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Experimental Investigation of AC insulation Breakdown Behavior in Air, Synthetic Oil, and Air-PE Composite Insulations

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Abstract—**Dielectric strength, of an insulating material depends on a complex combination of electrical, physical and environmental parameters. These factors interact to determine the efficiency and reliability of insulation systems in applications ranging from power grids to electronic devices. The main factors influencing system performance are structural parameters such as electrode spacing and geometry, which determine the distribution of the electric field between the electrodes and consequently the current collected at the ground plane.The insulating barriers position and configuration also play a critical role in limiting parasitic discharges and directing current flows.In addition, external environmental conditions - notably temperature, ambient pressure and relative humidity - modulate the dielectric performance of materials and the stability of interfaces.Les variations de température peuvent altérer la conductivité du milieu, tandis que les variations de pression modifient la résistance de l'arc. Humidity affects both surface film formation and the risk of corrosion.These interdependent parameters must be optimized jointly to guarantee the reliability and longevity of the device insulating systems. In this work, we have studied the influence of geometrical characteristics on the dielectric strength of materials frequently used in electrical equipment for different states of matter: gas, liquid and solid. The tests were carried out under 50 Hz sinusoidal alternating voltage with three electrode systems: sphere-plane, plane-plane and tip-plane. Experimental results revealed a marked influence of geometrical factors, in particular electrode spacing, on the breakdown voltage of the three insulation systems examined: air, borak 22 and air with solid polyethylene barrier. It has been experimentally demonstrated that the insulating properties of air are markedly enhanced under the effect of a solid polyethylene interface, with a significant rise in breakdown voltage. The optimum positioning of this barrier in the dielectric gas space between the electrodes has been determined, enabling maximum dielectric rigidity to be achieved.**

Keywords—**Dielectric strength, insulators, breakdown mechanism, insulating barrier**

I. INTRODUCTION

Materials play a preponderant role in the electrical equipment realization and the insulating materials are among those whose choice and use pose the most delicate problems to be solved in the design, construction and operation of electrical systems. These insulation systems can be composed of the three states of matter: gaseous, solid and liquid.

Dielectrics, in solid, liquid or gaseous state, are of interest in various industrial applications. In high voltage, dielectrics are used mainly to insulate one current carrying part from another when they operate at different voltages.The most common failure in electrical insulation systems occurs when the electric field exceeds the dielectric strength of the material, a critical threshold also referred to as the breakdown field.

The dielectric strength of an insulating material depends on many parameters: nature of the insulating material (chemical composition and molecular structure), geometry and physical configuration (thickness of the insulator, shape of the electrodes and uniformity of the material), environmental conditions (temperature, humidity, pressure and pollution), electrical parameters (type of voltage, frequency and duration of exposure) and finally defects and ageing (partial discharges, chemical ageing and mechanical stress).

Many electrical appliances use air as insulation, but some occasionally resort to other gases such as N_2 (dinitrogen), CO_2, CCl_2F_2 (freon) or SF_6 (sulfur hexafluoride). Under normal atmospheric conditions, gases are considered excellent insulators.The range of the conduction current is 10^{-10} A/cm^2. Many phenomena occur when a potential difference is applied between two electrodes trapping a gaseous dielectric.Experimentally, when a low voltage is applied to the active electrode while another electrode is grounded constituting the passive electrode, a

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small current flows through the space between electrodes and the insulator retains its electrical properties.The first studies on gas electrical breakdown, particularly in the air, date back to the 40s and 50s of the 20th centuries.Among others, we can mention Townsend's theory and the modifications that came later on the throttle breakdown mechanisms [1, 2] and the streamer theorythat takes into the short formative time lags experienced in uniform field breakdown at atmospheric pressure[3].Since then, research on gas breakdown has not stopped and several studies have been carried out to study the different parameters influencing the electricalfracture mechanisms [4-69].

In power transformers, insulation oil serves as both an insulating liquid and a coolant. During operation, the insulating oil in high-voltage equipment is exposed to thermal, mechanical, and electrical stress. This leads to the creation of carbon deposits, sulfur, acids, different kinds of gasses, and sludge, which is primarily an oxidation product and whose formation is accelerated by temperature and air contact, contaminating the oil. The breakdown voltage of the insulting oil will be lower if the levels of moisture and conductive impurities are higher. These impacts must be thoroughly investigated in order to provide a safe service.Due to its favorable physicochemical characteristics and low cost, mineral oil (petroleum product) is still the most commonly utilized dielectric liquid in power transformers.However, there is an issue with its effects on the environment, particularly on aquatic and soilresources.To solve this problem and improve the performance of the insulation fluid, synthetic oils with well-studied proportions have been developed [7,810-14].

