Impact of Contact Pressure on Breakdown Strength of Solid-Solid Interfaces

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Abstract

Solid-solid interfaces are considered as weak points of the insulation since combination of two solid dielectrics increases the risk of cavities and moisture at the interface against the tangential component of the applied electrical stress. The main objective of this paper is to investigate the impact of the applied contact pressure on shrinkage of the size of cavities on the interface that leads to enhancement in the breakdown strength. Experimental measurements of AC 50 Hz breakdown voltage of solid-solid interfaces assembled under standard laboratory conditions were conducted using two different specimens, namely XLPE and silicon rubber. For the same applied contact pressure, breakdown strength of XLPE-XLPE and silicon rubber-silicon rubber interfaces were also analyzed to yield the influence of elasticity modulus (softness) of the solid material on the effectiveness of the applied pressure. Two different levels of contact pressures were applied for each type of interface and higher interfacial pressure (8.02→11.59 bar) led to improved breakdown strength about 50% for XLPE-XLPE interface whereas the enhancement for the much softer interface (i.e. silicon rubber) was about 7% under increasing pressure (1.34→2.67 bar). Additionally, breakdown strength of silicon rubber interface was found to be higher than that of XLPE interface around 53% at the same applied pressure.

1. Introduction

Subsea installed components are preferred to have as much of their equipment in an arrangement that can be reclaimed for maintenance and repair effortlessly. For this purpose, subsea substations should allow quick and easy connection of additional offshore loads and generators. Besides, offshore wind farms necessitate multitude cable connections and all of these connections can either individually route to shore or be terminated to a subsea substation via wet-mateable connectors. Since individual connection reaching to shore is a much expensive solution, termination to a subsea substation via wet-mateable connectors is the preferred method nowadays [1]-[5]. Figure 1 displays a simplified drawing of a high voltage wet-mateable connector [1]. There is a contact area between insulating material of receptacle and plug components of wet-mateable connectors so-called "interfaces", as illustrated in Fig. 1. In general, the solid-solid interfaces are considered as weak points of the insulation, particularly if the applied electrical stress has a tangential (longitudinal) component [1]–[8]. Since the combination of two solid dielectrics enhances the risk of cavities at the interfaces. An exaggerated schematic drawing of contacting asperities is shown in Fig. 2.

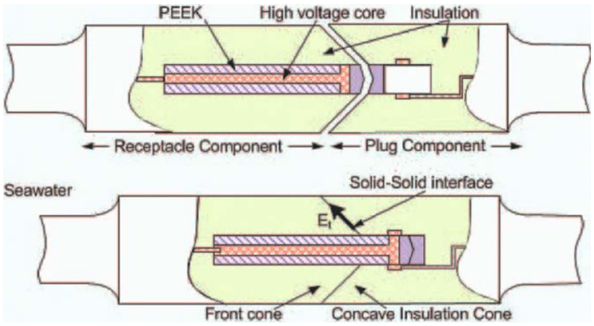

Fig. 1 – Illustration of wet-mateable connector design [1].

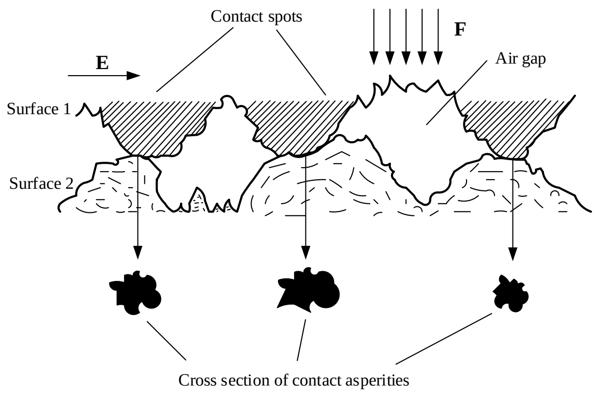

Fig. 2 – Schematic illustration of a solid-solid interface consisting of contact spots and asperities.

The main failure type of interfaces is the tracking failure defined as the formation of a conductive path. Even though the magnitude of electric field is insignificant compared to the dielectric strength of PEEK and cones insulation (Fig. 1), it is anticipated that the existence of the microscopic cavities (Fig. 2) and imperfections (contaminant and water droplets) at the interface can cause electric field enhancement [1]. The field enhancement results in initiation of partial discharge (PD) and when the discharges persist for a considerable time, the discharge energy induces carbon decomposition on the surfaces. Finally, the carbonized deposits bridge the electrodes and breakdown (BD) follows immediately [1].

