Breakdown Strength of Solid|Solid Interface

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Abstract—**Interfaces between solids are generally considered weak regions in electrical insulation systems. This is particularly so if the electrical stress is applied parallel to the interface. Important parameters, affecting the breakdown strength, are interface pressure, humidity, presence of liquid dielectric and the surface roughness of the solid in contact. The main aim of the work presented here is to examine, theoretically and experimentally, the effect of interfacial pressure and roughness on the tangential breakdown strength. The size and gas pressure of enclosed surface voids were estimated using mechanical contact theory. The dielectric $50\,Hz$ AC tangential strength of XLPE|XLPE interface was investigated for various values of pressure and roughness. The increase in breakdown strength due to increased pressure was largest in case of surfaces with the high degree of roughness. As expected the highest breakdown strength was observed in case of the smoothest surfaces. The estimated results of void size and gas pressure were found to be in good agreement with the experimental observations.**

I. INTRODUCTION

Most high voltage insulation systems consist of interfaces between different solid insulators, which are subjected to electrical stresses either in parallel or perpendicular to the surface. It is predicted that the microscopic cavities formed at the interface are regions where electrical discharges can initiate and breakdown develops.

The aim of this investigation has been to develop a physical model explaining the effect of surface roughness and applied pressure on the tangential AC-short term breakdown strength of interfaces between samples of XLPE cable insulation.

II. THEORY

A. Electrical Breakdown along the Interface

When making a contact between solids, voids and contact spots are formed at the interface due to surface asperities as indicated in Fig.1. The effect of increasing the mechanical surface pressure is to reduce the size of the voids, increase the effective contact areas, and possibly to increase the gas pressure of the voids. Correspondingly, it is reasonable to assume that a high degree of surface roughness would result in fewer but larger void enclosures.

Considering a simplified model of the interface, consisting of a series connections of voids and contact regions, the applied voltage will be distributed along the interface according to
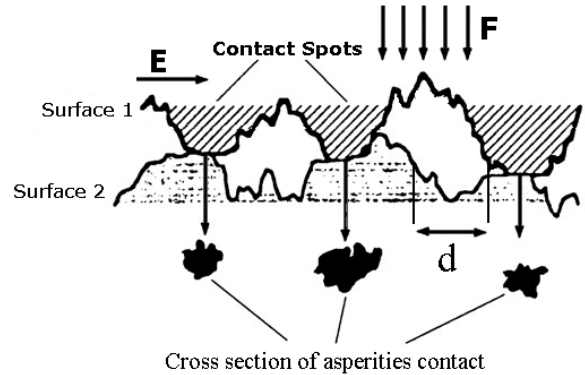
$$V_i = \sum V_v + \sum V_c \tag{1}$$

Fig. 1. Schematic drawing of contour of the contacting asperities

where V_i is the applied voltage, V_v is the voltage across a void, and V_c is the voltage drop across each contact spot located between two voids.

Due to the low permittivity of the void compared to the solid, electric field enhancement will cause partial discharge inception and breakdown of the voids at a relative low voltage. In the next section it will be shown that the real area of contact generally is very small compared to the nominal interface area even under heavy mechanical load. Therefore, in this work, the theoretical estimation of breakdown strength is based on the following assumptions:

I. The applied voltage across the contact area can be neglected.
II. Electric breakdown of one spherical void causes the breakdown of the entire interface.

Thus, the breakdown strength of the interface is considered proportional to the breakdown strength of the void, governed by its pressure and size according to the Paschen curve [1].

Two extreme assumptions were made for the value of pressure inside the cavities:

I. The voids are ventilated to the surroundings, meaning that the gas pressure is $1\,bar$ inside the voids
II. After applying the initial reference pressure, p_{ref}, the void pressure, p, increases with reduced size, d, according to the ideal gas law: $pV = nRT$

$$p = \left(\frac{d_{ref}}{d}\right)^3 p_0 \tag{2}$$

where d_{ref} is the diameter of void at applied pressure equals to $p_{ref} = 2.8\,bar$, and p_0 is $1\,bar$

B. Contact Analysis

In order to estimate the average size of voids, it is assumed that the voids have spherical shape and the surface of interface has been covered by voids and contact spots. It is also supposed that the number of air enclosed cavities is equal to the number of contact spots which means there is one contact spot between two consecutive cavities. The average area of void's cross section can be obtained by estimating the total area of voids and the number of voids. Figure 1 shows schematically the type of contact envisaged.