Numerous electrical circuits and devices employ solid dielectric as insulation materials. A reliable dielectric should be resistant to chemical and thermal deterioration, have a high mechanical strength, be free of moisture and gaseous inclusion, and have minimal dielectric loss. Compared to liquids and gases, solid dielectrics have higher electrical breakdown strength. While gases and liquids restore all or part of their dielectric stiffness once the applied electric field is withdrawn, solid dielectrics incur permanent damage during breakdown. This is the main disadvantage of solid dielectrics. In the case of solids, the breakdown mechanism is a complex phenomenon that changes according to the time of exposure to electrical stress. The different breakdown mechanisms are classified in the following categories: intrinsic or ionic breakdown, electromechanical breakdown, failure due to treeing and tracking, thermal breakdown, electrochemical breakdown, and breakdown due to internal discharges [915].

Inserting solid insulation into gaseous or liquid insulation greatly increases the dielectric strength of the medium.For gas-solid hybrid insulation, we can give insulators as examples that combine porcelain and air to provide a more rigid dielectric than air alone.In the case of solid-liquid insulation, power transformers often use cellulose insulators such as compressed cardboard or paper, which are always impregnated with mineral oil.

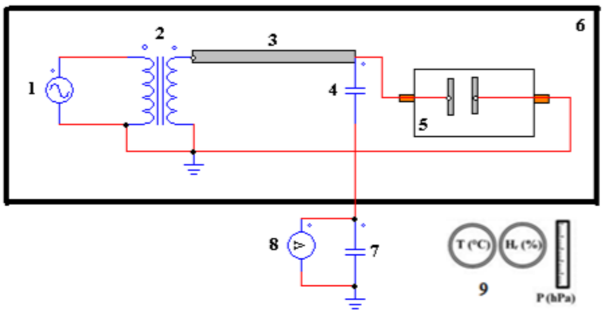
In this experimental work, we will focus on the measurement of the breakdown voltage of three isolation systems: gas (air), liquid (borak22) and gas with solid barrier (polyethylene PE). The experimental tests consist of applying an alternating high voltage to the active electrode of different geometries (plane, sphere, tip) and reading this voltage when the insulating medium breaks down. The second electrode (plane) is directly connected to the earth.

II. Materials and Methods

Our experimental study consists of applying a 50 Hz high alternating voltage to the high voltage electrode of different geometries (plane, sphere, tip) and recording this voltage during electrical breakdown. Note that the second electrode (plane) is connected directly to earth.The experimental tests were carried out at the High-Voltage Laboratory of the University of Bejaia (Algeria).

A. Experimental set-up

The diagram of the used experimental set-up is shown in figure 1. It consists of a power supply, a discharge cell and measuring equipment.



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1. Low voltage source, **2.** High voltage transformer, **3.**Metal connection,**4.** High voltagecapacitor, **5.** Glass cubic container, **6.** Protective grille, **7.** Low voltagecapacitor, **8.**Peak voltmeter (MU11), **9.** Instruments for measuringatmospheric conditions

Fig. 1 Experimental set-up diagram

The primary winding of the high-voltage transformer 0.8/135 kV T100 (2) is supplied with a variable alternating current voltage delivered by the low-voltage source SG1 (1). The T100 transformer can deliver voltages ranging from 0 to 100 kV for AC tests, and from 0 to 135 kV for DC tests.The low voltage SG1 can be varied in manual mode or in automatic mode by a motor with a ramp fixed on the control unit. The metal connection (3) is used to link the high voltage capacitor (4) to the T100 transformer. The high-voltage capacitor is connected in series with the low voltage capacitor (7). The second terminal of this last one is connected directly to earth. The series connection of the two capacitors forms a capacitive divider, enabling to deduce the value of the voltage on the HV side from a low-voltage measurement. The applied voltage is measured with the peak voltmeter MU11 (8). The electrode system is placed inside the cubic glass container (5). The laboratory atmospheric conditions, namely the temperature (T), humidity (H) and pressure (P) are revealed systematically before each test by the devices (9).

