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COMMUNICATION

On the Concept of Electrode Surface Roughness with Reference to Discharge Phenomena in Strongly Electronegative Gases

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ABSTRACT

The use of geometrically well-defined protrusions in studies of the effects of electrode surface roughness upon the insulation strength of strongly electronegative gases is discussed. It is argued that, with respect to the roughness associated with production processes, the dimensions of artificial protrusions are inevitably too large. Consequently, results from investigations using such protrusions are not necessarily applicable to practical conditions.

INTRODUCTION

When compressed SF_6 was first introduced as an electrical insulant in HV power equipment, it was discovered that the insulation strength of the system was less than that predicted by theory. An explanation for this apparent reduction in the dielectric strength of compressed SF_6 can be given by considering the perturbations of the macroscopic electric field produced either by the microscopic roughness of electrode surface or by conducting particles. That such perturbations of the electric field should play a major role in the dielectric strength of SF_6 is due to the effective coefficient of ionization $\bar{\alpha}$ being a strongly varying function of the electric field strength E, particularly for E E_{lim}, where E_{lim} is the value for which $\bar{\alpha}=0$. This sensitivity of SF_6 to electrode surface roughness has provoked considerable interest in the dielectric behavior of other strongly electronegative gases and gas mixtures with a view to finding a gas with superior insulating behavior [1-3].

Experimental investigations into the effect of electrode surface roughness upon the dielectric strength of strongly electronegative gases have adopted two different approaches, viz. (a) the use of geometrically well-defined artificial protrusions mounted on plane electrodes and (b) the use of an electrode having a surface finish comparable with that related to production processes, but which in comparison to (a) is ill-defined.

The latter approach represents, with respect to insulation strength, the normal operating situation and thus results obtained from any investigation into the dielectric behavior of a gas are directly applicable to a practical situation. Owing to the complex structure of the electrode surfaces utilized, we are unable to derive any information about the associated field perturbations, and hence a deeper analysis of the results cannot be undertaken. The former approach provides a well-defined perturbation of the macroscopic electric field, and thus lends itself to an analysis of, for example, onset conditions.

In the present contribution, such an analysis is used to determine the relevant dimensions of artificial protrusions These dimensions are found to be comparable with those of the roughness associated with production processes. To-date however, the dimensions of the artificial protrusions employed have all been much greater. This suggests an inability to obtain protrusions of the relevant dimensions. Consequently, as available artificial protrusions are unrepresentative of practical conditions, results from investigations using such protrusions are not necessarily applicable to practical conditions.

SIMULATION OF A ROUGH SURFACE

Several forms of artificial protrusion have been used

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in roughness investigations, e.g. a sphere [4], a hemisphere [5], or a circular wire [6]. For the purposes of the present discussion, we will examine the use of the last named, see Fig. 1.

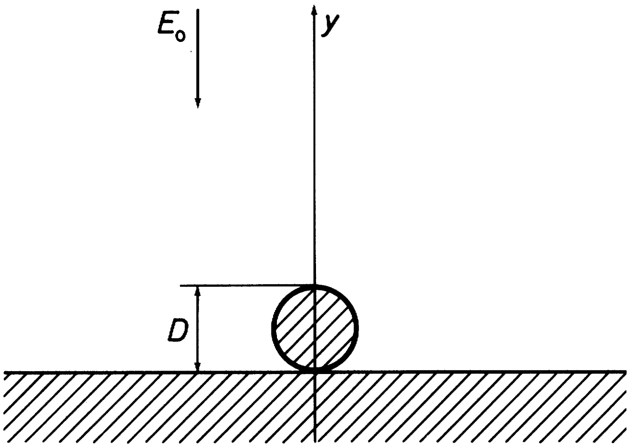

Fig. 1: Surface roughness model - circular wire.

In analyzing this roughness model, we assume that the plane electrode is of infinite extent and that the macroscopic electric field may be represented by a uniform field E_o. The solution of the Laplace equation for this electrode geometry can be obtained using conformal mapping. With this solution, the electric field distribution along the field line associated with the maximum field strength, i.e. the y-axis, see Fig. 1, can be shown to be given by

$$E(y) = \frac{(\pi D/2y)^2 E_o}{\sin^2(\pi D/2y)} \quad (1)$$

Hence for this protrusion model, the field enhancement factor m is $m = E_{max}/E_o = \pi^2/4 = 2.4674$.

On the basis of the streamer criterion and assuming that $\bar{\alpha}$ is, as a first approximation, a linear function of electric field strength E and gas pressure p, it is possible to derive a general expression for the discharge onset condition in a strongly electronegative gas [7]. This condition can be expressed, with reference to the macroscopic field and the present coordinate system, as

$$E_o/p = \frac{(M/p) + y_o - D}{\int_D^{y_o} f(y)\,dy} (E/p)_{lim}, \quad (2)$$

where M is the figure of merit for a strongly electronegative gas, and D is the wire diameter. The distance y_o is found from

$$E(y_o) = E_{lim} \quad (3)$$

and $f(y)$ is obtained from (1), i.e.

$$f(y) = E(y)/E_o \quad (4)$$

The concept of M is fully described in [7].

To quantify the reduction in E_o due to the presence of the protrusion, a surface roughness factor ξ is defined such that

$$E_o/p = \xi (E/p)_{lim}, \quad \text{with } 0 < \xi \leq 1. \quad (5)$$

Consequently upon utilizing Eqs. (2 to 5), the onset condition can be expressed in terms of the protrusion diameter D as

$$pD = \frac{M}{1 + \pi[\xi \cot(\pi D/2y_o) - (2y_o/\pi D)]/2} \quad (6)$$

As with other protrusion models of the present type for which the macroscopic electrode is assumed to be a plane and E_o is of infinite extent [8], a critical value of pD exists below which the surface roughness has no effect. For example, as $y_o \to \infty$, we find $\xi \to 1$ and $pD \to (pD)_{crit} = M$.

