COMPUTATIONAL PROBLEMS OF ELECTRICAL ENGINEERING

Vol. 6, No. 2, 2016

EFFECT OF WATER TREES "STRING OF PEARLS" CONFIGURATION ON THE DISTRIBUTION OF ELECTRIC FIELD, CURRENT AND STRESSED VOLUME IN XLPE INSULATION

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Abstract: The processes originating in local areas of cross-linked polyethylene (XLPE) insulation of extra-high voltage cables during water tree germination between closely disposed water micro-inclusions in insulation have been studied. According to current experimental data, water trees in XLPE have not solid cylindrical shape, as it was thought previously, but they consist of closely spaced nanoscale inclusions of spheroid form and nanoscale thin water channels between them (so-called "string of pearls" configuration). The electric field disturbances near such trees can significantly differ from the disturbances near solid ones. Therefore, the paper presents the results of mathematical modeling and analysis of the electric field strength distribution, changes in stressed volumes and densities of currents in XLPE insulation near the micro-inclusions connected by the tree of "string of pearls" configuration. The cases of nano-cracks appearing in a dielectric gap between micro-inclusions, their partial or complete filling with water, that is, the water tree formation with branches of different conductivity were simulated. It was shown that water tree germination between inclusions and the increase in the conductivity of its branches leads to connecting inclusions into a single conductive structure that disturbs the electric field stronger than single micro-inclusions. The regularities of increasing the electric field strength (which describes the rapid determined degradation mechanisms), increasing the stress volume (which describes the slow stochastic degradation mechanisms) and increasing current density in local areas (which describes the insulation overheating) were determined. The obtained results are useful for the analysis of interrelated processes of XLPE degradation and for the evaluation of insulation resource during its long operation.

Key words: electric field, XLPE, simulation, water micro-inclusions, water tree, degradation.

1. Introduction. Solving the tasks of the calculation of strong electric fields (EF) in heterogeneous dielectric mediums is nowadays an actual problem, interest to which still increasing. With the development of modern computational methods and their software implementations, it became possible to solve problems not solvable in the past [9]. They arise during the design of modern electrical power equipment and expand the electromagnetic field theory. One of the important practical problems is the calculation of EF in a cross-linked polyethylene (XLPE) insulation of high voltage and superhigh-voltage cables in the presence of various water micro-defects in this insulation [2, 7, 14].

Summarizing the results of numerous studies, the following algorithm for the cable insulation breakdown in a strong electric field in the presence of moisture can be described [2–4, 6–8, 15]. In micron-level and nano-level voids and cracks, which are always present in XLPE, water is gradually accumulated. As a result, micron-level and submicron inclusions occur. At the poles of such inclusions, liquid pressure on the surface of polyethylene is created and, in some cases, its magnitude can exceed the mechanical strength of a material and it leads to the appearance of new cracks [2].

Moreover, there are regions of increased field strength near the poles of inclusions, in which the new water molecules are drawn in due to the dielectrophoretic forces [8]. Such inclusions become centers of water trees – thin-branched structure forms [3]. Near the tips of tree branches the high pressure and field strength also appear. This enlarges the tree structure and promotes further XLPE degradation.

In the dielectric gap between closely approximating water micro-inclusions the EF additionally intensifies [11, 14]. The appearance of cracks in the polyethylene and germination of water trees can cause the appearance of conducting channel between the inclusions, which conductivity increases while it is being filled with water [3, 13]. Ultimately, closely disposed inclusions unite into one structure [14].

Fast deterministic processes of dielectric degradation are described by studies of the maximum levels of the electric field strength, which can exceed the breakdown voltage of XLPE insulation [2, 7]. To describe the slow stochastic processes of its degradation it was proposed to evaluate the dimensions of areas of stressed volumes in XLPE [14], i.e. those areas where EF tension is lower than the breakdown value E_{break}, but higher than a determined permissible value E_{perm}. The larger stressed volume V_{st} in insulation, the greater its breakdown probability in any region of this volume.