B. Electrodes configuration

During our experimental trials, we used three electrode configurations: plane – plane, sphere – plane and tip - plane. Fig. 2 illustrates the different electrode geometries used.

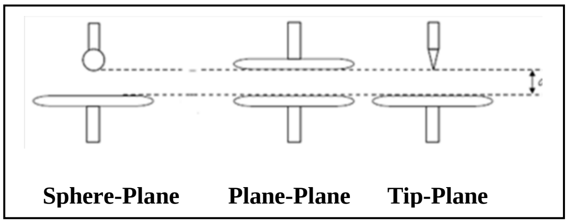

Fig. 2 Electrode configuration

The photos below show the actual plane-plane electrode system in the glass container and the different HV electrode configuration.

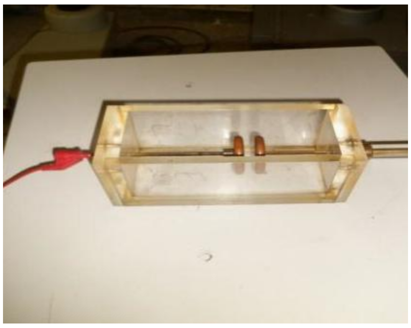

Fig. 3 plane-plane electrode system in the glass container

Fig. 4 HV Electrode configuration

C. Used materials

The dielectrics used during laboratory breakdown tests are:
Gas dielectric: air at laboratory conditions in terms of pressure, temperature and humidity.
Liquid dielectric: borak22 mineral oil.
Solid dielectric: 1mm-thick polyethylene plastic film. The films are sliced into rectangles that measure 75 mm in width and 125 mm in length.

D. Test sequence

The experimental methodology consists of a progressive application of electrical voltage, controlled according to the specific parameter of influence (inter-electrode distance, nature of the dielectric, environmental conditions, etc.) until the complete breakdown of the medium's insulating power.

Three types of insulation (gas, liquid and gas with solid barrier), three electrode configurations and several inter-electrode distances are taken into account in the breakdown tests.

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In air, we used all three electrode configurations while for liquid and gas insulation with barrier, we used only the tip-plane configuration.In configurations with active electrodes with a large radius of curvature, we recorded creepage distances during breakdown and the measurement results are not reproducible.

We would like to point out that the tests were carried out at a variable rate of voltage. In our case, we take the average of the six measurements.

E. Correction of results according to atmospheric conditions

Breakdown voltage is related to nominal atmospheric conditions, temperature, pressure and humidity of the surrounding air. In order to allow comparison of our work with that of other researchers, the voltage values measured under atmospheric conditions in the laboratory must be adjusted to normal conditions of temperature θ_0, pressure P_0 and humidity H_0 as follows:

$$U = \frac{K_h}{K_d} . U_m \qquad \text{(Eq. 1)}$$

With :

U_m: Breakdown voltage measured at temperature θ, pressure P and humidity H.

U: Breakdown voltage referred to standard conditions of temperature θ_0, pressure P_0 and humidity H_0.

K_d: Correction factor relating to temperature θ and pressure P:

$$K_d = \frac{293.P}{273+\theta} \qquad \text{(Eq. 2)}$$

To determine the correction factor K_h, relative to humidity, a transformation from relative humidity H_r (%) to absolute humidity H (g/m^3), is necessary, as K_h is given as a function of the latter. The abacus in Fig. 5, gives the transformation of relative humidity into absolute humidity, as a function of temperature. To deduce K_h, the absolute humidity value (Fig. 5) is plotted on the chart in Fig. 6.

