PROBABILISTIC FAILURE IN COMPRESSED SF_6 INSULATION DUE TO SURFACE ROUGHNESS

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Abstract

Electrode roughness greatly reduces the breakdown voltages of high voltage equipment insulated by compressed Sulphur Hexafluoride (SF_6). The situation is complicated by the presence of non-uniform fields which prevail in practice with gas-insulated systems (GIS). This paper models the insulation breakdown mechanism in the presence of such surface roughness, or protrusions, taking into account their random nature which lends the problem to probabilistic treatment. In order to generalize the surface roughness effect on the dielectric withstand of SF_6-insulated system, surface roughness is simulated by using a random event generator. The perturbations which these protrusions inflict on the field distribution in a nearly-uniform field gap are assessed. The corresponding breakdown voltages are estimated for different patterns of surface roughness. The results are statistically formulated .

INTRODUCTION

SF_6 gas-insulated power apparatus (GIS) are required to be operated with the highest insulation performance and reliability to ensure a stable electric power supply [1]. Therefore, the development of a preventive technology for insulation breakdown in GIS becomes important. One of the features which would produce service interruption is caused by the distortion of the electric field due to protrusions (or, roughness) on the electrode surface. The dielectric withstand of SF_6 insulated system is extremely sensitive to local inhomogeneity of the electric field, which may result from the presence of defects such as protrusions on electrode surface, metallic particles, contaminations, triple junction, etc. Investigations of ways to reduce the effect of such defects are thus important.

Electrode surface roughness causes a large reduction in the breakdown strengths of gas-insulated apparatus [2]. Surface roughness leads to the existence of localized microscopic regions with local field intensities larger than the average field in the gas near the electrodes. Depending on the gas pressure, such regions of enhancement field intensity would result in a large reduction of the breakdown voltage. Some of the main factors which influence those discharges in SF6 are the shape, size, distributions and chemical composition of the contaminants over the electrode surfaces. The statistical distribution of the electrodes surface and the degree of electrode surface roughness then become distinctly relevant .

Unlike the case of perfectly smooth surfaces, modeling rough electrode surfaces becomes complex because of the complexity of the geometrical structure of the surfaces. Efforts were recently made to model surface roughness and simulate the surface profile formed in the machining process [3,4].

In order to assess the influence of surface electrode roughness, the spatial distribution of electric field perturbed by surface protrusions must be modeled. This is followed by investigating the effect of such perturbation on the breakdown voltage. The present paper simulates a practical electrode rough surface taking into account the statistical nature of that roughness. The corresponding breakdown voltages as related to the degree of roughness for compressed SF_6 gaps are then assessed. In a recent paper, this approach was applied to air insulation [6].

METHODOLOGY

The analysis of the present problem runs in three consecutive yet interrelated steps. The electrode surface texture is modeled at first , the electric field enhancement due to surface roughness is then estimated, and ,finally, the discharge through SF_6 is modeled and the breakdown voltage is estimated.

Simulation of Surface Texture

In order to investigate the influence of surface roughness its random nature must be taken into consideration. Irregularities in the electrode surface are produced by the metal finishing process and also by system aging and ,therefore, surface features can be very complex [7]. It has been shown that the surface texture is either flat or wavy or a combination of both as seen in Figure (1). In addition to the rough texture imposed on the surface by the finishing process there is an inherent micro-structure irregularity due to the crystalline, or even molecular, structure of the material. Very few natural surfaces are known to be molecular smooth, such as mica. However, in metals, the presence of grain boundaries will give rise to troughs and ridges of the order of 100 μm. Mechanical studies [7] of this phenomena found that the irregularity over a surface is random and can be characterized:

- the center line of the irregularity height ; and
- the degree of sharpness which may be characterized by the protrusion's "mean sharpness angle" in this work.

