ABOUT THE SPACE ELECTRIZATION OF LOW-CONDUCTIVE DIELECTRICS AND ITS INFLUENCE ON THE EQUIPMENT RELIABILITY AND FACILITIES OF POWER ENGINEERING

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Abstract: The supposition is stated that conductivity is a functional of the electric field strength. By isolating a “charged” conductivity component an equation has been obtained for the charge density, and its solution has been found. The limiting cases have been considered. It has been shown that the distribution of space charges ρ is not stable. The method of its experimental determination in a dielectric plane-parallel layer is described.

Keywords: electrization, space charge, low-conductive dielectric, current density, electric field strength, conductivity, mobility, high voltage, inhomogeneous media, facilities of power engineering

1. INTRODUCTION

The problem of electrization of low-conductive dielectric media is one of the old ones in the theory of electricity. It has become the most topical due to the quick development of power equipment, new electrical techniques, high-voltage engineering, electric breakdowns, etc.

Despite many mechanisms and theories exist related to the electrization problem, in many cases still the processes are not well understood that occur first on the interface between a medium and a charged electrode and then spread into the dielectric medium.

Nowadays research in the field of electrization is carried on mainly in the frame of electrohydrodynamics [1], that part of the electrophysics of liquid dielectrics that studies such a hydrodynamic state of a liquid, when it loses its electrical neutrality and then electrohydrostatic stability, and due to these circumstances an electroconvective motion of the liquid arises, or name it adequately – electrohydrodynamic (EHD) flows. The processes related to the medium electrization are the primary ones, but EHD phenomena themselves are the secondary ones. Therefore, the problem of the electrization is the fundamental or key one in the EHD. Its solution creates the necessary prerequisites for the solution of such problems as stability of mechanical equilibrium and generation of EHD flows, stability of these flows and their transition to a turbulent regime, and, at last, the electric breakdown in liquids. The EHD flows themselves influence significantly the processes of the mass, heat and charge transfer. The latter created by the electroconvective current $\vec{j}_\kappa = \rho\vec{\upsilon},$ where ρ is the density of space charges, $\vec{\upsilon}$ is their electroconvective velocity, play the most important role in the power engineering. The electrization problem is formulated correctly in the electrohydrostatic case $\left(\vec{\upsilon} \equiv 0\right),$ though some eliminations are possible, when the motion (that is, $\vec{\upsilon} \neq 0$) is the necessary electrization condition (see below).

The authors proposed a number of mechanisms [2] that elucidate some electrization cases that are observed in practice, strictly say, the distributions of the electrical potential $\varphi(x)$ in the transversal direction (Ox) of a plane-parallel dielectric layer between capacitor plates. More complicated theories on these problems [3–6] also cannot cover the experimentally observed $\varphi(x)$ curves that unambiguously define the space electrization according to equation $\rho = -\varepsilon\varphi''(x)$.

Below the mechanism of the space electrization of a dielectric is proposed that, as we hope, will widen the range of those available by the moment and will be useful. The dielectric is assumed to possess the binary ionic conductivity

$$\sigma = \kappa^{+}\rho^{+} + \kappa^{-}\rho^{-}, \tag{1}$$

where $\kappa^{\pm}, \rho^{\pm}$ are the mobility and density of positive and negative charges, respectively. The density of the non-compensated required charge is given by the formula

$$\rho = \rho^{+} - \rho^{-}, \tag{2}$$

which shows that the dielectric medium loses its electric neutrality due to excessive generation of one kind of the charge with respect to the other one. Hence, the asymmetry in electrical properties of charge carriers, for example, their mobility or the rate of chemical reactions (ability to electroneutralization, etc.) [2], may be the reason of this charge excess. More thorough theoretical research taking into account these points leads to complicated calculations that contain a lot of unknown kinetic parameters, of the collision integral type. It is difficult to interpret their physical meaning and to adapt them for practical purposes.

Moreover the aim may be reached using the most general classical electrodynamics equations approved by many experiments.