The experimental results has shown that the distribution of heights on most surface profiles and the distribution of peaks on those profiles can approximately be of the Gaussian shape [2]. For simplicity, the contact considered is between a plane and a nominally flat surface covered with a large number of asperities which, at least near their summits, are spherical. This means that the contact of two rough surfaces can be reduced to an equivalent, single, rough surface with a reference plane [2]. It is assumed that there are only elastic contacts at the interface. The ratio of real contact area to nominal area, $A_{re}/\mathscr{A}$, versus the apparent pressure, $p_a = \frac{F}{\mathscr{A}}$, for elastic contact is derived from Ref. [2]

$$A_{re}/\mathscr{A} \approx 2.4 \frac{p_a}{(E'\sqrt{\sigma/\beta})} \qquad (3)$$

where A_{re} and $\mathscr{A}$ are the real area of contact and the nominal contact area, respectively; η is the surface density of asperities; β is the radius of asperity summits; σ is the standard deviation of peeks height and E' is the composite elastic modulus [2]. Considering the number of contact spots, n, given by [2]

$$n = 1.21\,\eta\,\mathscr{A} \left(\frac{p_a}{(\eta\beta\sigma)(E'\sqrt{\sigma/\beta})} \right)^{0.88} \qquad (4)$$

The average diameter of voids, d, will be expressed by

$$\text{Average size of voids} = \frac{A_{void}}{n} = \frac{\mathscr{A} - A_{re}}{n}$$

$$d = 2\sqrt{\frac{(\mathscr{A} - A_{re})}{n\,\pi}} \qquad (5)$$

In order to estimate the size of voids, we need to experimentally determine the three parameters: η, β and σ.

C. Roughness characterization

Main asperities on rough surfaces are analyzed using the following parameters which are sufficient to describe the surface topography:

I. Standard deviation of peaks height, σ
II. Radius of curvature at the peaks of asperities, β
III. Surface density of asperities, η

The standard deviation of peaks height was measured by a surface roughness tester and the last two parameters were obtained by means of a so-called "*motif*" defined as that part of the profile found between two peaks as schematically
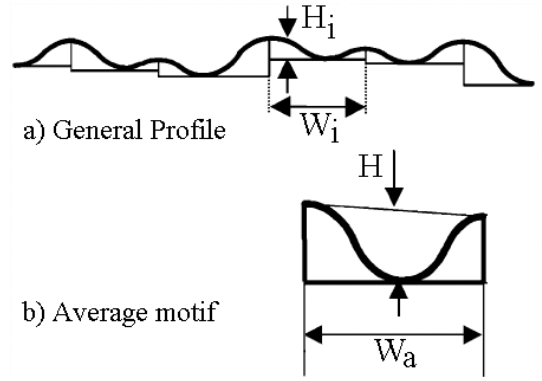

Fig. 2.   Geometrical characteristics of a) a profile; b) a motif

shown in Fig.2. Considering two spherically shaped peaks, their average radius is defined according to Ref. [3],

$$\beta = \frac{1}{16}\frac{W_a^2 + W_s^2}{H} \qquad (6)$$

where H is the average of the height values, H_i; W_a is the average of the width values W_i; and W_s is the root mean square of the W_i values of the motifs. These three parameters were obtained by measuring the roughness of the surfaces along a profile.

Switching from profile to surface entails modifications in densities; and the relationship between η (surface density of asperities) and D (density of asperities on a profile) is given by Ref. [4],

$$\eta = 1.2\,D^2, \;\; D = \frac{1}{W_a} \qquad (7)$$

III. EXPERIMENT

A. Test Samples

All XLPE samples used were cut from the insulation of a commercially available high voltage cable. The values of Elastic modulus E and Poisson's ratio v were assumed to be similar to that of LDPE, using $E = 0.47\,GPa$ and $v = 0.5$ [5]. The thickness of the samples (the length of the interface) was $4.0\,mm$ (see Fig. 3(a)). The contact surface of samples were made plane using a rotating grinding disc and different grids of sand paper, from 180 for rough up to 1000 grid paper for smooth surface. After grinding, the surfaces were rinsed in water and additionally cleaned in isopropanol and then dried at room temperature.

