DOI: https://doi.org/10.15407/techned2018.05.022

INFLUENCE OF THE DENSITY INCREASING OF CLOSE LOCATED WATER MICRO-INCLUSIONS ON ELECTROPHYSICAL PROCESSES IN NONLINEAR SOLID DIELECTRIC

M.A. Shcherba*
Institute of Electrodynamics National Academy of Sciences of Ukraine,
pr. Peremohy, 56, Kyiv, 03057, Ukraine. E-mail: m.shcherba@gmail.com

Some features of the electro-physical processes that arise in solid dielectric media with the presence of water under the action of strong electric fields are determined. On the example of cross-linked polyethylene insulation of superhigh-voltage cables, the amplifications of the electric field, the increase in current densities and the rise of surface forces in the local regions of the insulation with increasing density of close located water micro-inclusions are calculated. Using the developed mathematical model on the basis of the finite element method, the dependences of the abovementioned values on the number and mutual distances between inclusions are determined. It is demonstrated that the fragmentation of micro-inclusions (i.e. an increase in their number with an unchanged total volume of water) increases the stressed volume of the dielectric, as well as the number of areas with increased field strength and pulsating forces. An increase in the field disturbance can also be caused by a change in the configuration of a set of close located inclusions, in particular, with a decrease in the distances between them. The fragmentation of micro-inclusions is dangerous process for a dielectric, since it can lead to further combining the fragmented micro-inclusions into a single conducting structure along the field and results in irreversible degradation of the dielectric. References 12, figures 3.
Keywords: electric field, XLPE insulation, superhigh-voltage cable, water micro-inclusions, electric current, surface forces, stressed volume.

Introduction. At present, there is an increasing interest in electro-physical processes study (local amplification of the electric field, increasing the current densities, increasing the forces of action) in solid dielectric media with various microdefects. This interest caused by an increase in voltage of modern electric power equipment, which requires ensuring high reliability and a long service life of insulating materials [1]. One of such materials, having a number of advantages and widely used is cross-linked polyethylene (XLPE). Based on the performed studies, the main reason that limits the electrical strength of the XLPE insulation is the appearance of structural defects and external micro-inclusions in this insulation. Such defects arise during both insulation manufacture and its operation [2]. Special attention is paid to the emergence of water micro-inclusions, which can have different configurations (size, shape, orientation relative to the external field, relative position), because the electric field (EF) and surface forces can increase dozens of times near their poles [3]. Such a cumulative electromechanical effect leads to an irreversible degradation of the dielectric and a decrease in its strength and service life [4].

Since it is impossible to ensure the complete absence of water inclusions in the XLPE insulation, it is important to identify the most dangerous of their configurations and to develop recommendations for their minimization in order to increase the reliability and service life of such insulation. It is necessary to take into account that the most intensive degradation of XLPE insulation occurs when the electrical, mechanical and thermal processes in it under the influence of strong nonuniform EF are combined [5]. In addition, the effects that can be neglected in insulation at low voltages, at high and ultrahigh voltages can manifest themselves to a large extent and even become the main ones [6].

In order to estimate the degree of amplification of the EF in the dielectric, in [1] it is proposed to evaluate not only maximal field strength $E_{\max}$, but the dimensions of so-called stressed volumes regions V_{st} (insulation volumes, in which the EF strength is less then breakdown value, but it exceeds the permissible value). With the growth of the dimensions of such regions, the probability of the breakdown of the material in one of the local regions of the stressed volume increases. In other work [7] it is shown that the accumulation of water in the XLPE insulation in the form of a number of close located micro-inclusions of a small size ("cloud") can be more dangerous than the concentration of the all liquid in one large inclusion, as the number of micro-regions of the disturbed field increases with increasing number of micro-inclusions. So, according to modern requirements for the quality of XLPE insulation for cables for high and superhigh voltages, not only the maximum permissible sizes of micro-inclusions, but also their maximum concentrations are regulated [1].

In the study of electro-physical processes in dielectrics with conducting microdefects, the most difficult problem is to determine the regularities of such processes, depending on the configuration of the defects, which can be complex and even vary with time.

