論 文
27~2~2

壓縮 SF_6가스의 絕緣破壞에 대한 理論的 硏究

Theoretical Investigation of Electrical Breakdown in Compressed SF_6

李 東 仁*
(Dong In Lee)

Abstract

By applying the streamer breakdown criterion and the surface roughness factor, the effect of field distortion due to conductor surface roughness on breakdown is investigated theoretically in a uniform-field of compressed SF_6.

It has been shown that the streamer constant has a significant influence on the threshold of breakdown and different shapes of protrusions do not result in different thresholds of breakdowns. Moreover, uniform-field tests can give results which apply to e-ratio coaxial-electrode systems of practical dimensions, and may offer some advantages compared with coaxial-electrode tests.

1. Introduction

Sulphur hexafluoride is used as an insulating medium for compact substation components and gas-insulated cables because of its high dielectric strength and good heat transfer properties. However, recent studies have shown that because of the rapid variation of the effective ionization coefficient α with the parameter E/p (electric field/pressure), SF_6 is extremely sensitive to local field enhancement owing to electrode surface imperfections[8] or to the presence of contaminant particles[9], so that the ideal Paschen-value of electric strength may not be achieved in practical systems.

In the present paper, on the basis of streamer model in which an electrode protrusion is presented by a conducting hemisphere or sphere on a smooth electrode, the breakdown strengths are calculated as a function of pR (pressure×height of protrusion) by the aid of a computer and results are analyzed.

2. Normalized critical avalanche length

In an ideal uniform field the critical avalanche length, within which the multiplication of the free electrons prior to the formation of a streamer is possible but beyond which the value of α (effective ionization coefficient) is everywhere negative, i.e. all free electrons may be captured to form negative ions, is equal to the gap spacing. On the other hand the critical avalanche length Z_0 can be reduced to a very small fraction of the gap spacing even in slightly non-uniform fields.

By applying Pedersen's model[1] for the effect of field distortion due to electrode surface roughness, the normalized critical avalanche length $U_0(=Z_0/R$, Z_0=critical avalanche length) can be calculated as a function of pR for a hemispherical and 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

$$E(Z)=E_0\cdot f(Z) \qquad (1)$$

where E_0 is the macroscopic uniform field strength and $f(Z)$ the field enhancement factor along the axis of the symmetrical protrusion and is described by

$$f(Z)=1+2(R/Z)^3 : \text{hemispherical protrusion} \qquad (2)$$

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

$$: \text{spherical protrusion} \qquad (3)$$

where Z is the distance from the base surface. For compressed SF_6 ($p\gtrsim 1$ bar)[2], the effective ioni-

---

*正會員：嶺南大工大 副教授・工博

接受日字：1978年 1月 27日

zation coefficient α can be written as

$$\alpha(Z)=\beta\cdot E(Z)-\frac{KP}{Z(P)} \qquad (4)$$

where $\beta=27.8\text{kV}$
$K=246(\text{bar mm})$
$Z(P)$=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). However, this value is reduced by the enhanced field near the protrusion to a value

$$E_0/p=\xi(E/p)_{\lim} \qquad (5)$$

where ξ is the surface roughness factor[1].

An electron avalanche developing along the line of force may lead to breakdown. This threshold of breakdown in SF_6 is determinded by the streamer breakdown criterion[3]

$$\int_R^{R+Z0}\alpha(Z)dZ=k \qquad (6)$$

in which k is the streamer constant.

Using equations form (1) to (6), the normalized critical avalanche length, breakdown field strength and corresponding surface roughness factor were computed as a function of pR for hemispherical and spherical protrusions by the aid of a computer.

Figure 1 and 2 show the normalized critical avalanche length U_0 for hemispherical and spherical protrusions respectively. In both cases U_0 decreases very rapidly with increasing pR reaching ~1 at pR$\gtrsim$100 bar μm.

