高氣壓 SF_6 가스에서 電極表面 狀態가 絕緣破壞 强度에 미치는 영향

論 文
30～3～2

Influence of Electrode Surface Conditions on Breakdown Field Strength in Pressurized SF_6

李 東 仁*
(Dong - In Lee)

Abstract

The reduction in the breakdown field strength due to electrode surface roughness was calculated by applying the streamer breakdown criterion and the surface roughness factor, and measurements of static breakdown voltage for a gap with an artificial protrusion were made under the uniform field at pressures up to 4 bar in pressurized SF_6. The effect of polarity of highly stressed electrode on the breakdown field strength was also investigated.

The measurements have shown that the measured breakdown levels for a protrusion located on the cathode agree with those calculated and the values measured with an identical anode protrusion are substantially higher and more scattered. This may be explained if it is assumed that a high rate of production of initiatory electrons is maintained at the tip of a cathode protrusion by field emission. In practical point of view, the breakdown levels in pressurized SF_6 can bereliably estimated from the values calculated.

1. Introduction

As a result of current interest in the development of compressed-gas insulated high voltage equipments, the determination of discharge thresholds in SF_6 at pressures of a few bar has received considerable attention.

In reality, electrode (conductor) surfaces are not the ideally smooth and uniform shapes often assumed. On engineering point of view, their surfaces can be extremely irregular so that localized regions of field intensification caused by irregularities exist at high field stress. When the mean free path lengh for gas molecules is greater than this region of intensified field, collisions do not take place within this region and the irregularity does not cause additional ionization. However, as more molecules occupy the small intensified region at higher pressures, sufficient ionization can occur even in this localized region to initiate breakdown.

Measurement[1] of the effective ionization coefficient $\bar{\alpha}$ ($=\alpha-\eta$, α=Towsend first ionization coefficient, η=attaching coefficient) for SF_6 has shown that $\bar{\alpha}/p$ (p=pressure) increases particularly rapidly with E/p(E=electric field strength). Thus in pressurized SF_6, increased ionization in this regions of even highly localized field enhancement can not be neglected when formulating a criterion for breakdown or corona onset.

In the present paper, some measurements of static breakdown field strengths for a protrusion perturbed uniform-field gaps in SF_6 at pressures

*正會員：嶺南大 工大 電氣工學科 敎授
接受日字：1981年 2月 17日

up to 4 bar are presented. With the adoption of a streamer breakdown criterion, the reduction in dielectric strength of SF_6 caused by single protrusion was calculated by the aid of a computer and results are compared with measurements. The effect of polarity of highly stressed electrode on the breakdown field strength is also studied.

2. Experimental Apparatus and Techniques

The general apparatus used for the determination of static breakdown voltages and associated high voltage supply have been fully described previously[2].

A choice of a protrusion, determination of test gap spacing and the general test procedure adopted have been also mentioned in previous paper[3].

The applied voltages was initially set at approximately 80% of the anticipated breakdown level and thereafter raised at about 500 volts persecond until a breakdown ocurred.

The results[3] obtained from a study on the effects of repeated breakdowns of the gap examined showed that the breakdown lev l did not vary significantly with 50 or 100 breakdowns. Consequently, in these tests the breakdown levels quoted correspond to the average of about 10 measurements for each condition.

In some tests, the system was artificially irradiated using a 0.5-mg cesium γ source which was placed on the outside wall of the pressure vessel level with the test gap. The gas pressures quoted are referred to 20°C.

3. Calculation of Breakdown Field Strengths

By applying Predersen's model[4] for the effect of field distortion due to electrode surface roughness, and the streamer breakdown criterion[6], the breakdown field strengths can be calculated as a function of gas pressures for a spherical protrusion.

The field along the line passing through the axis of a symmetrical protrusion of height R on the cathode surface in an uniform field, may be expressed as

$$E(x)=E_0\cdot f(x) \tag{1}$$

where x=distance from the base surface of an electrode.

E_0=macroscopic uniform field strength.

$f(x)$=field enhancement factor along the axis of the symmetrical protrusion.

