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THE ELECTRIC FIELD INTENSITY AMPLIFICATION INITIATED BY THE MICROPOINT ON THE SURFACE OF PLANE-PARALLEL ELECTRODES

The research is devoted to the determination of local electric field intensity in the plane-parallel electrode system with the micropoints on the electrodes' surface. The study has revealed that the electric field intensity at the tops of the Gaussian micropoints on the metal electrodes surface exceeds the average electric field intensity between the plane-parallel electrodes no more than 10-20 times. To consider the real pattern of the electric field in a polymer dielectric it is necessary to take into account not only its distortion by asperities on the surface of the electrodes, but also the result of injection of charge carriers into local states - space charges' accumulation. New approach to the determination of electric field pattern between plane-parallel electrodes with micropoints enable the exact solution's finding. Thorough knowledge of processes occurring in the insulation of high voltage equipment clears the way to the equipment's quality and reliability increasing.

Keywords: electric field distortion; point; plane-parallel electrodes, local intensity.

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ЗБІЛЬШЕННЯ НАПРУЖЕНОСТІ ЕЛЕКТРИЧНОГО ПОЛЯ, ІНІЦІЙОВАНЕ МІКРОВІСТРЯМ НА ПОВЕРХНІ ПЛОСКОПАРАЛЕЛЬНИХ ЕЛЕКТРОДІВ

Дослідження присвячено визначенню локальної напруженості електричного поля в пласко-паралельних електродних системах з мікровістрями на поверхні електродів. Дослідження показали, що напруженість електричного поля при вершинах мікровістрів Гаусової форми на поверхні металевих електродів перевищує середню напруженість електричного поля в діелектрику не більше ніж в 10 – 20 разів. Встановлено, що для визначення реального розподілу електричного поля в полімерному діелектрику необхідно враховувати не тільки спотворення, що їх вносять виступи на поверхні електродів, але і результати інжекції носіїв зарядів з електродів на локальні стани в полімерних молекулах – накопичування об'ємних зарядів. Новий підхід до визначення розподілу електричного поля в пласко-паралельних електродних системах з мікровістрями на поверхні електродів дозволив отримати точне рішення для форми вістря, яка найбільш близька до форми реальних виступів.

Ключові слова: спотворення електричного поля; вістря; пласко-паралельні електроди; локальна напруженість.

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УВЕЛИЧЕНИЕ НАПРЯЖЕННОСТИ ЭЛЕКТРИЧЕСКОГО ПОЛЯ, ИНИЦИИРОВАННОЕ МИКРООСТРИЕМ НА ПОВЕРХНОСТИ ПЛОСКОПАРАЛЛЕЛЬНЫХ ЭЛЕКТРОДОВ

Исследование посвящено определению локальной напряженности электрического поля в плоско-параллельных электродных системах с микроостриями на поверхности электродов. Проведенные исследования показали, что напряженность электрического поля у вершин микроострий гауссовой формы на поверхности металлических электродов превышает среднюю напряженность поля между плоскопараллельными электродами не более чем в 10-20 раз. Для рассмотрения реальной картины распределения электрического поля в полимерном диэлектрике необходимо учитывать не только его искажение выступами на поверхности электродов, но и результат инжекции носителей зарядов на локальные состояния в полимерных молекулах – накопление объемных зарядов. Новый подход к определению распределения электрического поля в плоско-параллельных электродных системах с микроостриями на поверхности электродов позволил получить точное решение для формы острия, наиболее близкой к реальной.

Ключевые слова: искажение электрического поля; острие; плоско-параллельные электроды; локальная напряженность.

Introduction. The development of power engineering, automatization of production processes and the electric energy usage area expansion pose to the developers of electrical insulation the task of reliability increasing at the early design stage. The demands to the new electrical materials application and the tightening of the requirements for the reliability of electrical equipment increase the importance of the insulation life-time prediction and its trouble-free operation probability forecasting. Capacitor-building is an important branch of electrical engineering that meets the growing needs of the energy complex. The development of capacitor-building poses ever rising requirements for the reliability and durability of polymer insulation, as it is often operated under rather severe conditions. For example, in pulse capacitors of electric storage power plants the operating electric field intensity in the dielectric between capacitor plates runs up to 100-200 MV/m (provided that capacitor life-time is limited).