B. Measuring Roughness

The values of H, W_a, W_s and σ were measured using a surface roughness tester TR200. This is a classical stylus profile instrument measuring the roughness along a $12.5\,mm$ long path. The two parameters, β and η, were then obtained by Eqs. 6–7, respectively.
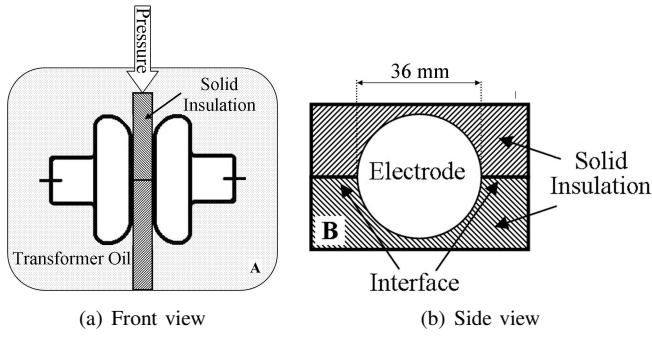
(a) Front view   (b) Side view

Fig. 3. Sketch of sample mounted between the Rogowski shaped electrodes

C. Test Procedure

In this experiment, the two cubes $(4 \times 55 \times 2.5\,mm^3)$ of XLPE samples were placed on top of each other between two horizontally placed Rogowski shaped electrodes as indicated in Fig. 3. Variable interfacial pressure was then applied by using different mechanical loads. All breakdown tests were performed with the samples soaked in transformer oil to prevent external partial discharges prior to breakdown. Surface pressure was applied prior to filling the test chamber with the transformer oil; preventing ingress of transformer oil into the interfaces. The $50\,Hz$, AC voltage was generated by a Bauer-dieltest and increased at a constant rate of approximately $0.5\,kV/sec$ until breakdown. All experiments were performed at room temperature and the test equipment was prepared according to the ASTM D149 standard.

In order to verify the low breakdown strength of air enclosed voids at the interface, we also investigated the dielectric strength of interfaces assembled in oil. Additionally, the dielectric strength of bulk air and oil was measured using the same electrodes and distance.

D. Statistical treatment of Data

For each test sample, seven breakdown measurements were made, additionally 2–3 experiments were performed in case of large deviation. The results were statistically evaluated using the two-parametric form of the Weibull distribution.

IV. RESULTS AND DISCUSSION

A. Simulation

Table I summarizes the data from roughness testing of the investigated interfaces. First, it is seen that the real area of contact, A_{re}, is in general much smaller than the nominal area, $\mathscr{A}$. Estimations, using Equ. 3, show that even under heavy loads the hills on rough surfaces are not flattened. The model indicates that the real area of contact expands by applying more pressure and using smoother surface. Second, the diameter of the cavities decreases significantly if the applied pressure rises which corresponds to higher dielectric strength of void and interface. Finally, it is shown that smoother sand paper (higher grade) will result in smaller voids and higher breakdown strength.

TABLE I
EFFECT OF PRESSURE AND ROUGHNESS ON THE SIZE OF VOIDS

Paper grade	180		320		1000	
Applied pressure (bar)	2.89	8.19	2.89	8.19	2.89	8.19
$A_{re}/\mathscr{A}$	0.005	0.012	0.013	0.036	0.037	0.099
$p_0 d\,(bar\,mm)^a$	0.28	0.18	0.17	0.10	0.07	0.05

