UDC 621.315.687.2 : 004.94

NUMERICAL STUDY OF ELECTRIC FIELD DISTRIBUTION IN HIGH-VOLTAGE CABLE TERMINATION WITH STRESS CONTROL CONE

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

The electric field distribution in the vicinity of stress cone of high-voltage XLPE insulated cable termination (110 kV) is studied by computer modeling. The dependence of cable insulation conductivity on electric intensity and the different cone positions relative to the cutting ends of the cable outer semiconducting layer and copper wire shield are taken into account. The stress control cone is considered both in the form of only cone reflector and as a complete stress cone with insulation body. The peculiarities of field distribution depending on the cone shape and surface roughness are analyzed. The attained results are of interest for designing and improvement of up-to-date high- and extra- high-voltage cable terminations. References 13, figures 5, table 1.
Key words: cross linked polyethylene (XLPE) insulated power cable, high-voltage cable termination, stress control cone, cone position relative to cable components, surface roughness of cone, computer modeling.

Introduction. The end terminations are an important part of power cable systems. Their enough complex construction includes insulation, cable components, in particular the cable insulation and shield cut-back. The terminations are based on the field control within the inner and ambient space. The reduction in electric field nonuniformity inside high-voltage cable terminations is realized, as a general rule, by stress control cone. The stress cone prevents the insulation failure in the termination of a shielded cable caused by high concentration of electric flux and high potential gradient. The stress cone is a two-component element that consists of cone reflector placed into insulating material of insulation body (fig. 1).

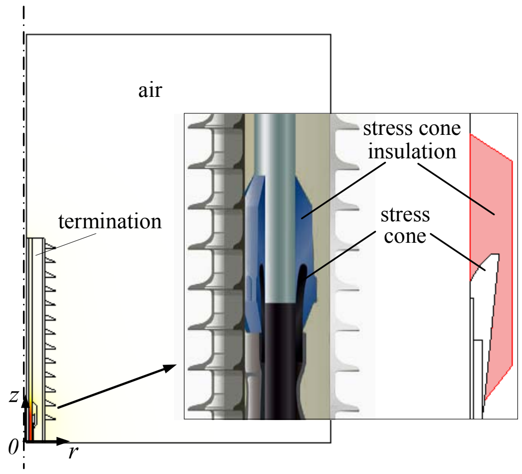

Fig. 1

The modern high- and extra- high-voltage (HV/EHV) cable terminations serve to ensure high reliability operation of cable lines. This depends on cable termination construction, used insulating materials, stress control methods as well as mounting practice.

The major developments in construction of HV/EHV cable terminations are presented in table [8]. The elastomers (rubbers), used as field grading materials, possess the adequate both mechanical properties (invariable radial pressure on cable and reaction to its changing temperature) and electrical characteristics (depending on cable voltage) [9]. The insulation of cable terminations of the last generation and their stress cones are made with silicone materials having all required service properties [12]: high dielectric strength (26–36 kV/mm [1]), long-term electrical ageing resistance, heat stability, resistance to water and contaminations, chemical stability, elasticity.

At the same time, the test findings of paper [6] show that the sliding discharges take place at the surface of stress cone of EHV (220 kV) cable termination.

The destructive phenomena and failures in cable terminations are associated with high electric intensity, ingress of moisture, foreign inclusions inside the termination, incorrect installation of stress control cone relative to cable components (in particular, outer semiconducting layer of insulation [2]), surface roughness of stress cone and defects of insulation [2, 6–8]. As is stated in [7], the rough-

Generation	Elements, materials
I	Porcelain insulators; oil filled; condenser cone
II	Porcelain insulators; oil filled; EPDM (ethylene propylene diene monomer) stress cone
III	Porcelain insulators; oil filled; EPDM & silicone stress cone
IV	Composite & porcelain insulators; oil filled; EPDM & silicone stress cone
V	Composite & porcelain insulators; oil free; EPDM & silicone stress cone

ness and micro-sized defects in the form of protrusions (1–10 μm in height) at stress cone surface lead to the increase of electric intensity (100 times greater at the tops of the micro-protrusions) and discharge initiation.