In addition to solving electrical and mechanical tasks, it is also expedient to solve the heat problem of the calculation of the heating of local insulation areas by displacement currents, as well as the heating the areas of water defects by the flow of conduction currents [1, 14]. These studies are particularly relevant in situations of a sharp change in the cross section of conductive defects, i.e. on the inclusion surface turning into the water tree. On the defect-dielectric boundary the conduction currents close through the displacement currents in the XLPE insulation and their high densities can lead to the material heating and thus a reduction of its electrical and mechanical strength [2].

In [3] it was shown that the water tree branches in XLPE do not have a solid cylindrical shape, as it was considered, but they consist of closely located micro-inclusions of spheroidal shape with a thin nanoscale water channels between them (“string of pearls” configuration), as it is shown in Fig. 1.

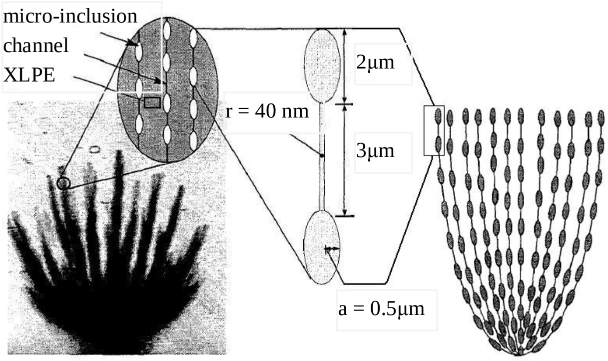

Fig. 1. Water tree simulation by closely located spheroids, connected by conductive channels [3].

The distribution of EF near such a tree may significantly differ from the homogenous one with cylindrical branches of a constant cross-section. Such trees can germinate between the surfaces of closely disposed water micro-inclusions combining them into a single conductive structure. Therefore, the modeling and analysis of the field distribution near the “string of pearls” tree configurations should be done. It is expedient to determine the levels of the appearing EF amplification, the values of stressed volume and currents density in the dielectric, as well as to identify the factors with the greatest impact on the insulation resource.

The aim of the work is to conduct calculations and comparative analysis of changes in the values of electric field strength, stressed volumes and current density occurring in XLPE insulation of high-voltage cables near water micro-inclusions connected by the “string of pearls” water tree depending on its conductivity.

2. Physical and mathematical problem formulation. The average EF intensity in XLPE insulation of the cable for voltage of 330 kV at a distance up to 5 mm from the surface of a semi-conductive layer is $E_{av} \geq 10$ kV/mm. The insulation layer with thickness of 0.6 mm, to which sinusoidal voltage of 6 kV at 50 Hz is applied (see Fig. 2), was simulated.

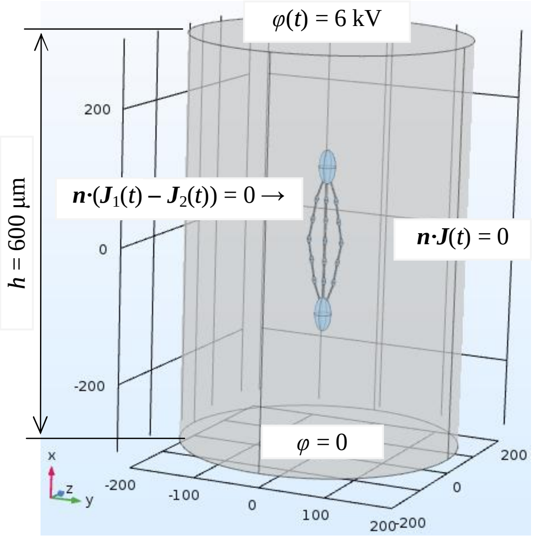

Fig. 2. Computational domain of XLPE insulation with water micro-inclusions and boundary conditions.

The shape of a water droplet in XLPE under the influence of external EF is characterized by a balance of the Coulomb forces, the interfacial tension forces and the elastic reaction forces of medium. According to the calculation in [15], the most characteristic shape of water micro-inclusions in XLPE is a spheroid with semi-axes ratio a/b in the range of 1.5 to 3.