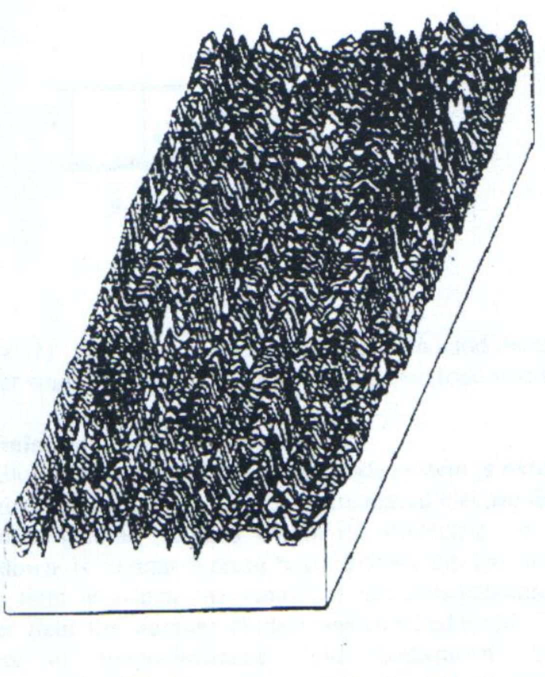

Figure (1) : The Constituents of Surface Texture.

To model the roughness of a complex surface texture the "Monte Carlo" technique is used. Two statistical variants are identified, namely, the protrusion's height and its mean angle (sharpness degree of the protrusion). Appropriately chosen standard probability distributions are assigned to the above two variants based on the physical data of the surface. The parameters of the distributions of the two variants are computed and the correlation between them is determined. The following steps are subsequently implemented :

1. Random number generator (RNG1) is used to generate the protrusion's height from its fitted Normal (gaussian) distribution $N(\overline{R}, \sigma_r)$, where $\overline{R}, \sigma_r$ are the mean and standard deviation of the marginal roughness distributions, respectively. For a given protrusion height ,the conditional normal distribution parameters (mean and standard deviation) of the protrusion mean angle $\overline{\theta}$ are calculated by

$$\hat{\theta} = \overline{\theta} + r(\sigma_\theta / \sigma_r)(\overline{R} - R_i)$$

$$\sigma = \sigma_\theta \sqrt{(1 - r^2)}$$

Where R_i is the i^{th} protrusion height generated by RNG1, r is the correlation coefficient between the roughness height and its width ; $\overline{\theta}$ and σ_θ are the marginal values of the protrusion sharpness.

2. Random number generator (RNG2) is used to produce a protrusion sharpness angle from the conditional normal distribution $N[\hat{\theta}, \sigma]$.

3. The steps 1,2 are repeated to scan the whole electrode width.

Assessment of Field Enhancement

To quantify the effect of surface roughness , the electric field enhancement due to the presence of a protrusion must be assessed and its distribution inside the proposed gap must be determined. Basically, the computation of electric fields is to solve Poisson's equation:

$$\nabla^2 . \Phi = -\frac{\rho}{\varepsilon_0}$$

in the presence of free space charge ,in which Φ is the potential, ρ is the space charge density, and ϵ_0 is space permittivity. In the case of a space charge-free field the above equation reduces to Laplace's equation:

$$\nabla^2 . \Phi = 0$$

Laplace's equation is solved by the charge simulation method (CSM) where the electrodes surfaces and dielectric interfaces are replaced by a system of discrete charges located outside the domain of field computation. The form of the simulating charge is predetermined to best suit the electrode shapes and the boundary conditions. The optimum positions and numbers of those simulation charges are determined according to the accuracy required.

In the present problem the uniform electric field is synthesized by a set of finite charge segments placed along the axis of symmetry beyond the electrode. The surface roughness is simulated by a complex of protrusions located over the electrode surface. Each single protrusion is simulated by a ridge of height R_i, sharpness angle θ_i and length L, as seen in Figure (2). To avoid singularities caused by the sharp edges of the protrusion, each protrusion is terminated by a hemi-cylindrical cap. Finite line charges are placed inside the protrusion whose number ranged from one to three according to the protrusion dimensions. Charge magnitudes are determined by solving the system's linear equations. The simulation validity is evaluated by verifying whether the boundary conditions are fulfilled. The mean field error in the present study is forced to be less than 5% over the entire electrode surface.

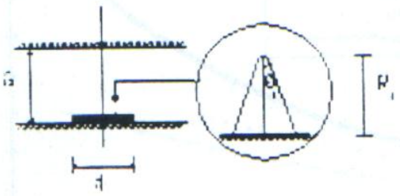

Figure (2) . Simulation of a single protrusion , and the gap under study : G: the gap length, d: the electrode width.

