論 文
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空氣中 絕緣破壞에 있어서 電極表面의 요철에 의한 影響

The Effect of Surface Roughness on Breakdown in Air

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Abstract

In a uniform field, when an electrode with a hemispherical protrusion is set in atmosphere, by applying the streamer breakdown criterion and the surface roughness factor, the effect of field distortion due to electrode surface roughness on breakdown is investigated theoretically.

A quantitative relation between the threshold of breakdown and the air pressure times the heigh of protrusion is derived by the aid of a computor and the results are compared with that of SF_6.

I. Introduction

The effect of surface roughness on breakdown in SF_6 which is used as an insulating medium because of its high dielectric strength and good heat transfer properties, has been studied deeply by A Pedersen[1], T. Nitta[2], P.W. Karlsson[3] and so on.

Though SF^6 gas has high dielectric strength, local field enhancement owing to electrode surface roughness cause a large reduction of the dielectric strength depending on gas pressure. This phenomenon can be explained satisfactorily by the streamer theory of breakdown.

In the present paper, on the basis of pederson's theory, it was investigated how the local field enhancement due to the electrode surface roughness affect the dielectric strength.

In the present paper, two intervals of E/P value are set because α/P varies differently with different E/P. When the value of E/P increases, that of α/P (α is ionization coefficient) of air increases too.

In the range of 200 and 600V/cm·mmHg, the relation of them is $\alpha/P=Ae^{-B}/\frac{E}{P}$[4] ($A=14.6$ 1/cm·mmHg, $B=365$ V/cm·mmHg)[4] However, in this calculation, for the sake of convenience and reduction of errors, a linear relation, that is, $\bar{\alpha}/P=\bar{\beta}\frac{E}{P}-|\bar{K}|$, is assumed and used. Here the bar on a letter means the effective value, the two intervals of E/P value are 200~400V/cm·mmHg and 400~600V/cm·mmHg and for the each range the calculation was performed. The values of $\bar{\beta}$ and $\bar{K}$ used in the calculation are as follows for 200~400V/cm · mmHg: $\bar{\beta}=17.54$ 1/KV $\bar{K}=865.8$ $(\text{bar}\cdot\text{cm})^{-1}$ and for 400~600V/cm·mmHg: $\bar{\beta}=10.42$ 1/KV, $\bar{K}=-1270.92$ $(\text{bar}\cdot\text{cm})^{-1}$

II. Basic Theory of the Calculation

(1) Breakdown Mechanism

It is a characteristic feature of the streamer theory that breakdown is started by a single electron avalanche. When a cirtical number of free electron is achieved in the head of the avalanche, the anode and cathode-directed streamers.

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from the avalanche head lead to the formation of a conduction plasma channel between the electrodes and finally the spark breakdown follows. The threshold of breakdown is determined by the streamer breakdown criterion, $\int_0^{Z_0}\bar{\alpha}(Z)\,dZ=K$(1) (where Z is the distance from the surface of the electrode.)

A net gain of free electron prior to the formation of streamer is possible only within a distance Z_0 from the electrode. Outside this region $\bar{\alpha}$ is negative everywhere, i.e. all free electrons will be trapped by negative ion formation. In this region, the field strength is below the limiting value for which $\bar{\alpha}=0$. This value is given as $(E/P)\ \mathrm{lim.}=\frac{|\overline{K}|}{\bar{\beta}}$

(2) Calculation of Breakdown Field Strength and Corresponding Surface Roughness Factor.

There are various shapes of the protrusion to be selected. But, choosing one of the varicus shapes of protrusion may not affect on making a general conculsion.(5) Here, a hemispherical geometry is chosen to simplify the mathematical analysis.

The field along the line passing through the axis of a symmetrical protrusion of height R on the cathod is expressed as

$$E(Z)=E_0\cdot f(Z)^{(5)} \qquad (1)$$

Where E_0 is the macroscopic uniform field strength and $f(Z)$ is the field enhancement factor along the axis of the symmetrical protrusion. $f(Z)$ is known as

$$f(Z)=1+2(R/Z)^3{}^{(5)} \qquad (2)$$

for hemispherical protrusion.