In this work the presence of two micro-inclusions of the most typical spheroidal shape with semi-axes ratio $a/b = 2/1$ connected by “string of pearls” water trees in the XLPE is considered (see Fig. 2). The semi-axes of the inclusions are 25×12.5×12.5 μm. Each branch of ′strings of pearls′ type consists of 5 micro-inclusions with semi-axes 6×3×3 μm and 6 connecting channels about 25 μm long with a radius of 1 μm. All inclusions are considered to be the water ones with corresponding conductivity σ_{water} and dielectric permittivity ε_{water}, though the values of conductivity and dielectric permittivity of connecting channels vary from quantities specific to XLPE to those characteristic of water.

Such water defect configuration simulates the case when water droplets are retracted in the dielectric gap between two closely disposed micro-inclusions, being the area of maximum EF strength, due to dielectrophoretic forces, following germination of water channel between them and emergence of water tree with it subsequent branching.

The XLPE insulation medium was considered to be piecewise homogeneous, isotropic and linear, as in [10, 11, 14]. The problem was formulated in the quasi-static approximation and the interrelations of the EF vectors were described by Maxwell's equations, written using the method of complex amplitudes [5].

$$\mathrm{rot}\,\vec{H} = \vec{J}_{total}, \qquad \mathrm{rot}\,\vec{E} = -i\omega\vec{B}, \qquad (1,2)$$

$$\mathrm{div}\,\vec{B} = 0, \qquad \mathrm{div}\,\vec{D} = \rho. \qquad (3,4)$$

The equation for scalar electric potential $\dot{\varphi}$ is:

$$\vec{E} = -\mathrm{grad}\,\dot{\varphi}. \qquad (5)$$

The final equation for the scalar electric potential $\dot{\varphi}$ in computational domain of XLPE insulation is [11, 14]:

$$\mathrm{div}[-\sigma + i\omega\varepsilon_0\dot{\varepsilon}]\cdot\mathrm{grad}\,\dot{\varphi} = 0. \qquad (6)$$

To obtain the unique solution to the equations (6), the Dirichlet conditions (values of electric potentials) were set for the upper and lower boundaries of the computational region (Fig. 2), and the Neumann conditions (values of the surface normal derivative of potentials) were set for the side faces of the computational region and for the water-XLPE interface (i.e., interface between the inclusion and the medium).

The estimation of the distribution of scalar electric potential $\dot{\varphi}$ in the computational domain was performed using the numerical finite element method implemented in a Comsol Multiphysics software package. As shown in [11, 14], the value of stressed volume V_{st} for the three-dimensional computational domain was determined according to the equation:

$$V_{st} = \int_V f(E)dV, \qquad (7)$$

where V is the computational domain of XLPE, $f(E)$ is a function, which for the EF strength higher then permissible value ($E \geq E_{perm}$) takes the value of $f(E) = 1$, and for $E < E_{perm}$ takes the value of $f(E) = 0$.

The vector J_{total} of total current density is a sum of vectors of a conduction current in the water micro-defects J_{cond} and a displacement current J_{dis} in XLPE insulation:

$$\vec{J}_{total} = \vec{J}_{cond} + \vec{J}_{dis} = \sigma\vec{E} + \varepsilon\varepsilon_0\frac{\partial\vec{E}}{\partial t}. \qquad (8)$$

3. Simulation results

3.1. Closely spaced inclusions. At the first part of the work, independent closely spaced micro-inclusions without connecting channels were simulated. Values of E and V_{st} were represented in relative units as the electric field gain factor $k_E = E/E_{av}$ and stressed volume coefficient $k_{Vst} = V_{st}/V$. Coefficient k_E was defined as the ratio of field strength E in the calculated points in dielectric to its average value E_{av} in the computational domain. Coefficient k_{Vst} was defined as the ratio of V_{st} throughout the computational domain to the total volume V of all water micro-defects in XLPE.

Fig. 3 displays: *a*) an EF distribution; *b*) a stressed volumes V_{st} on cut-plane through all inclusions centers; *c*) an EF distribution; and *d*) a total current density on a cut-line through the centers of the two biggest inclusions and five smaller in a middle tree branch. Colors correspond to the E value according to a scale on the right side of Fig. 3. Colored area in Fig. 3, *b*) is a stressed volume area, where the EF intensifies by 20 % and more.