Determination of Breakdown Voltage

The dielectric withstand of any electrode system is reduced by stress enhancements that cause increased electric fields in small volume regions within the dielectric. In SF_6 breakdown is certain to occur beyond 90kV/cm-bar, which is the field at which the number of electrons generated is greater than the number of electrons attached by SF_6. The process of inhomogeneous field breakdown for a nonuniform field is much more complex but at least as important [8]. SF_6 - insulated apparatus for power engineering use is designed to have very little, if any, critical volume (gas stressed above 90 kV/cm-bar) at its lightning impulse rating. Therefore, if such apparatus fails, some defect is thought to have caused an increase of the field over the design value, i.e. means an inhomogeneous field condition.

The process by which a small stress enhancement can cause breakdown of the total gap in SF_6 is explained as follows. With an applied electric field, discharges in the gas occur as a result of ionization created from the enhanced electric field at the protrusion tips on the electrode surface. The discharges may lead to streamer formation and ultimate breakdown of the gas. For a non-uniform field gap, corona discharges will occur when the conditions for a streamer formation in the gas are fulfilled. Streamer formation is dependent on the gas pressure and field distribution. Therefore, it depends on the electrode profile, geometry of the surface protrusions and on the instantaneous value of the ambient field. The condition for streamer formation is given by:

$$\int \left[\alpha(x) - \eta(x)\right] dx \geq K \qquad (1)$$

Where, $\alpha(x)$ and $\eta(x)$ are the first ionization coefficient and the coefficient of attachment, respectively; both being functions of field and thus of geometry. The distance x_c from the protrusion tip is where the net ionization is zero, normally known as the ionization boundary. The constant K is taken to satisfy an electron avalanche size in the order 10^8, i.e. K = 18.4. The effect of avalanche space charge was taken into consideration. Over a certain pressure range the field at the high-stress electrode is stabilized near its corona onset value by the shielding effect of the corona discharge, resulting in a relatively high breakdown voltage. With increasing pressure, the corona stabilization weakens until, at a critical pressure P_c, breakdown occurs directly at onset. However, the space charge effect in this case was found to have only a little effect as it was reported once before [4].

RESULTS AND DISCUSSIONS

The breakdown voltages for non-uniform field SF_6 gaps due to protrusions on electrode surface are computed under DC voltages. The electrode protrusions are synthesized by the random generators events which reproduce the true roughness texture. The effects of different parameters such as gas pressures, the protrusions height and sharpness degree are presented.

Influence of SF_6 Gas Pressure and Protrusion Height

The influence of the protrusion height on the breakdown voltages for the study case is represented in Figures (3) and (4) for gas pressures of 1 and 5 bar; respectively, over a height range of R = 10 to 100 μm. The results are shown for various protrusion angle of sharpness, namely, 10°, 20°, and 30°. As the gas pressure increases, the breakdown voltages also increases due to a corresponding increase in inception voltage. The breakdown voltage decreases with an increased protrusion height and increased sharpness.

To have an over view of the effect of the protrusion height on the breakdown voltage, the mean breakdown voltage-for a given protrusion height- for the entire range of scanned sharpness angles is computed. This latter "global effect" of protrusion height is represented in Figure (5). From this figure, it is generally concluded that as the protrusion height increases, the field enhancement is also increased and so, the breakdown voltage is decreased.

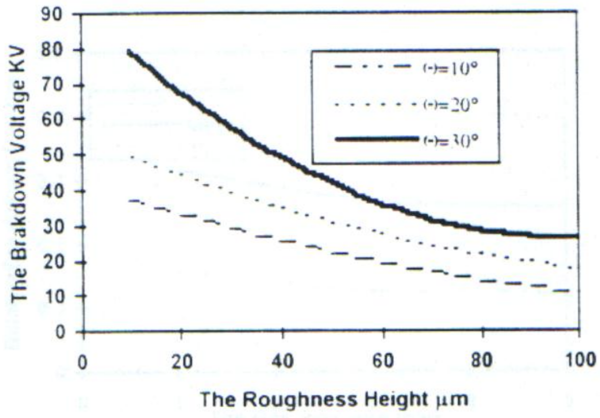

Figure (3) : Effect of roughness height on breakdown voltage P = 1 bar

In figs. (3 & 4) at roughness height = 0 the B.D.V. (for different cases) must be the same.