The parameters, which mostly influence the interfacial breakdown strength, are surface roughness, contact pressure on the interface and extraneous particles or water droplets [1]-[3]. Several studies in the literature considered the electrical behavior of the solid-solid interface [9], [10]. The effect of contact pressure and surface roughness on the breakdown strength of the interfaces has also been evaluated [2], [5]. The higher interfacial pressure and smoother surfaces lead to higher breakdown strength [1]-[5]. There are, however, many fuzzy issues waiting to be answered. First of all, the impact of contact pressure on breakdown strength of interfaces assembled in standard laboratory conditions is still vague. Assembly of the interface under water or in an oil chamber escalates this issue even further. Therefore, the difference between air filled, water-filled or oil-filled voids present on the interface should also be considered when modeling the breakdown strength of the interface under a certain contact pressure. Last, there are not any obvious models and/or methods showing how to test and quantify the degree of dielectric deterioration.

The aim of this paper is to reveal the effect of applied contact pressure on the tangential AC-short term breakdown strength of interfaces between samples of solid insulation materials. For this purpose, two different solid materials, namely XLPE and silicon rubber (SR) are used respectively. Moreover, the influence of elasticity modulus (softness) of the solid material on the effectiveness of the applied pressure is also investigated. Thus, the effect of applied contact pressure is attributed to the type of the solid material used. In the following, first, a brief model of interfacial structure and an analytical expression to disclose the model of breakdown voltage of dry interfaces (i.e. air-filled voids) are provided. Second, experimental setup together with specimen preparation process is described and, then the AC breakdown test results of dry interfaces are presented. Third, the breakdown voltage of XLPE-XLPE interface and SR-SR interface are evaluated under different contact pressures individually. Then, BD voltage of each interface is also compared under the same applied pressure. Last, the difference between air-filled and oil-filled cavities is analyzed in terms of the interfacial breakdown voltage value.

2. Solid-Solid Interface Models in Literature

In this section, a model developed in [2] is introduced to describe the voltage distribution across voids and contact spots at the interface. When there is a contact surface between solids, voids and contact spots are formed at the interface due to surface asperities as shown in Fig. 2. The influence of increasing the mechanical surface/contact pressure is to shrink the size of the voids, and hence to increase the effective contact areas, and possibly to increase the gas pressure inside voids. Consistently, assumption of a high degree of surface roughness would result in fewer but larger void spaces [2]. Series connections of voids and contact regions construct a simplified model of the interface where the applied voltage is distributed along the interface according to

$$V_i = \sum V_{void} + \sum V_{contact} \tag{1}$$

where V_i is the applied voltage, V_{void} is the voltage across a void, and $V_{contact}$ is the voltage drop across each contact spot located between two voids as highlighted in Fig. 4.

The inception of discharges inside the majority of voids is to be followed simultaneously by breakdown across contact spots. Thus, ΣV_{void} is the sum of the breakdown voltages of voids at the interface and each depends on the geometry and orientation of the void together with the gas pressure inside the void. Thus, the model developed in [2] assumes spherical voids at the interface and the electric field enhancement within the cavity is calculated by

$$E_h = \frac{3\varepsilon_r}{1+2\varepsilon_r} E \tag{2}$$

where E_h is the enhanced electric field strength inside the cavity, E is the field strength at the insulation, and ε_r is the relative permittivity of the insulation.

As discussed in [1]-[3], two scenarios are possible for the estimation of gas pressure inside the cavities. First case is the ventilated voids where 1 atm air pressure is retained inside the voids irrespective of the applied pressure. Second case, on the other hand, is the enclosed voids where the air pressure inside the voids is 1 atm prior to the application of contact pressure. Then with the increase of applied pressure, the void is compressed and air behaves as ideal gas, and hence the pressure inside the voids rises proportional to the reduced size of them (third order characteristics) [3]. It is shown for the case 1 that the estimated results agreed well with the measured ones in [3]. On the contrary, in case 2, the difference between the measured and estimated results deviated significantly [3]. Accordingly, the assumption of fixed gas pressure inside voids found to be valid and the gas pressure did not increase by applying higher contact pressure [1]-[3]. Therefore, enhanced breakdown voltage against increased contact pressure can be interpreted referring the left hand-side Paschen minimum curve at 1 atm (Fig. 3) and the impact of reduced void size (i.e. spherical voids) can be realized much easier.