The field enhancement factor $f(x)$ for a spherical protrusion is described[5] by

$$f(x)=1+\sum_{n=1}^{\infty}8\cdot\left(\frac{2x}{R}\right)\cdot n\cdot\frac{\left(\frac{2x}{R}\right)^2\cdot n^2+1}{\left[\left(\frac{2x}{R}\right)^2\cdot n^2-1\right]^3} \tag{2}$$

For pressurized SF_6 ($p\gtrsim 1$ bar), the effective ionization coefficient $\bar{\alpha}$ can be written as[2]

$$\bar{\alpha}(x)=\tilde{\beta}\cdot E(x)-\frac{K\cdot p}{Z(p)} \tag{3}$$

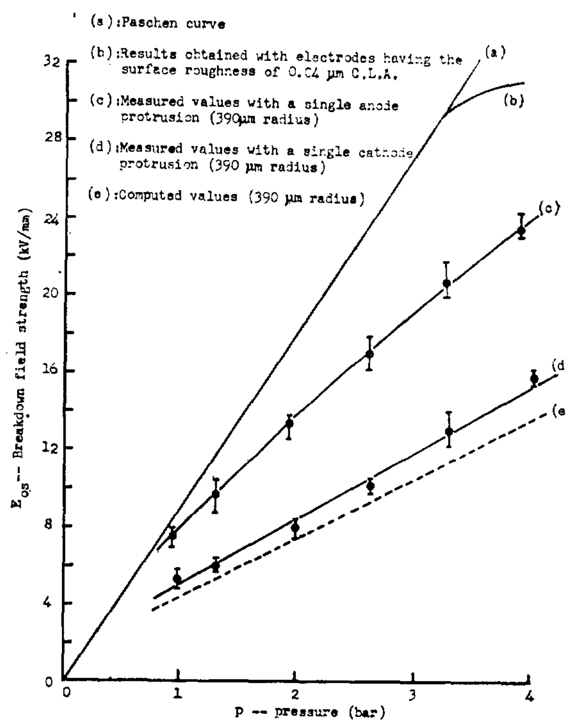

Fig. 1. Breakdown in SF_6 with a single spherical protrusion.

where $\bar{\beta}=27.8[KV]^{-1}$

$\bar{K}=246[bar\cdot mm]^{-1}$

$Z(p)$=compressibility factor

For perfectly smooth electrodes, the value of E_0/p at threshold for breakdown would be approximately equal to $(E/p)_{lim}$ (limiting value of $E_0/p=8.84KV[bar\cdot mm]^{-1}$). However, this value is reduced by the enhanced field near the sphere to a value

$$E_0/p=\xi(E/p)_{lim} \quad (4)$$

where ξ is the surface roughness factor[4].

An electron avalanche developing along the line of force may lead to breakdown. This threshold of breakdown in pressurized SF_6 is determined by the streamer criterion[6].

$$\int_R^{R+x_0}\bar{\alpha}(x)dx=k \quad (5)$$

in which x_0 is the critical avalanche length and k the streamer constant. Using equations from (1) to (5), the breakdown field strength was computed as a function of pressure for a single spherical protrusion by the aid of a computer.

4. Results

In figure 1, curve (a) shows the Paschen curve calculated using the following equation(6)

$$E_0/p=0.38/pd+8.84/Z(p) \quad (6)$$

where d is the gap spacing.

Curve (c) and (d) illustrate the present measurements for a 10mm gap with a single spherical anode protrusion and cathode protrusion of 390μm radius respectively under non-irradiated conditions, and curve (e) presents theoretical values for the same protrusion-perturbed gap computed as described in above section. For comparison purposes, the results obtained with highly-uniform electrodes having the surface roughness of 0.04μm center line average are also included in figure 1 (curve b). In case of an anode protrusion, at a pressure of 1 bar, the measured value of the breakdown field strength E_{0s} lies close to these for the highly polished electrodes. But with increasing pressure curve (c) deviates increasingly from the Paschen curve. Resulte are very far above the computed values [curve (e)].

At 1 bar the value of E_{0s} obtained for the cathode protrusion lies 40% below the value found for the smooth electrodes, and this reduction reaches to about 55% at 4 bar. The minimum measured values of E_{0s} lie between about 0 and 15% above the computed results.