The aim of the work is the calculation and analysis of the dependencies of the amplification of the electric field, increase in current densities and the rise of surface forces in the local regions of the XLPE insulation on the number and mutual distances between water micro-inclusions at increase their density.

Physical-mathematical problem statement. The EF distribution in a solid dielectric was calculated using the

*ORCID: http://orcid.org/0000-0001-6616-4567

example of cross-linked polyethylene insulation of an superhigh-voltage cable for voltage up to 330 kV. The EF strength E_Δ in the XLPE insulation on a distance Δ from the surface of the semiconducting layer of the cable core is determined according to the equation $E_\Delta = U[(R_1+\Delta)\ln(R_2/R_1)]^{-1}$, and for Δ < 5 mm the average strength is E_{av} = 10–13 kV/mm. To calculate the field disturbance in the micro-region of a dielectric, according to the multi-scale modeling approach [5], the boundary conditions of the computational domain at the micro-level of the problem solution are determined from the solution of the distribution of the scalar potential φ at the macro-level.

The simulation is carried out in the micro-region of a cylindrical dielectric with a height of 500 μm and a diameter of 300 μm, to which a sinusoidal voltage of 5 kV with a frequency of 50 Hz is applied (see Fig. 1). Therefore, an average field strength is E_{av} = 10 kV/mm. The presence of group of close located ("cloud") water micro-inclusions of a spherical shape in the insulation is considered. The radius of micro-inclusions is set according to their number, so that the total volume of the liquid remained invariable and corresponded to a single spherical micro-inclusion with a radius of 50 μm (the maximum permissible value according to existing requirements).

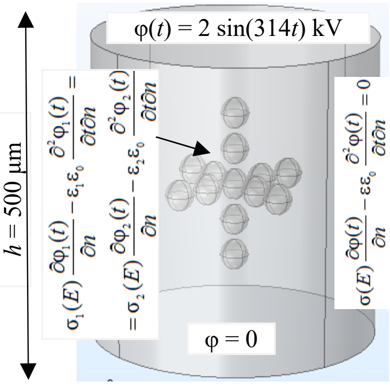


Fig. 1

The media are assumed to be homogeneous, isotropic and linear at E_{av} < 20 kV/mm. At $E_{av} \geq$ 20 kV/mm, the dependence of the electrical conductivity of the XLPE insulation σ (*E*) on the EF strength is taken into account, according to experimental and theoretical data in [8, 9]. According to the model developed in these works, the dependence σ(*E*) is represented by the following expression:

$$\sigma(E) = \sigma_{const}\left(2kT/aeE(t)\right)\mathrm{sh}\left(aeE(t)/2kT\right). \tag{1}$$

Here $\sigma_{const} = 10^{-14}$ S/m is the constant conductivity of the XLPE in a weak EF, *e* is the charge of the carrier, *T* is the absolute temperature, $k = 1.38\ 10^{-23}$ J/K is the Boltzmann constant, and *a* is the distance between the potential energy barriers, which for polyethylene is about 2 nm.

Taking into account that the EF has low-frequency, the problem was formulated in the quasi-static approximation according to the system of Maxwell's equations [10]. The calculation equation for the scalar electric potential, φ(*t*) (***E***(*t*) = – grad φ(*t*)), is written as

$$\mathrm{div}\left[\sigma(E)\,\mathrm{grad}\,\varphi(t) - \varepsilon\varepsilon_0\,\partial\,\mathrm{grad}\,\varphi(t)/\partial t\right] = 0\,. \tag{2}$$

Here σ(*E*), ε are the electrical conductivity and permittivity of the medium, respectively.

The total current density vector $\boldsymbol{J}_{total}(t)$ is calculated as the sum of the conduction current vectors $\boldsymbol{J}_{cond}(t)$ and the displacement current $\boldsymbol{J}_{displ}(t)$:

$$\boldsymbol{J}_{total}(t) = \boldsymbol{J}_{cond}(t) + \boldsymbol{J}_{displ}(t) = \sigma(E)\boldsymbol{E}(t) + \varepsilon\varepsilon_0\,\partial\boldsymbol{E}(t)/\partial t\ . \tag{3}$$

Thus, for a weak EF, the main current in the local region of the insulation is the displacement current $\boldsymbol{J}_{displ}(t)$, and in micro-inclusions – the conduction current $\boldsymbol{J}_{cond}(t)$. For strong EF, the nonlinear dependence of the conductivity σ(*E*) in the insulation was taken into account, which can substantially increase the conduction currents in it.