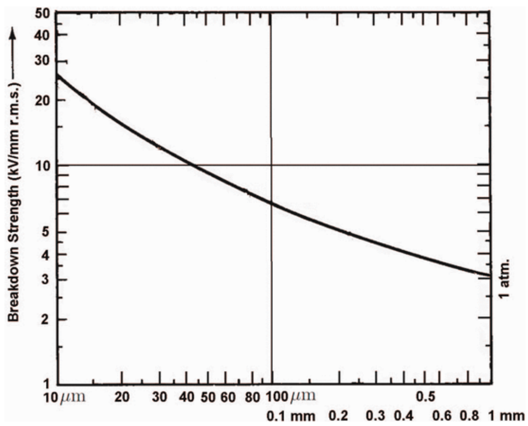

Fig. 3 – Breakdown strength of spherical air gaps as a function of the electrode gap.

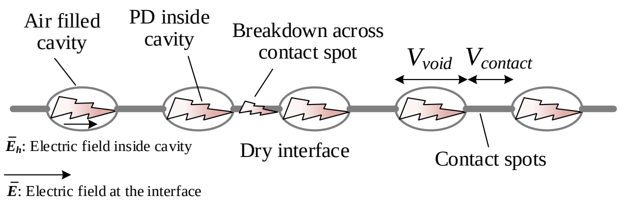

Fig. 4 - The electrical model of voltage drop at the interface.

Due to the low permittivity of the void compared to the solid, electric field enhancement is likely to cause PD initiation and breakdown of the voids at relatively low voltages. In [2], it is shown that the real area of contact is generally very small compared to the nominal interface area even under heavy mechanical load. Thus, the theoretical estimation of breakdown strength in [2] states that the electric breakdown of one spherical void causes the breakdown of the entire interface since the model is based on the assumptions that the applied voltage across the contact area can be neglected. Hence, the breakdown strength of the interface is considered proportional to the breakdown strength of the voids on the interface where pressure and size of the voids plays a big role according to the Paschen curve in Fig. 3. In the next sections, experimental setup and results are displayed to support this interface model and to shed light on the effect of contact pressure on shaping the voids at the interface.

3. Experimental Setup

This study employs two different insulation materials, namely, XLPE and SR in the shape of rectangular prisms. The breakdown strength of XLPE-XLPE interface and SR-SR interface were investigated. Figure 5 displays a detailed sketch of the experimental setup along with the shape and assembly of the samples whereas Fig. 6 depicts the experimental setup constructed in the laboratory.

3.1. Specimen Preparation

All XLPE samples used were cut from the insulation of a commercially available high voltage cable in the size of 4 x 55 x 25mm^3 rectangular prisms. The thickness of the samples (i.e. the length of the interface) is 4.0 mm as depicted in Fig. 5. The contact surface of samples were made plane/smooth using a rotating grinding disc using sand papers of grit size no. 320. Besides, in order to investigate the effect of the sliding direction during the grinding process, the surface of selected specimens was grinded in different direction. This resulted in mono-directional, highly anisotropic textures orthogonally oriented to the sliding direction. After grinding, the surfaces were rinsed in water, additionally cleaned in isopropanol, and then dried at room temperature.

All SR samples used were produced in laboratory conditions. For this purpose, first 4 x 500 x 500 mm^3 sized mold was used to produce large SR samples and then they were cut in dimensions of 4 x 55 x 25 mm^3 rectangular prisms. The thickness of the samples (i.e. the length of the interface) is 4.0 mm as that of XLPE samples. The contact surface of samples were made plane using the rotating grinding disc and no. 500 grit size sand paper was used to provide a smooth surface. As a remark, grit size of no. 320 sand paper was too rough for SR and it yielded uneven and rippled interface surfaces. Hence, according to the softness of the material used, the optimal grit size of the sand paper must be determined. As per [2] and [3], yielded results of XLPE interface under grit no. 320 and no. 500 does not deviate considerably. Yet, the impact of different grit size was considered by reflecting a normalization constant in the results part so that a fair comparison between XLPE and SR could be made.