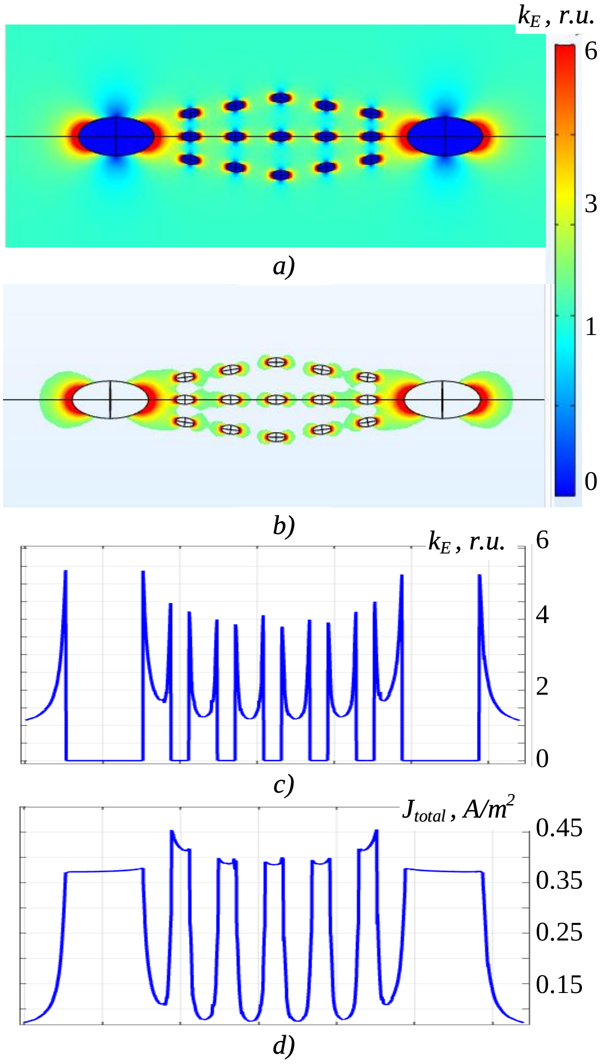

Fig. 3. a) EF distribution; b) location of stressed volumes V_{st} on plane of section; c) EF distribution; d) total current density J_{total} on cut-line near independent inclusions.

According to the numerical experiment, small micro-inclusions get into the field of nearby large inclusions, which manifests itself through the increase in k_E and J_{total} near small inclusions (Fig. 3). The largest EF strengths are observed near the micro-inclusion poles, where field could increase 5 times and more. It means that if the average field strength near the core of a HV cable with XLPE insulation equals 10 kV/mm, in local areas the highest field strength is $E_{\max} \geq 50$ kV/mm. Such EF can exceed the XLPE dielectric strength (40–80 kV/mm) and can lead to local breakdowns.

3.2. Inclusions connected by channels with low conductivity. The second part of this work is dedicated to the computation of the EF distribution in the XLPE insulation near the complex micro-defect consisting of closely located spheroid micro-inclusions with thin water channels between them (water tree with “string of pearls” configuration). Channels of the tree were simulated as tubes of cylindrical shape with radius of 1 µm and length of 25 µm. The channels are gradually being filled with water and their conductivity σ_{ch} increases from the XLPE value $\sigma_{\text{XLPE}} = 1 \cdot 10^{-14}$ S/m to the salt water value $\sigma_{\text{water}} = 1 \cdot 10^{-2}$ S/m. In this simulation the conductivity of channels was 4 orders higher than σ_{XLPE}, but 8 orders less than σ_{water} ($\sigma_{\text{ch}} = 1 \cdot 10^{-10}$ S/m) and corresponded to partial filling cracks with water.

It should be noted that if the dimensions of micro-inclusion (from 12.5 to 25 µm) are more than 10 times greater than the tree radius (1 µm), its volume is about 100 times smaller than the volume of the inclusion. Thus, the volume of micro-inclusion stays approximately unchanged after filling channels with water and, considering the dielectrophoresis of water molecules at durable operation term of insulation, the volume of liquid inside the inclusions could be assumed constant.

