DOI: https://doi.org/10.15407/techned2018.02.011

ELECTRIC FIELD ENHANCEMENT IN POLYETHYLENE CABLE INSULATION WITH DEFECTS

I.M. Kucheriava
Institute of Electrodynamics, National Academy of Sciences of Ukraine,
pr. Peremohy, 56, Kyiv, 03057, Ukraine, e-mail: rb.irinan@gmail.com

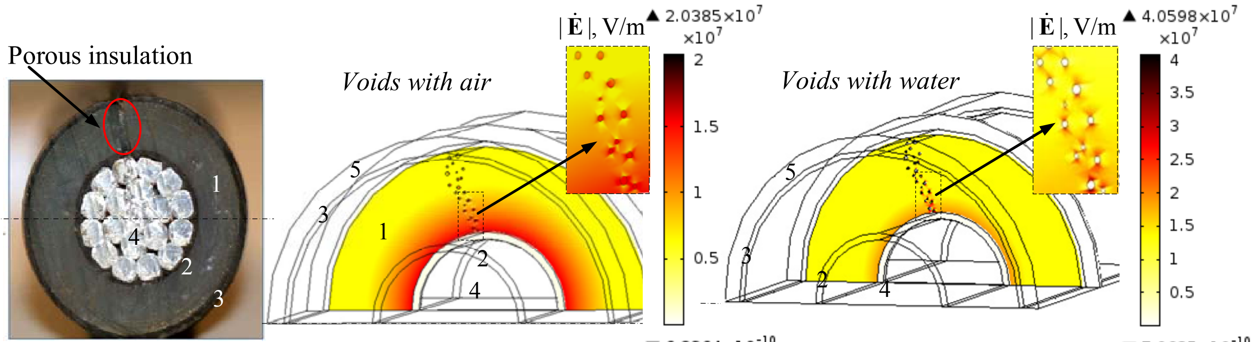
The computer modeling of electric field distribution in the cable polyethylene insulation with defects (porosity along the insulation in radial direction and contamination due to the fault at application of insulation layers during the production process) is carried out. The distributions of volumetric electric force and equivalent tensile stress in the insulation are computed in the case of the contamination. The effect of the defects on electric intensity near the conductor screen (inner semiconducting layer) and the dependence of the distributions and maximum electric intensity on the electric properties of the porous medium, shape of the contamination and its proximity to the cable conductor are revealed. References 11, figures 5.
Key words: polyethylene insulation of power cable, macro-sized defects, electric field problem, electric field enhancement, electromechanical stress, computer modeling.

Introduction. At the present time the cables insulated with cross-linked polyethylene (XLPE) are preferred in the world practice of construction of power cable projects. Such cables are in general use in high-voltage and extra-high-voltage power transmission and distribution networks. The cables are designed to provide the high reliability, failure-free performance and long service life (at least 30 years) needed for today's power sector.

The insulation of the cables is structured by three elements: main polyethylene insulation (marked by label 1 in fig. 1) between the inner and outer semiconducting layers (marked by labels 2 and 3, respectively). The elements are simultaneously extruded during the manufacturing process. That prevents void formation, treeing, other irregularities and smoothes out the conductor surface. The semiconducting layers are intended to minimize electrical stresses and to protect the main insulation.

The reliability and service life of power cables are determined largely by initial quality and actual state of XLPE insulation under operating conditions as well as depend on the level of technological excellence, design solution, service and environmental conditions. The manufacturing defects are one of the types of cable defects. They result from an error in the production process and include all kinds of contaminants (small particles, thin films, chemicals, oxygen), voids, microcracks in the insulation, protrusions, air-gap spacing, delamination [4, 9, 10]. The contaminated insulation surface as a manufacturing defect formed after application of the first insulation layer is described in [8] and shown in fig. 3, *a* below. As noted in [8], a cable with such insulation quickly fails.