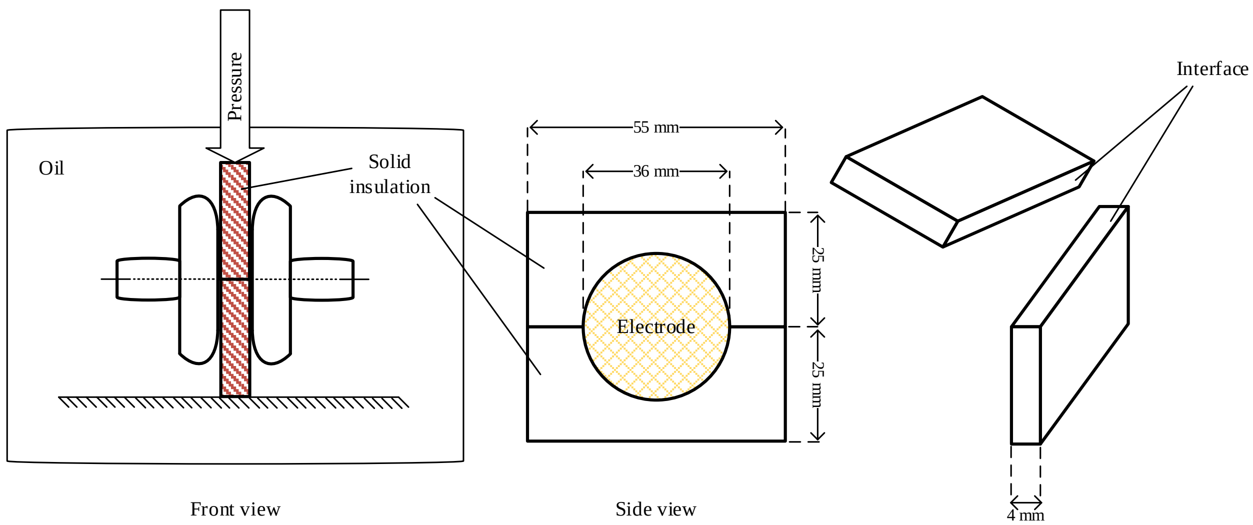

Fig. 5 – Sketch of the experimental setup with the samples mounted between the Rogowski electrodes.

3.2. Test Procedure

In this experiment, the two rectangular prisms (4 x 55 x 25mm^3) of XLPE samples were placed on top of each other between two horizontally placed Rogowski shaped electrodes as indicated in Fig. 5-6 (for SR the same procedure was followed as well). Variable interfacial pressure was then applied by using different mechanical loads. All breakdown tests were performed with the samples soaked in Midel oil [11] to prevent external partial discharges prior to breakdown. To prevent ingress of oil into the cavities on the interfaces (i.e. oil-filled cavities), surface pressure was applied prior to filling the test chamber with the oil. Additionally, to verify the low breakdown strength of air enclosed voids at the interface, we also investigated the dielectric strength of interfaces assembled in oil (oil-filled voids). Results are shown at the end of the Section 4. The 50 Hz, AC voltage was generated using a 100 kV PD free transformer and increased at a constant rate of approximately 0.6 kV/sec until breakdown. All experiments were performed at room temperature and the test equipment was prepared according to the ASTM D149 standard.

3.3. Data Processing with Statistical Methods

For each test sample, 7-8 breakdown measurements were made; additionally 2–3 experiments were performed in case of large deviation. Each time a new pair of samples was used. The results were statistically evaluated using the two-parametric form of the Weibull distribution.

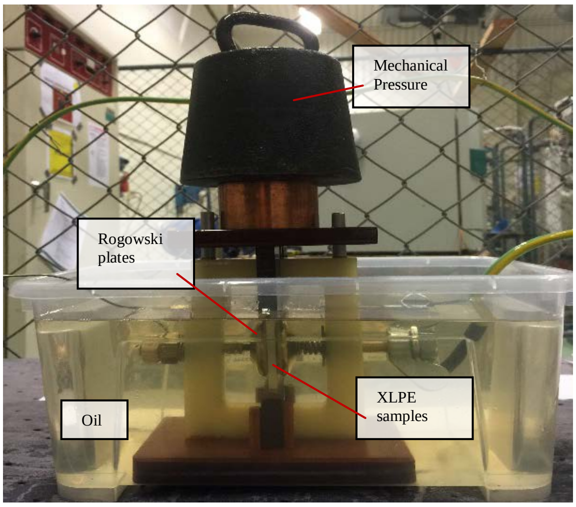

Fig. 6 – Experimental setup of Rogowski electrodes with samples attached and mechanical pressure applied.

4. Results and Discussion

Due to the shape of the Rogowski plates, electric field strength tends to be more inhomogeneous near the edges whereas more homogeneous field strength can be assumed at the close vicinities of the center. Samples after each breakdown were examined and it was observed that majority of breakdown channels had been formed near the central portions of the specimens.

