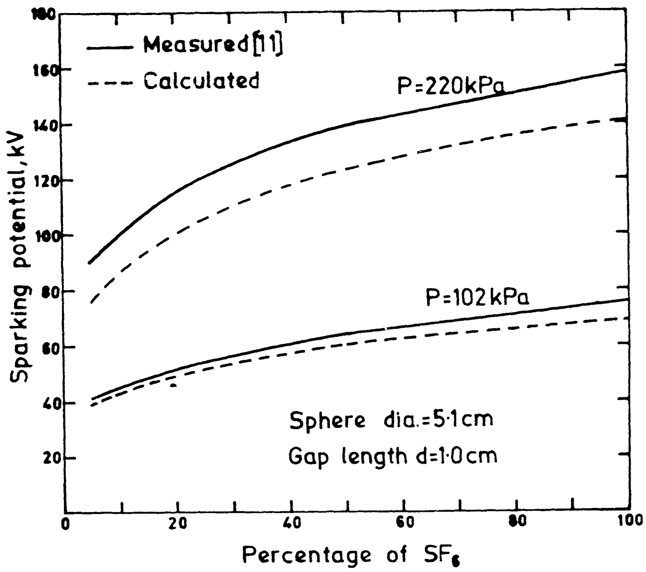

Fig. 6: Measured [11] and calculated values of sparking potentials for a sphere-plane gap insulated with SF_6-N_2 mixtures.

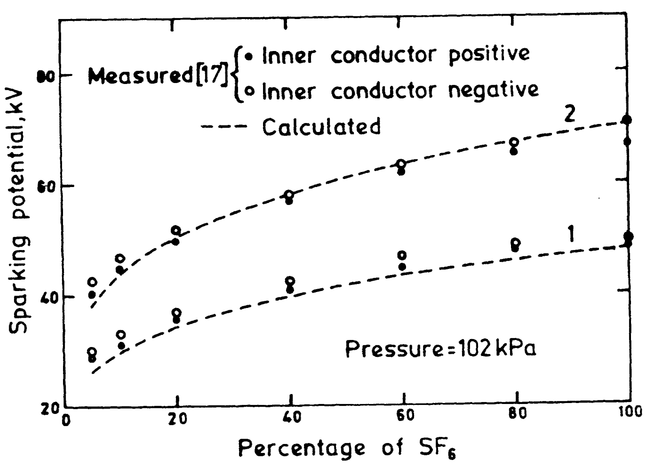

Fig. 7: Measure [17] and calculated values of static sparking potentials for SF_6-N_2 mixtures in coaxial electrode systems.

The radius of the outer cylinder is 2.0 cm. while that of inner cylinder is (1) 1.4 cm and (2) 0.75 cm.

(b) Cylindrical Electrode Systems

Christophorou et al. [17] have measured the static sparking potentials of SF_6-N_2 mixtures in coaxial systems having different inner and outer radii. Their measurements with positive and negative polarity and the calculated values from Eq. (9) agree remarkably well as can be seen from Fig. 7.

(c) Rod-Plane Gap Systems

In such gaps the corona inception occurs first [4] and the sparking potential can be higher than the corona inception level. The onset level for cathode corona has a lower value than for positive corona and the onset of cathode corona occurs as single pulses [18]. Thus, while in uniform and quasi-uniform fields corona inception and spark formation can be said to have occurred simultaneously, in case of rod-plane systems the corona onset has a special significance highlighting the action of localized high field conditions. In such cases Eq. (9) signifies the preferential corona onset conditions, breakdown being left to a critical case of streamer propagation. Measurement [11] of corona inception level when negative direct voltage is applied to a 2.0 cm gap of a hemispherically capped 0.1 cm diameter stainless steel rod and plane electrode system are shown in Fig. 8 in which our computed values using Eqs. (6) and (9) for various mixture proportions are also shown. As can be seen, the calculated values are in good agreement with the experimental measurements. The validity of Eq. (9) up to high *pd* values of the order of 1800 kPa·cm and in highly non-uniform fields can be demonstrated if we compare the results of measurements of rod-plane system negative corona onset voltages for various rod-diameters at quite high pressures. A comparison of our calculations based on Eqs. (6) and (9) with the measured values elsewhere [11] can be said to be in good agreement as seen from Fig. 9. Much more information, however, is needed to understand the onset nature of corona and breakdown in SF_6 and its mixtures to successfully apply this analysis and the example cited above is just to illustrate this possibility.

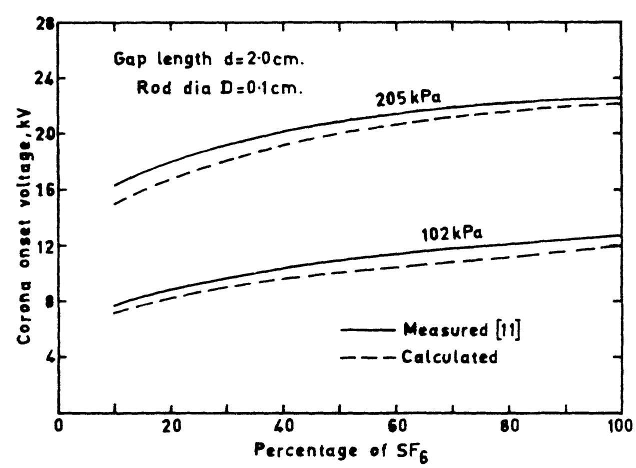

Fig. 8: Measured [11] and calculated values of corona onset voltages in 2.0 cm. rod-plane gap using 0.1 cm. diameter rod electrode in SF_6-N_2 mixtures.