[a]Assuming that the pressure of void is equal to atmospheric pressure

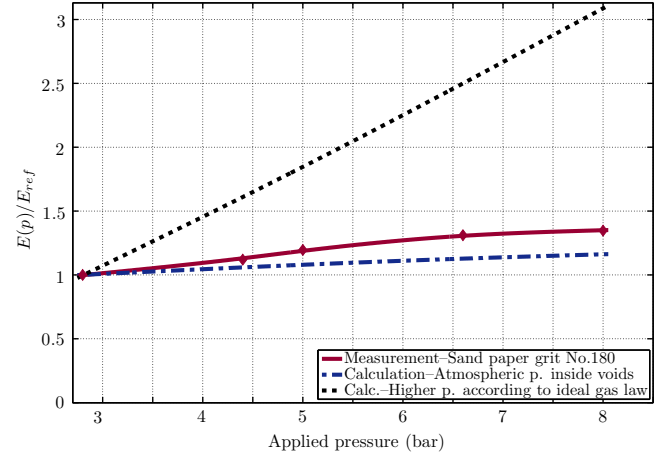Fig. 4. Comparison of measured and calculated breakdown field strength of interface–Roughest surface: Measured $E_{ref} = 7.5\,kV/mm\,(r.m.s.)$

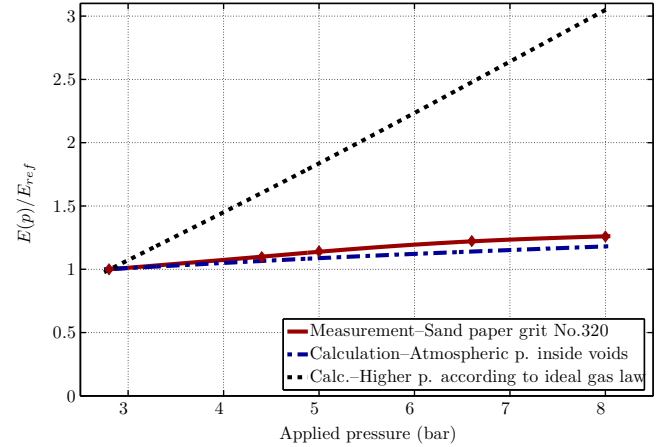Fig. 5. Comparison of measured and calculated breakdown field strength of interface: Measured $E_{ref} = 8.9\,kV/mm\,(r.m.s.)$

B. Electrical Breakdown

The ratio of the measured $63\,\%$ breakdown strength and the calculated results from the model to the initial reference breakdown, E_{ref}, versus applied pressure are for comparison plotted as shown in Figs. 4–6 for different values of roughness. The value of E_{ref} in theses figures is the measured and calculated breakdown strength at the lowest applied pressure (p_{ref}).

These figures show that the measured breakdown strength in all cases rises with increasing surface pressure. An increase (35% enhancement in Fig. 4) which was found to be largest in
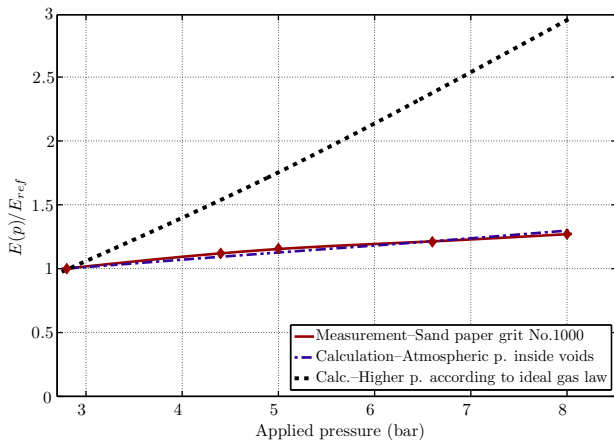
Fig. 6. Comparison of measured and calculated breakdown field strength of interface–smoothest surface: Measured $E_{ref} = 9.6\,kV/mm\,(r.m.s.)$

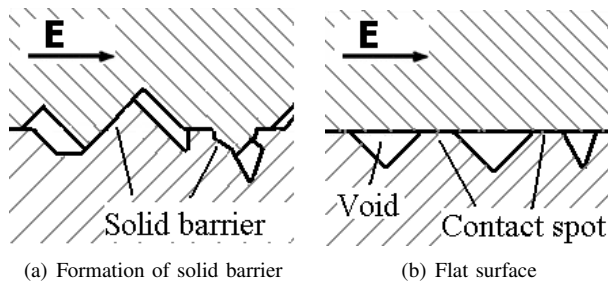(a) Formation of solid barrier   (b) Flat surface