Fig. 4 displays: *a*) EF distribution; *b*) stressed volumes V_{st} on the plane of section through the centers of all inclusions; *c*) EF distribution; and *d*) total current density J_{total} on the cut-line through the centers of the two biggest inclusions and five smaller ones in a middle tree branch. Colors also correspond to the E value according to the scale on the right side of Fig. 4 and colored area in Fig. 4 *b* displays a stressed volume V_{st}.

According to the numerical experiment, after emerging of tree channels, the maximum value of EF gain coefficient $k_{E\,max}$ and stressed volume coefficient k_{Vst} increase a little, while the maximum density of total current J_{total} rise considerably. If in the first simulation (Fig. 3, *c*) $k_{E\,max} = 5.2$, then in the second one (Fig. 4, *c*) – $k_{E\,max} = 5.4$ (4 % larger), simultaneously k_{Vst} increases by 21 %. Increasing of the k_{Vst} value shows increasing of dielectric breakdown probability at any point of the stressed volume.

The maximum density of total current J_{total} rose from 0.45 A/m (Fig. 3, *d*) to 7 A/m (Fig. 4, *d*). Characteristic difference in the currents distribution is that the density J_{cond} of conduction currents in the inclusions remains approximately at the same levels of 0.3-0.4 A/m, but the displacement current density J_{dis} in dielectric gaps between the inclusions in the second simulation rose from 0.1 A/m to 7 A/m (peaks in Fig. 4 (*d*)). Increasing the current density in the XLPE leads to heat dissipation in it and reduces the electrical and mechanical strength of insulation, as noted in [2, 7].

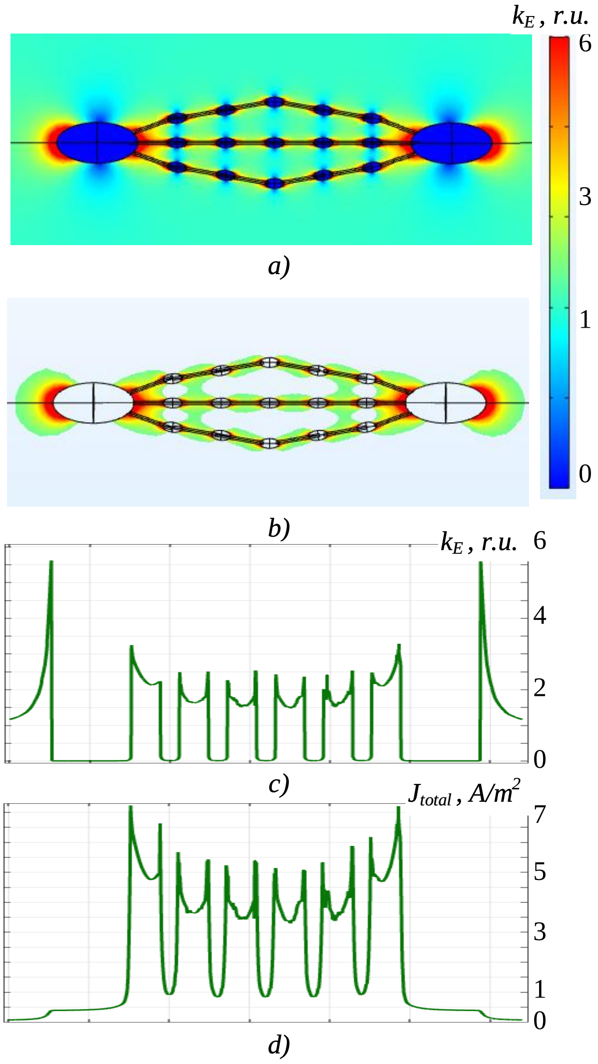

Fig. 4. a) EF distribution; b) stressed volumes V_{st} location on plane of section; c) EF distribution; d) total current density J_{total} on cut-line near connected inclusions.

It can be concluded that the connection of closely spaced micro-inclusions by conductive channels in a one single structure is more dangerous to the XLPE insulation because of greater stressed volumes and local current densities. Due to the positive feedback of the processes, the degradation of XLPE insulation intensifies during its exploitation over a long period of time.