The other cable defects are the operating defects and damages of XLPE insulation due to loss of leak-proofness, moisture penetration, treeing growth, corrosion of the conductor and metal shield [4, 6, 7]. The moisture inside the insulation leads to micro-cracking in the polymer, subsequent chemical decomposition, water and electrical treeing, partial discharges, insulation breakdown, corrosion of conducting elements [6, 7]. In its turn, the corrosion causes the changes in the physical properties and structure of the insulation, e.g., the porous structure of XLPE shown in fig. 1, *a* [6]. Note that, in addition to water, the corrosive chemi-



a *b* *c*

Fig. 1

cals penetrate into the cable, chiefly into the underground cable contacting with polluted water, oil. Under the action of electric field, this promotes the initiation of micro-sized voids and cracks, gives rise to treeing structures expanding.

The defects and imperfections in the insulation are the initiation sites for the fatigue cracks and water treeing owing to the local electric field and presence of water. Then the defects are growing with time, lead to degradation of insulation and its failure [4, 7, 8, 10]. They need special attention and careful study. That is why the study of electric field distribution, electrical and mechanical stresses in and around the manufacturing and operating defects in XLPE insulation is the topical problem to provide the long-term reliability of power cables.

The purpose of the present paper is to study the effect of typical macroscopic defects in the polyethylene insulation of power cables on the electric field distribution and mechanical stress in the insulation, and particularly near the defects. The two types of defects are examined:

– the operating defect as the porous structure all through the insulation in radial direction (fig. 1, *a*) when the pores are filled with both air (at the initial stage of cable operation) and water (after moisture penetration inside the cable from a wet environment);

– the manufacturing defect as the insulation contaminated by carbon black during production process (fig. 3, *a*); the semiconducting carbon black compounds are used in the manufacture of power cables; the carbon black content in polymer composites has a substantial influence on their electrical properties [2]; additionally, the multiple carbon black inclusions in XLPE insulation of high-voltage cables are detected by experiment in paper [10].

The study is realized by two- and three-dimensional numerical modeling in Comsol Multiphysics [3] using finite element method. The computer modeling of other typical defects of power cables is performed in work [9].

Model for computations. *Electric field problem.* The problem is quasi-static at frequency of 50 Hz. The space charges are ignored. The mathematical model is based on the next differential equation

$$\nabla \cdot (\sigma + j\omega\varepsilon_0\dot{\varepsilon}_r)\nabla\dot{\varphi} = 0, \qquad (1)$$

where $\dot{\varphi}$ is the complex electric potential; ε_0 and $\dot{\varepsilon}_r$ are the vacuum permittivity and the complex relative permittivity of material, respectively; σ is the conductivity of material; $\omega = 314$ rad/s is the angular frequency; j is the imaginary unit.

As assumed, the electric properties of materials are invariable and independent of the electric intensity and, in the general case, temperature.

Equation (1) is supplemented with the following boundary conditions for electric potential: $\dot{\varphi} = U_m$ (where U_m is the peak value of phase voltage) is specified on conductor surface; $\dot{\varphi} = 0$ is defined on the surface of copper shield. The electric-insulation condition $\mathbf{n} \cdot \dot{\mathbf{J}} = 0$ ($\mathbf{n}$ is the unit external normal; $\dot{\mathbf{J}}$ is the total current density including conduction current and displacement current) is set on the other outer boundaries of the models.

After solving the boundary problem, the electric intensity is determined by expression: $\dot{\mathbf{E}} = -\nabla\dot{\varphi}$.

Structural mechanical problem. The problem is solved under assumptions that there are no external loads and pressure applied to the insulation and only electric force is taken into account.

The electromechanical stresses produced in polyethylene insulation by applied electric field are defined according to the mechanical equilibrium equation

$$-\nabla\hat{\sigma}_M = \mathbf{F},$$

where $\hat{\sigma}_M$ is the stress tensor; $\mathbf{F}$ is the electric force per unit volume (the average over a time period) acting on the dielectric. The force is expressed by

$$\mathbf{F} = \varepsilon_0 \nabla(\varepsilon - 1)|\dot{\mathbf{E}}|^2 / 2.$$

The symmetry boundary condition is assigned on the bottom surface of the models given in figs. 1, *b*, *c* and 4, *a*, *c*. The free constrain conditions are specified on the outer boundaries of the computational domain when no external force is applied.