Analysis of last researchers. The electric field intensity is the main factor determining the specific characteristics, materials consumption and reliability (in particularly the resource) of the capacitor [1]. For power (including high-voltage pulse) capacitors an assortment of electrotechnical materials, used in the isolation constructions, is very narrow. These are special condenser paper and thin (10-20 μm) synthetic polymer films, as well as liquid electroinsulating materials that fill pores and gaps between layers of insulation. High-voltage capacitor electrodes are usually an aluminium foil or an aluminium layer, applied to a capacitor film (paper) [2]. Ceteris paribus, the foil design has better thermal characteristics, this is very important condition for high-voltage pulse capacitors, as their operation implies the large discharge currents' flow. Metallized capacitor plates allow to use the self-healing effect of the capacity, this effect significantly increases the service life of the products [3]. It is assumed during capacitors design planning (excepting specially specified cases of segmented metallized plates), that the plate's material is homogeneous and have the equal thickness. The average electric field intensity in the dielectric between plates is normally defined as the ratio of the applied voltage to the distance between the plates. However, there are unremovable asperities and points on the real electrodes' surface and such objects distort the electric field pattern in the dielectric. Even when the aluminium layer is deposited on an optically smooth glass, the images obtained with the atomic-force microscope indicate the presence of a huge number of micropoints of various shapes and sizes. Their height can reach 0,1 μm, and the ratio of the height to the basis' width varies from 1 to 10. Thus, the distortion of the electric field pattern by micropoints in the capacitor dielectric is unavoidable at this stage of electrotechnical materials' development and subject to intensive study. The plates' thickness and their displacement's influence on the electric field pattern, the field distortion by current outlets and by heterogeneities in the structure of the dielectric components, the electric field intensity near the electrode plate's edge are studied in depth, meanwhile the electric field intensity at the top of the micropoint and the size of the region, where the field distortions reach the highest values, have not yet been studied.

There are several works in which the intensity of inhomogeneous electric fields in various two-electrode systems was estimated. In the needle-plane electrode system, the field amplification (in comparison with the average electric field intensity) can be quite significant. At the same time, the electric field amplification factor *q* (in other words the coefficient of electrical overvoltage) strongly depends on the shape of the needle [4]. Often the coefficient of electrical overvoltage at the top of point is assumed to be approximately equal to the ratio *h*/*r*, where *h* is the height of the point, and *r* is its radius. For the cylindrical point with a hemispherical top more exact expression was obtained: $q = 1{,}2(h/r + 2{,}15)$ [5], though earlier it was assumed that in these conditions $q = h/r + 2$ [6]. The mutual influence of closely located surface asperities on a local electric field can be taken into account using the expression:

$$q_{1-2} = q(1 - e^{\frac{12{,}32S}{h}}), \qquad (1)$$

where *S*is the distance between the asperities [5].

Inhomogeneous electric field between two plane-parallel electrodes with semi-ellipsoidal asperity on the surface of one of electrodes was considered in [6]. An expression was obtained for describing the field change endwise the axis of the ellipsoid, as one moved away from its top:

$$q(\Delta x) = \frac{\beta}{1 + 2\frac{\Delta x}{r}} \cdot \frac{h}{r} + 1, \qquad (2)$$

herein Δx is the distance from the top of the asperity, $\gamma = (\mathrm{arth}(c/h) - c/h)^{-1}$, where c is a half of the distance between focuses of the ellipse. When the ratio *h*/*r* is not too large, the value of γ is approximately equal to one and $q \approx 1 + h/r$.

Formulation of the work purpose. The aim of the research is a deep understanding of the physical processes, upcoming in polymers under the influence of strong electric fields, and finding the limits of the micropoints' influence on the electric field pattern in the dielectric between plane-parallel electrodes.