3.3. Increasing the conductivity of tree channels. The next step of research was to simulate the EF distribution in XLPE insulation, when a conductivity of connecting channel σ_{ch} between micro-inclusions rises to the water value 10^{-2} S/m. It models the situation when whole channels are filled with water. The results of: *a*) EF distribution; *b*) stressed volumes V_{st} on plane of section through the centers of all inclusions; *c*) EF distribution; and d) total current density J_{total} on cut-line through the centers of the middle tree branch are presented in Fig. 5.

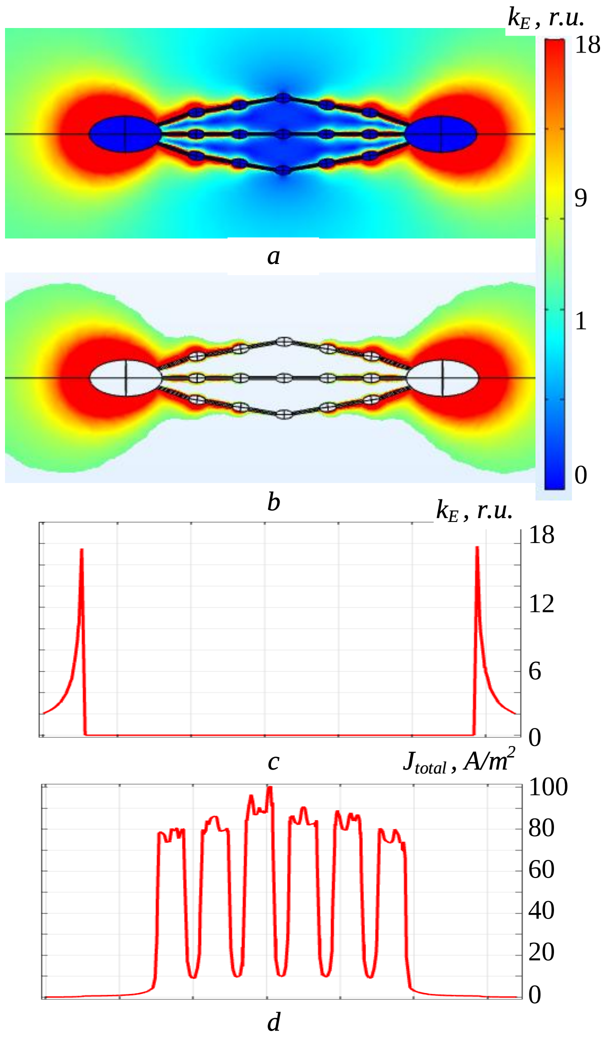

Fig. 5. a) EF distribution; b) stressed volumes V_{st} location on plane of section; c) EF distribution; and d) total current density J_{total} on cut-line near connected inclusions, while conductivity of channels increases.

The increase in channel conductivity leads to the situation when the maximum value of EF gain coefficient $k_{E\,max}$ grows 3 times (from 5,4 in Fig. 4, *c*) to 18 times in Fig. 5, *c*; stressed volume coefficient k_{Vst} grows by 150 % comparing to the integrals of colored areas in Fig. 4, *b* and Fig. 5, *b*; and maximum value of total current density J_{total} grows 14 times (from 7 A/m in Fig. 4, *d* to 100 A/m in Fig. 5, *d*).

The comparative results of all tree simulations are represented in Table 1.

Note that when the channel conductivity reaches the water value, inclusions connected by the tree behave like a solid conductive structure, inside which the EF is close to zero, and the maximum values are at the poles of side inclusions (see Fig. 5, *a* and *c*). It also manifests itself in developing significantly larger stressed volume areas, as it can be seen comparing colored areas in Fig. 4, *b* and Fig. 5, *b*.

Table 1

Comparative results of all tree simulations

#	σ_{ch}, S/m	$k_{E\,max}$, r.u.	k_{Vst}, μm^3	$J_{total\,max}$, A/m
1	$1 \cdot 10^{-14}$	5.2	0.8	0.450
2	$1 \cdot 10^{-10}$	5.4	1.2	7
3	$1 \cdot 10^{-2}$	18	7.4	100

3.4. Influence of the amount of tree branches. Another important factor, which significantly changes the distribution of the electric field, stressed volume and current density is water tree branching. Because of stochastic configuration of nano- and micro-cracks in the insulation and stochastic breaks of material due to local mechanical pressures, the amount of tree branches could significantly change.