The structural mechanical problem is solved only in polyethylene insulation after solving the electric field problem. The polyethylene insulated cable (fig. 1, *a*) is studied. Owing to symmetry of the cable in cross-section, the spatial computational domain includes the half part of the cable for examination of porous insulation (fig. 1, *b*, *c*). The similar two-dimensional model is built to simulate the contaminated insulation as presented in fig. 3, *b*. In this context, the porous structure is assumed to be in the single cross-section of the cable and the contamination is extended over a considerable distance along the cable length. The cable symmetry means that the same defects exist in the other half of the cable. The computational domains are chosen correctly because the electric field enhancement takes place only in the immediate vicinity of the defects.

The domains consist of the main polyethylene insulation (marked by 1 in fig. 1) and semiconducting layers (labels 2 and 3 in fig. 1). The availability of the cable conductor and copper shield is taken into consideration by preset boundary conditions.

The finite-element mesh is generated with high resolution in sites of the defects. The solver relative tolerance in Comsol is 10^{-6}.

The electric intensity in the insulation without any defects is calculated analytically using expression from [11]

$$E(r) = \frac{U}{r\ln(r_{sh}/r_c)}, \tag{2}$$

where U is the voltage between the cable conductor and metallic shield; r is the distance from the cable center (from longitudinal axis); r_{sh} and r_c are the radii of the shield and conductor, respectively.

Computer results and discussion. The numerical simulation is performed for 110 kV single-core XLPE insulated cable. The conductor diameter is 25.2 mm. The thickness of polyethylene insulation is equal to 16 mm. The thickness of each semiconducting layer is 1 mm.

The electrical conductivity of main insulation is set to be $\sigma_1 = 10^{-15}$ S/m, the conductivity of semiconducting layers is $\sigma_2 = 10^{-7}$ S/m. The relative dielectric permittivity of the insulation and layers is $\varepsilon_1 = \varepsilon_2 = 2.3$.

The mechanical properties of polyethylene are as follows: the Young's modulus is 700 MPa, the Poisson's ration is equal to 0.46 and the density is 930 kg /m^3.

The porosity of polyethylene insulation is represented by a cluster of the spherical voids-inclusions with various diameter bridging the insulation in radial direction (figs. 1, 2).

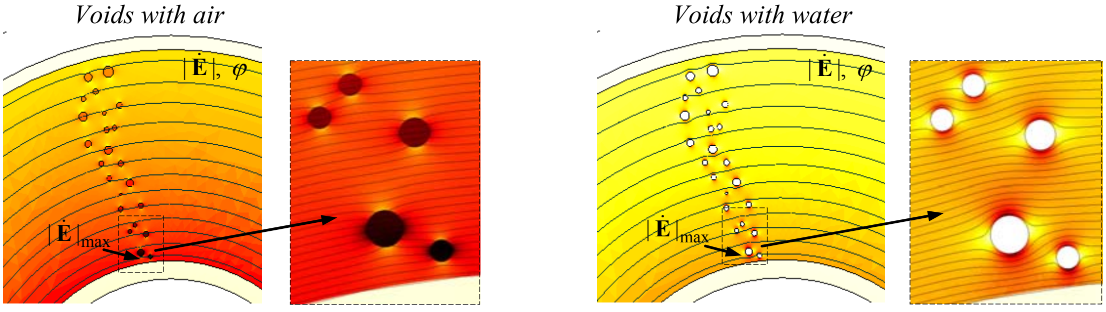
Fig. 1 gives the distributions of electric intensity $|\dot{\mathbf{E}}|$ in the porous insulation when all pores are filled with both air (fig. 1, *b*) and water (fig. 1, *c*). The field patterns are also displayed in selected insulation fragments in an enlarged view. As shown, the higher electric intensity $|\dot{\mathbf{E}}|_{\max} = 40.6$ kV/mm takes place for water pores. The degree of field inhomogeneity (or electric field enhancement factor) in that case is

$$k = \frac{|\dot{\mathbf{E}}|_{\max}}{E_0} = \frac{40.6\cdot 10^6}{15.3\cdot 10^6} \approx 2.7\,. \tag{3}$$

Here $E_0 = 15.3$ kV/mm is the maximum value of electric intensity in homogeneous insulation (without pores and other defects) defined by expression (2).