Expounding the main material and results analysis. The existence of regions where the electric field intensity is much higher than the mean value in polymers has been confirmed experimentally. Increasing of the hyperfine splitting constant in the electron paramagnetic resonance spectra of stable nitroxide radicals (introduced into the polyethylene film by diffusion) has been revealed in [7] when the $1 \cdot 10^8$ V/m electric field was applied to polymer film. To ensure the experimentally observed shift of this constant, the component of the field intensity by the $N - O$ bond should reach (3-4) $\cdot 10^9$ V/m. In this case most likely reason for the appearance of regions with heightened intensity of electric field is the presence of micropoints on the surface of the electrodes. The electric field amplification factor (the electric overvoltage coefficient) can be evaluated by the ratio of the electric field intensity at a given point of the interelectrode space to the average electric field intensity in the dielectric. The electric field amplification factor depends strongly on the shape of the points on the electrodes' surface [8, 9]. It should also be noted, that whereas the distance between the electrodes decreases, the electric field amplification factor increases. This circumstance should be taken into account in the course of the properties' of thin polymer insulating films considering. Nevertheless, as shown in [10], with a ratio of the distance between the planar electrodes to the height of the point equal to two, the increasing of the electric field amplification factor count only 10 % versus the case when this ratio is by order of magnitude greater.

The field distribution in the plane-parallel electrode system has been reviewed. It was supposed, that one of plane electrode has an axisymmetric protrusion (micropoint) on its surface, the shape of point was determined by the Gaussian function: $z = B\mathrm{e}^{-\left(\frac{x^2+y^2}{\beta B^2}\right)}$, *B* and β are the distribution parameters. This function completly describes the geometry of the real protrusions on the electrodes and allows to vary the shape of the micropoint in a wide range. The electrical potential of the plane, containing the micropoint, has been varied during calculations, and the potential of the opposite electrode was always set to be zero.

The following parameters were selected in the calculations:

– distance between plane electrodes – 1000 nm;

– micropoint's height (*B*) – 250 nm;

– parameter β – varied from 0,0001 to 0,5, as this parameter increases, the micropoint becomes flater.

Numerical simulation method, well-known as finite element method (FEM) was used to calculate the distribution of the electric field. According to the FEM the region where the distribution of the electric potential was defined was divided into triangular subregions. Within each triangular element the potential distribution was assumed to be linear. Knowing the potential at the vertexes of a triangle, one can calculate it at any point inside. Thus, the problem of the potential distribution turns to a system of linear algebraic equations solving. The number of equations in system corresponds to the number of triangular elements. Solving this system enable the potential at the vertexes of all triangles definition, then the true solution is replaced by a piecewise-planar function, and the smooth surface of the real potential distribution is replaced by the polyhedral approximation surface. Taking into account the axial symmetry of the problem, it can be reduced to a two-dimensional one and limited by the first quadrant of the axial section of the plane point, for example, ZX.

Triangulation of the solution search area was carried out in the following way:

– 25 lines parallel to the axis of symmetry of the point were drawn so that the first line coincided with the axis of symmetry of the micropoint (the Z axis), and the subsequent lines were positioned with an interval, increasing as the distance from the axis of symmetry rises;

– between parallel planes 90 Gaussian curves were drawn, these curves were determined by the expression $z = \mathrm{e}^{-\left(\frac{x^2}{\beta B^2}\right)}$, the parameter β was varied in such way as to ensure a smooth change in the shape of the curve from the "needle" to the "plane". Points of intersection of Gaussian curves with vertical lines determined the location of the vertexes under triangulation.

The electric field intensity at the point with the (*x*,*z*) coordinates was determined in the following way. First the potentials at three points: $U(x,z)$, $U(x + \Delta x, z)$, $U(x, z + \Delta z)$ were calculated, then the components of the intensity E_x and E_y according to the expressions $E_x = \frac{(U(x,z) - U(x+\Delta x, z))}{\Delta x}$, $E_z = \frac{(U(x,z) - U(x, z+\Delta z))}{\Delta z}$ were defined, and finally the scalar of the electric field intensity vector was determined: $E(x,z) = \sqrt{E_x^2 + E_z^2}$.

It should be noted that at each node the function that determines the field intensity undergoes a discontinuity, since the right- and left-side derivatives are different. This difference decreases if the density of the grid rises.

