Electrode Roughness Effects on the Breakdown of Air-insulated Apparatus

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ABSTRACT

The dielectric breakdown of air insulating systems is believed to be sensitive to local irregularity of the electric field which may result from the presence of defects such as contaminants adhering to electrode surfaces and surface roughness. Normally metal machining methods are used to eliminate such electrode surfaces irregularities. However, system aging and harsh operating conditions create and sustain such rough surface conditions which may,in turn, lead to the failure of insulation under the resulting enhanced electric stresses. Electrode surface roughness causes a large reduction in the breakdown strengths of gas insulated apparatus. 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. 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 air-insulated systems, 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.

1 INTRODUCTION

AIR is still the most widely used gas for electrical insulation and is, therefore, receiving ample attention. Electrical breakdown of air has been investigated by many researchers for many years, and it is well established that the gas insulation strength is dependent on many factors such as the geometrical form of the electrodes, and the nature of the partial,or prebreakdown,discharges through the gas which in turn depend on the form of the applied voltage.

Electrode surface roughness causes a large reduction in the breakdown strengths of gas-insulated apparatus. 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 air are the shape, size, distributions and chemical composition of the contaminants over the electrode surfaces. The statistical distribution of the particles present in the environment and on the electrodes surface and the degree of electrode surface roughness then become distinctly relevant [1, 2].

While the breakdown characteristics of clean air gaps with smooth electrodes are reasonably well understood [3, 4] fewer efforts were made to investigate and model the effect of surface roughness. Unlike the case of perfectly smooth surfaces, modeling rough electrode surfaces becomes complex because of the complexity of the geometrical structure of the surfaces.

Attempts were made [5] to investigate experimentally the influence of sand particles of different sizes and concentrations on the breakdown voltage of air. However, the influence of different particle distributions on the breakdown voltage was not examined. It was found that the breakdown voltages of asymmetrical gaps in the presence of dust and sand particles generally decreased under positive lightning impulses and was even more significant under negative lightning impulses.

The effect of surface roughness was investigated experimentally for a coaxial cylinder configuration where inner electrodes with surface roughness were employed. The surface finish of these electrodes was produced by a turning process and the respective roughness magnitudes were determined according to the American National Standard B46–1-1978. Discharge onset voltages (corona or direct breakdown) were detected oscillographically under negative dc applied voltage [6].

In order to assess the influence of surface electrode roughness, the spatial distribution of the electric field perturbed by surface protrusions

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must be modeled. This is followed by investigating the effect of such perturbation on the breakdown voltage. The present paper simulates a practical rough electrode surface taking into account the statistical nature of that roughness. The corresponding breakdown voltages as related to the degree of roughness for air gaps are then assessed.

2 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 air is modeled and the breakdown voltage is estimated.

2.1 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 the 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 microstructure irregularity due to the crystalline, or even molecular, structure of the material. Very few natural surfaces are known to be molecularly 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 [9] of this phenomenon found that the irregularity over a surface is random and can be characterized Figure 2 by the center line of the irregularity height; and the degree of sharpness, which may be characterized by the protrusion's 'mean sharpness angle'.

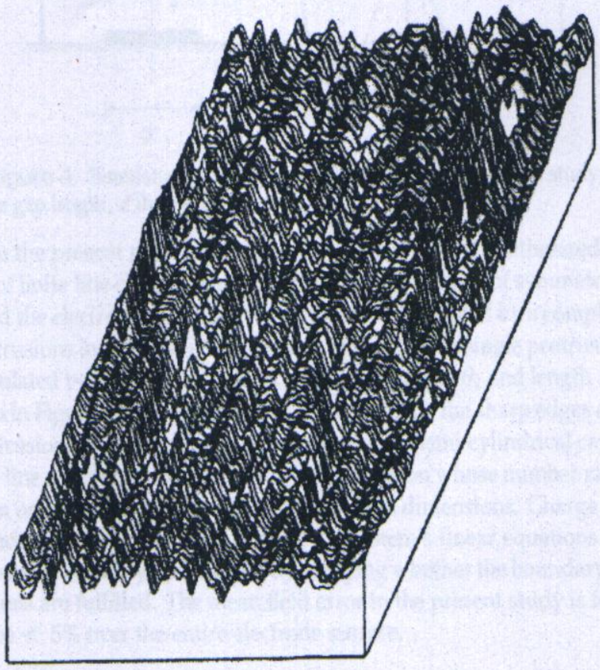

Figure 1. The Constituents of Surface Texture.