The microscopic field distribution along the axis around the apex of a protrusion changes very rapidly into the macroscopic field distribution. We are, furthermore, interested in the field only within a short distance which is much smaller than the radii of curvature of the electrodes. This allows that the macroscopic field to be constant as a field strength E_0. The effective ionization coefficient and the streamer breakdown criterion can be written as

$$\bar{\alpha}(Z)=\bar{\beta}\cdot E-|\overline{K}|P^{(1)} \qquad (3)$$

$$\int_R^{R+Z_0}\bar{\alpha}(Z)dZ=K^{(1)} \qquad (4)$$

Where K is streamer constant. The value of K for the air is 18.42 in the calculation and it is derived from the basic formular, $N=N_0\cdot\int_0^Z\bar{\alpha}dZ$(6) for the number of electron in an avalanche, when the avalanche is proceeded as much as Z. Where $N_0=1$ and $N=10^8$ are used.

For perfectly smooth electrodes, the value of E_0/P at the threshold for breakdown would be approximately equal to be (E/P) lim. However this value is reduced by the enhanced field near the protrusion to a value,

$$E_0/P=\xi(E/P)\mathrm{lim}=\xi\left(\frac{|\overline{K}|}{\bar{\beta}}\right)^{(1)} \qquad (5)$$

here ξ is the surface roughness factor.

At $Z=R+Z_0(\bar{\alpha}=0)$ point, using equations (1) (2) (3) following expressions are easily derived

$$\frac{|\overline{K}|P}{\bar{\beta}}=E_0\left[1+2\left(\frac{R}{R+Z_0}\right)^3\right] \text{ and}$$

$$Z_0=R\left(\sqrt[3]{\frac{2\bar{\beta}E_0}{|\overline{K}|P-\bar{\beta}E_0}}-1\right)$$

If we substitute $\bar{\beta}E_0=\xi|\overline{K}|P$, which is from equation (5), into the above equation, Z_0 is described as

$$Z_0=R\left(\sqrt[3]{\frac{2\xi}{1-\xi}}-1\right).$$

Combining equations (1) (2) (3) (4), the surface roughness factor can be obtained

$$\int_R^{R+Z_0}[\bar{\beta}E_0\{1+2(R/E)^3\}-|\overline{K}|P]\ dZ$$

(apply $\bar{\beta}E_0=\xi|\overline{K}|P$)

$$=|\overline{K}|P\int_R^{R+Z_0}[\xi\{1+2(R/Z)^3\}-1]\ dZ$$

$$=|\overline{K}|P\left(\xi+\frac{\xi R(2R+Z_0)}{(R+Z_0)^2}-1\right)$$

(apply $Z_0=R\left(\sqrt[3]{\frac{2\xi}{1-\xi}}-1\right)$ to the above eq.)

$$=|\overline{K}|PR\left[\xi\frac{\sqrt[3]{2\xi}}{\sqrt[3]{1-\xi}}-\frac{\sqrt[3]{2\xi}}{\sqrt[3]{1-\xi}}-\frac{\xi\sqrt[3]{(1-\xi)^2}}{\sqrt[3]{4\xi^2}}+1\right]$$

$$=|\overline{K}|PR\left[1-3\sqrt[3]{\frac{1}{4}\xi(1-\xi)^2}\ \right]=K$$

$$PR=\frac{K|\overline{K}^{-1}|}{1-3\sqrt[3]{\frac{1}{4}\xi(1-\xi)^2}}=\phi(\xi)$$

$$\therefore\ \xi(1-\xi^2)=4\left(\frac{\phi|\overline{K}|-K}{3\phi|\overline{K}|}\right)^3 \cdots\cdots\cdots\cdots\cdots\cdots\cdots (A)$$

If values of ξ for different values of ϕ is obtained using eq. (A), we can calculate E/P, the breakdown field strength, over the the air pressure from eq. (5),

Ⅲ. Results

In the range of 200 and 600 V/cm·mmHg the breakdown threshold value with the increasing *PR* is lower than the expected value from the dielectric property of the air. That is, the point from which the breakdown field strength start to be affected by the electric field distorsion due to the protrusion is 250 bar μm in the range of 200 ~400V/cm·mmHg Fig. 1) and 150 bar μm in the range of 400~600V/cm·mmHe(Fig. 2). We can compare these valus with 42bar μm for SF_6 whn K=10.5 (80 bar μm, when K=18) (Fig. 3) Though the air has low dielectric strength, the air is affected less by the protrusion than the case of SF_6.