Fig. 7. Deformation of asperities along (a) rough and (b) smooth surface

case of surfaces with the highest degree of roughness whereas the breakdown strength rises about 25% for the smoothest surface. The trend of calculated results (supposing there is atmospheric pressure inside voids) from simulation (dashdot line) agrees very well with the measured ratio in all cases covering the whole range of applied mechanical pressure. Whereas the calculated voltage is approximately three times in all cases if the increase of pressure inside the cavities accords with the ideal gas law. Since measurement (solid line) is between two extreme assumptions of air pressure, close to ventilation assumption, one explanation is that the pressure inside the voids is close to $1\,bar$.

Furthermore it can be concluded from the difference between calculated results (dashdot line) and measured data in Fig.4 (rough surface) that by applying pressure, surface protrusions may interlock to form solid barriers across the interface. Even though, the size of voids is bigger for rougher surface but surface asperities enhance the breakdown strength by forming solid barriers perpendicular to the surface as indicated in Fig.7.

C. Interface assembled in oil

The measured dielectric strength of interface is still considerably lower than the dielectric strength of bulk XLPE ($\geq 40\,kV/mm$). The Weibull plots of measured breakdown voltage presented in Fig. 8 show the breakdown strength of air at $1\,bar$ plus that of interface assembled in oil and transformer
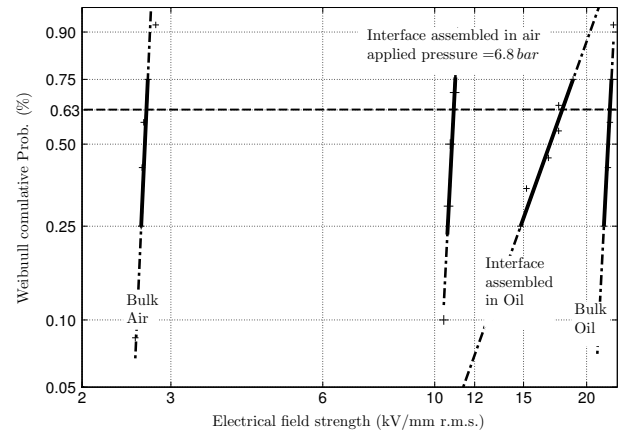

Fig. 8. Measured breakdown field strength of bulk air, interface assembled in oil transformer and bulk oil using same electrode arrangement and test setup

oil. By comparing these results with those presented in Figs. 4–6 with Fig. 8, it is indicated that the dielectric strength of the investigated interface with air filled void enclosures is about 50% lower than an interface with oil-filled voids or bulk transformer oil. This supports the assumption that air enclosed cavities are limiting factor in dielectric strength of interface.

V. CONCLUSION

- The results indicate that the longitudinal ac breakdown of XLPE|XLPE interfaces is governed by breakdown of micro-void enclosures with a atmospheric gas pressure at the interface.
- The interface breakdown stress increases with applying more mechanical pressure and is reduced by increasing roughness.
- The average diameter of the voids can be estimated by combining results from measured surface roughness with mechanical modeling of elastic contact between solid insulators

REFERENCES

[1] F. H. Kreuger, *Partial Discharge Detection in High-Voltage Equipment*. Butterworth & Co Ltd, 1989.
[2] B. Bhushan, "Analysis of the real area of contact between a polymeric magnetic medium and a rigid surface," *ASME Journal of Tribology*, vol. 106, pp. 26–34, 1984.
[3] F. Robbe-Valloire, "Statistical analysis of asperities on a rough surface," *WEAR Journal*, vol. 249, pp. 401–408, 2001.
[4] P. R. Nayak, "Random process model of rough surfaces," *ASME Journal of Lubrication Technology*, 1971.
[5] D. H. Gracias and G. A. Somorjai, "Continuum force microscopy study of the elastic modulus, hardness and friction of polyethylene and polypropylene surfaces," *Macromolecules*, vol. 31, no. 4, 1998.