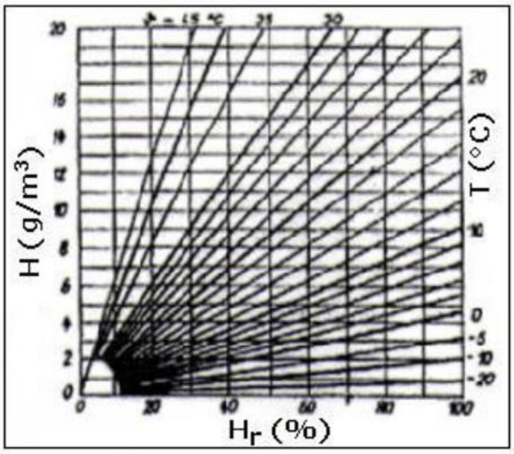

Fig.5 H = $f(Hr, \mathrm{T})$

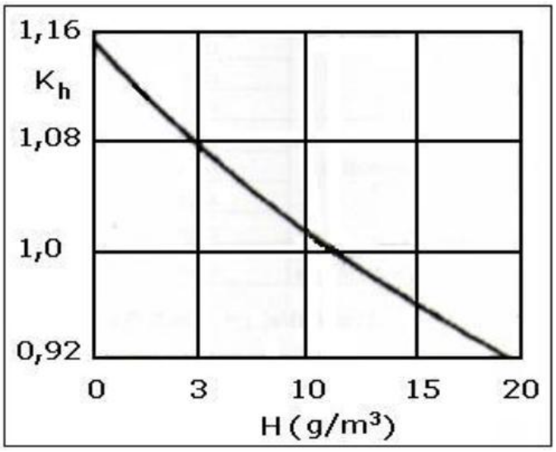

Fig.6K_h = $f(H)$

III. RESULTS AND DISCUSSION

A. Influence of the electrode gap distance on the breakdown voltage

In this section, we used the rod-plane electrode configuration for all three types of insulation. The voltage rise rate is set at a maximum value 5.48 kV/s.We varied the distance between the active and ground electrodes, and recorded the breakdown voltage each time.

1) Gas insulation

Fig.7 illustrates the variation of the breakdown voltage as a function of the inter-electrode distance in the case of gas insulation (air).

From the Fig. 7, it can be seen that the breakdown voltage increases in a non-linear manner with the distance between electrodes. The increase in the latter causes the electric field between the electrodes to decrease. For dry air, the commonly accepted value of the disruptive field of the air is 3 kV/mm, so as soon as the mean field between the electrodes is greater than this value there will be a passage of an electric current between the electrodes. Thus, when the distance between electrodes increases with the same voltage level, the average field between the electrodes decreases and to reach the disruptive field it is necessary to increase the voltage applied to the HV electrode.

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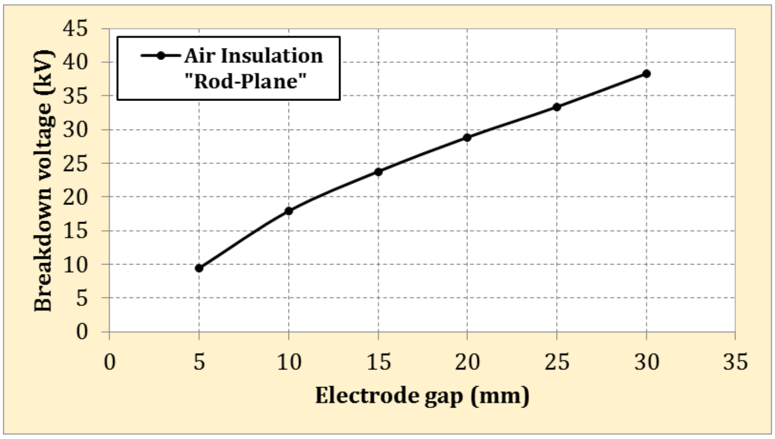

Fig. 7Effect of electrode spacing on air breakdown voltage in tip-plane geometry

The phenomena leading to breakdown in the case of alternating voltage are highly complex. This complexity is due to the influence, during each alternation, of the space charges created during the previous alternation. The breakdown voltage in this case will be relatively low. In general, at intermediate pressures, the discharge corresponding to the lowest disruptive voltage is the one measured in positive polarity. In this case, the breakdown under alternating voltage therefore appears mainly during the positive alternation.The repetition frequency of the crowns is in the audible range. This is precisely the buzzing noise heard under HV lines. In this case, the streamers develop all around the HV cable and are called corona discharge.

A minimum voltage of appearance of the 1st streamer is defined, when this voltage is applied to the active electrode or exceeded, a streamer develops. If the latter reaches the ground electrode, a short circuit limited by the external circuit takes place. Previous experimental work has shown that the air breakdown voltage at sinusoidal AC voltage is lower than at DC voltage.

