Influence of Surface Roughness on Breakdown in Air Gaps at Atmospheric Pressure Under Lightning Impulse

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***Abstract*—In high voltage equipment, gases are often used as insulation material. Several parameters can influence the dielectric withstand voltage of gaseous insulation systems, such as the degree of inhomogeneity, gas pressure and type as well as surface roughness. This study focuses on the influence of surface roughness on the withstand voltage of atmospheric pressure air gaps under lightning impulse stresses. For this purpose, surface profiles of different rough metallic surfaces have been characterized using an optical surface scanner with a resolution of 3 nm. Based on the extracted features of the surface roughness, axial symmetric random surface profiles have been generated in a multi-physics simulation tool, electric field simulations performed, and streamer criterion applied to estimate the breakdown voltage. To verify the simulation results, lightning impulse breakdown voltage measurements have been carried out in simple configurations (sphere plate and rod plate) for four different degrees of surface roughness of the plate electrode. The experimental results confirm the observed trend in simulations, where the breakdown voltage is only to a limited extend reduced even for considerably rough surface profiles.**

I. Introduction

In high voltage equipment, gases are often used as insulation materials. One parameter that has an impact on the insulation properties of gas is surface roughness, especially under high pressure. This has been studied for different gases and pressures [1]–[5]. The impact of surface roughness has also been simulated using a Monte Carlo approach to generate the rough surfaces [6].

This work aims to investigate the impact of surface roughness by creating a model in the Finite Element Software COMSOL that generates random surface profiles and finds the breakdown voltage based on the streamer inception criterion from electric field simulations for simple geometries. The paper also aims to verify this model through experiments with $1.2/50\mu$s lightning impulse voltages in atmospheric air.

II. Theory

A. Streamer inception

For short gaps in atmospheric air, breakdown can be predicted from the streamer inception criterion

$$\int_{\Gamma} \alpha_{eff}(E) = ln(N_c) \tag{1}$$

Where $\alpha_{eff}(E)$ is the field dependent effective ionization coefficient and N_c is the critical number of electrons needed to create a self-propagating streamer head. Typical values for $ln(N_c)$ in air at atmospheric pressure are in the range from 9 to 18 [7], [8]. Γ is the integration path of the streamer and is often assumed to follow the most critical field line in the geometry for simplicity. $\alpha_{eff}(E)$ can be determined from empirical fit functions as presented in Eq. 2 and 3 given in [7].

$$\frac{\alpha_{eff}(E)}{p} = 1.6053 \cdot \left[\frac{E}{p} - 2.165\right]^2 - 0.2873 \tag{2}$$

For $E/p < 7.94$ kV/(mm·bar)

$$\frac{\alpha_{eff}(E)}{p} = 16.7766 \cdot \frac{E}{p} - 80.006 \tag{3}$$

For $E/p \geq 7.94$ kV/(mm·bar).

B. Surface Roughness

No real surface is ideally smooth and there are several parameters commonly used to characterize a surface. Fig. 1 shows an example of a surface profile with the mean line, R_a and R_p illustrated. R_a is the *arithmetic mean deviation* of the profile of the line segment L. R_p is the highest peak in the segment L. R_{dq} (not illustrated) is the *root mean square surface slope*, which gives an indication of how sharp the peaks of the surface are. A higher value of R_{dq} means sharper peaks. The method of determining these parameters can be found in literature [9].

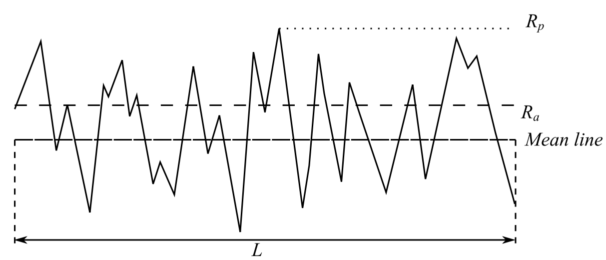
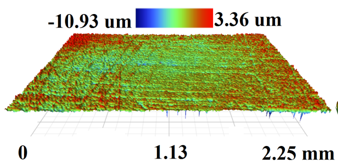


Fig. 1. Example of a surface profile with some parameters illustrated.

