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High voltage testing of functional dielectric coatings with thickness from 25 μm and more

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Abstract. The high-voltage spark testing method for protective dielectric coatings is applied in almost all manufacturing areas and is governed by ISO, ASTM etc. However, they do not take into account high voltage generation (DC or AC) and its polarity, the impact of the environment and electric field inhomogeneity. A detailed analysis and modeling of the sparking process was carried out given the polarity of the applied control voltage and the design principles of creating a strongly inhomogeneous electric field in the interelectrode gap. The possibility of monitoring dielectric coatings with a thickness of 25 μm or more while reducing the control voltage without reducing the reliability of the results is shown, which is especially important when testing the continuity of paint coatings of large area objects.

1. Introduction

To reach the ever increasing level of technological development, modern industry needs a wide range of functional dielectric coatings that betray waterproofing, anti-corrosion, dielectric, or other special properties of the treated surface. The violation of the coating process can lead to the formation of structural defects that impair the parameters of functional coatings.

Pores, cracks, metallic or air inclusion etc. can act as defects affecting the functional parameters of dielectric coatings. Currently, domestic and foreign standards (1-4) regulate the use of various methods for defects searching: a high voltage testing method (HVTM), a low voltage testing method (LVTM), a method for visual detection of defects, and an electric field vector mapping method. Of all the methods listed above, the HVTM has the highest productivity, especially for products of large areas or extended objects.

The HVTM (figure 1) implies the creation of an electric field between the electrode and the conductive substrate of coating, the intensity E of which shod be sufficient to form a spark breakdown of defective areas of the coating (for example, air gaps in areas of discontinuity). The electric current I causing by spark is registered by the device, which, informs the operator by sound and light signaling.

Until now, in relation to the HVTM, the dependence of the electrical strength of the air gap on its size, the effect of a number of geometrical and electrophysical parameters of electrodes on the sensitivity and reliability of control (the probability of detecting coating defects) has not been studied. Standards do not pay proper attention to the formation of a control voltage U (constant or pulsed), the polarity of its application, the influence of the non-uniformity of the electric field on the magnitude of the required control voltage, which significantly limits the use of this method. It is assumed that taking into account the factors described below, which determine the nature and course of the processes of coating defective areas breakdown, will allow for the HVTM testing of coatings with an insulation thickness from 50 μm to 25 mm with greater reliability.

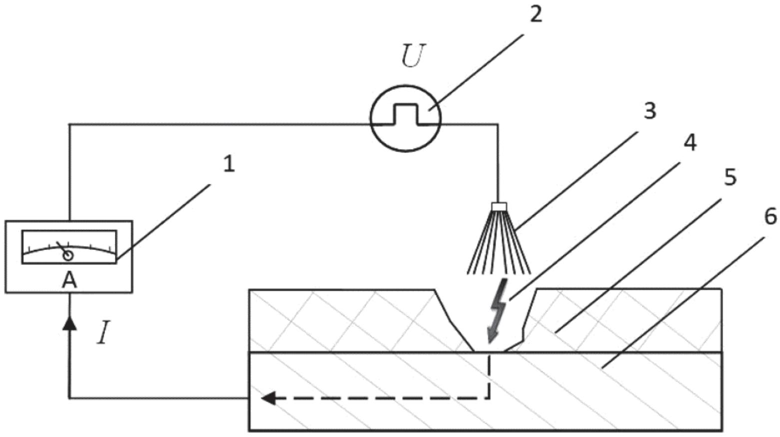

Figure 1. Schematic illustration of the HVTM operation principle. 1 – scheme for fixing the current of spark breakdown and signaling, 2 – high voltage source, 3 – electrode, 4 – spark breakdown of the air gap (defective area of the coating), 5 – dielectric coating, 6 – electrically conductive substrate.