Several models exist in the literature for expressing the air breakdown voltage as a function of the distance between electrodes. For example, Stephenson's empirical formula of 1933 [19], the breakdown voltage of the airin function of electrode spacing (*d in cm*) between two plane electrodes (circular disks) is given by equation 3. We can also cite the empirical formula proposed by Meek and Graggs in 1978 [20] given by equation4 (*d in mm*). Both formulas are valid for uniform electric fields

$$V_b(kV) = 24{,}22.d + 7{,}50.\sqrt{d}\ (d\ in\ cm) \qquad \text{(Eq.3)}$$

$$V_b(kV) = 2{,}44.d + 2{,}065.\sqrt{d}\ (d\ in\ mm) \qquad \text{(Eq.4)}$$

2) Liquid insulation

Fig. 8shows the electrode gap effect on the breakdown voltage of borak22 oil insulation.

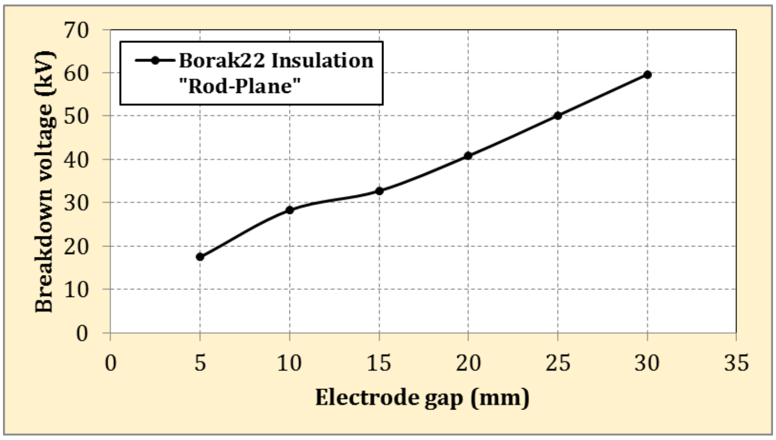

Fig. 8Effect of electrode spacing on borak22 oil breakdown voltage in tip-plane geometry

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The evolution of the borak 22 synthetic oil breakdown voltage with inter-electrode distance is similar to that observed in gaseous insulation systems, such as air.For both types of insulation, increasing the inter-electrode distance requires an elevation in the applied voltage to reach the electric field necessary for dielectric breakdown.

In synthetic oil, breakdown is assumed to be initiated by the formation of conductive streamers through the oil. This process is influenced by field-enhanced electron emission at the electrode surface. This mechanism is equivalent to Townsend's avalanche effect in gases, with differences in charge carrier mobility and energy dissipation.

The experimental results are in good agreement earlier works obtained by other authors under AC voltage [21–23],where it was shown that cyclic reversals of voltage polarity in AC systems accelerate insulation ageing but do not fundamentally alter the relationship between breakdown voltage and electrode spacing.

In liquids, dielectric breakdown is not instantaneous; it is preceded by pre-discharges, which produce a luminous phenomenon that propagates in the form of a more or less branched arborescence forming a streamer. This is what we noticed during all our tests on borak 22 oil.

Two out of the three phases of liquid breakdown were clearly observed during our experimental tests:

1. 1st phase "generation phase": during this phase, several phenomena occur: electrical (current pulse), optical (light emission), hydrodynamic (liquid movement, cavitation) and streamer.
2. 3rd phase "arc phase": this is the phase when the insulation breaks down, an electric arc is established between the electrodes and an electric current flows through the inter-electrode space; itscurrent intensity can reach kA.

Unlike air, which is self-regenerating, oil loses part of its dielectric characteristics and changes color after a certain number of tests.The photos below (Fig. 9) show the electric arcs obtained on borak22 oil.