Fig. 1 shows the distribution of the electric field along the axis of symmetry of the micropoint as observer moves away from the top (the origin of the X-axis is coincidal to the top of the micropoint). Calculations were carried out for three micropoints: $\beta = 5{\cdot}10^{-4}$ (curve 1), $\beta = 5{\cdot}10^{-3}$ (curve 2) and $\beta = 0{,}15$ (curve 3), $U = 500$ V.

It's easy to see that increasing of β leads to the more homogeneous fields' formation and to the electric field amplification factor's diminution.

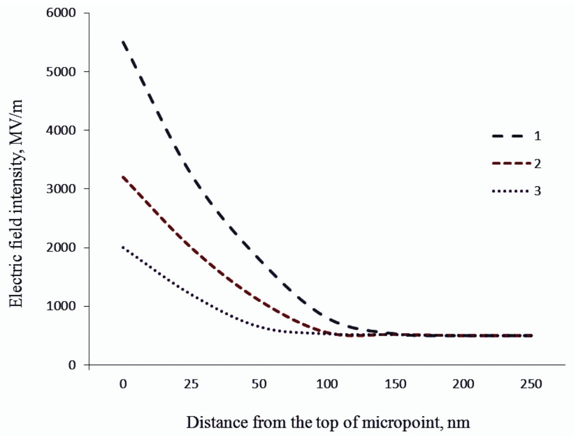

Figure 1 – Distribution of the electric field along the axis of symmetry of the micropoint depending on the distance from the top for $U = 500$ V ($1 - \beta = 5{\cdot}10^{-4}$, $2 - \beta = 5{\cdot}10^{-3}$, $3 - \beta = 0{,}15$)

It is significant that regardless of the β the region where *q* is much greater than unity do not exceed half the height of the point. Exactly such region (where $q >> 1$) suppose the one where local amplification of the electric field is observed.

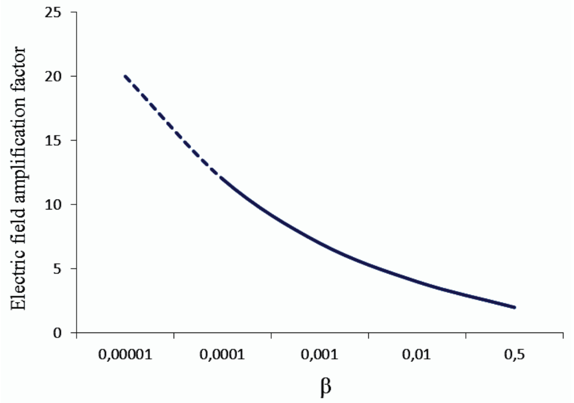

Figure 2 – Dependence of the field amplification factor at the tip of the Gaussian micropoint on the β – parameter

Such a result agrees with the conclusions of [10]. It is noted therein that for single asperity the field distortion region is commensurable with the height of the point, thus the received results can be considered as reliable. It is significant that for $\beta = 5{\cdot}10^{-4}$ when the *q* near the top of micropoint comes to 11, the width of the point at its half-height (125 nm) is only 10 nm, and the radius by which the top can be approximated does not exceed 1 nm. It should be noted that the evaluation of the electric field intensity amplification at the top of similar point according to the technique proposed in [6] gives a value of 100. However, in [6] the projection of the ellipsoidal shape is considered and the domain of reliable solutions' existence is strictly limited by the ratio of the height and the radius of curvature of the projection. The methodology proposed in this paper implies a more reliable description of the projection shape and simulation results are more appropriate.

Fig. 2 illustrates the electric field amplification factor – parameter β dependence.

The findings enable the estimation of the q near the top of any asperity. The magnitude q for $\beta < 1\cdot10^{-4}$ were obtained by approximating the results of calculations for larger magnitudes of the parameter. For example, for $\beta = 5\cdot10^{-5}$ the width of the point at the half-height level is only 1 nm, but the electric field amplification factor does not exceed 20.

Conclusions. The theoretical studies have revealed that the electric field intensity at the tops of the Gaussian micropoints on the metal electrodes surface exceeds the average electric field intensity between the plane-parallel electrodes no more than 10-20 times. To consider the real pattern of the electric field in a polymer dielectric it is necessary to take into account not only its distortion by asperities on the surface of the electrodes, but also the result of injection of charge carriers into local states - space charges' accumulation.

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