The stress control means in cable terminations are made with materials characterized by different electric properties (dielectric permittivity, dielectric loss factor, conductivity) and by their dependence on electric intensity and temperature [4, 5, 9].

The purpose of the present work is to study the electric field distribution inside the high-voltage cable termination with stress cone depending on the cone shape, surface roughness, position of stress cone relative to cutting points of cable components and also on cone structure (cone with and without insulation body). The termination of single conductor 110 kV XLPE insulated power cable is considered. The stress cone and termination insulation are made with silicone. The computer modeling is carried out by finite-element method in professional code Comsol [3]. The dependence of cable insulation conductivity on electric intensity is taken into account.

The preliminary examination of electric filed in medium-voltage cable termination with stress control tube is implemented in [10].

Model for computations. The following assumptions and statements are taken in the model:

– the model is presented as two-dimensional and axially symmetric one (in cylindrical coordinates *rOz* in fig. 1) because the cable termination is symmetric about an axis *Oz*;

– the electric field varies slowly with time; the problem is stated in quasi-static approximation at frequency $f = 50$ Hz;

– the environment for the end cable termination is the surrounding air;

– the cable components such as copper shield, primary polyethylene insulation, its inner and outer semiconducting layers are considered;

– the insulation materials of the cable and termination are isotropic; they are characterized by their invariable values of dielectric permittivity; the cable insulation conductivity depends on electric intensity and, in the general case, is a function of temperature [11].

The following laws and relations in terms of complex vector quantities are used to derive the equation for electric potential:

– Gauss' law in the differential form

$$\nabla \cdot \dot{\mathbf{D}} = \rho \quad \text{making an assumption that } \rho = 0;$$

– the constitutive relation $\dot{\mathbf{D}} = \varepsilon_0 \varepsilon \dot{\mathbf{E}} = -\varepsilon_0 \varepsilon \nabla \dot{\varphi}$ using the relationship between electric field and potential: $\dot{\mathbf{E}} = -\nabla \dot{\varphi}$;

– Ohm's law $\dot{\mathbf{J}} = \sigma \dot{\mathbf{E}}$;

– the continuity equation $\nabla \cdot \dot{\mathbf{J}}_t = 0$, where $\dot{\mathbf{J}}_t = \sigma \dot{\mathbf{E}} + j\omega\varepsilon_0\varepsilon \dot{\mathbf{E}}$.

Here $\dot{\mathbf{D}}$ is the electric displacement vector; ρ is the electric charge density or charge per unit volume ($\nabla \cdot \dot{\mathbf{D}} = 0$ when $\rho = 0$); $\varepsilon_0 = 8{,}85 \cdot 10^{-12}$ F/m is the free-space permittivity; ε is the relative permittivity of the material; $\dot{\mathbf{J}}$ is the conduction current density vector; $\dot{\mathbf{J}}_t$ is the total current density; σ is the electrical conductivity of the material; $\dot{\mathbf{E}}$ is the electric field; $\dot{\varphi}$ is the electric potential; $\omega = 2\pi f$ is the angular frequency; j is the unit imaginary number.

Hence the governing equation for electric potential is

$$-\nabla \cdot [(\sigma \nabla \dot{\varphi} + j\omega\varepsilon_0 \dot{\varepsilon} \nabla \dot{\varphi}] = 0. \quad (1)$$

This equation is written for complex quantities – electric potential $\dot{\varphi}$ and permittivity $\dot{\varepsilon}$ in consequence of time-harmonic electric field.

The next boundary conditions are defined. The phase voltage U ($\dot{\varphi} = U$) is set on the cable conductor boundaries; the condition $\dot{\varphi} = 0$ is specified on the boundaries of cable shield; the continuity condition is prescribed on the inner interfaces; the outer boundaries of the computational region (see fig. 1) excepting axial symmetry are assumed as electric insulation boundaries.

The differential equation (1) with the boundary conditions formulates the boundary value problem for electric potential solved numerically in Comsol. The electric intensity is determined from solution of the problem by expression: $\dot{\mathbf{E}} = -\nabla \dot{\varphi}$.