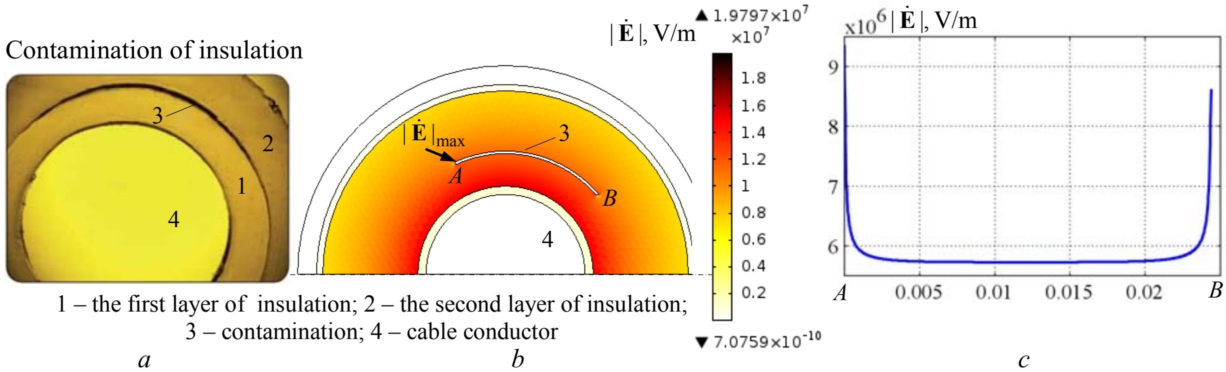
In the general case, the problem of insulation reliability implies the reduction of the degree of field inhomogeneity k (or the increase of insulation utilization coefficient $1/k$) along with the condition that $|\dot{\mathbf{E}}|_{\max} < E_p$, where E_p is the maximum permissible electric intensity determined by the dielectric strength of material and by mean electrical stress for specified voltage class of the cable.

In the case under consideration, the last condition is not satisfied for the pores filled with water because according to fig. 1, *c* $|\dot{\mathbf{E}}|_{\max}$ exceeds the dielectric strength of polyethylene E_p = 21.7 kV/mm [1]. It means that the region containing the porosity in the insulation is the weak area with the most probable degradation.



a *b*

Fig. 2



a *b* *c*

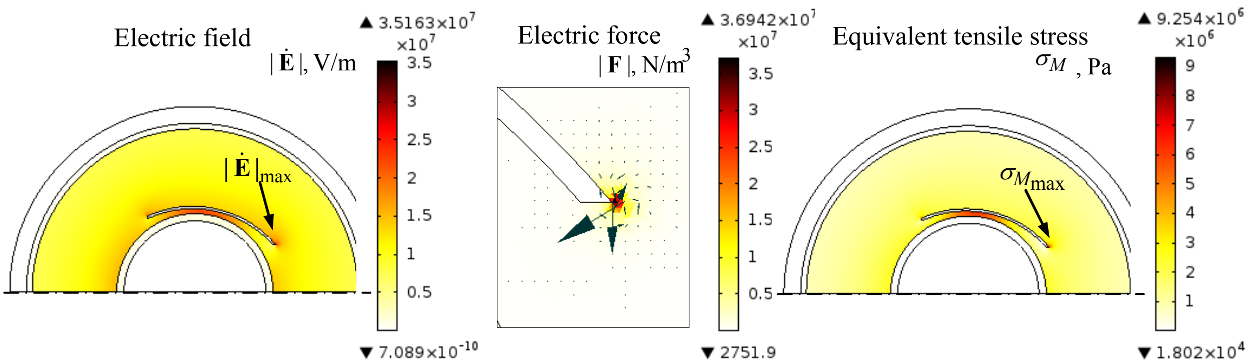
Fig. 3

In addition to computational results in fig. 1, the simulated electric intensity distributions and equipotential lines near the air and water pores in the insulation are given in fig. 2. Here the fragments of enlarged patterns in proximity to the cable conductor are presented too. The field distributions show the mutual effect of the closely spaced pores, largest values of electric intensity near the inner semiconducting layer and penetration of electric field inside the air pores. At the same time there is no practically electric field in the pores filled with water. This is explained by the dielectric permittivity of air $\varepsilon_a < \varepsilon_1$ and the permittivity of water $\varepsilon_w > \varepsilon_1$, where ε_1 is the permittivity of polyethylene material. The entire pore cluster according to fig. 2 produces an effect on the electric field distribution along the radius of the insulation. The electric intensity increases considerably for water pores (see expression (3)).