Equation (2) is supplemented by conditions on the boundaries of the computational domain shown in Fig. 1: at the upper and lower boundaries – by specifying the values φ(*t*), and on the side boundaries – by zeroing the derivative of the potentials φ(*t*) along the normal ***n*** to the surface. At the interface "water-XLPE insulation" the following conditions are set:

$$\sigma_1(E)\,\partial\varphi_1(t)/\partial n - \varepsilon_1\varepsilon_0\,\partial^2\varphi_1(t)/\partial t\partial n = \sigma_2(E)\,\partial\varphi_2(t)/\partial n - \varepsilon_2\varepsilon_0\,\partial^2\varphi_2(t)/\partial t\partial n\,, \tag{4}$$

i.e. it is determined the equality of the normal components of the total current density: $\boldsymbol{n}\cdot(\boldsymbol{J}_{total\,1}(t) - \boldsymbol{J}_{total\,2}(t)) = 0$.

To calculate the electromechanical surface forces $\boldsymbol{f}_s(t)$ arising at the interface "conductor-dielectric" under the action of an external EF, we used the Maxwell tensor $\hat{\mathrm{T}}(t)$ [10, 11]:

$$\mathbf{f}_s(t) = \hat{\mathrm{T}}(t)\cdot\mathbf{n} = \left[\frac{1}{2}(\mathbf{D}(t)\cdot\mathbf{E}(t))\hat{\mathbf{I}} - \mathbf{D}(t)\otimes\mathbf{E}(t)\right]\cdot\mathbf{n}\,. \tag{5}$$

Here $\hat{\mathrm{I}}$ is the unit tensor, ⊗ is the dyadic (tensor) product, $\boldsymbol{D} = \varepsilon\varepsilon_0\boldsymbol{E}$.

As in [1, 7], the value of the stressed volume V_{st} is determined according to the equation:

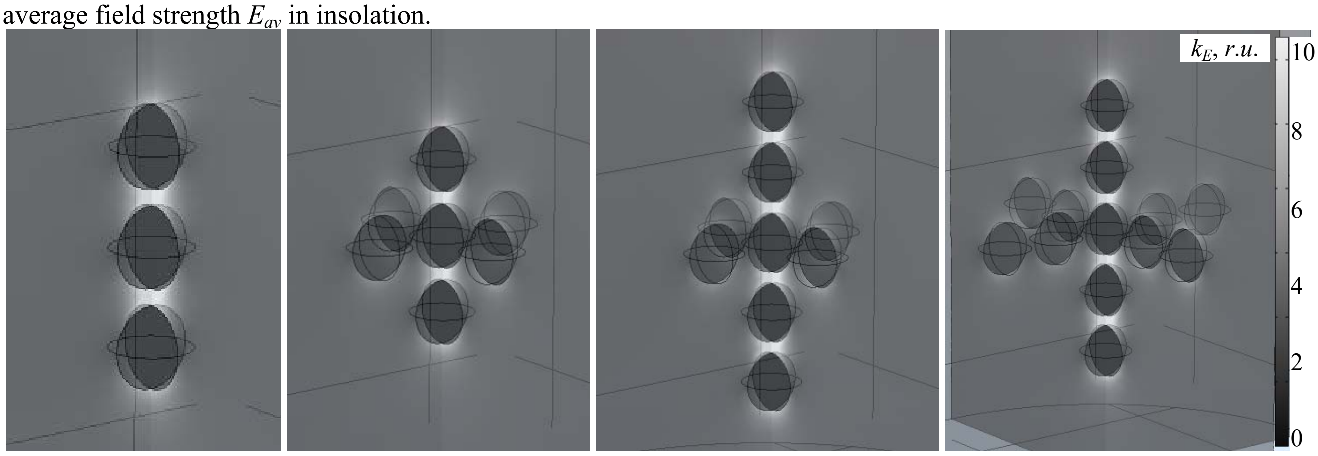
$$V_{st} = \int_V f(E)dV. \tag{6}$$

Here *V* is the computational domain of the XLPE, *f*(*E*) is the function that to possess the value *f*(*E*) = 1 for EF above the permissible value ($E \geq E_{perm}$), and at $E < E_{perm}$ it takes the value *f*(*E*) = 0.