The effective conductivity of polyethylene insulation is expressed as [11]

$$\sigma = \sigma(|\dot{\mathbf{E}}|, T) = a \cdot \exp(-\frac{A_E \cdot q_e}{k_B \cdot T}) \frac{\sinh(b \cdot 10^{-7} |\dot{\mathbf{E}}|)}{|\dot{\mathbf{E}}|}, \quad (2)$$

where $q_e = -1{,}602 \cdot 10^{-19}$ C is the charge of the electron; $k_B = 1{,}381 \cdot 10^{-23}$ J/K is the Boltzmann constant; $a = 3{,}2781$ and $b = 2{,}7756$ are the constants found by experiment; $A_E = 0{,}56$ eV is the activation energy; T is the temperature chosen to be equal to 20^0C.

The effective insulation conductivity is introduced under condition that the harmonic component of current density at 50 Hz frequency is related to the sinusoidal component of electric potential by expression: $\dot{\mathbf{J}} = \sigma(|\dot{\mathbf{E}}|)\dot{\mathbf{E}}$. Then equation (1) defines, as a first approximation, the fundamental harmonic of the potential in a dielectric with nonlinear properties. In fact the non-sinusoidal variations of electric potential and current density are replaced by equivalent sinusoids. The analogous approach is used in [13] for calculation of nonlinear circuits, in particular for the analysis of ferroresonance when the consideration of the non-sinusoidal current, voltage and magnetic flux presents substantial difficulties.

Computer simulations. The computer modeling is performed for end termination of 110 kV XLPE insulated power cable having conductor cross-section area of 500 mm^2 (conductor diameter of 26 mm), insulation thickness of 16 mm, 35 mm^2 cross section area of copper wire shield (shield thickness of 4 mm).

The components of cable and termination have the properties given in paper [10]. The conductivity of stress cone is equal to $\sigma = 2 \cdot 10^{-4}$ S/m; the permittivity of stress cone is ε = 2,5. The cone insulation is characterized by electric parameters: $\sigma = 0$; ε = 22.

Without any additional field grading means, the regions near the edges of cable elements are the weak areas with the dense concentration and high magnitudes of electric intensity. In this connection, the different positions of stress cone relative to the cutting ends of the cable outer semiconducting layer and copper wire shield are considered and illustrated in fig. 2.

The fragment of the high-voltage cable termination under study is shown on the left-hand side of fig. 2. The configuration of equipotential lines, the electric field distribution shown in color near the stress cone and also the variation of electric field along the outer boundary of cable insulation (plots on right-hand side) are given for two variants: when the stress cone is placed above the cutting end of copper shield and envelops the cutting point of semiconducting layer (fig. 2, *a*) and when the cone is arranged above the layer and the shield (fig. 2, *b*). As shown, the abrupt change of electric intensity at the ends of copper shield and semiconducting layer takes place for the last variant. Note that the values of ratio $|\dot{\varphi}|/U$ corresponding to displayed equipotential lines are indicated in the centre of fig. 2.

As a result, the data of fig. 2 reveal that the stress cone must be installed correctly and cover the cutting ends of cable copper shield and outer semiconducting layer of cable insulation to avoid high stress area inside termination, to prevent discharge initiation and to protect cable insulation against accelerated ageing.