In figure 2, curves (a) and (b) show measured values of E_{0s} as a function of pressure for a 10mm gap with a single protrusion, consisting of a 390μm radius sphere. The effect of changing the location of this protrusion from the cathode to the anode was investigated by simply changing the polarity of the upper electrode. The gap was not irradiated. With the protrusion on the anode (i.e. with the highly-stressed electrode positive) the measured values of E_{0s} lie considerably above the results obtained with the protrusion on the cathode (i.e. with the highly stressed electrode negative): at 1 bar the value

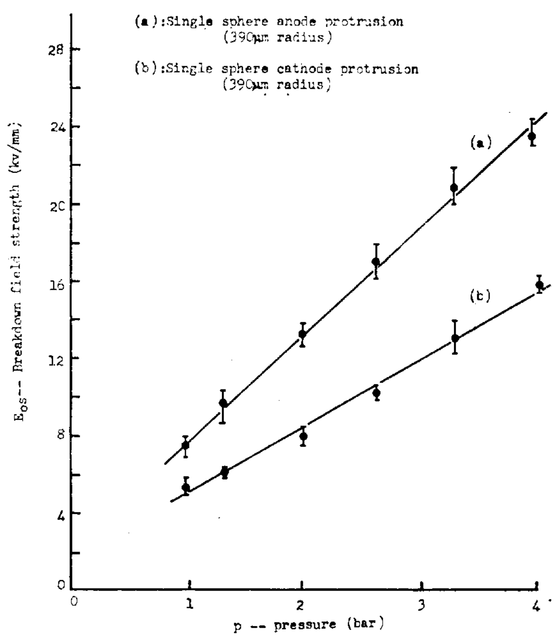

Fig. 2. Effect of the polarity of a protrusion on the breakdown field strength in SF_6 (without irradiation)

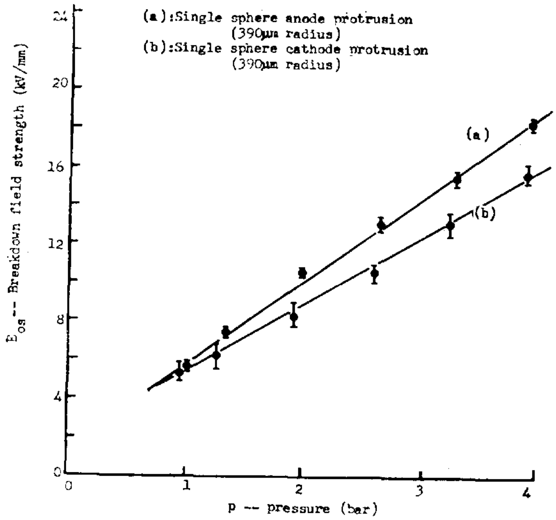

Fig. 3. Fffect of the polarity of a protrusion on the breakdown field strength in SF_6 (with irradiation)

of E_0, for the ancde protrusion lies 40% above the value found for the identical cathode protrusion, and at 4 bar this difference has increased to about 50%. On the other hand, when this gap was irradiated, this difference in E_0, was drastically reduced as shown in figure 3: at a pressure of 1 bar, both breakdown levels show a similar value but with increasing pressure above about 2 bar this difference has risen, and at 4 bar it is about 20%.

5. Discussion

According to the simple streamer breakdown criterion, $\int \bar{\alpha} dx = k$, the d.c. breakdown level in protrusion-perturbed test gaps such as those examined above should be affected only by gas pressure, gap spacing and the localized enhancement due to the protrusion. However, the measurements have shown that large effects result from altering the polarity of the highly stressed electrode. This is shown more explicitly in figure 2 where it is seen that the breakdown level for a gap with a single spherical protrusion of 390μm radius was observed to increase by about 50% when the location of the protrusion was changed from cathode to anode.

The d.c. voltage levels recorded in these tests were determined by applying a ramp voltage to the test gap, increasing at about 500 volt per second. Consequently, the rate of production of initiatory electrons may affect the recorded breakdown levels. Under the present circumstances initiatory electrons may be formed as a result of the passage of radiation through the gap, emission processes at the cathode or detachment of negative ions in the gas. Consider first the case with the cathode protrusion. With the spherical protrusion used in these tests the field at the protrusion tip is about 4.2 times the macroscopic field E_0. From figure 1 [curve(d)], E_0, lies between about 5 to 15KV/mm and so the field at the protrusion tip at breakdown lies between about 20 to 60KV/mm. These fields are high enough to allow field emission of electrons from the tip of the cathode protrusion[6)7)]. So it is reasonable that the results with cathode protrusion agree relatively well with the computed curve and are not greatly changed by irradiating the gap. Such a mechanism would also explain the observation[3)] that the scatter measured for gaps with cathode protrusion decreases with increasing pressure above 1 bar, since as pressure is increased at constant E_0/p then E_0 rises and so the rate of production of initiatory electrons would increase.