The calculated time interval Δ*t* is digitized, and equation (2) is solved by the finite element method for all the moments t_i, taking into account the nonlinear dependence determined according to the expression (1). The calculation of the problem begins with zero initial conditions and the effective values of the calculated temporal functions in the steady-state oscillation mode are analyzed. The solution is implemented in the Comsol Multiphysics package [12].

Results of numerical experiment. The cases of fragmentation of the total volume of liquid into micro-inclusions from 1 to 25 pieces were simulated. The dependences of the maximum field strength $E_{\max}$, the total current density J_{total}, the values of the stressed volume V_{st}, and the maximum surface force $f_{S\,\max}$ in the XLPE insulation on the number and mutual distances between micro-inclusions were investigated.

Fig. 2 shows the results of calculating the field strength E distribution in computational domain, depending on the number of micro-inclusions (3, 7, 9 and 13 ones). Colors correspond to a scale on the right side of Fig. 2 and E value was given in dimensionless units in the form of the electric field amplification factor $k_E = E/E_{av}$, i.e. referred to the average field strength E_{av} in insolation.

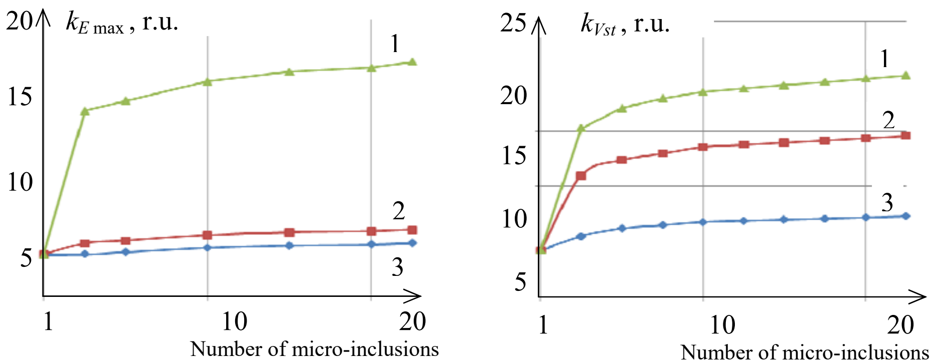


a ***b*** ***c*** ***d***

Fig. 2

The distances l between the inclusions are also given in dimensionless units, they are reduced to the diameter d of the inclusions l/d. For the calculation on Fig. 2 mutual distances are l/d = 0.2. Maximal field strength E_{max} is observed at poles of the central inclusion in the "cloud" and equals $k_{E\,max}$ = 13–17 depending on a number of inclusions. Calculations have shown that the "cloud" consisting of multitude of inclusions can be considered as close located chains of inclusions oriented along the EF. The main influence on the field distortion is provided by the configuration of the inclusions in each chain, while the mutual effects of the chains on each other are insignificant.

The value of stressed-volume was also given in dimensionless units in the form of the stressed-volume coefficient $k_{Vst} = V_{st}/V_w$, i.e. referred to the total volume of water V_w and the dependences of the $k_{E\,max}$ and k_{Vst} coefficients on the number of micro-inclusions are shown in Fig. 3.



a **Fig. 3** ***b***

Curves *1*, *2* and *3* correspond to the different distances between inclusions l/d = 0.2; 0.1 and 0.04. Thus, when the inclusions are broken, the value of V_{st} increases by a factor of 2 or more when distances between inclusions are greater than 0.1 of their diameter, if not, the V_{st} increases by a factor of 3 or more. At the same time $k_{E\,max}$ could be increased by a factor of 6 for l/d = =0.04. The EF amplification described above can be explained by the fact that during the fragmentation of micro-inclusions in the "cloud" its length along the field increases. If we assume that the distances between micro-inclusions remain the same, then the dimensions of the "cloud" along the field increase by 5 times or more when "cloud" configuration similar to spherical form and by 10 times or more when the inclusions are arranged mainly along the electric field.