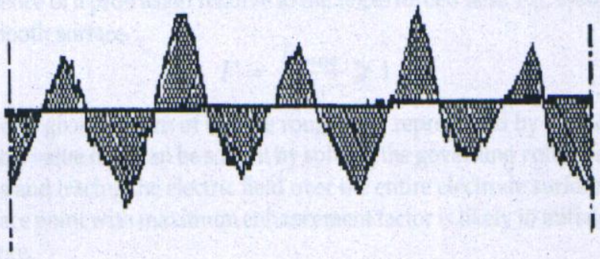

Figure 2. Graphic derivation of surface Roughness [7].

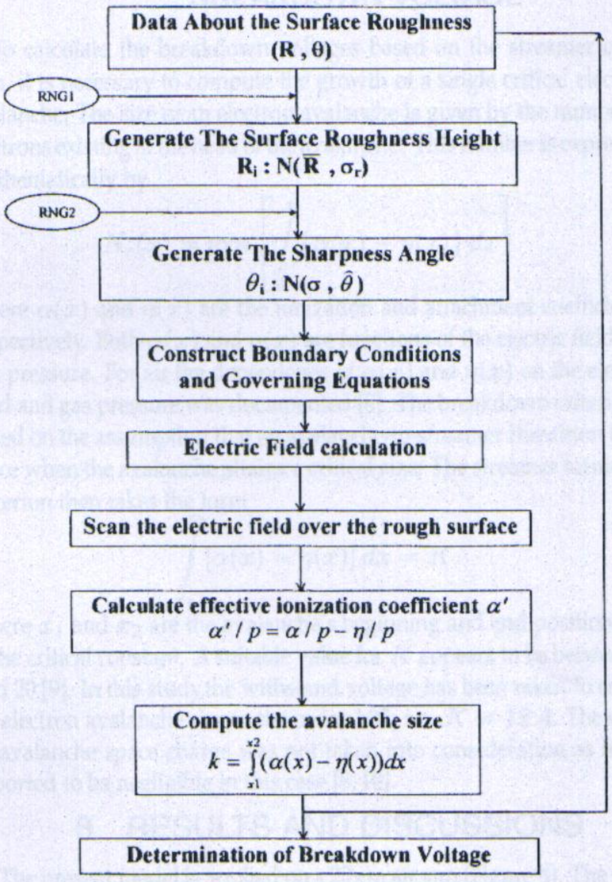

Figure 3. Main Calculation Procedures.

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 (protrusion sharpness). 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, summarized in Figure 3, are subsequently implemented.

1. random number generator (RNG) 1 is used to generate the protrusion's height from its fitted Normal (gaussian) distribution $N(\overline{R}, \sigma_r)$, where $\overline{R}$, σ_r are the mean and standard deviation of the marginal roughness height distributions, respectively, as illustrated in Figure 2. For a given protrusion height, the conditional normal distribution parameters (mean and standard deviation) of the protrusion mean angle θ are calculated by Equation 1, where R_i is the i-th protrusion height generated by RNG 1, r

the correlation coefficient between the roughness height and its angle of sharpness; $\hat{\theta}$ and σ_θ are the marginal values of the protrusion sharpness angle.

2. RNG 2 is used to produce a protrusion sharpness angle from the conditional normal distribution $N(\hat{\theta}, \sigma)$.
3. Steps 1,2 are repeated to scan the whole electrode width.

$$\begin{aligned} \hat{\theta} &= \overline{\theta} + r\left(\frac{\sigma_\theta}{\sigma_r}\right)(\overline{R} - R_i) \\ \sigma &= \sigma_\theta\sqrt{1 - r^2} \end{aligned} \tag{1}$$

2.2 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 based on solving Poisson's equation

$$\nabla^2 \cdot \Phi = -\frac{\rho}{\varepsilon_o} \tag{2}$$

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

$$\nabla^2 \cdot \Phi = 0 \tag{3}$$

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.