Figure 7 shows the Weibull plots of breakdown voltages of XLPE-XLPE interface under two different values of the contact pressure. Results show that higher interfacial pressure increased 63% quantile breakdown voltage (i.e. voltage resulting in 63% probability for BD) from 18.44 kV to 28.11 kV (about 50%) where applied pressure is increased from 8.02 bar to 11.59 bar (approx. 45% increase). Likewise, Fig. 8 displays the same characteristics for SR-SR interface under two distinct values of the contact pressure. Plots reveal that the increase in the contact pressure from 1.34 bar to 2.67 bar raised the 63% quantile BD voltage about 7% (from 35.53 kV to 37.69 kV). The Weibull lines in Fig. 8 are rather close; concluding that even the lowest applied pressure was sufficient to mate the interfaces accurately. Additionally, after each BD test, specimens were checked if there had been oil leakage/ingress to the interface. Thus, all the results shown in Fig. 7-9 ensure air-filled cavities throughout each experiment.

Since SR is much elastic/soft material compared to XLPE, we could not apply the same levels of the mechanical pressure because SR samples were heavily deformed under high mechanical pressure and the surface of each sample could not be mated properly. Consequently, the lowest pressure value applied to XLPE interface was the highest possible value for SR (2.67 bar), ensuring proper mating within the oil chamber without any ingress of oil molecules towards the cavities on the interface. Hence, this facilitated us to come up with a comparative study between XLPE and SR, enabling to observe the impact of elasticity of the solid material on the effectiveness of the applied contact pressure. In this sense, 63% quantile breakdown voltage of SR interface was found to be higher than that of XLPE interface about 53% (37.69 kV vs. 24.71 kV) at the same applied pressure, 2.67 bar.

Overall, Table 1 and Table 2 summarizes and tabulates the resulting 63% breakdown voltage value U_{63}, shape factor b and deviation σ as a result of the obtained Weibull plots for each type of solid material (Fig. 7-9) under different contact pressure values.

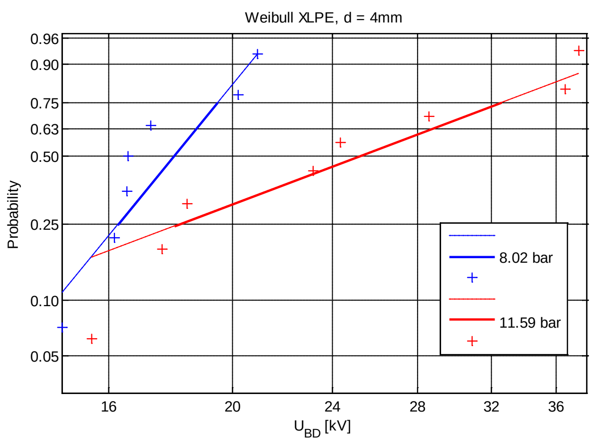

Fig. 7 – The Weibull plot of measured AC breakdown voltage of XLPE-XLPE interface.

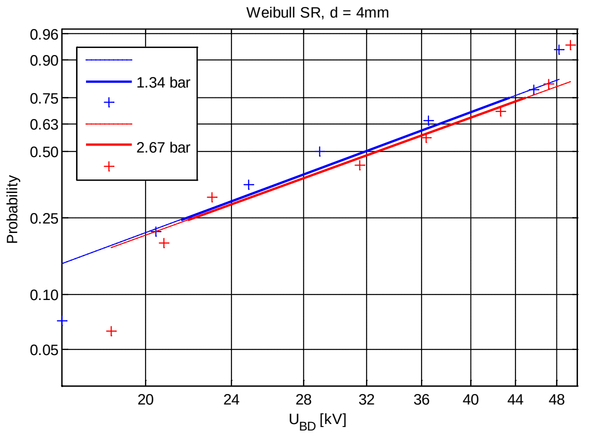

Fig. 8 – The Weibull plot of measured AC breakdown voltage of SR-SR interface.

Table 1 – Effect of applied contact pressure on the 63% quantile of the Weibull distribution.