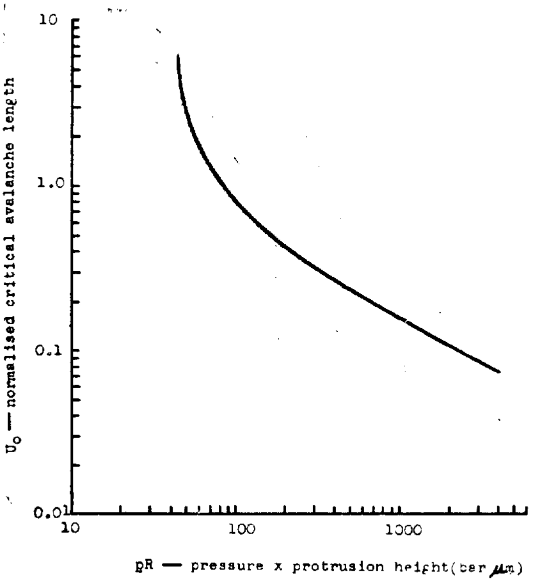

Fig. 1. Normalised critical avalanche length for a hemispherical protrusion in SF_6

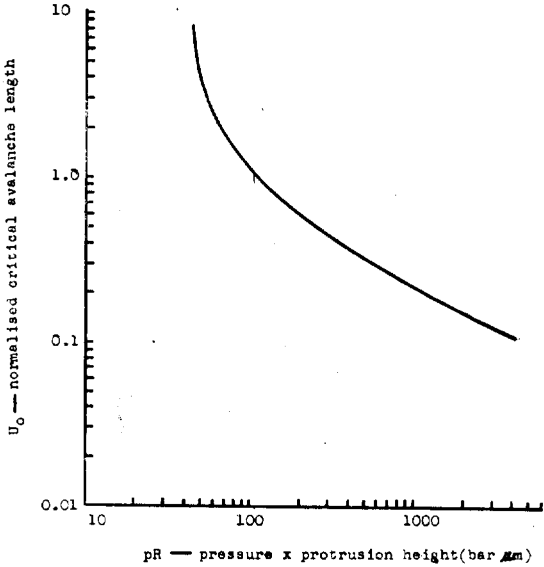

Fig. 2. Normalised critical avalanche length for a spherical protrusion in SF_6

3. Theoretical comparison of the streamer constant

It is generally assumed[3] that for most common gases a streamer may be formed when the number of charge carriers in an avalanche reaches a value of ~10^8. However, Pedersen[4] showed, using the experimental results from Boyd and Crichton[5], that the streamer constant $k$for SF_6 may be as low as 10.5. In contrast Radwan[6] suggested k to be 18 for the range of pressure from 1 to 8 bar and for pressures from 6 to 12 bar be considered that the value of k rose to 22. An uncertainty as to the value of this constant for SF_6 still exists.

Fig. 3 presents the influence of the value of streamer constant on the threshold of the surface roughness effect on breakdown calculated as described in above section. When 10.5 is used as the value of stramer constant, 42 bar μm is determined as the value of pR above which the influence of surface roughness is effective, whereas 80 bar μm is obtained when 18 is chosen for the value of k. The