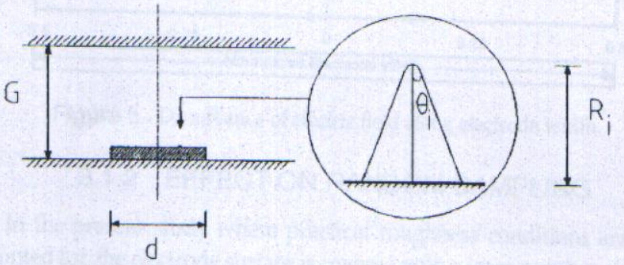

Figure 4. Simulation of a single protrusion, and the gap under study; G the gap length, d the electrode width.

In the present problem the uniform electric field is synthesized by a set of finite line 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 4. 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 $< 5\%$ over the entire electrode surface.

To quantify the perturbation of electric field on a rough surface a field enhancement factor F is defined as the maximum field E_{max} in the presence of a protrusion relative to the unperturbed field E_0, assuming a smooth surface.

$$F = \frac{E_{max}}{E_0} \geqslant 1 \tag{4}$$

For a given pattern of surface roughness, represented by $\overline{R}$ and $\overline{\theta}$, a critical value of F can be sought by solving the governing voltage equations and tracing the electric field over the entire electrode surface. The surface point with maximum enhancement factor is likely to initiate discharge.

2.3 DETERMINATION OF BREAKDOWN VOLTAGE

To calculate the breakdown voltages based on the streamer criterion, it is necessary to compute the growth of a single critical electron avalanche. The size of an electron avalanche is given by the number of electrons existing at the head of the avalanche. This number is expressed mathematically by

$$N_e(x) = \exp\left[\int_0^x \{\alpha(x) - \eta(x)\}\, dx\right] \tag{5}$$

where $\alpha(x)$ and $\eta(x)$ are the ionization and attachment coefficients, respectively. Both $\alpha(x)$ and $\eta(x)$ are functions of the electric field and gas pressure. For air the dependence of $\alpha(x)$ and $\eta(x)$ on the electric field and gas pressure was documented [8]. The breakdown criterion is based on the assumption that an avalanche-to-streamer transition takes place when the avalanche attains a critical size. The streamer formation criterion then takes the form

$$\int_{x_1}^{x_2} [\alpha(x) - \eta(x)]\, dx = K \tag{6}$$

where x_1 and x_2 are the avalanche's beginning and end positions, K is the critical constant. A suitable value for K appears to be between 15 and 20 [9]. In this study,the withstand voltage has been taken to satisfy an electron avalanche size in the order 10^8; *i.e.* $K = 18.4$. The effect of avalanche space charge was not taken into consideration as it was reported to be negligible in this case [8, 10].

3 RESULTS AND DISCUSSIONS

The present model is applied on a 20 cm air gap (Figure 4). The minimum breakdown voltage is computed at the location where field distribution is most likely to cause breakdown along the gap, *i.e.*, at the maximum integrated ionization coefficient path. Several factors are known to influence the minimum breakdown voltage,namely, the electrode width, the roughness distribution, and the degree of sharpness.

3.1 EFFECT OF ELECTRODE WIDTH

The electrode width has two significant influences on the above model. The electrode width affects the inherently assumed uniformity of the unperturbed field, and the electrode width shows an influence over the model's sample size which,in turn, affects the 'faithfulness' of the random event generation process. These two aspects of electrode width influence are discussed in Sections 3.1.1 and 3.1.2.

3.1.1 EFFECT ON UNPERTURBED FIELD UNIFORMITY

The model assumes that the electric field in the absence of roughness (the unperturbed field) is uniformly distributed along the flat electrode and within the gap. For an electrode of a markedly limited width the end effect of the electrode surface is enhanced and the unperturbed field is not perfectly uniform along the electrode width. In this case, the field tends to increase significantly at the two ends. However, the extent of this increase into the surface depends on the gap-to-width ratio G/d as seen in Figure 5. For a $G/d < 20$, it is found that the enhancement field factor maintains a constant value within 1% over more than 90% of the electrode. Outside this uniform field zone, *i.e.* near the edges the enhancement field factor remains within 10% of its value.