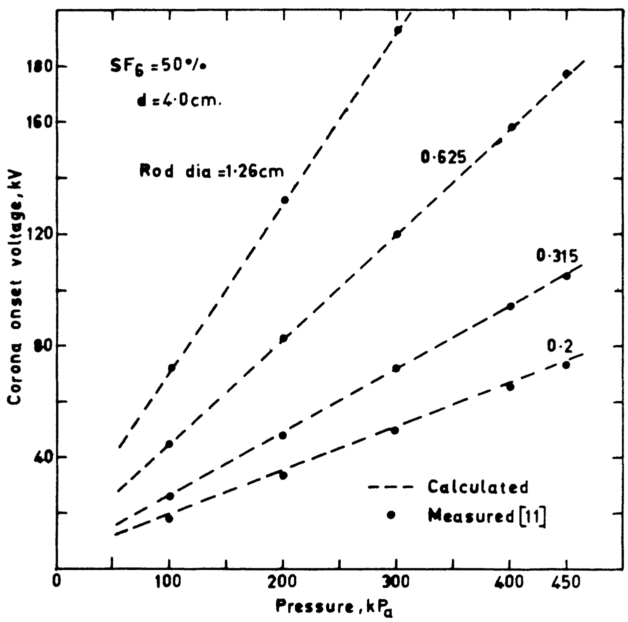

Fig. 9: Measured [11] and calculated values of corona onset levels for rod-plane gaps in 50% SF_6-N_2 mixture

Table 1.

Relative sparking potentials, RSP of Air, N_2, N_2O and CO_2 and their mixtures in different proportions with SF_6 in uniform fields.

Gas	RSP	Ratio SF_6/Gas	RSP	Reference
SF_6	100	—	—	—
Air	37	10/90	62	7
	37	25/75	74	7
	37	50/50	83	7
	37	75/25	94	7
	40	40/60	87	19
	40	60/40	92	19
N_2	37	50/50	80	7
	40	40/60	87	19
	40	60/40	92	19
N_2O	50	50/50	90	12
CO_2	36	40/60	87	19
	36	60/40	92	19

SF_6-CO_2 MIXTURES

Data on 60 Hz [5,19] and dc [9] breakdown of SF_6-CO_2 mixtures indicate that the sparking potentials of such mixtures are nearly same as those of SF_6-air or SF_6N_2 mixtures. This is to be expected since the sparking potential of air, N_2, and CO_2 relative to SF_6 is approximately same for the three cases. A comparison of the results [5,9,19] shows that Eqs. (3) and (9) also hold for SF_6-CO_2 mixtures. More data, however, is necessary under different conditions of electrode gap, pressure and mixture ratios to consolidate analysis in this case. Among the simple binary mixtures, usually SF_6-N_2 or SF_6-CO_2 are preferred since the oxygen present in SF_6-air mixtures can affect electrodes and other materials.

IMPULSE BREAKDOWN DATA

Measurements [5] in mixtures of SF_6 with air, N_2 or CO_2 show that percentage impulse breakdown voltage of the mixtures in relation to impulse breakdown voltage of SF_6 are in the same proportion as in case of power frequency measurements. Therefore, the impulse breakdown voltage of the mixtures is possible to calculate using Eq. (2) if the impulse strength of SF_6 is known which in turn may be possible to estimate from power frequency sparking potentials of SF_6 knowing the impulse ratio of the system. It is however to be noted that this is true for lightning impulses and not for switching impulses.

CONCLUSIONS

In SF_6-gas mixtures a formula of the form $V=K(pd)^a N^b U^c$ is capable of giving sparking potentials in uniform and non-uniform fields. The numerical values of a, b, and c are 0.915, 0.21, and 0.85 respectively for SF_6-N_2, SF_6-air and SF_6-N_2O mixtures. The value of K is 502.40 for the first two mixtures and 527.70 for SF_6-N_2O mixtures. If U is 1, this expression is applicable to uniform field geometries in mixtures, while if $N=100$ and $U=1$ the equation gives the sparking potentials of SF_6 in uniform fields. The expression is true with an error of ±3.5% in the practically useful pd range of 50 to 1200 kPa·cm.

It is to be noted [20] that this expression has been obtained from data available for clean and well polished electrode systems and cannot be used as is to predict the voltages for practical gas insulated systems with some degree of electrode roughness. In the future, however, when more measurements similar to those of Malik and Qureshi [20] become available, it should be possible to incorporate an additional term to account for the surface roughness factor in this expression. Their results also show that SF_6-air, SF_6-N_2, and SF_6-CO_2 mixtures have more or less similar uniform and quasi-uniform field breakdown characteristics for rough electrodes. Thus the above expression has an excellent potential of being used widely by insulation designers in systems.

The available data on sparking potentials is scattered and show variability from source to source. There is, therefore, a need for developing standard measuring electrode systems such as ASTM Seavey Cell [21] and test procedures to get more accurate data which will be helpful in improving empirical expressions such as those developed in this paper for the sparking potentials of new insulating gases and their mixtures.

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