The electric field $|\dot{\mathbf{E}}|$ in the insulation with carbon black contamination is depicted in fig. 3, *b*. The contamination has an arched form as shown in fig. 3, *a*. It is characterized by sufficient conducting properties ($\sigma_c = 10$ S/m) and dielectric permittivity $\varepsilon_c = 7$ exceeding the permittivity of polyethylene insulation. According to fig. 3 *b*, there is no almost electric field inside the contamination and the maximum value $|\dot{\mathbf{E}}|_{max} = 19.8$ kV/mm takes place at the edges of the contamination.

The electric field strength value is important for the cable fault analysis. The variation of electric intensity in the insulation along the contamination (along the arc *AB*) is given in fig. 3, *c*. Then the degree of field inhomogeneity is defined to be $k = 19.8 \cdot 10^6 / (15.3 \cdot 10^6) \approx 1.3$. In that case the condition $|\dot{\mathbf{E}}|_{max} < E_p$ is true, but $|\dot{\mathbf{E}}|_{max}$ approximates to the maximum permissible electric intensity E_p [1]. In such limiting case, while the cable is in use, the time factor and different external effects can affect destructively the cable insulation, especially in the vicinity of the contamination.

When the carbon black contamination is located nearer to the cable conductor, the electric intensity increases and exceeds the permissible value E_p (fig. 4, *a*), then $k \approx 2.3$. There is no electric field inside the contamination. The field increases near the inner semiconducting layer. The maximum field is generated at the ends of the contamination.



a *b* *c*

Fig. 4

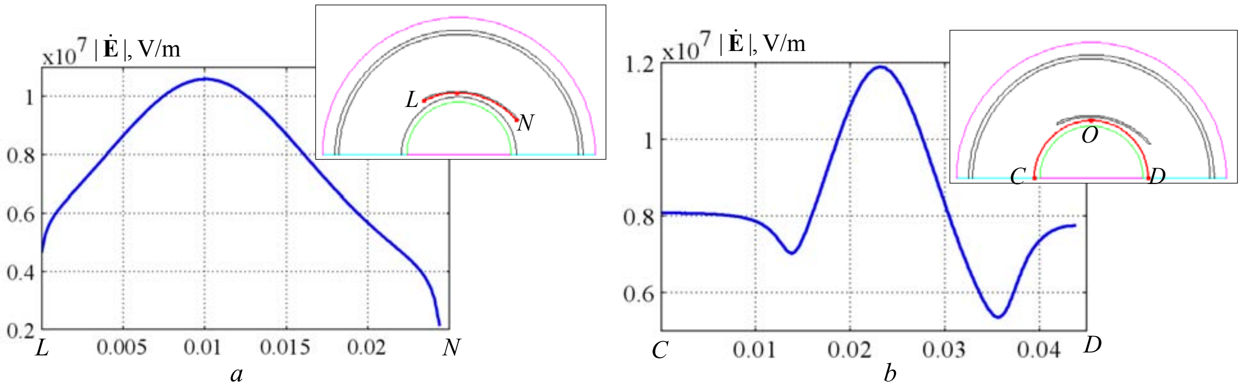


Fig. 5

The vector electric force $\mathbf{F}$ at the edge of the contamination is presented in fig. 4, *b* in color and by arrows. The force has a compressing effect on the edge and is concentrated in its area.

The equivalent tensile stress (or von Mises stress) in the insulation with defect is shown in fig. 4, *c*. The largest stress is lower than the ultimate strength of polyethylene [5]. Nevertheless the concentration and high values of all quantities under consideration in fig. 4 promote the weakening and subsequent degradation of the insulation.

Fig. 5 presents the computed plots of electric intensity $|\dot{\mathbf{E}}|$ in the insulation along the contamination in accordance with fig. 4 (along the line *LN* indicated at the upper right in fig. 5, *a*) and on the surface of the inner semiconducting layer (along the semicircle *COD* shown in fig. 5, *b*). The electric field varies depending on the contamination shape. In general, the electric intensity near the semiconducting layer is more than 1.7 times greater than for similar contamination depicted in fig. 3.