It is to be expected that all curves will eventually converge and meet at a zero roughness height giving a breakdown voltage equal to that of a clean surface [89 kV in Fig (3), and 445 kV in Fig. (4)]

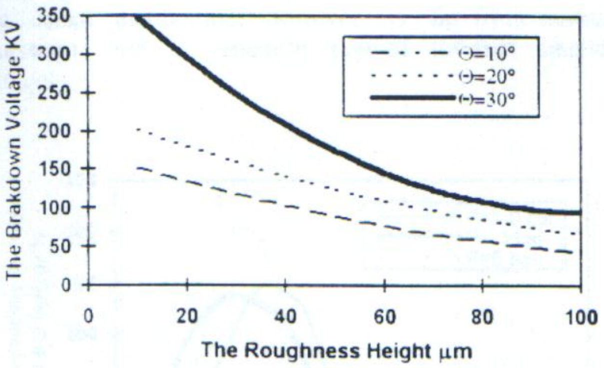

Figure (4) : Effect of roughness height on breakdown voltage P = 5 bar

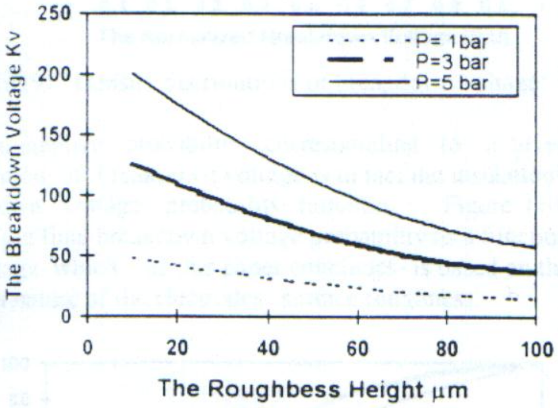

Figure (5) : Global effect of roughness height.

Influence of Sharpness Degree

Following a similar definition of "global" effects. Figure (6) shows the global effect of the sharpness degree of protrusion on the breakdown voltages under different SF_6 gas pressure. It is generally noted that, as the sharpness degree is increased the breakdown voltages increases due to the subsequent decrease in field enhancement.

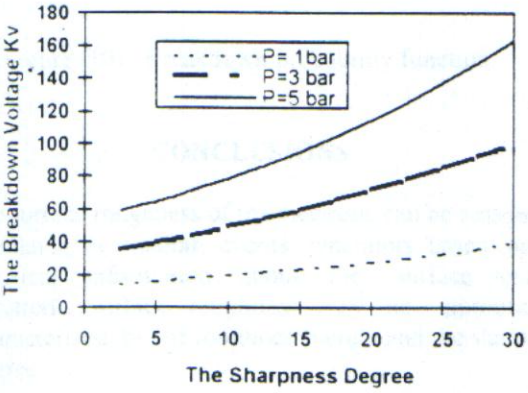

Figure (6) : Global effect of sharpness angle.

Overall and Relative Breakdown Voltages

For a given gas pressure the simultaneous random variation in both the protrusion's height and sharpness over the electrode surface resulted in an "overall" statistical distribution for the breakdown voltages. The mean and standard deviation of that distribution was calculated for each gas pressure, and the results are depicted in Figure (7).

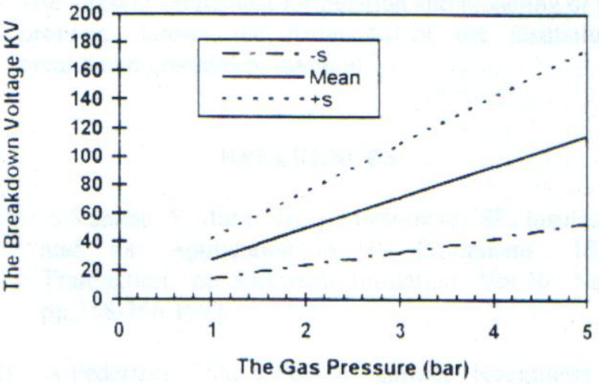

Figure (7) : Statistical scatter of breakdown voltage.

The relative role of electrode roughness in reducing the breakdown voltage is different from one gas pressure to the other. To be able to detect this feature, the results are re-expressed in a "normalized" manner where the breakdown voltage is referred to its highest value attained in the absence of roughness, i.e. using perfectly smooth electrodes. Figure (8) expresses the breakdown voltage in a relative (normalized) fashion. It appears that at higher gas pressures the insulation is relatively more sensitive to surface roughness as indicated by the decrease in relative breakdown voltage.