2. The processes leading to the air gaps spark breakdown formation in the case of HVTM

The mechanism for the formation of a breakdown for air gaps d_g in size from about 5 μm to 50 mm is explained by the Townsend theory of electrical breakdown of gases. If a free electron appears in a gas between two electrodes that create an electric field, then, moving to the anode with sufficient electric field strength, it can ionize an atom or gas molecule in a collision. As a result, a new electron and a positive ion appear. A new electron together with an initial electron ionize new atoms and molecules, and the number of free electrons is continuously increasing, and an avalanche of electrons arises. According to the above theory, a streamer is formed from electron avalanches (figure 2) arising in the electric field of the discharge gap. The elongating streamer closes the discharge gap and connects the electrodes, forming a breakdown.

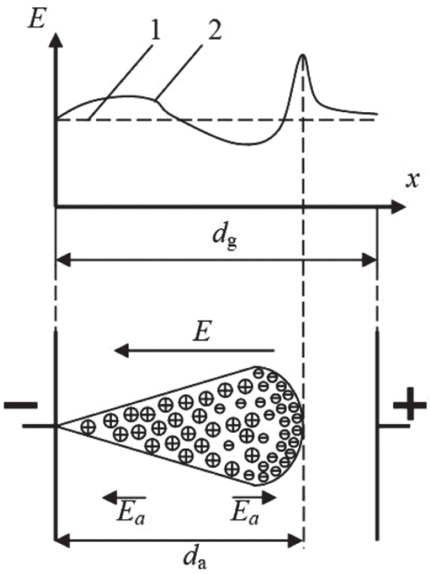

Figure 2. The deformation of the electric field in the interelectrode gap when an electron avalanche occurs: 1 – the average field strength when there is no an avalanche, 2 – the resulting electric field strength, E_a – the electric field strength created by the avalanche.

When analyzing the ongoing processes, it should be taken into account that during the development of an avalanche, simultaneously with electrons, positive ions are formed, whose mobility is much smaller than electrons, and during the development of an avalanche they hardly have time to move in the gap to the cathode. Thus, positive ions, which distort (decrease or increase) the electric field remain, remain after the passage of an avalanche of electrons in the interelectrode gap. Figure 3 shows the electric field strength E distribution in the interelectrode gap during its passage by an avalanche of electrons. It can be seen that E is increased at the front of the avalanche, but in the middle part is decreased, where the remaining positive ions are located, and near the cathode, it is slightly increased again.

As a rule, the appearance of free electrons during discharge is caused by surface ionization from the cathode or photoionization of gas atoms.

A key element of a reliable HVTM is to ensure the conditions for the independence of the discharge in places of coating defects (for example, their discontinuity). The avalanche process resumes when the discharge has independent form, because the primary avalanche (and subsequent secondary ones) creates the condition for the process to resume. Terms of renewal:

– the positive ions remaining after the avalanche passage move to the cathode, bombard it and cause the emission of electrons from the cathode;

– excited atoms and molecules, which are formed along with ionization, emit photons, which can lead to both photoionization in the gap volume, and to the photoemission of electrons from the cathode. The thus formed secondary electrons lead again to the formation of avalanches in the discharge gap.

The electron multiplication intensity in an avalanche is characterized by a shock ionization coefficient (the first Townsend coefficient) α, equal to the number of ionizations produced by an electron on a path of 10 mm in the direction of the electric field. The total process of secondary electrons formation from the cathode is characterized by a secondary ionization coefficient (second Townsend coefficient) γ, which depends on the cathode material, composition and pressure of the gas, while $\gamma \ll 1$. The number of formed after the passage secondary electrons of the primary avalanche at the independent form of the discharge must satisfy the condition:

$$\gamma \cdot \left(e^{(\alpha-\eta)\cdot d_{\mathrm{g}}} - 1\right) \geq 1 \quad (1)$$

where: η is sticking coefficient, equal to the number of electrons bound to neutral atoms on a path of 10 mm in the direction of the electric field.

It shows that the passage of a primary avalanche requires the formation of at least one effective electron capable of igniting a secondary avalanche.