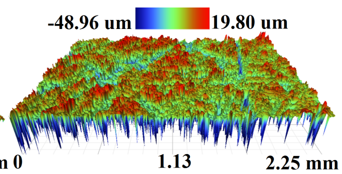
III. Method

A. Surface Measurements

To create rough electrodes, aluminum plates were treated with different degrees of sandpaper from very fine to rough (grit no. 2500, 80 and 40). To generate an extreme degree of roughness one electrode was treated with a Dremel engraving tool, in a rather non-reproducible way. The electrode surfaces have been scanned at 10 random locations with a Bruker Countour GT-K1 optical microscope, which has a vertical resolution of 3 nm. The area for each scan was a square with the dimensions 1.69×2.25 mm. The averages of the measured parameters of each plate are given in Table I. The electrodes were named A - D in ascending order of surface roughness. Fig. 2 shows the resulting surface scans of plates A (Fig. 2a) and B (Fig. 2b).



(a) Plate A.



(b) Plate B.

Fig. 2. Surface scans of plates A and B.

TABLE I
AVERAGE VALUES OF MEASURED SURFACE VARIABLES

Variable	Plate A	Plate B	Plate C	Plate D
R_a [μm]	0.428	2.613	4.251	26.19
R_p [μm]	5.046	22.539	32.754	176.98
R_{dq}	17.589	36.517	42.579	77.413

B. Simulations

The sphere - plate and rod - plate geometries, which are explained in Section III-C, have been created in the Finite Element Method Software COMSOL Multiphysics as 2D axi-symmetric models. For the ground electrodes the built-in random function of COMSOL was used combined with the possibility to represent surfaces as a function of spatial frequencies and elementary waves. According to [10], a three dimensional surface can be represented as:

$$f(x,y) = \sum_{m=-M}^{M} \sum_{n=-N}^{N} a(m,n) cos(2\pi(mx+ny) + \phi(m,n)) \tag{4}$$

Which is similar to a truncated Fourier series. In Eq. 4, x and y are spatial coordinates, m and n are spatial frequencies, $a(m,n)$ and $\phi(m,n)$ are amplitudes and phase angles, respectively. The phase angles $\phi(m,n)$ were randomly generated from uniform distribution. To generate more natural looking surfaces $a(m,n)$ was determined as a product between a normal distribution $g(m,n)$ and

$$h(m,n) = \frac{1}{(m^2+n^2)^{\frac{\beta}{2}}} \tag{5}$$

Where β is the spectral exponent and represents the decay of high frequencies. Eq. 4 was implemented, as explained in [10], as a parametric line that was scaled with the measured R_p from Table I. The spectral exponent was set to $\beta = R_{dq} \cdot \pi/360$ from the measured surfaces. The electric field lines of the solution have been exported to Matlab where Eq. 1 was calculated with the approximation given in Eq. 2 and 3 for all field lines in the model. The applied voltage was then increased in incremental steps until Eq. 1 was satisfied for at least one field line. The value of $ln(N_c)$ was calibrated for the model with an ideal ground electrode in a sphere-plate configuration to come close to the reference value of a sphere-sphere configuration given in the standard IEC60052 at 59.0 kV, which yielded a value $ln(N_c) \approx 16.5$. This value was kept constant for the rest of the simulations. The breakdown voltage was simulated for a new randomly generated surface, based on the surface parameters of plates A-D, 100 times per plate.

C. Experiments

A sphere with a diameter of $d = 20$ cm or a rod with a diameter $d = 2$ cm and hemispherical tip with the radius $r = 1$ cm (Fig. 4), was placed at a distance $g = 2$ cm above the rough electrodes which were connected to ground. The electrode gap was then stressed applying $1.2/50$ μs positive lightning impulses according to the up and down method as presented in [11] to estimate the U_{BD-50} value. The voltage was measured through a voltage divider with a Tektronix MSO 2024B Mixed Signal Oscilloscope as shown in the schematic illustration of the test circuit in Fig. 3. The temperature, pressure and humidity have been logged during the experiments and the results adjusted to standard reference atmosphere given in the standard IEC60060.

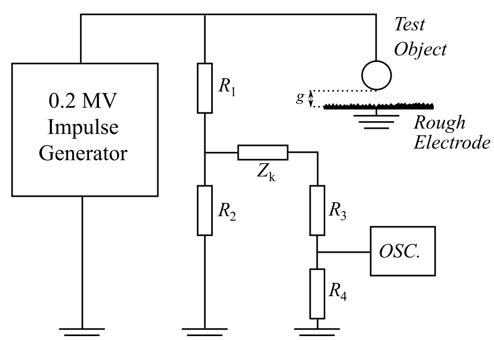


Fig. 3. Schematic drawing of the test circuit.

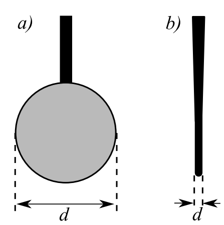


Fig. 4. Drawing of the test objects used, a) spherical electrode with $d = 20$ cm and b) rod electrode with thickness $d = 2$ cm and hemispherical tip with radius $r = 1$ cm.