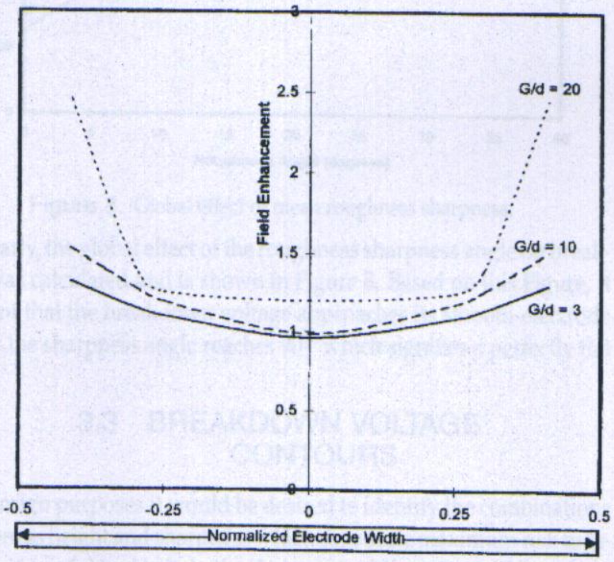

Figure 5. Disturbance of electric field along electrode width.

3.1.2 EFFECT ON RANDOM SAMPLING

In the present study where practical roughness conditions are accounted for, the electrode surface is covered with a large number of protrusions whose number depends on the electrode width. Unlike a standalone protrusion where significant field enhancement materializes depending on its dimensions, the maximum field enhancement factor in the case of a true rough surface is lower due to the mutual shielding effect among protrusions. This mutual shielding,in turn, is influenced by the electrode width.

The present model generates a random sample of protrusions which is limited in size as the surface is scanned uniformly. This random selection process leads to a computed breakdown voltage which, in turn, differs from one sample to the next and its value fluctuates statistically over a certain range. However, as the electrode becomes wider the random sample becomes larger and,consequently, the statistical fluctuation in the results diminishes and the resulting breakdown voltage becomes more consistent. This fact is demonstrated in Figure 6 for arbitrarily chosen values of mean roughness height and sharpness (angle). The results are normalized by referring them to the ultimate value reached when a wide enough electrode is used.

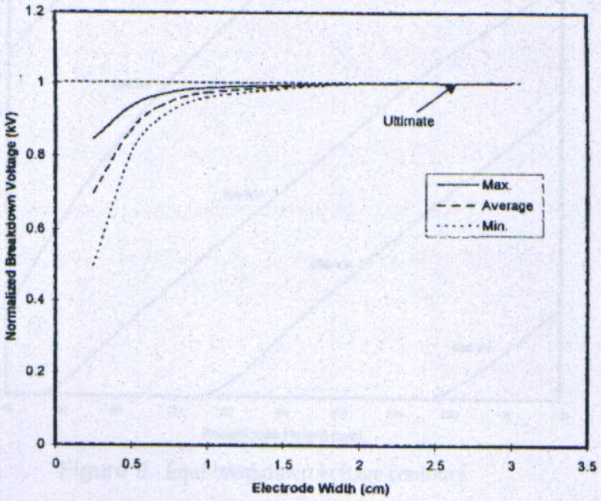

Figure 6. Effect of the electrode width on the breakdown voltage.

3.2 EFFECT OF ROUGHNESS DIMENSIONS ON BREAKDOWN

The breakdown voltage was calculated, as explained above, for the case shown in Figure 4. True physical data obtained from machining handbooks were used to obtain the statistical parameters of electrode surface roughness.