As mentioned above, the number of electrons and positive ions continuously increases during the growth of an avalanche. With an increase in the number of electrons in the avalanche head, the field strength at the front of the avalanche increases, and at the same time in the avalanche tail, the field strength decreases. This leads to the fact that electrons in the avalanche head stop and can recombine with ions, emitting photons, which are capable to ionize neutral molecules near the tail of the primary avalanche, forming secondary avalanches. Secondary avalanches, following the lines of force and having an excess negative charge on the head, are drawn into the region of positive space charge left by the primary avalanche. The electrons of the secondary avalanches mix with the positive ions of the primary avalanche and form a streamer – the area with the highest current density, which begins to glow and extremely heated. The highest concentration of particles (current density) is formed near the cathode. The photon energy must be greater than the ionization energy for photoionization in a gas volume. Calculations show that the avalanche goes into a streamer when the critical number of electrons is $n_{\mathrm{c}} > 10^7 \ldots 10^9$. To accumulate such a number of electrons, an avalanche must pass a certain critical distance. Consequently, the avalanche will inevitably turn into a streamer form of discharge with an increase in the distance between the electrodes above critical distance. The pattern of streamer formation is shown in figure 3.

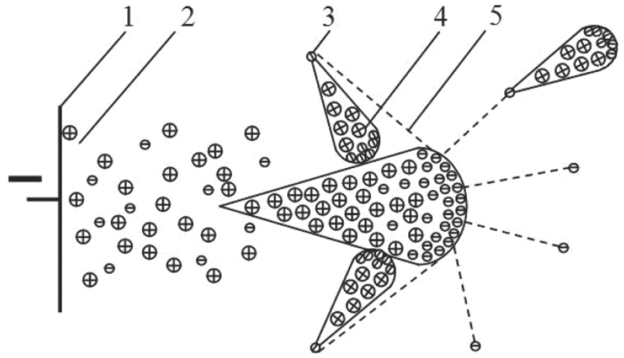

Figure 3. The mechanism of the cathode streamer growth: 1 – the cathode, 2 – a streamer channel, 3 – the electron of photoionization, 4 – the electron avalanche, 5 – a photon trajectory.

According to the Townsend electrical breakdown theory, the breakdown (discharge) voltage U_b is determined by the following formula for a homogeneous electric field:

$$U_\mathrm{b} = \frac{B_0 \cdot P \cdot d_\mathrm{g}}{\ln \frac{A_0 \cdot P \cdot d_\mathrm{g}}{\ln\left(1+\frac{1}{\gamma}\right)}} \qquad (2)$$

where, P is gas pressure; A_0 is a coefficient depending on the gas composition; B_0 is a coefficient depending on the ionization energy of the gas.

It follows from (2) that with a constant external temperature, the breakdown voltage of air U_b in a uniform field is a non-linear function of the multiplication of the gas pressure P by the interelectrode gap d_g, thus $U_b = f(P \cdot d_g)$.

However, within the framework of this article, an interest is the dependence of air gap electrical strength $E_b = U_b / d_g$ on the width of the interelectrode gap d_g. The dependence is determined at normal atmospheric pressure ($P = 10^5$ Pa):

$$E_\mathrm{b} = \frac{B_0 \cdot P}{\ln \frac{A_0 \cdot P \cdot d_\mathrm{g}}{\ln\left(1+\frac{1}{\gamma}\right)}} \qquad (3)$$

This pattern is presented in figure 4.