Conclusion. The computer modeling of electric field distribution in the main polyethylene insulation of high-voltage cable with defects as a porosity of the insulation and its carbon-black contamination reveals the field enhancement around the defects. As a result, the dielectric strength of the insulation is reduced. The insulation can suffer degradation due to the concentration and high values of the electric force and mechanical stress near the defects. It is shown that the nature of electric field distributions in XLPE insulation depends on the electric properties of porous medium, contamination shape, arrangement of the defects and their proximity to the cable conductor.

The results of this paper allow, from view point of the electrical and electromechanical phenomena in the insulation with defects, to understand more fully the major causes of its degradation and eventual failure. As confirmed, the high-purity and defectless production of XLPE insulation, proper operating conditions of the cables and limited water penetration inside them are needed to provide the high reliability and long service life of XLPE insulated power cables.

1. Berger L.I. Dielectric strength of insulating materials. In CRC Handbook of Chemistry and Physics. Boca Raton FL: Taylor & Francis, 2015. Pp. 15-44 – 15-49.

2. Bezprozvannykh A.V., Naboka B.G., Moskvitin E.S. Grounding of electrophysical characteristics of semiconducting shields of high-voltage power cables with cross-linked insulation. *Electrical engineering & Electromechanics*. 2010. No 3. Pp. 44–47. (Rus)

3. *Comsol* multiphysics modeling and simulation software. URL: http://www.comsol.com/ (accessed 29.05.2017)

4. Hampton N. HV and EHV cable system aging and testing issues. Chapter 3. University System of Georgia, Institute of Technology NEETRAC. National Electric Energy Testing, Research and Application Center: Georgia Tech Research Corporation, February 2016. 19 p.

5. Handbook of elastomers. New York, Basel: Marcel Dekker, Inc, 2001. 929 p.

6. Hvidsten S., Kvande S., Jäger K.M. Severe degradation of the conductor screen of service and laboratory aged medium voltage XLPE insulated cables and cable models. 2008. 19 p. URL: https://www.pesicc.org/iccWebSite/-subcommittees/A/Presentations/Spring08/A5.Hvdisten.pdf (accessed 29.05.2017)

7. Hvidsten S., Kvande S., Ryen A., Larsen P.B. Severe degradation of the conductor screen of service and laboratory aged medium voltage XLPE insulated cables. *IEEE Trans. on Dielectrics and Electrical Insulation*. 2009. Vol. 16. No 1. Pp. 155–161. https://doi.org/10.1016/j.jmmm.2005.08.010

8. Kovrigin L.A. The technological and operational defects in cable insulation. *Kabel-news*. 2008. No 10. Pp. 58–60. (Rus)

9. Kucheriava I.M. Power cable defects and their influence on electric field distribution in polyethylene insulation. *Tekhnichna Elektrodynamika*. 2017. No 2. Pp. 19–24.

10. Shuvalov M.Yu., Romashkin A.V., Ovsienko V.L. Analysis of defects in high-voltage power cable insulation by methods of video-microscopy and micro-experiment. *Elekrichestvo.* 2000. No 5. Pp. 49–57. (Rus)

11. Weedy B.M. High-voltage cable lines. Moskva: Energoatomizdat, 1983. 232 p. (Rus)

УДК 621.315.2:004.94

ПОСИЛЕННЯ ЕЛЕКТРИЧНОГО ПОЛЯ В ПОЛІЕТИЛЕНОВІЙ ІЗОЛЯЦІЇ СИЛОВИХ КАБЕЛІВ З ДЕФЕКТАМИ

І.М. Кучерява, докт.техн.наук
Інститут електродинаміки НАН України,
пр. Перемоги, 56, Київ, 03057, Україна, **e-mail: rb.irinan@gmail.com**

Проведено комп'ютерне моделювання електричного поля в поліетиленовій ізоляції силового кабелю з дефектами – пористістю вздовж ізоляції в радіальному напрямку та забрудненням ізоляції внаслідок технологічного порушення операції накладання ізоляційних шарів. Для випадку забруднення розраховано розподіли об'ємної електричної сили та еквівалентного механічного напруження в ізоляції. Показано вплив дефектів на значення електричного поля поблизу напівпровідного шару по жилі кабеля, а також залежність характеру розподілу та максимального значення напруженості поля від електричних властивостей пористого середовища, форми забруднення та близькості його розташування до жили кабелю. Бібл. 11, рис. 5.