Really, the three simplest equations:

$$\rho = \nabla\left(\varepsilon\vec{E}\right), \;\; \vec{j} = \sigma\vec{E}, \;\;\; \nabla\vec{j} = 0 \tag{3}$$

lead to an elegant formula for the charge density

$$\rho = \vec{j}\cdot\nabla\tau, \tag{4}$$

where $\vec{j}$ is the charge density, $\tau = \varepsilon/\sigma$ is the electric relaxation time (ε is the absolute dielectric constant), and clear from the physical point of view charge mechanism as a result of penetration of the electric field through inhomogeneous by its electrophysical parameters (ε and/or σ) dielectric (low-conductive) medium. Formula (4) explains well the generation of surface charge at the interface between media with different τ, as well as electrization of thermally inhomogeneous media taking into account $\varepsilon = \varepsilon(T)$, $\sigma = \sigma(T) \Rightarrow \tau = \tau(T) \Rightarrow \nabla\tau \sim \nabla T$. However, experience shows that a dielectric with perfectly homogeneous composition placed between the plates of a parallel-plate capacitor connected with direct voltage source gains a charge, the potential distribution φ (x) is not linear, this gives evidence that $\rho(x) \neq 0$.

2. HYPOTHESIS THAT CONDUCTIVITY DEPENDS ON THE ELECTRIC FIELD STRENGTH $\sigma = \sigma(E)$ AND ITS INCONSISTENCY

To overcome the difficulty mentioned above we have to suppose that the field itself may be the source of the inhomogeneity taking into account the dependence $\sigma(E)$, for example, according the formula [4–6]

$$\sigma = \sigma_* e^{\alpha(E-E_*)} \cong \sigma_* \left[1+\alpha\left(E-E_*\right)\right], \tag{5}$$

where the first (linear) approximation of the Taylor series is also shown, and E_* is the critical strength, for which dependence (5) becomes valid. This formula is really useful, but only for "geometrically" inhomogeneous fields, in cylindrical capacitor, for example. In principle, the charging is most interesting of a parallel-plate dielectric, because if this case is explained, it obviously may be successfully applied for any (inhomogeneous) field. Unfortunately, the hypothesis about dependence $\sigma(E)$, as a reason of dielectric charging in a parallel-plate capacitor, proves to be inconsistent. In fact, the differential Ohm's law for the plane case has the form

$$\sigma(E)\cdot E = j = \text{const}, \tag{6}$$

assuming $div\vec{j} = 0.$ But equation (6) is a finite (algebraic or transcendental) one, its solution is a constant value E = const, hence,

$$\rho = j\frac{d\tau}{dE}\cdot\frac{dE}{dx} = 0,$$

because $dE/dx = 0$, for example, if $\sigma(E)$ dependence in (5) is linear, equation (6) has two constant roots for E. If the field is inhomogeneous, we have in (6) $j = j(\vec{r}) \neq \text{const},$ then $E = E(\vec{r}) \Rightarrow \rho \neq 0,$ and in inhomogeneous fields the charging may be explained by the dependence $\sigma(E)$, but we should stress that this mechanism is false, because it cannot explain charging for the case of homogeneous field.

3. ISOLATION OF "CHARGED" COMPONENT IN CONDUCTIVITY

It was shown in the previous section that assuming $\sigma = \sigma(E)$ we do not reach our goal, because equation (6) is a finite one with its solution $E = \text{const}$. However, for a liquid medium introducing the convection current density ($\vec{\upsilon} = \vec{i}\,\upsilon$) we obtain

$$j = \sigma\cdot E + \rho\upsilon = \sigma E + \varepsilon E'\cdot\upsilon = \text{const},$$

but it is a differential equation, and its solution is a function of coordinates. Hence, as was mentioned above, the supposition about motion in principle may be used to explain electrization phenomena, but for the case of liquids we generally seek the solution if the framework of electrohydrostatic conditions, here the motion is a secondary effect.

Thus, we return to equation (6), but from some another point of view. Namely, if σ depends on E, but is not a function, we have to admit that it is a functional, that is it depends on E via an operator, most likely a differential one. Then $\sigma = \sigma(E') = \sigma(\rho)$ and in the linear approximation

$$\sigma = \sigma_0 + \alpha E' = \sigma_0 + \kappa\rho, \;\; \kappa \equiv \alpha / \varepsilon. \tag{7}$$

Thus, we have obtained a simple result (7). One can also obtain it using simple physical consideration, because in any system of unequilibrium charges (in the sense of $\rho^+ \neq \rho^-$) one can isolate a "charged" conductivity component $\sigma_e \equiv \kappa\rho$. For this it is enough to eliminate form (1) using (2) one of the partial densities, for example, ρ^+, then we obtain an expression of type (7)

$$\sigma = \left(\kappa^+ + \kappa^-\right)\rho^- + \kappa^+\rho,$$

here we can see that κ is the mobility of excessive charges.

4. SOLUTION OF PROBLEMS

We emphasize that the ρ presence in (7) is of principle character, because only in this case it is possible to take into account the charging process itself.