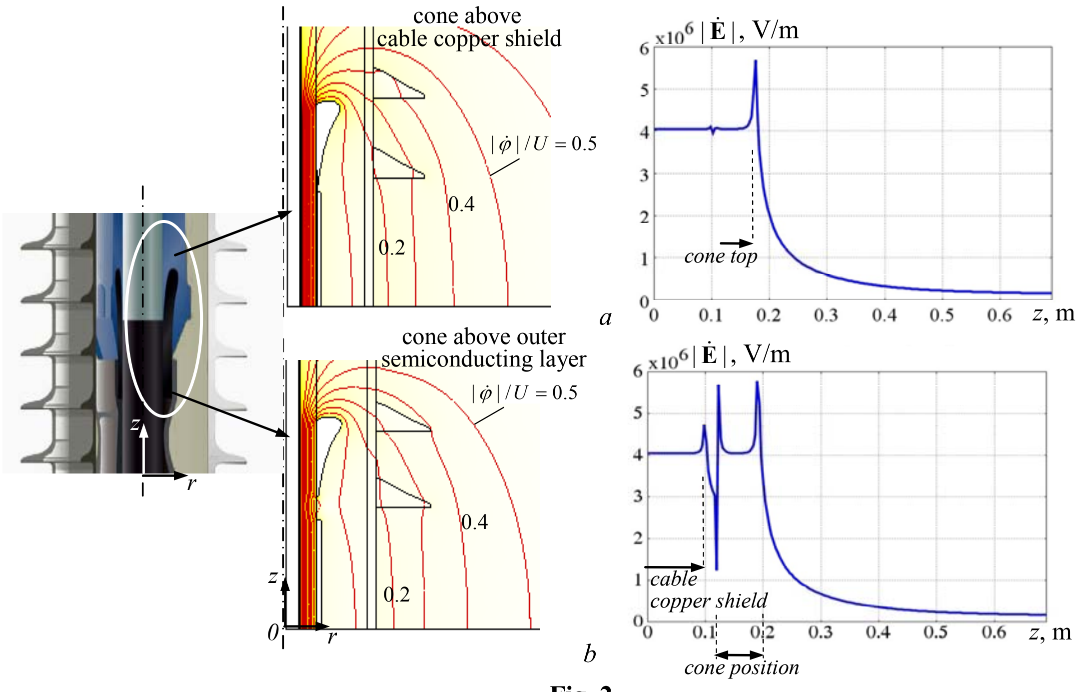

Fig. 2

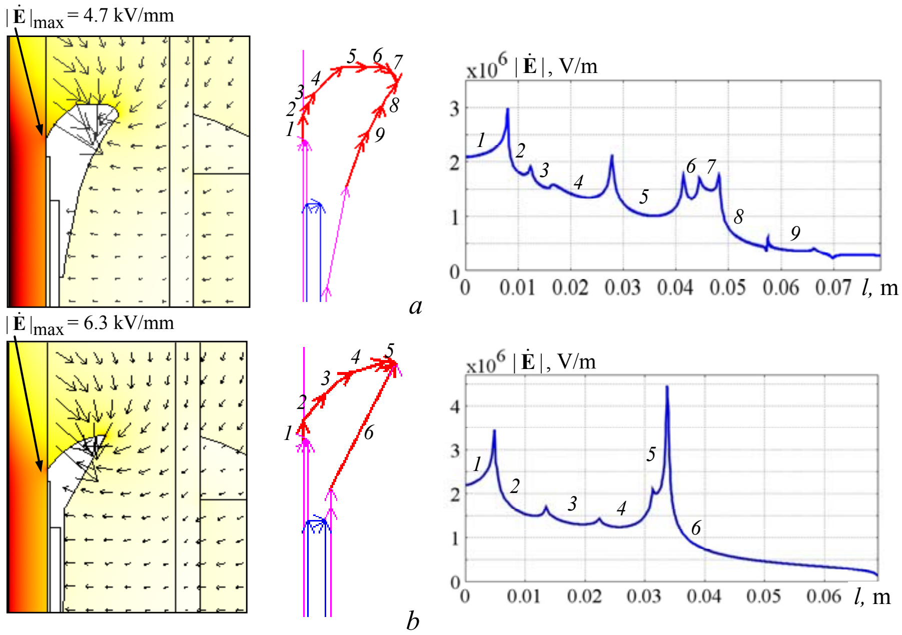

Fig. 3

The correlation between stress cone shape and electric field distribution near the cone and cable surface is studied. The two cones with the different rounding radii and shapes: rounded cone (fig. 3, *a*) and sharper cone (fig. 3, *b*) are examined. Fig. 3 shows the electric field distribution (in color and by arrows) with maximum electric intensity $|\dot{\mathbf{E}}|_{max}$ on the outer surface of cable insulation (left-side patterns). The labels of a number of sections on the cone surface are given in the centre of fig. 3. Here the ends of the sections are marked by arrows; the cone boundary consists of the displayed sections-segments of polygonal line.