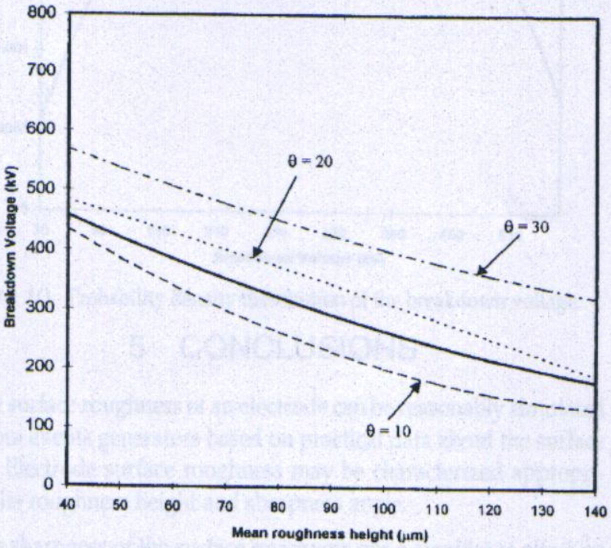

Figure 7. Effect of mean roughness height on breakdown voltage. (The solid line shows the mean breakdown voltage for a given roughness height for the entire range of sharpness angles).

Figure 7 shows the effect of the mean roughness height on the breakdown voltage of a 20 cm uniform air gap under dc voltage for different degrees of sharpness. The expected fact is noted that the breakdown voltage decreases as the mean roughness height increases. The rate of reduction in the breakdown voltage is affected by the degree of sharpness and becomes more significant with smaller roughness sharpness angle θ.

To have an overview of the effect of the roughness height on the breakdown voltage, the mean breakdown voltage, for a given roughness height and the entire range of scanned sharpness angles is computed. This latter global effect of roughness height is also depicted in Figure 7. It is noticed that as the roughness height decreases, the breakdown voltage increases and approaches its smooth-electrode value.

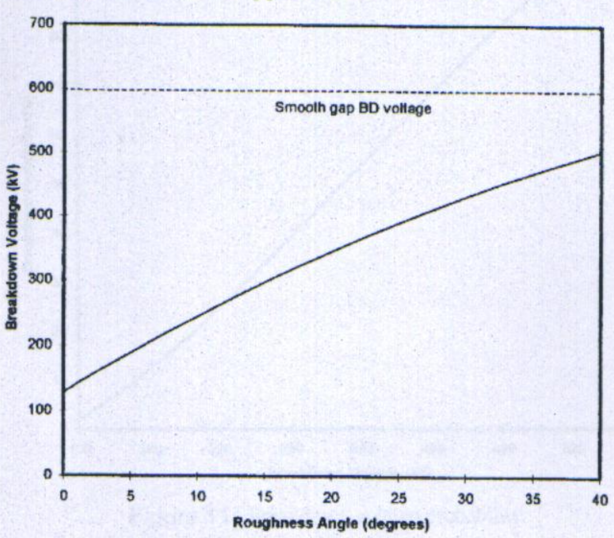

Figure 8. Global effect of mean roughness sharpness.

Similarly, the global effect of the roughness sharpness angle on breakdown was calculated and is shown in Figure 8. Based on this Figure, it is evident that the breakdown voltage approaches its smooth-electrode value as the sharpness angle reaches 90° which signifies a perfectly flat surface.

3.3 BREAKDOWN VOLTAGE CONTOURS

For design purposes it would be desired to identify the combinations of roughness height and sharpness which constitute maximum risk to insulation. A useful tool to help the designer in this area would be a chart such as that shown in Figure 9. On the chart the equi-breakdown voltage contours are plotted on a (roughness height *vs.* roughness sharpness) plane. The chart demonstrates the expected fact that a large roughness height combined with a small roughness angle of sharpness constitutes the worst condition.

4 PROBABILISTIC EXPRESSION OF RESULTS

The random event generation algorithm described earlier was applied to the example electrode configuration using realistic electrode surface roughness statistics. Correspondingly, a large enough sample of computed breakdown voltages was obtained. When the results were statistically treated, it was found that the probability density distribution of the breakdown voltage nearly obeys a truncated Gaussian distribution as seen in Figure 10.

The cumulative probability derived from the breakdown voltage distribution is in fact the breakdown voltage probability function. Figure 11 shows the final breakdown voltage probability as a function of voltage which is based on the random nature of the electrodes' surface roughness. This function is known to be indispensable in coordinating insulation with overvoltage protective devices in power systems.