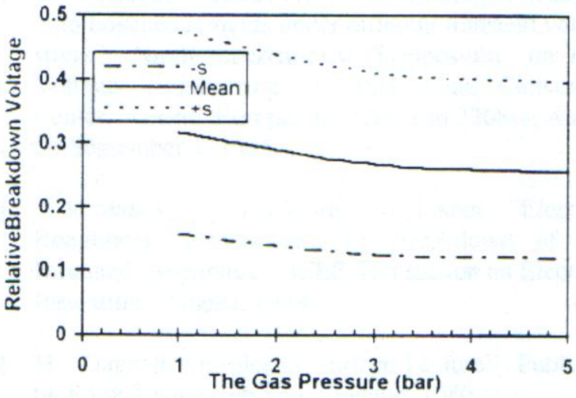

Figure (8) : Relative effects of gas pressure.

PROBABILISTIC EXPRESSION OF RESULTS

When the results were statistically analyzed, it was found that the probability density distribution of the breakdown voltage nearly follows a skewed distribution, Figure (9). This figure must be viewed in the light of the results of Figure (8) in which the relative mean breakdown voltage is seen to slightly decrease with pressure up to nearly 3 bar.

following which the breakdown voltage tends to level off. The actual distribution, however, is far from normal (gaussian) and is generally skewed towards smaller voltages.

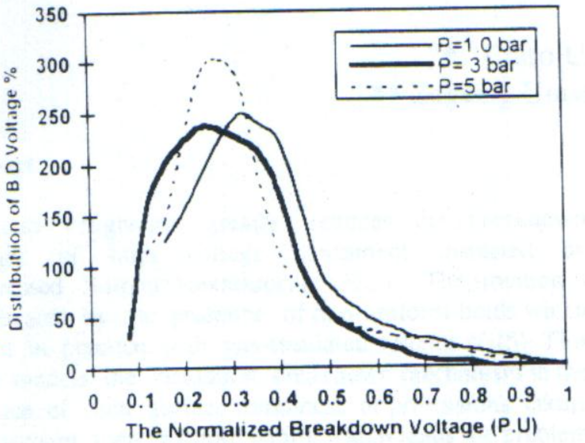

Figure (9) : Density distributions of breakdown voltage.

The cumulative probability corresponding to a given distribution of breakdown voltage is in fact the insulation's breakdown voltage probability function.. Figure (10) shows the final breakdown voltage probability as a function of voltage which -as this paper concludes- is based on the random nature of the electrodes' surface roughness.

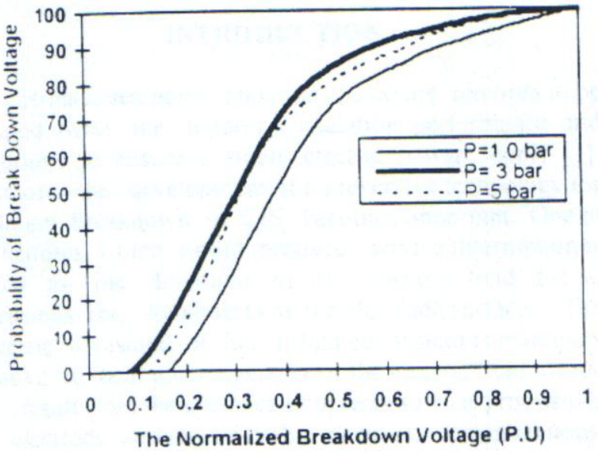

Figure (10) : Breakdown probability function.

CONCLUSIONS

1- The surface roughness of the electrode can be reasonably simulated by random events generators based on the practical information about the surface texture. Electrode surface roughness may be appropriately characterized by the roughness height and the sharpness degree.

2- The sharpness degree has a significant effect on the breakdown voltage. As the sharpness degree increases the breakdown voltage increases also.

3- As the roughness height increases the breakdown voltage decreases.

4- Expressing the results in a normalized fashion permits the detection of the insulation's sensitivity to surface roughness. As the gas pressure increases the SF_6 insulation becomes more sensitive to electrode surface roughness.

5- The present statistical formulation and modeling of the problem allows the deduction of the insulation's breakdown probability function.

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