Ключові слова: поліетиленова ізоляція кабелю, макророзмірні дефекти, електрична польова задача, посилення електричного поля, електромеханічні напруження, комп'ютерне моделювання.

УДК 621.315.2:004.94

УСИЛЕНИЕ ЭЛЕКТРИЧЕСКОГО ПОЛЯ В ПОЛИЭТИЛЕНОВОЙ ИЗОЛЯЦИИ СИЛОВЫХ КАБЕЛЕЙ С ДЕФЕКТАМИ

И.Н. Кучерявая, докт.техн.наук
Институт электродинамики НАН Украины,
пр. Победы, 56, Киев, 03057, Украина, **e-mail: rb.irinan@gmail.com**

Проведено компьютерное моделирование электрического поля в полиэтиленовой изоляции силового кабеля с дефектами – пористостью изоляции в радиальном направлении и загрязнением изоляции вследствие технологического нарушения операции наложения изоляционных слоев. Для случая загрязнения рассчитаны распределения объемной электрической силы и эквивалентного механического напряжения в изоляции. Показано влияние дефектов на значения электрического поля вблизи полупроводящего слоя по жиле кабеля, а также зависимость характера распределения и максимального значения напряженности поля от электрических свойств пористой среды, формы дефекта и близости его расположения к жиле кабеля. Библ. 11, рис. 5.

Ключевые слова: полиэтиленовая изоляция кабеля, макроразмерные дефекты, электрическая полевая задача, усиление электрического поля, электромеханические напряжения, компьютерное моделирование.

1. Berger L.I. Dielectric strength of insulating materials. In CRC Handbook of Chemistry and Physics. Boca Raton FL: Taylor & Francis, 2015. Pp. 15-44 – 15-49.

2. Беспрозванных А.В., Набока Б.Г., Москвитин Е.С. Обоснование электрофизических характеристик полупроводящих экранов силовых кабелей высокого напряжения со сшитой изоляцией. *Електротехніка і Електромеханіка*. 2010. № 3. С. 44–47.

3. Comsol multiphysics modeling and simulation software. URL: http://www.comsol.com/

4. Hampton N. HV and EHV cable system aging and testing issues. Chapter 3. University System of Georgia, Institute of Technology NEETRAC. National Electric Energy Testing, Research and Application Center: Georgia Tech Research Corporation, February 2016. 19 p.

5. Handbook of elastomers. New York, Basel: Marcel Dekker, Inc, 2001. 929 p.

6. Hvidsten S., Kvande S., Jäger K.M. Severe degradation of the conductor screen of service and laboratory aged medium voltage XLPE insulated cables and cable models. 2008. 19 p. URL: https://www.pesicc.org/iccWebSite/-subcommittees/A/Presentations/Spring08/A5.Hvdisten.pdf

7. Hvidsten S., Kvande S., Ryen A., Larsen P.B. Severe degradation of the conductor screen of service and laboratory aged medium voltage XLPE insulated cables. *IEEE Trans. on Dielectrics and Electrical Insulation*. 2009. Vol. 16. No 1. Pp. 155–161. https://doi.org/10.1016/j.jmmm.2005.08.010

8. Ковригин Л.А. Технологические и эксплуатационные дефекты в изоляции кабелей. *Кабель-news*. 2008. No 10. С. 58–60.

9. Kucheriava I.M. Power cable defects and their influence on electric field distribution in polyethylene insulation. *Tekhnichna Elektrodynamika*. 2017. № 2. Pp. 19–24.

10. Шувалов М.Ю., Ромашкин А.В., Овсиенко В.Л. Анализ дефектов в изоляции силовых высоковольтных кабелей методами видеомикроскопии и микроэксперимента. *Электричество*. 2000. № 5. С. 49–57.

11. Уиди Б. Кабельные линии высокого напряжения. М.: Энергоатомиздат, 1983. 232 с.

Надійшла 19.06.2017
Остаточний варіант 10.07.2017