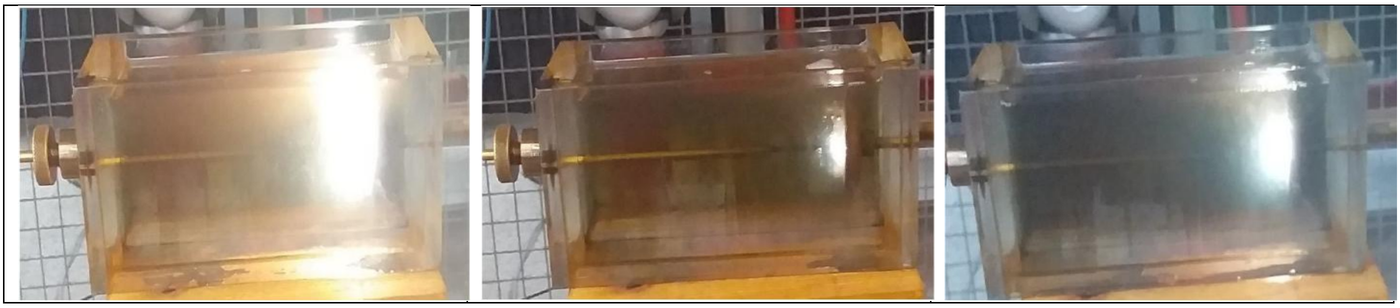

Fig. 9Photos of the electric arcs formed and the color change of borak22 oil

From the photos in the previous figure, we can see that the discharges are volumetric, and the oil changes color (blackens) as we perform breakdown tests on it.

3) Gas insulation with solid barrier

In this part of our experimental work, we interposed a solid polyethylene dielectric barrier in the air space between the HT electrode (tip) and the ground electrode (plane). The barrier is placed on the side of the grounded electrode. The curve giving the variation of the breakdown voltage as a function of the inter-electrode distance isshown in figure 10.

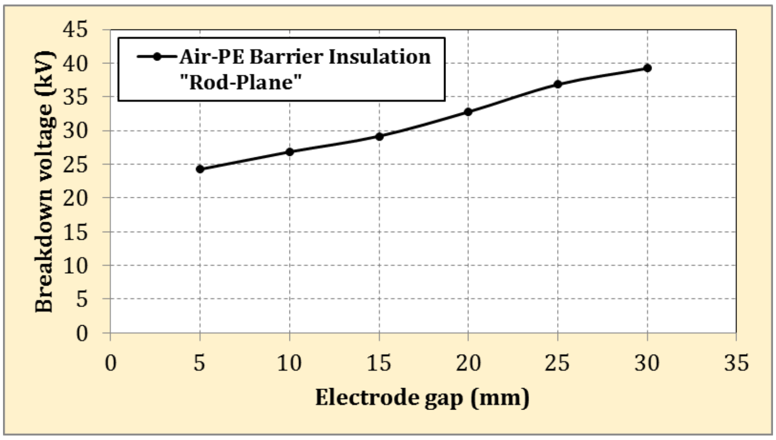

Fig. 10Effect of electrode gap onbreakdown voltage of air-PE barrier-air insulation in tip-plane electrode configuration

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Electrical breakdown of an insulating medium results in the formation of an electric arc between the electrodes (Fig. 11). In the case of gas insulation with a solid barrier, this electric arc creates a permanent carbonised conductive channel. In some tests, we noticed perforations in the barrier (Fig. 12). In both cases, the barrier cannot be reused after the breakdown because it completely loses its insulating power.

Fig. 11 Formation of the electric arc in air with solid barrier

Fig. 12Perforations in the PE solid barrier caused by electrical breakdown

Like any otherinsulation, the breakdown voltage of the space between the electrodes isolated with air and a polyethylene barrier increased with the inter-electrode distance in order to reach the disruptive field of the medium.

In practice, inserting an insulating barrier in the air gap between the electrodes serves reinforcing the insulation of the medium by increasing its dielectric strength.

Fig.13 shows the variation in breakdown voltage as a function of electrode spacing in the gaseous medium with and without a solid dielectric barrier.

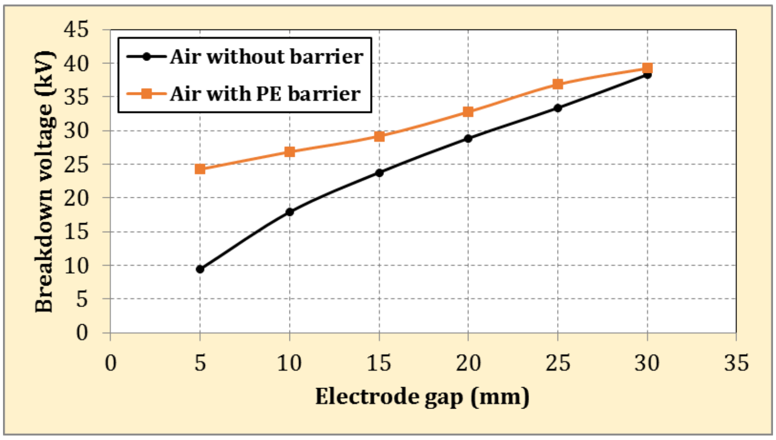

Fig. 13Effect of the a solid barrier insertion in an air gap on the breakdown voltage

By analyzing the curves in figure 13, we notice a clear increase in the breakdown voltage in the gaseous medium with barrier compared to that without barrier. The difference between the two voltages decreases with increasing inter-electrode distance. This phenomenon is due to the decrease in the contour line of the solid dielectric when the inter-electrode distance increases [24].