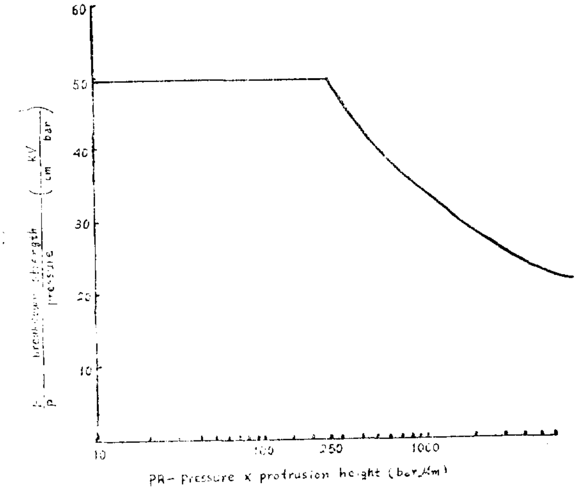

Fig. 1. Value of E/P for a hemispherical protrusion between 200 and 400 V/cm·mmHg in air.

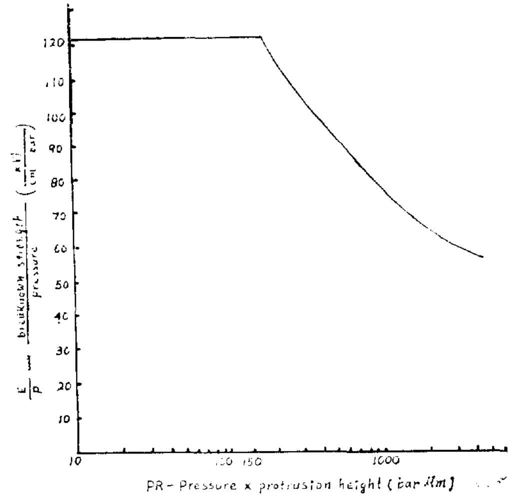

Fig. 2. Value of E/P for a hemispherical protrusion between 400 and 600V/cm·mmHg in air.

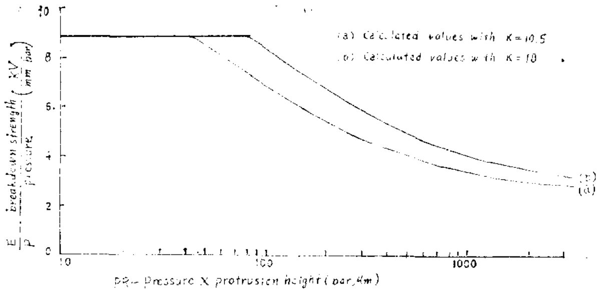

Fig. 3. Value of E/P for a hemispherical protrusion in SF_6.

Since microsocopic field strength is enhanced due to some surface defects as well as small conducting particles or dust particles which may be left in the gap, the air is affected smaller by the surface of the electrode system and small particle than SF_6. And, normalized critical avalanche length (Z_0) in air is longer than in SF_6. This can be understood from that $\bar{\beta}$ value in air is smaller than that in SF_6(27.8 1/KV), and maximum value of E/P in the range of 200~400V/cm·Hg is larger than that in the range of 400~600V/cm·mmHg in air.

Ⅳ. Conculusion

On breakdown in air, in the range of 200 and 400V/cm·mmHg, 250 bar μm is determined as value of PR (Pressure × height of protrusion) below which the influence of surface roughness is not effective on threshold of breakdown while in the range of 400 and 600V/cm·mmHg, 150 bar μm is obtained as value of PR. Hence, though the air has low insulation strength, the effect of the surface roughness on threshold of the breakdown of air is smaller than that of SF_6.

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