Interface	Pressure [bar]	U_{63} [kV]	b	σ [kV]
XLPE-XLPE	8.02	18.44	8.66	2.26
XLPE-XLPE	11.59	28.11	3.50	8.42
SR-SR	1.34	35.53	3.10	12.24
SR-SR	2.67	37.69	3.37	12.15

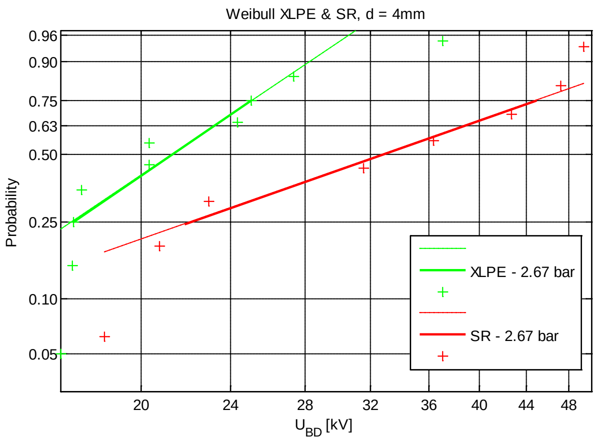

Fig. 9 – The Weibull plot of measured AC breakdown voltage of XLPE-XLPE interface vs. SR-SR interface at 2.67 bar.

Table 2 – Effect of softness of the material on the 63% quantile of the Weibull distribution.

Interface	Pressure [bar]	U_{63} [kV]	b	σ [kV]
XLPE-XLPE	2.67	24.71	3.72	6.32
SR-SR	2.67	37.69	3.37	12.15

The figures and plots reveal that the measured breakdown strength in all cases rises with increasing surface pressure. However, the experiments conducted under 2.67 bar for XLPE-XLPE interface (U_{63}=24.71 kV) and under 1.11 bar for SR-SR interface (U_{63}=41.47 kV) do not agree with the abovementioned deductions. The possible reason why these two results were odd is the likelihood of oil ingress to the voids on the interface because of relatively low mechanical pressure.

The last but not the least, to show the difference in breakdown voltages between air-filled cavities and oil-filled cavities, a single oil drop with a specific volume was added on the contact surface prior to SR specimens were assembled and put in the oil chamber. It is indicated that the dielectric strength of the investigated interface with air-filled void enclosures is about 62% lower than an interface with oil-filled voids (see Fig. 10). This supports the assumption that air enclosed cavities are limiting factor in dielectric strength of interface. Table 3 also tabulates the resulting 63% quantile breakdown voltage value U_{63}, shape factor b and deviation σ as a result of the obtained Weibull plots for SR at the same contact pressure.

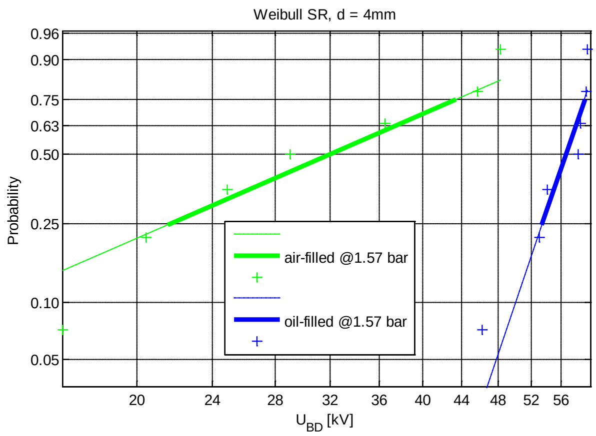

Fig. 10 – The Weibull plot of measured AC breakdown voltage of SR/SR interface at 1.57 bar (air-filled vs. oil-filled voids).

Table 3 – Effect of oil-filled cavities on the 63% quantile of the Weibull distribution.

Interface	Pressure [bar]	U_{63} [kV]	b	σ [kV]
SR-SR (air)	1.57	35.53	3.10	12.24
SR-SR (oil)	1.57	57.51	18.01	4.89

As a remark, the oil-filled cavity case could have been realized using XLPE samples as well. For simplicity, only SR was preferred in this paper.

5. Conclusion

The longitudinal breakdown strength of the solid-solid interfaces was found to be governed by the breakdown of the voids having an atmospheric gas pressure. Referred contact model approach led to an improved understanding of the interface breakdown mechanism, deducing the fact that the interface breakdown stress increases with higher contact pressure. Experimental results agreed with the theoretical model that higher interfacial pressure led to improved breakdown strength around 50% for XLPE-XLPE interface whereas the enhancement for SR-SR interface was about 7% under the specified pressure values. Moreover, breakdown strength of SR-SR interface was found to be higher than that of XLPE-XLPE interface approximately 53% at the same applied pressure. Finally, oil-enclosed cavities showed nearly 62% enhancement in breakdown strength of the interface compared to air-enclosed cavities.

6. References

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