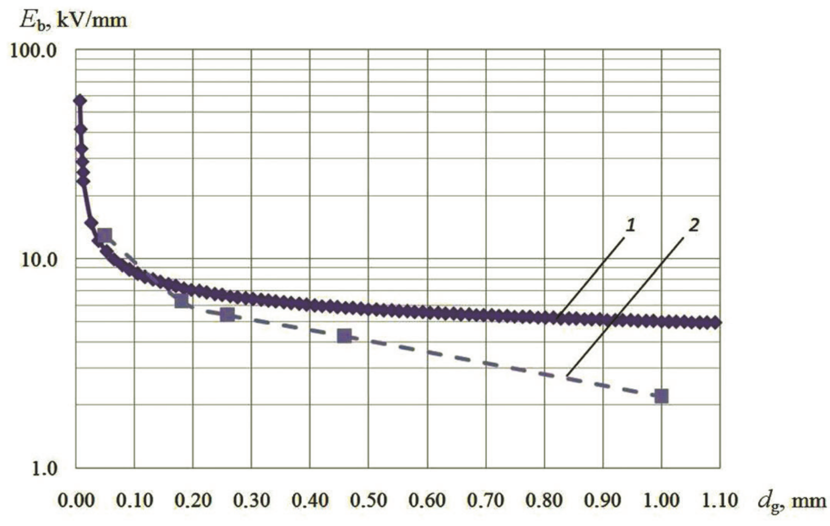

Figure 4. Calculated and experimental (system of electrodes: a cylindrical electrode with a diameter = 0.6 mm - plane) dependences of the air gap breakdown electrical strength E_b on d_g for 1 – homogeneous and 2 – highly heterogeneous electric fields.

The interelectrode gap d_g increasing (at $P = const$) leads to an electron free path length increasing , and as a result, electrons are able to accumulate sufficient kinetic energy to produce ionization impact of gas atoms with a lower external field strength, which leads to decreasing of the electrical strength of the air. The air electrical strength increase abrupt in $d_g < 0{,}1$ mm area, because the electrons free path length value becomes close with interelectrode gap value. On the other hand, the electrical strength of the interelectrode gap can be reduced by creating a highly heterogeneous electric field in it.

3. The influence of electric field form and the polarity on the magnitude of the interelectrode gap breakdown voltage

As mentioned above, the formation of a spark discharge and a streamer is determined by the magnitude of the control voltage U and the form of the interelectrode gap electric field. Traditionally, in electrical engineering, the forms of electric fields are divided into homogeneous, slightly inhomogeneous and highly heterogeneous. A degree of heterogeneity of the electric field between two electrodes is characterized by the inhomogeneity coefficient K_h. K_h is equal to the ratio of the maximum electric field strength E_{max} to the average electric field strength division in the interelectrode gap.

$$K_h = \frac{E_{max}}{E_{av}} \quad (4)$$

wherein,

$$E_{av} = \frac{U}{dg} \quad (5)$$

For a homogeneous field the inhomogeneity factor is $K_h = 1$, for a weakly inhomogeneous is $K_h \leq 3$, for a highly inhomogeneous is $K_h \geq 3$. At the same time, E_{max} depends on the voltage applied to the electrodes, the configuration and size of the electrodes, and the distance between them.

In the general case, the strength E in the inhomogeneous field at various points of the interelectrode gap is different in magnitude and in direction. Heterogeneous fields are created in pairs of rod - rod, rod - plane, wire - earth, and some others. The greatest practical interest for the problem under consideration is the pair rod – plane.

In homogeneous fields (for example, in a system of flat electrodes) in which the intensity $E_0 < E_b$, corona and spark discharges do not occur. In a sharply inhomogeneous field (for example, in a system of electrodes, the rod and the plane) it is possible that the field strength near the rod $E_r > E_b$. In this case, an independent corona discharge occurs, which is localized in around rod area. The discharge will be maintained either by photoionization from the gas volume (in case positive polarity of the rod), or through photoemission or autoelectronic (cold) emission from the cathode (in case negative polarity of the rod). With a slight increase in the field strength in the gap ($E_{av} < E_h$), the corona discharge region moves from the rod to the flat electrode. When a flat electrode is reached, a conductive channel (streamer) of a spark discharge is formed in the entire air gap. Thus, a spark discharge is formed at smaller U in inhomogeneous electric fields than in homogeneous fields.

In the highly inhomogeneous field ($K_h > 3$), with asymmetric electrodes (for example, fan or brush electrodes), polarity has a significant effect on the magnitude of the discharge voltage. In homogeneous and weakly inhomogeneous fields, the effect of polarity is small. Thus, when monitoring the continuity of the coating with rubber electrodes, the control voltage polarity does not matter.