B. Influence of the solid barrier position on the air breakdown voltage

In this part, we vary the position of the ‘polyethylene film’ barrier in relation to the earth electrode and each time we measure the breakdown voltage of the medium. The chosen electrode configuration is point-plane and the inter-electrode distance is set at 30 mm (Position 0 mm: film is on the ‘plane’ earth electrode side, Position 30 mm: film is on the ‘rod’ HV electrode side).

Fig. 14 shows a complex relationship between the position of an insulating barrier in a rod-plane electrode configuration and the dielectric breakdown characteristics. Observations reveal that the breakdown voltage, and consequently the overall dielectric strength of the system, exhibits a non-linear and apparently random increase as the barrier is progressively moved away from the ground plane. This behavior suggests a complex interaction between the electric field, the system geometry and the dielectric properties of the various media involved (air and barrier material).

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A particularly notable phenomenon occurs when the barrier is positioned at 90% of the distance from the plane: a significant reduction in breakdown voltage is observed. This reduction in performance can be explained by a specific discharge propagation mechanism. In this configuration, the breakdown process takes place in two distinct phases: firstly, the discharge propagates in the air gap between the rod electrode (subjected to high voltage) and the edge of the barrier; secondly, it crosses the gap between the edge of the barrier and the ground plane. This behavior clearly demonstrates that the electrical discharge does not pass directly through the insulating barrier, but rather follows the path of least electrical resistance, i.e. the air path around the barrier. This phenomenon is technically referred to as “breakdown by bypassing”.

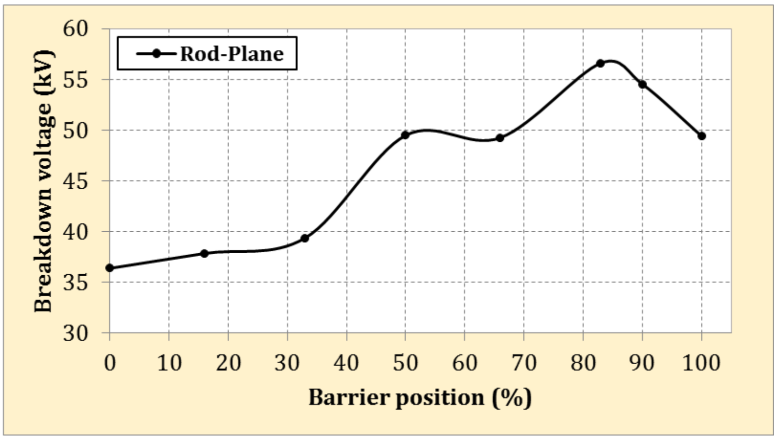

Fig. 14Influence of the PE film position on the air breakdown voltage in point-plane geometry

For the specific experimental configuration studied (comprising electrodes of defined geometry and a particular type of insulating barrier), the results indicate that dielectric strength reaches its optimum level - corresponding to the maximum breakdown voltage - when the barrier is positioned between 66% and 83% of the distance from the ground plane. These observations are complemented by additional AC voltage tests, which confirmed that a significant improvement in the system's dielectric strength is obtained for barrier positions covering a wider range, between 40% and 80% of the inter-electrode distance measured from the ground electrode. This difference between direct current (DC) and alternating current (AC) behavior underlines the influence of the type of electrical stress on breakdown mechanisms.

Analysis of these experimental results provides valuable insights for the optimal design of electrical insulation systems, highlighting the critical importance of the relative position of insulating barriers in rod-plane electrode configurations. This knowledge can be exploited to improve the performance of electrical discharge protection devices in various industrial applications.

C. Influence of the high-voltage electrode shape on the breakdown voltage

In this section, we have carried out tests only on gaseous insulation with air.In figure 15, we plot the air breakdown voltage as a function of the inter-electrode distance for three different electrode configurations: plane-plane, sphere-plane and tip-plane.