IV. Results

A. Simulations

Fig. 5 shows a close up of one randomly generated plate (sphere- plate geometry and Plate C parameters) with the electric field strength as a surface plot. When setting the lower limit for field plot, the microscopic high field regions due to the surface roughness become visible.

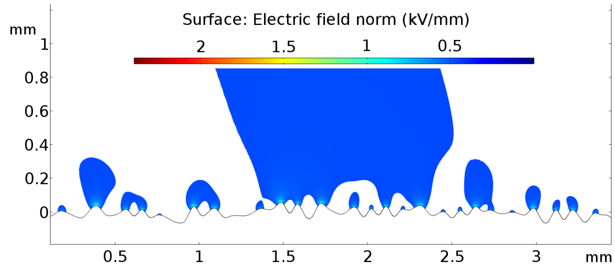


Fig. 5. Randomly generated surface in COMSOL with electric field strength above 0.47 kV/mm with 10 kV applied to the sphere electrode. The symmetry line is located at 0 mm, where the gap distance between the sphere and plate is the shortest.

Fig. 6 shows the average U_{BD-50} value of the 100 simulations for each plate in the sphere-plate geometry. The standard deviation of each simulation series, σ, is given as error-bars. The simulations show that there is a slight impact of surface roughness. However, even at the very rough plate D, the breakdown voltage is only about 2.3 % lower compared with Plate A, even when the roughness parameter R_p used in the simulation is increased with a factor of ~ 35.

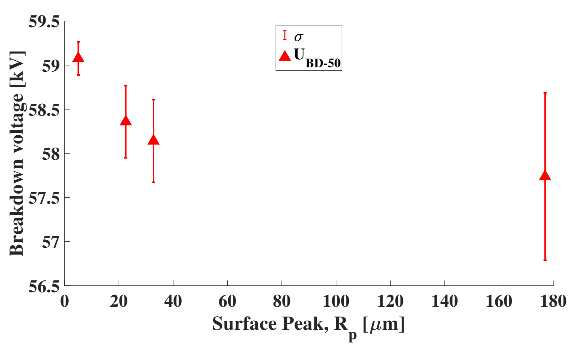


Fig. 6. Simulated breakdown voltages for the sphere-Plate geometry.

Keeping the value for $ln(N_c) = 16.5$, the results from simulating the rod-plate geometry are presented in Fig. 7. Due to the minimal change that was observed while the simulations were running, they were ended after only 5 simulations for each plate. The small impact is likely because the field enhancement caused by the rod is more important to initiate breakdowns than the surface roughness.

A small note on the use of the value $ln(N_c) = 16.5$, even if it isn't the correct value, the simulation model still shows the relative impact from one roughness to another as long as $ln(N_c)$ is kept constant.

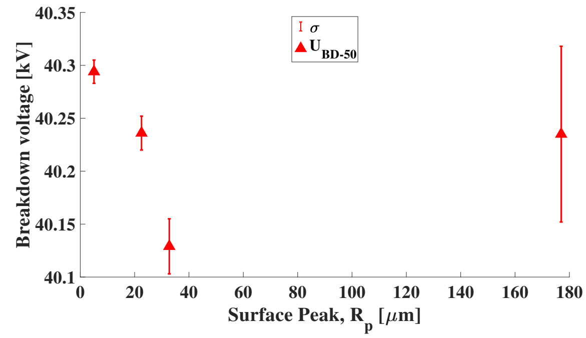


Fig. 7. Simulated Breakdown voltages for the rod-plate geometry.

B. Experimental

The experimental results for the sphere-plate setup for the different plates after 25 lightning impulse shots are presented in Fig. 8.

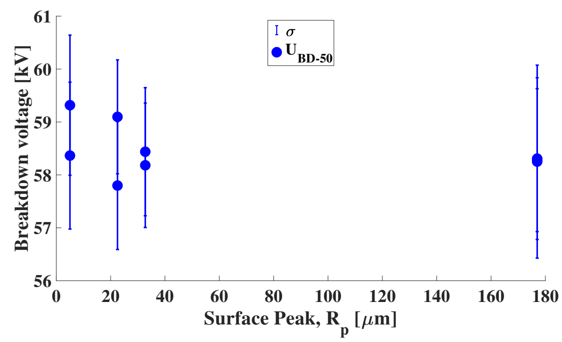


Fig. 8. Experimental breakdown voltages for the sphere-plate geometry.

The results indicate that there might be a small change, about 1.2% for plate D compared to the 59.0 kV given in the standard IEEC60052 for a 2 cm sphere-sphere gap.