4. The Influence of control voltage polarity on spark breakdown in highly inhomogeneous fields

With a negative polarity of the rod, the electric field directly at the rod tip leads to the emission of electrons from the cathode, which immediately enter a strong field and produce ionization, forming a large number of avalanches. The electrons of avalanches move to a weak field near the anode, lose their speed, and capture by neutral molecules, become negative ions scattered in gap. Positive ions form a volume charge at the rod tip, and increase the field directly at the rod tip and reduce the rest of the gap (figure 5 (a)). The field strength increasing at the rod tip leads to an increasing of the cathode

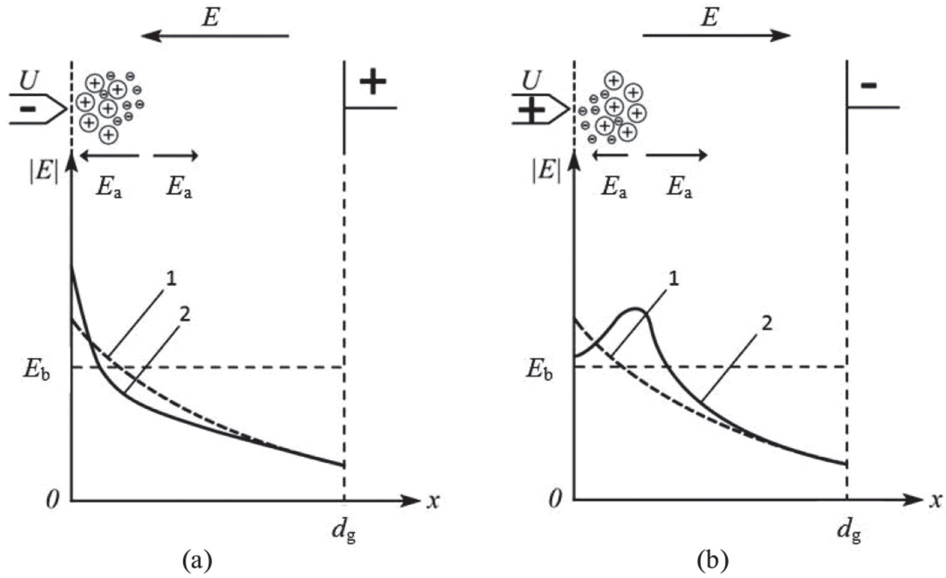

Figure 5. Formation of anode (a) and cathode (b) streamer: 1 – dependence of the electric field strength for the system pointed rod – a plane on the axis of the rod; 2 – the resulting electric field strength in the gap after the occurrence of avalanches; E_b – the electric field strength of the emergence of an independent form of discharge.

surface emission of electrons, and form an embryo of the streamer at the cathode. Due to the large number of initial avalanches at the cathode, the plasma channel here is a more or less homogeneous layer. Therefore, the electric field is somewhat leveled and the intensity in the outer region decreases. The decrease in the electric field strength in the external space leads to the fact that for further ionization in this part of the gap, it is necessary to significantly increase U between the electrodes. With a further increase in voltage, ionization to the right of the plasma layer occurs. A large number of avalanches result to elongate of the streamer. However, just as at the beginning, due to the large number of avalanches, the head of the streamer is blurred, and the increase in tension on the head of the streamer turns out to be much smaller than with a positive rod tip. Due to the features discussed above, the growth of the streamer with a negative tip occurs with great difficulty, therefore the discharge voltage with a negative polarity of the rod tip is greater than with a positive polarity of the rod tip.

With a positive polarity of the rod, the electrons in the gap move to the rod tip in the region of a strong field, make ionization, and form an avalanche of electrons. When the avalanche reaches the rod tip, the avalanche electrons are neutralized at the anode, and the positive ions, due to the low speed, remain at the tip and create a positive space charge, which has its own electric field. The positive space charge, interacting with the external field in the gap, weakens the field near the tip and enhances it in the rest of the gap (figure 5 (b)). If the voltage between the electrodes is large enough, then an electron avalanche arises to the right of the positive space charge. The avalanche electrons, mixing with positive ions of the space charge, create the nucleus of the channel of the anode streamer filled with plasma. The streamer corona discharge is ignited. The positive charges of this avalanche will be located on the head of the streamer and create an area of increased tension in the outer area. The presence of a strong field provides the formation of new avalanches, the drawn into the streamer channel electrons gradually length it. The streamer sprouts to the cathode, causing gap breakdown at a relatively small value of the discharge voltage.