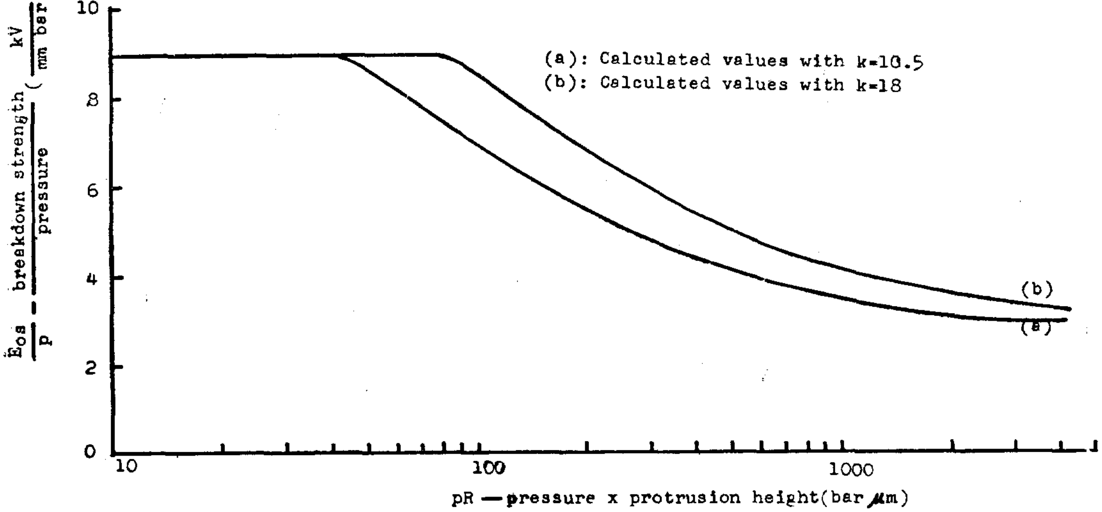

Fig.3. Calculated effect of the streamer constant on the value of E_{0s}/p in SF$_6$

threshold where the value of E_0/p becomes dependent on pR, is markedly dependent on the value of k : this contrasts with the usual assumption that breakdown thresholds calculated using the streamer criterion are insensitive to the value chosen for k. The difference in the the values of E_0/p at identical pR, however, is gradually reduced with increasing pR. It is interesting to note that for values of pR $\gtrsim 2\times10^3$ bar μm, the value of the streamer constant does not affect very much the predicted values of E_0/p but for pR$\gtrsim$500 bar μm and the point of threshold, the values of E_0/p are strongly dependent on the value of the streamer constant.

Therefor, in SF$_6$ the value of k governs strongly the threshold value of pR, as shown in figure 3, which may be of importance in the use of such curves to the practical design of SF$_6$-insulated systems and in the interpretation of electrical discharge data for this gas in general. If the measured plot of E_s/p(E_s=static breakdown field strength) against pR lies below the curve calculated for the value of k=18, it lends weight to the interpretation that the breakdown processes may be dependent a field emission7). On the other hand the same measurements may be plotted lying above the curve calculated using k=10.5 in which case it may be argued that localised gas amplification alone may explain the observation1).

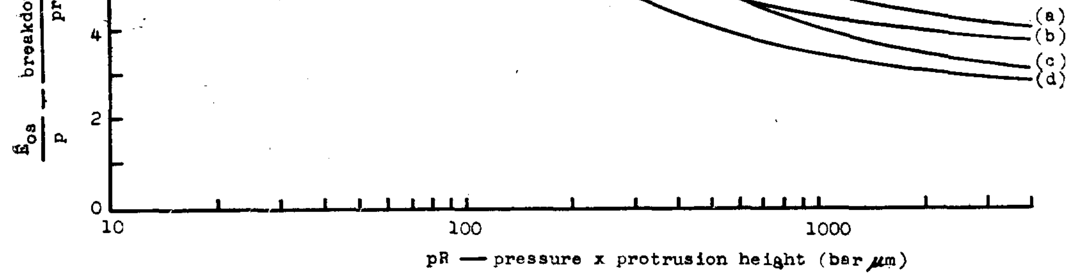

Fig.4. Calculated effect of protrusion shape on the value of E_{0s}/p in SF$_6$

4. Protrusion shape

Figure 4 presents values of E_s/p at static breakdown as a function of the product of the gas pressure and the protrusion height calculated as described in section 2. Curves (a) and (c) are for hemispherical and spherical protrusions respectively with the streamer constant $k=18$, and curves (b) and (d) are for hemispherical and spherical protrusions respectively with $k=10.5$.

With the same value of the streamer constant k (for example curves (a) and (c) or (b) and (d)), the point from which the breakdown field strength starts to be affected by the protrusion is at a common value of pR forboth hemispherical and spherical protrusions. This point is 42 bar μm for $k=10.5$ or 80 bar μm for $k=18$. The field enhancement on the tip of the hemispherical protrusion is 3 from equation 2 and 4.207 for the spherical protrusion from equation 3. Even with these different field ennancement factors, the onset of field reduction occurs at the same value of pR. Consequently, it may be concluded that the pR value from which the breakdown strength starts to be lowered is not dependent upon the magnitude of the field enhancement, i,e. protrusion shape.