The variations of electric intensity along the cone border lines with indicated 9 and 6 sections for two different-shaped stress cones are plotted in fig. 3 on the right hand side. As seen, the largest value of electric intensity on the outer boundary of cable insulation is higher for sharper cone and equal to $|\dot{\mathbf{E}}|_{max} =$ = 6.3 kV/mm (fig. 3, *b*).

The roughness of stress cone surface leads to the increase of electric intensity and in accordance with data of paper [7] causes the initiation and propagation of discharges. The maximum value of electric intensity (~ 5.0 kV/mm) takes place at the top of sharp stress cone (fig. 3, *b* on the right).

The comparative results for two variants of stress cone are depicted in fig. 4, *a* and *b*, respectively for cone in the form of only reflector and for stress cone with insulation. Here the electric field distributions (in color and by arrows) near the stress cones and the values of electric intensity at the tops of the cones are presented for the two variants under consideration. As it can be seen in fig. 4, the electric field intensity is reduced almost 2.7 times when using the stress cone with insulation body.

Fig. 5 gives the change of electric intensity $|\dot{\mathbf{E}}|$ along the outer surface of cable insulation for two types of stress cone (fig. 5, *a*) as well as the plot of field on the surface of insulating body of stress cone with the indication of three sections of the body and cone peak – point *A* (fig. 5, *b*). The two segments of this surface as the most probable regions for discharge initiation owing to field variation in the local zones are

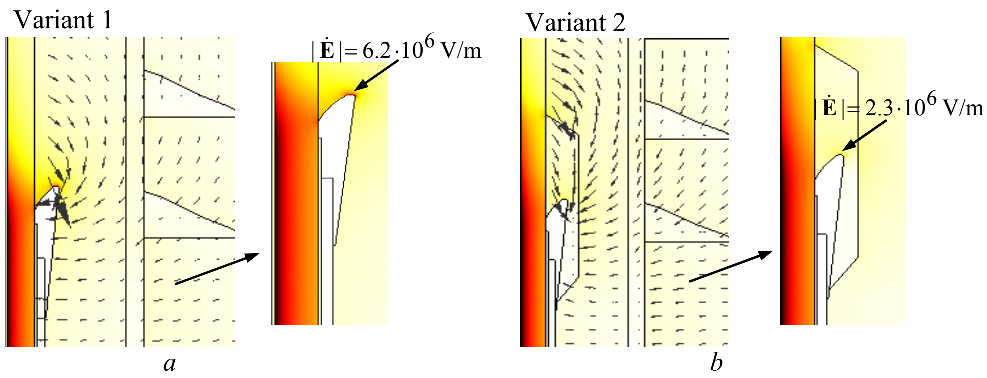

Fig. 4

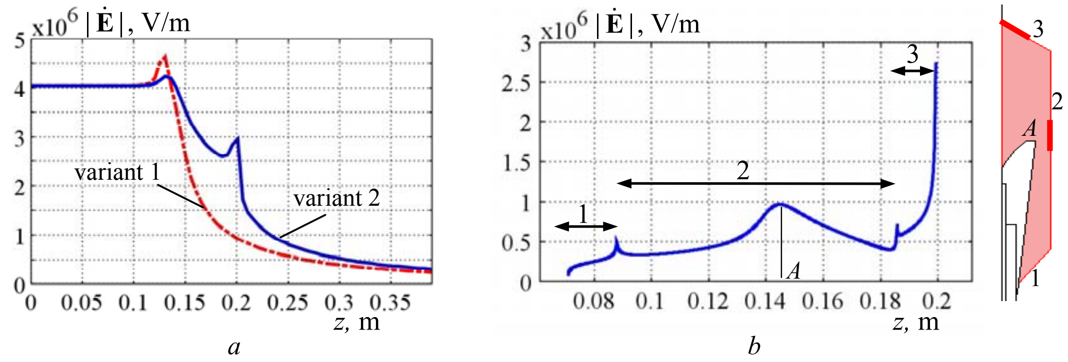

Fig. 5

marked by red lines with increased thickness. Such regions are at the level of cone peak and in close proximity to contact with cable insulation.