On the other hand, with the anode protrusion, the initiatory electrons must be produced in the gas. In order to cause breakdown these electrons must arrive in what has been termed[9)] a "critical volume" at the locally enhanced field close to the anode protrusion tip. This critical volume is bounded on the side furthest away from the anode by the limiting field value corresponding to $\bar{\alpha}=0$ and on the other side, closer to the protrusion, by the condition that for breakdown an avalanche must be allowed to progress to critical length before reaching the anode surface. At the threshold value of the d.c. breakdown voltage this volume is therefore vanishingly small. This voltage will be that computed from the streamer criterion but, because the critical volume is vanishingly small, the rate of production of initiatory electrons will be low and so the statistical time lag correspondingly long. Consequently, with a voltage applied as a ramp, there is a high probability that the gap will be substantially overvolted before a breakdown is initiated. Thus measured results with the anode protrusion always lie above the corresponding levels found with the identical cathode protrusion. This explanation also accounts for the reduction in E_0, found for the anode protrusion when the gap is irradiated as shown in figure 3. The irradiation may lead to increase the chance of forming an electron inside the critical volume.

6. Conclusions

The most interesting conclusions to be drawn from the results presented in this study are that the computed breakdown levels for a protrusion-perturbed test gap correspond to the values measured when the protrusion is located on the cathode and that, although these measured values may show some scatter, no breakdowns should be detected below the calculated level.

Whereas the measured breakdown levels for a cathode protrusion agree with those calculated using the streamer criterion and the Pedersen roughness factor, the values measured with an identical anode protrusion are substantially higher and more scattered. This may be explained if it is assumed that a high rate of production of initiatory electrons is maintained at the tip of a cathode protrusion by field emission, so that for this case the statistical time lag is short, but at an anode protrusion the statistical time lag is much greater because initiatory electrons have to be produced in the gas within the critical volume either by the passage of ionizing radiation or detachment from negative ions.

In order to gain more information on the mechanisms promoting the production of initiatory electrons and the development of avalanches to breakdown of the gas it was considered that the techniques such as irradiation of the test gap, multiple protrusions and observation of the current pulses due to individual avalanche would be introduced for the further investigation.

The author wishes to express his gratitute to the Ministry of Education for the receipt of research grants to undertake the present investigation.

References

1. Nitta, T. and Shibuya, Y.; Electrical Breakdown of Long Gaps in Sulphurhexafluoride, IEEE Trans PAS 90, p. 1065 (1971)
2. Lee, Dong-in; The Effect of Compressibility on Breakdown and Modification of the Surface Roughness Factor in Compressed SF_6, KIEE vol. 27, no. 1, p. 45 (1978)
3. Lee, Dong-in; A Study on the Repeated Breakdown Field Strength of Compressed SF_6 in Uniform Field Perturbed by Protrusion, KIEE vol. 29, no. 2, p. 55 (1980)
4. Pedersen, A.; The Effect of Surface Roughness on Breakdown in SF_6, IEEE Trans PAS 94, p. 1749 (1975)
5. Charrier, J., LeNy, R. and Boulloud, A.; Influence of a Spherical Protrusion on One of the Electrodes on the Breakdown Voltages in Room Air, 3rd. Int. Conf. on Gas Discharges, London, p. 394 (1974)
6. Raether, H.; Electron Avalanches and Breakdown in Gases, London Butterworths (1964)
7. Ermel, M.; Electron Emission Currents in Compressed SF_6 in the Coaxial Cylindrical Field, 4th. Int. Conf. on Gas Discharges, Swanses, p. 191 (1976)
8. Shibuya, Y., Yamada, N. and Nitta T.; Electrical Breakdown and Prebreakdown Dark Current in Compressed SF_6, 2nd. Int. Conf. on Gas Discharges, London, p. 320 (1972)
9. Hepworth, J.K., Klewe, R.C. and Vrey, R.H.; Analysis of the First Corana Pulse, Electra, CIGRE, 23, p. 105 (1974)