With increasing pressure, or height of protrusion, i.e. pR value, however, higher field enhancement does lead to a lower breakdown field strength at a given value of pR.

5. Application to practical systems

For practical coaxial-electrode systems with small protrusions ($\lesssim 500\mu$m), the critical avalanche length over which $\alpha>0$, is also extremely short compared to the interelectrode distance. In coaxialelectrode geometry the electric field $E(Z)$ at a radial distance Z can be given as

$$E(Z)=C/Z \qquad (7)$$

where $C=q/2\pi\varepsilon$ and $a<Z<b$ (a, b=radius of inner and outer conductor respectively). Hence at the inner conductor,

$$E(a)=C/a \qquad (8)$$

and field at $Z=a+Z_0$ is given by

$$E(a+Z_0)=C/(a+Z_0) \qquad (9)$$

The field change ΔE over Z_0 can be written as

$$\Delta E=E(a)-E(a+Z_0)=CZ_0/(a(a+Z_0)) \qquad (10)$$

As $Z_0 \ll a$, and from equation (8),

$$\Delta E \simeq CZ_0/a^2$$

$$\simeq \frac{Z_0}{a}\cdot E(a) \qquad (11)$$

Assuming that, for a practical coaxial-electrode systems, $a \simeq 100$mm and $Z_0 \lesssim 500\mu$m (i.e. $U_0 \lesssim 1$ corresponding to pR$\gtrsim$100 bar μm), the macroscopic field has decreased by only 0.5% along the critical avalanche length and may be considered asconstant and equal to the field $E(a)$ at the inner conductor.

Consequently, this indicates that relatively low-voltage uniform-field tests can give results which directly apply to e-ratio coaxial-electrode systems of practical dimensions. Such uniform-field tests may offer some advantages since the energy dissipated for each discharge can be kept relatively small and so the conditions under test maintained relatively constant.

6. Conclusions

Since the value of E/p are strongly dependent on the streamer constant for the point of threshold of breakdown and pR$\lesssim$500 bar μm in SF_6, the breakdown mechanism in this range may be misinterpreted. Different protrusion shapes, i.e. different field enhancement of protrusions can not lead to affect on the threshold of breakdown in compressed SF_6. Finally as far as the streamer breakdown is concerned in breakdown mechanism, the results obtained with relatively low voltage uniform field tests can be applied to coaxial-electrode systems of practical dimensions which require relatively high voltage source for tests.

References

(1) Pedersen, A. : The Effect of Surface Roughness on Breakdown in SF_6, IEEE Trans. PAS 94, p. 1749 (1975).

(2) Lee, Dong-in : The Effect of Compressility on Breakdown and Modification of the Surface Roughness Factor in Compressed SF_6, To be Published in KIEE (Vol. 26 No. 6)

(3) Raether, H. : Electron Avalanches and Breakdown in Gases, London Butterworths (1964)

(4) Karlsson, P.W. and Pedersen, A. : Inherent Limitations in Uniform Field Discharge Data for SF_6, IEEE Trans. PAS 91, p. 1597 (1972)

(5) Boyd, H.A. and Crichton, G.C. : Measurement of Ionization and Attachment Coefficient in SF_6, Proc. IEE, 118, No. 12, p. 1872 (1971)

(6) Radwan, R.M. and Salama, M.M. : Calculations of Breakdown Voltages of Electronegative Gases, IEEE PES Winter Meeting, New York, C75 076—5 (1975)

(7) Nitta, T. : Electrical Breakdown Characteristics of Sulphur Hexafluoride, Joint Meeting of Kansai Branch of IEE of Japan (1974)

(8) Nitta, T., Yamada, N., and Fujiwara, Y. : Area Effect of Electrical Breakdown in Compressed SF_6, IEEE Trans. PAS 93, p. 623 (1974)

(9) Cookson, A.H. and Farish, O. : Particle-Initiated Breakdown Between Coaxial Electrodes in Compressed SF_6, ibid PAS 92, p. 871 (1973)