Since SF_6 is the reference gas against which other strongly electronegative gases are assessed, the calculations were undertaken only for this gas. The variation of ξ with p is shown in Fig. 2 for various values of D. For SF_6 we have $M = 0.004$ MPa mm [9]. In the present study, the non-ideal gas behavior of SF_6 [10] was neglected. It should be noted that the actual value of $(E/p)_{lim}$ is not required in the calculations.

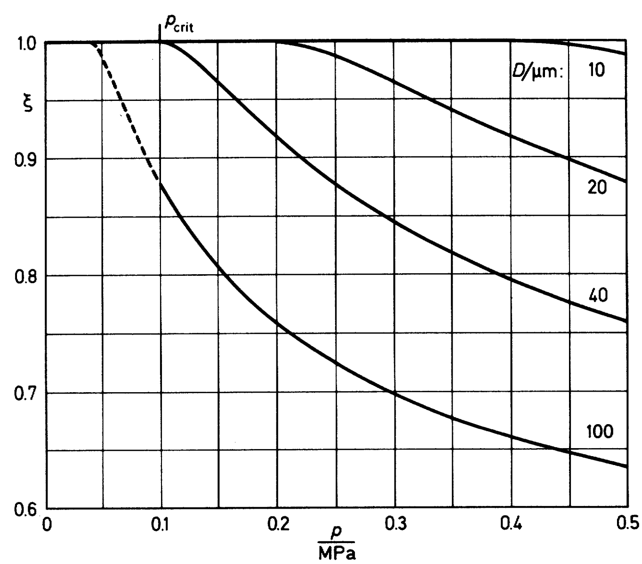

Fig. 2: Surface roughness factor ξ for SF_6.

DISCUSSION AND CONCLUSION

In practical compressed SF_6 insulated systems, the effect of electrode surface roughness is to produce a reduction in the insulation strength of the system from that predicted on the basis of the idealized macroscopic geometry. This effect is readily observed at high gas pressures, i.e. $p>0.1$ MPa. In the present paper, we will take the lower pressure limit for the onset of the reduction in the insulation strength to be *0.1* MPa, i.e. $p_{crit}=0.1$ MPa. This choice enables a maximum tolerable dimension for the protrusion under discussion to be determined.

From Fig. 2 it is clear that investigations into the influence of surface roughness upon discharge phenomena in SF_6 should employ wires with diameters less than *40* μm; $\xi<1$ at $p>0.1$ MPa. It must be emphasized that this particular limit of *40* μm is a specific feature of the roughness model under discussion. However, because this model displays a low *m*-value, this upper limit is not unrealistic.

Most production processes are associated with surface roughness dimensions of <25 μm, see Fig. 3 [11]. Hence it would seem desirable to employ artificial protrusions of similar dimensions. To-date however, the dimensions of the different protrusions have all been >100 μm [4-6], suggesting that it is not readily possible to obtain single, artificial protrusions of the appropriate dimensions, see Fig. 2 for the influence of $D=100$ μm. That it is necessary to consider protrusions of smaller dimensions is clear from a comparison of the results of Biasiutti et al. [6] with those of Vibholm and Crichton [12]. In this latter study, the authors found that a considerable degree of corona stabilization could develop when utilizing electrodes having $R_a\leq 35$ μm. In contrast, Biasiutti et al. recorded no pre-breakdown phenomenon using wires of *200* and *400* μm diameter.

Consequently, although artificial protrusions having well-defined geometrical shapes can be used to check the validity of onset calculations, the difficulty in obtaining artificial protrusions of dimensions comparable to the roughness associated with production processes restricts their usefulness with respect to investigations of discharge development under practical conditions. Investigations into the sensitivity of strongly electronegative gases to electrode surface roughness should be undertaken using electrodes having a surface roughness of relevant dimensions. For example, <25 μm if a pure surface effect is to be examined, whereas larger dimensions would be appropriate if conducting particles are considered the main area of interest.

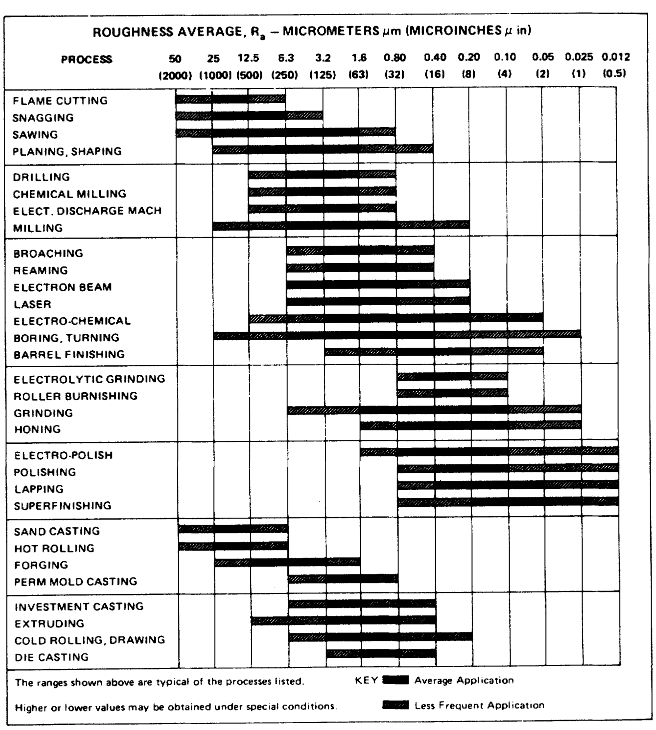

Fig. 3: Surface roughness dimensions associated with different production processes [11].

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