5. High voltage control of dielectric coatings by a highly inhomogeneous electric field

As mentioned above, the highly inhomogeneous electric field creation in the high voltage testing method is achieved by using fan-shaped and brush electrodes, which are a set of small-diameter metal rods.

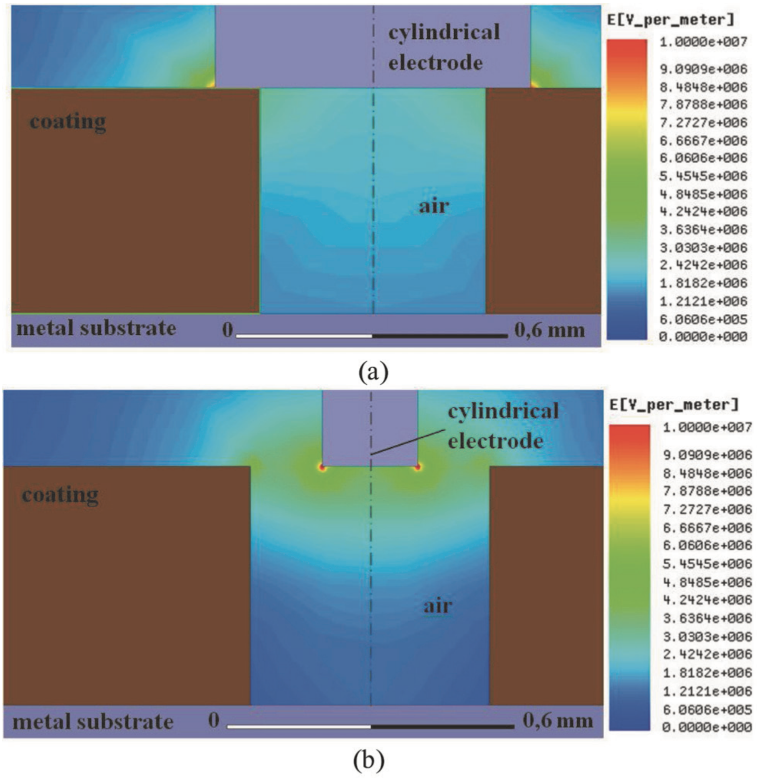

Figure 6. Calculated patterns of the electric field strength distribution in defect of the coating with a diameter of 500 μm (applying voltage is 1 kV): (a) a positive cylindrical electrode with a diameter of 800 μm, (b) a positive cylindrical electrode with a diameter of 200 μm.

However, the shape of the rod tip begins to influence the results of the control when such electrodes are using to detect defects with a diameter of D < 1000 μm in coatings of relatively small thickness (d < 500 μm). Currently, the rods of the electrodes have a cylindrical shape with a diameter of D = 50 ... 800 μm. In case of comparable values of d and D with a strictly perpendicular application of the rod to a thin coating, an almost homogeneous electric field creates in the air gap of the defect. Thereby the breakdown voltage of the gap is increased, which is confirmed by the simulation results and calculations of the electric field strength distribution in the rod – plane system (figure 6).

Reducing the diameter of the cylindrical electrode or giving it a conical shape allows increasing the field inhomogeneity in the defect air gap and, as a result, decreasing the breakdown voltage of the gap. Reducing the breakdown voltage of defective areas allows lowering the control voltage of method to monitor the coatings with a lower value of electrical strength.

6. Conclusion

The ability to control coatings of significantly smaller thickness while reducing the control voltage without reducing the reliability of the results was showed, considering the polarity of the applied voltage and the principles of creating a strongly inhomogeneous electric field in the high voltage testing method. These results are important for controlling the continuity of coatings at large objects.

Reference

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