Further we omit the index in σ_0 assuming $\sigma_0 \to \sigma = \text{const}.$ Taking this into account instead of equation (6) we now have a differential equation

$$\sigma E + \kappa\varepsilon E'E = j = \text{const}. \tag{8}$$

Besides, in more complicated theoretical models σ in this equation may be also treated as a function of E, for example, of type (5); here we consider only the case $\sigma = \text{const}.$ Note, that for the non-stationary problem equation of type (8) may be found in other papers [7] for $j = 0$.

Solution of equation (8) have been found [8] in the form:

$$\frac{j}{\sigma}\ln\left|\frac{j - \sigma E}{j - \sigma E_0}\right| = -\frac{x - x_0}{\kappa\tau} - \left(E - E_0\right),$$

but it is not possible to find the charge density ρ from this equation. Therefore we compose an equation just for ρ. Assuming the case of arbitrary fields we apply div operation to the equation:

$$\vec{E} = \frac{\vec{j}}{\sigma + \kappa\rho} \Rightarrow \varepsilon\kappa\vec{j}\nabla\rho = -\rho\left(\sigma_0 + \kappa\rho\right)^2. \tag{9}$$

For a parallel-plate capacitor we obtain a simple equation

$$\rho' = -\frac{\rho\left(\sigma + \kappa\rho\right)^2}{\varepsilon\kappa j} \tag{10}$$

with implicit solution

$$\ln\frac{\rho(1 + \alpha\rho_0)}{\rho_0\left(1 + \alpha\rho\right)} + \frac{1}{1 + \alpha\rho} = \frac{1}{1 + \alpha\rho_0} - \frac{x - x_0}{\delta}, \tag{11}$$

where

$$\alpha \equiv \frac{\kappa}{\sigma};\ \ \delta \equiv \frac{\tau\kappa j}{\sigma}. \tag{12}$$

Let us consider two limiting cases directly based upon equation (10), because it is much more difficult to analyse equation (11).

a) The case of weak electrization $\kappa\rho << \sigma$.

We obtain from (10)

$$\rho = \rho_0 \cdot e^{-\frac{x-x_0}{\delta}} \tag{13}$$

The density of charges falls exponentially from the electrode ($x = x_0$) into the layer as approaching the counter electrode.

b) The case of strong electrization $\kappa\rho >> \sigma$.

From the same equation

$$\rho = \frac{\rho_0}{\sqrt{1+2\kappa\rho_0^2\left(x-x_0\right)/\varepsilon j}}. \tag{14}$$

The density also falls when x increases. The charge decreasing when the distance from the electrode increases is obvious from equation (10) that shows $\rho' < 0$. When $\rho > 0$ (as we have supposed to the moment), negative charge carriers are more active (mobile and inclined to interchange reactions) ones, which faster electroneutralize on the positive electrode. Otherwise ($\rho<0$), the situation with electrodes and charge carriers is quite opposite.

Note, that condition when the electroconvection occurs is fulfilled automatically [2] $\vec{E}\cdot\nabla\rho < 0$. About ρ time evolution you can see in [7].

5. EXPERIMENTAL VERIFICATION OF RESULTS

$\rho\left(x\right)$ distribution may be determined and compared with theoretical dependences obtained for samples of solid dielectric of various length. According to formula (4) (E = const)

$$\rho_i = \frac{\varepsilon I_i}{S}\cdot\frac{\Delta\chi_i}{\Delta x_i}, \tag{15}$$

where $\chi \equiv \sigma^{-1}$ is resistivity,

$$\Delta\chi_i = \chi_{i+1} - \chi_1;\quad \Delta x_i = x_{i+1} - x_i \tag{16}$$

$i = 0,1,2,...$ is the trial (sample) number.

From the Ohm's law

$$\chi = \frac{U \cdot S}{I \cdot x} \Rightarrow \chi_i = \frac{US}{I_i x_i} = \xi_i \cdot US; \quad \xi_i = \left(I_i x_i\right)^{-1}. \tag{17}$$

From (15), (17)

$$\rho_i = \varepsilon U I_i \cdot \frac{\Delta \xi_i}{\Delta x_i}, \tag{18}$$

where x_i is the *i*-th layer (sample) length.

Note that for $\rho = 0$ one would have $Ix = \text{const}$. Nonobservance of this equation (Ohm's law) will characterize the charge value. Besides, the technique does not involve a probe insertion in the interelectrode gap, this is a method advantage if compared with common ones. One only needs to measure currents vs the length at a given voltage *U*. Another distributions (φ, *E*) may be found in the similar way.

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