Conclusion. Calculation and analysis of the distribution of the electric field in the local volume of cross-linked polyethylene insulation with the presence of a "cloud" of close located micro-inclusions of various configurations is carried out. The analysis showed that the fragmentation of micro-inclusions (an increase in their number and a decrease in size with an unchanged total volume of liquid in the insulation) can cause an increase in the total stressed insulation volume by a factor of 3 or more at close distances between inclusions. In this case, the magnitude of the electric field strength in the dielectric gaps between the inclusions increases by 17 times or more.

The fragmentation of water micro-inclusions leads to an increase in the dimensions of the "cloud" along the the field by 5 times or more when "cloud" configuration similar to spherical form and by 10 times or more when the inclusions are arranged mainly along the electric field. Near the poles of each of the inclusions in the insulation the regions with increased field strength are created. In the course of time micron droplets of water and sub-micron ones are drawn into these regions. This phenomenon together with the pulsating pressures on the dielectric material creates the conditions for the appearance and germination of water treeing from the inclusions surface in the direction of combining the elements of the "cloud" into one whole conductive structure, what reduces XLPE dielectric strength.

1. Shcherba A.A., Podoltsev A.D., Kucheriava I.M. Electromagnetic processes in 330 kV cable line with polyethylene insulation. *Tekhnichna Elektrodynamika*. 2013. No 1. Pp. 9–15. (Rus)

2. Wang W., Tao W., Ma Z., Liu J. The mechanism of water tree growth in XLPE cables based on the finite element method. Proc. IEEE Intern. Conf. *on High Voltage Engineering and Application* (ICHVE), Chengdu, China, 19-22 September 2016. Pp. 1–4.

3. Shcherba M.A. Multi-physical processes during electric field disturbance in solid dielectric near water micro-inclusions connected by conductive channels. IEEE Intern. Conf. on *Intelligent Energy and Power Systems* (IEPS), Kyiv, Ukraine. 2016. Pp. 1-5.

4. Kurihara T., Okamoto T., Hozumi N., Miyajima K., Uchida K. Evaluation of relationship between residual charge signal and AC breakdown strength of water-tree degraded XLPE cables removed from service using. *IEEE Trans. on Dielectrics and Electrical Insulation*. 2017. Vol. 24(1). Pp. 656–665.

5. Podoltsev A.D., Kucheriava I.N. Multiphysical modeling of electrical devices. *Tekhnichna Elektrodynamika*. 2015. No 2. Pp. 3–15. (Rus)

6. Burkes K.W., Makram E.B., Hadidi R. Water Tree Detection in Underground Cables Using Time Domain Reflectometry. *IEEE Power and Energy Technology Systems Journal*. 2015. Vol. 2(2). Pp. 53–62.

7. Shcherba M.A., Zolotarev V.M., Belyanin R.V. The comparison of electric field perturbations by water inclusions in linear and nonlinear XLPE insulation. IEEE Intern. Conf. on *Computational Problems of Electrical Engineering* (CPEE), Lviv, Ukraine. 2015. Pp. 188-191.

8. Tokoro T., Nagao M. and Kosaki M. High Field Dielectric Properties and ac Dissipation Current Waveforms of Polyethylene Film. *IEEE Trans. on Electrical Insulation*. 1992. Vol. 27. No 3. Pp. 482–487.

9. Boggs S.A. Semi-empirical high-field conduction model for polyethylene and implications thereof. *IEEE Trans. on Dielectrics and Electrical Insulation*. 1995. Vol 2.1. Pp. 97–106.