In [12], the results of numerical experiment of calculation of EF disturbance near the micro-inclusion at the presence of water trees with cylindrical branches on the surface are shown. Tree branching could reduce the maximum value of EF strength *E* on its tip, due to shielding the central tree branches by side branches. Simulation results are well agreed with other studies [2, 3, 7], which show that intensive tree branching leads to the slowdown of its growth and even to its extinction.

At the same time, tree branching leads to the increase in the stressed volume in XLPE insulation, which, in turn, increases the breakdown probability. Also the amount of regions with increased pressures *p* as well as with increased total current density J_{total} rises which, in addition to the electric ageing, results in mechanical and thermal degradation of the dielectric medium.

Since water tree branching can significantly impact on the calculated values of water tree “string of pearls” configuration, it is necessary to simulate the EF, stressed volume and current density distribution depending on the number of tree branches and their ramification. It is the aim of further research, which surely will be performed in the future.

4. Conclusion

The mathematical simulation and the comparative analysis of changes in the values of electric field strength, stressed volumes and current densities occurring in the cross-linked polyethylene insulation of high-voltage cables near the water micro-inclusions connected by “string of pearls” water trees with different conductivity have been made.

The germination of water channels between closely spaced micro-inclusions and increasing of their conductivity leads to the electric field amplification and rising of the stressed volumes and the total current densities a few dozen times.

When a channel conductivity reaches a water value, inclusions connected by the tree behave like a solid conductive structure, inside which the EF is close to zero, and the maximum values are observed at the poles of side inclusions. Such a conductive structure is more dangerous to the XLPE insulation in terms of its breakdown because of larger stressed volumes and local current densities.

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ВПЛИВ ВОДНИХ ТРИЇНГІВ КОНФІГУРАЦІЇ “НИТКА ПЕРЛІВ” НА РОЗПОДІЛ ЕЛЕКТРИЧНОГО ПОЛЯ, СТРУМУ ТА НАПРУЖЕНОГО ОБ’ЄМУ В ЗШИТІЙ ПОЛІЕТИЛЕНОВІЙ ІЗОЛЯЦІЇ

Максим Щерба

Досліджено процеси, які виникають у локальних областях зшитої поліетиленової (ЗПЕ) ізоляції кабелів надвисокої напруги під час проростання водних триїнгів між наявними у ній водними мікровключеннями, що близько розташовані. Згідно із сучасними експериментальними даними водні триїнги в ЗПЕ мають не суцільну циліндричну форму, як вважалося раніше, а складаються з близько розташованих нанорозмірних включень сфероїдної форми з тонкими нанорозмірними водними каналами між ними (конфігурація “нитка перлів”). Збурення ЕП біля такого триїнгу може значно відрізнятися від розподілу біля суцільного, тому в роботі було виконане математичне моделювання та аналіз розподілу напруженості електричних полів, зміни напружених об’ємів та густин струмів у ЗПЕ ізоляції біля мікровключень конфігурації “нитка перлів”. Моделювалися ситуації появи в ізоляції між мікровключеннями нанотріщин, їхнє часткове або повне заповнення водою, тобто утворення каналів водних триїнгів з різною провідністю. Показано, що проростання між включеннями водних триїнгів і збільшення їх провідності приводить до об’єднання включень у єдину провідну структуру, яка сильніше збурює електричне поле. Визначено закономірності збільшення напруженості електричного поля (яка характеризує швидкі детерміновані механізми деградації), збільшення напруженого об’єму (який характеризує повільні стохастичні механізми деградації) і збільшення густини струму в локальних областях (яка характеризує перегріви ізоляції). Отримані результати корисні для аналізу взаємопов’язаних процесів деградації ЗПЕ ізоляції та для оцінювання її ресурсу під час тривалого використання.

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Research interests: electrical engineering, electromagnetic fields in heterogeneous mediums, threshold electro-physical processes in XLPE insulation of high voltage cables.