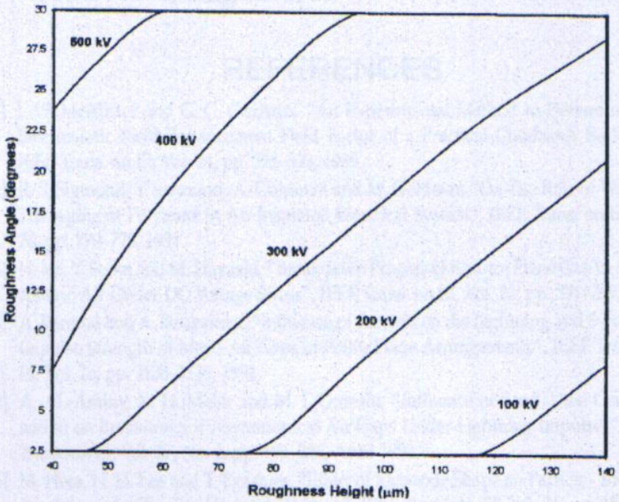

Figure 9. Equi-breakdown voltage contours.

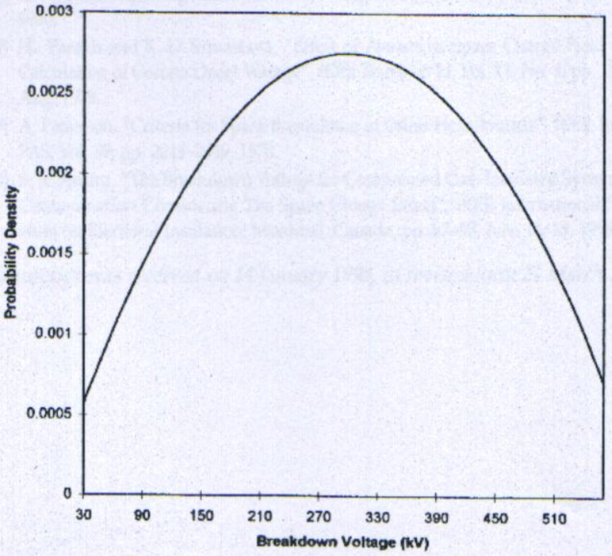

Figure 10. Probability density distribution of the breakdown voltage.

5 CONCLUSIONS

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

2. The sharpness of the surface roughness has a significant effect on the breakdown voltage. As the sharpness angle increases the breakdown voltage increases. In the typical case shown in this work, the breakdown voltage may randomly range between 180 and 600 kV for a corresponding variation in sharpness between 2.5° to 90°.

3. As the height of surface roughness increases the breakdown voltage decreases. In the typical case shown in this work, the breakdown voltage may randomly range between 600 and 160 kV as the roughness heights correspondingly range between 0 and 140 μm.

4. The breakdown voltage probability characteristics of a given gas insulation gap may be deduced using the random event generator tech-

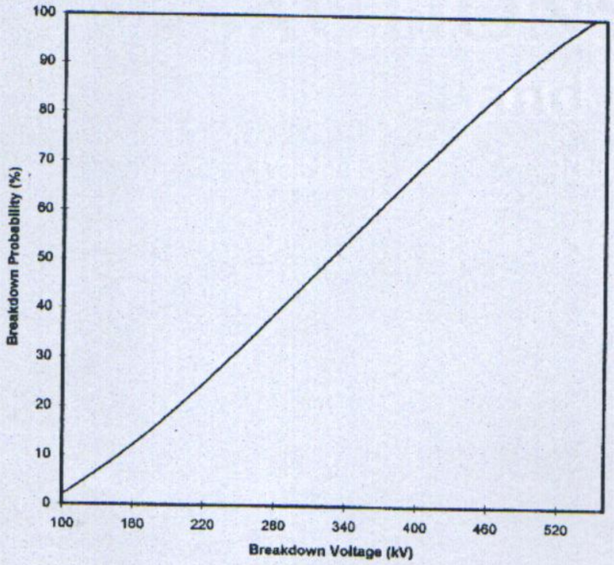

Figure 11. Breakdown voltage probability.

nique. Surface roughness may reduce the breakdown voltage of a typical air-gap by as much as 50% of its original (smooth surface) value.

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