10. Landau L.D., Livshitz E.M. Electrodynamics of continuous media. Moskva: Fizmatlit, 2003. 560 p. (Rus)

11. Shcherba M.A. Force interaction between close placed conducting micro-inclusions in dielectric medium in external electric field. *Tekhnichna Elektrodynamika*. 2012. No 3. Pp. 11–12. (Rus)

12. Comsol Inc. Burlington, MA. URL: https://www.comsol.com (Accessed at 15.12. 2017).

УДК 621.3.01:537.212

ВПЛИВ ПІДВИЩЕННЯ ГУСТИНИ БЛИЗЬКО РОЗТАШОВАНИХ ВОДНИХ МІКРОВКЛЮЧЕНЬ НА ЕЛЕКТРОФІЗИЧНІ ПРОЦЕСИ В НЕЛІНІЙНОМУ ТВЕРДОМУ ДІЕЛЕКТРИКУ

М.А. Щерба, канд.техн.наук
Інститут електродинаміки НАН України,
пр. Перемоги, 56, Київ, 03057, Україна. **E-mail: m.shcherba@gmail.com**

Визначено деякі особливості електрофізичних процесів, що виникають у твердих діелектричних середовищах у сильних електричних полях в присутності води. На прикладі зшитої поліетиленової ізоляції надвисоковольтних кабелів розраховані підсилення електричного поля, підвищення густини струмів і зростання поверхневих сил в її локальних областях при підвищенні густини близько розташованих водних мікровключень. Використовуючи розроблену математичну модель на основі методу скінченних елементів, розраховано залежності зазначених величин від кількості і взаємних відстаней між включеннями. Продемонстровано, що дроблення мікровключень (тобто збільшення їхньої кількості при незмінному сумарному об'ємі води) збільшує напружений об'єм діелектрика, а також кількість областей підвищеної напруженості і пульсуючих сил. До збільшення збурень поля може призводити також зміна конфігурації сукупності близько розташованих включень, зокрема при зменшенні відстаней між ними. Дроблення мікровключень є небезпечним для діелектрика, оскільки може призводити до їхнього подальшого об'єднання в єдину провідну структуру вздовж поля і призводити до незворотної деградації діелектрика. Бібл. 12, рис. 3.

Ключові слова: електричне поле, ЗПЕ ізоляція, надвисоковольтний кабель, водні мікровключення, електричний струм, поверхневі сили, напружений об'єм.

УДК 621.3.01:537.212

ВЛИЯНИЕ ПОВЫШЕНИЯ ПЛОТНОСТИ БЛИЗКО РАСПОЛОЖЕННЫХ ВОДНЫХ МИКРОВКЛЮЧЕНИЙ НА ЭЛЕКТРОФИЗИЧЕСКИЕ ПРОЦЕССЫ В НЕЛИНЕЙНОМ ТВЕРДОМ ДИЭЛЕКТРИКЕ

М.А. Щерба, канд.техн.наук
Институт электродинамики НАН Украины,
пр. Победы, 56, Киев, 03057, Украина. **E-mail: m.shcherba@gmail.com**

Определены некоторые особенности электрофизических процессов, возникающих в твердых диэлектрических средах в сильных электрических полях в присутствии воды. На примере сшитой полиэтиленовой изоляции сверхвысоковольтных кабелей рассчитаны усиления электрического поля, повышения плотностей токов и рост поверхностных сил в ее локальных областях при повышении плотности близко расположенных водных микровключений. Используя разработанную математическую модель на основе метода конечных элементов, рассчитаны зависимости указанных величин от количества и взаимных расстояний между включениями. Продемонстрировано, что дробление микровключений (т.е. увеличение их количества при неизменном суммарном объеме воды) увеличивает напряженный объем диэлектрика, а также количество областей повышенной напряженности и пульсирующих сил. К увеличению возмущений поля может приводить также изменение конфигурации совокупности близко расположенных включений, в частности при уменьшении расстояний между ними. Дробление микровключений является опасным для диэлектрика, поскольку может приводить к их дальнейшему объединению в единую проводящую структуру вдоль поля и приводить к дальнейшей необратимой деградации диэлектрика. Библ. 12, рис. 3.

Ключевые слова: электрическое поле, СПЭ изоляция, сверхвысоковольтный кабель, водные микровключения, электрический ток, поверхностные силы, напряженный объем.

Надійшла 02.03.2018
Остаточний варіант 15.03.2018