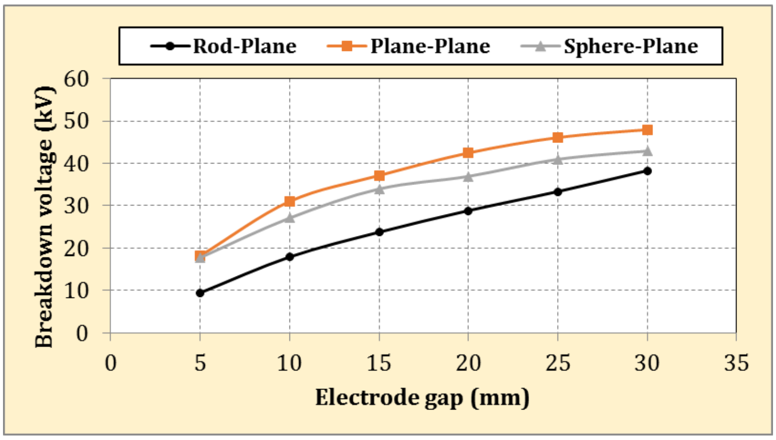

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Fig. 15Effect of the high-voltage electrode shape on the breakdown voltage of air

Fig. 15shows that the breakdown voltage is higher for larger HV electrode bending radii. This phenomenon is certainly due to the tip effect.As the radius of curvature of the HT electrode increases, the electric field distribution becomes less concentrated. For a given applied voltage, this results in a reduced average electric field between the electrodes. Consequently, a higher external voltage is required to trigger breakdown, which explains the observed increase in breakdown voltage.

Figure 15 also highlights a striking disparity between the breakdown voltages observed in rod-plane and sphere-plane configurations, whatever the distance between the electrodes. This difference is due to the distinct electric field distributions in these geometries. In rod-plane electrodes configuration, the sharp tip of the rod electrode creates a strongly non-uniform field, with an intense localization near the tip. This region serves as the active zone for discharge initiation [25-27].In sphere-plane electrodesconfiguration, the larger curvature radius of the spherical electrode homogenizes field distribution, reducing peak field strength and increasing breakdown voltage.

We can also see from in Fig. 15 that the breakdown voltage in the sphere-plane configuration is virtually equal to that in the planar-planar geometry for very small inter-electrode distances (e.g. for d=5mm). When the inter-electrode distance becomes sufficiently small, the sphere-plane geometry behaves almost like a conventional planar arrangement, with the electric field becoming progressively uniform in the inter-electrode space.More precisely, for these small values of distance d, the radius of curvature of the spherical electrode becomes negligible compared to the electrode spacing, which has the effect of considerably attenuating electric field concentration phenomena near the sphere.However, it is important to note that this equivalence between the two configurations does not persist as the inter-electrode distance increases. In fact, the difference between the breakdown voltages of the two geometries becomes increasingly marked as the parameter d rises. This progressive divergence results from the appearance and amplification of electric field inhomogeneity in the sphere-planar case, whereas the planar geometry maintains a uniform field distribution whatever the distance.

IV. Conclusions

Generally, a breakdown voltage of a solid material is higher than that of liquids, and that of liquids is higher than that of gases. Three insulations were chosen during the experimental tests: air, oil and air with PE barrier.

During this work, we treated the influence of certain parameters on the dielectric strength of three dielectric materials: air, borak 22 and air with PE solid dielectric barrier.From the experimental results obtained, we can conclude

1. For the three types of insulation: air, borak 22 oil and air with barrier; the breakdown voltage increases in a non-linear manner with the increase in the electrode gap.
2. The breakdown voltage of the gas insulation with air decreases with the reduction in the curvature radius of the HT electrode, this is the power of the tips
3. Inserting an insulating barrier into the air space between the electrodes improves the dielectric strength of the medium. Indeed, the presence of an insulating screen between the two electrodes transforms the initial air gap into a stratified system (air-barrier).
4. In the case of the tip-plane electrode configuration, the increase in breakdown voltage is observed when the barrier is moved away from the plane then decreases from a certain distance while heading towards the tip.
5. An optimal position of the barrier (between 66 and 83% relative to the plane, d = 30 mm) provides the highest rigidity of the system.

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