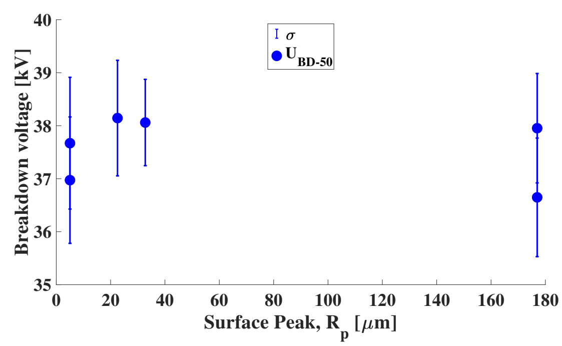


Fig. 9. Experimental breakdown voltages for the rod-plate geometry.

Fig. 9 shows the experimental results for the rod-plate setup for the different plates after 35 lightning impulse shots. As for the sphere-plate geometry, the scatter of the results are assumed to be because of inaccuracy of the measuring of the gap distance. These results show that there is very little impact of the surface roughness on the breakdown voltage in the non-uniform field at atmospheric pressure.

C. Comparing Experimental and Simulation Results

Fig. 10 shows the simulations compared with the experimental results for the sphere-plate geometry. The simulation model is close to the experimental results, which confirms the observation that the impact of surface roughness has very little impact in quasi-uniform fields at atmospheric pressures.

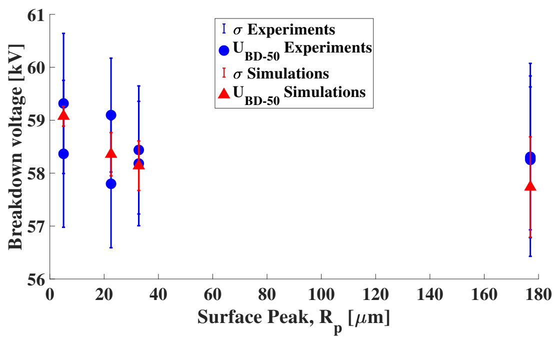


Fig. 10. Comparison between simulated and experimental breakdown voltages for sphere-plate geometry.

Fig. 11 shows the simulated and experimental results for the rod-plate geometry. Without adjusting the value of $ln(N_c)$, the simulations miss the actual voltage. However, the experimental results confirm the relatively small change of breakdown voltage from the simulations for plates A - D.

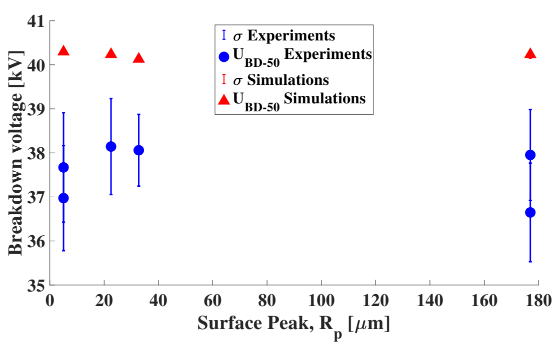


Fig. 11. Comparison between simulated and experimental breakdown voltages for rod-plate geometry.

The simulations showed a trend of increasing standard deviation with increasing roughness. This was not confirmed by the experimental work, which was assumed to be because of inaccuracies in setting the precise voltage with the impulse generator. This gave a relative large standard deviation for each measurement. To investigate the trend further, a more precise impulse generator with small voltage steps should be used.

V. Conclusion

After performing simulations and experiments the following conclusions have been made about the impact of surface roughness on the breakdown voltage in atmospheric air:

For both quasi-uniform and non-uniform fields in atmospheric air, the microscopic field enhancement region due to surface roughness has a very limited effect on the breakdown voltage, even at high degrees of surface roughness ($R_a = 26.19\,\mu$m and $R_p = 176.98\,\mu$m).

The simulation model predicts satisfactory close estimates to the actual breakdown voltages in the quasi-uniform field and would be interesting to test for other gases and pressures where surface roughness is expected to have a significant bigger impact. For the non-uniform field, the model should be adjusted more to better predict the breakdown voltage.

As the value for the spectral exponent β was more or less arbitrarily determined from R_{dq} by trial and error, it should be investigated more in depth on how to determine it.

It should be investigated if there is a more suitable parameter other than R_p for scaling the randomly generated surface in COMSOL. Using a different parameter may result in a different value for $ln(N_c)$.

Finally, since this was an axisymmetric model, the generated surface protrusions would be circular. It would be interesting to expand the model into three dimensions.

Acknowledgment

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