Conclusion. The various positions of stress control cone in 110 kV XLPE insulated cable termination relative to the cutting points of the cable outer semiconducting layer and copper wire shield are studied by computer simulation (fig. 2). The dependence of cable insulation conductivity on electric intensity is taken into account (by expression (2)). As shown, the stress cone must cover the edges of the cable semiconducting layer and shield in order to provide more uniform electric field distribution in this region.

The shape and surface roughness of stress cone are two important parameters for high-voltage cable terminations. The sharper cone as well as its surface roughness causes the increase of electric intensity in the local zones near the stress cone and also in cable insulation (fig. 3). This is a dangerous phenomenon because of the potential initiation and propagation of discharges.

The construction of stress cone with insulation body gives more low electric intensity at the cone peak and on the outer surface of cable insulation (figs. 4 and 5, *a*). The segments of the insulation body at the level of cone top and near the contact with cable insulation can be liable to discharge processes (fig. 5, *b*).

The attained results extend the understanding regarding the electric processes in multi-component cable termination and give a possibility to use the computed data and conclusions for designing of high- and extra- high-voltage cable terminations with stress cone.

1. *Berger L.I.* Dielectric strength of insulating materials. Handbook of Chemistry and Physics. – CRC Press/Taylor and Francis Group: Boca Raton, FL, 2006. – Pp. 42–46.

2. *Chen C., Liu G., Lu G., Jin W.* Influence of cable terminal stress cone install incorrectly // Proceedings of IEEE 9-th Internat. Conference on the Properties and Applications of Dielectric Materials, ICPADM 2009. – 19–23 July 2009. – Pp. 63–65.

3. *Comsol* multiphysics modeling and simulation software. – http://www.comsol.com/ (accessed 12 July 2016).

4. *Donzel L., Greuter F., Christen T.* Nonlinear resistive electric field grading. Part 2: materials and applications // IEEE Electrical Insulation Magazine. – 2011. – Vol. 27. – No 2. – Pp. 18–29.

5. *Egiziano L., Tucci V., Petrarca C., Vitelli M.* Effect of thermal and mechanical stresses on the electrical properties of stress grading materials // IEEE Internat. Conference on Conduction and Breakdown in Solid Dielectries. – Sweden, June 22–25, 1998. – Pp. 553–556.

6. *Guk D.A., Kamenskij M.K., Makarov L.E., Obraztsov V.L., Shuvalov M.Yu.* New high-voltage testing center of Joint-stock company "VNIIKP". Experience of testing and study of power cables, accessories and materials for their production // Kabeli i Provoda. – 2014. – No 5 (348). – Pp. 35–42. (Rus)

7. *Gurin A.G., Gontar Yu.G.* Failure of surface layer of a dielectric in end cable terminations under the action of lightning surges // Visnyk NTU "KhPI". – 2013. – No 59 (1032). – Pp. 53–60. (Rus)

8. *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. – http://www.cdfi.gatech.edu/publications/3-HV-Issues-7_with-Copyright.pdf (accessed 12 July 2016).

9. *Kotov R.V.* Electric field distribution in cable cold shrink terminations // Elektro. – 2006. – No 5. – Pp. 40–44. (Rus)

10. *Kucheriava I.M.* Modeling of electric field in cable termination with stress control tube // Tekhnichna Elektrodynamika. – 2016. – No 6. – Pp. 3–9. (Rus)

11. *Olsson C.O.* Modelling of thermal behaviour of polymer insulation at high electric dc field // Proceedings of the 5-th European Thermal-Sciences Conference. – The Netherlands, 18–22 May, 2008. – 8 p. – http://citeseerx.ist.psu.edu /viewdoc/download?doi=10.1.1.491.3890&rep=rep1&type=pdf (accessed 12 July 2016).

12. *Pilling Yu., Haim K-D, Bersh R.* Silicone for cable accessories. Advantages are in chemical characteristics // Novosti Elektrotekhniky. – 2004. – No 4 (28). – http://www.news.elteh. ru/arh/2004/28/11.php (accessed 12 July 2016). (Rus)

13. *Zeveke G.V., Ionkin P.A., Netushil A.V., Strakhov S.V.* Foundations of the circuit theory. – Moskva: Energoatomizdat, 1989. – 528 p. (Rus)

УДК 621.315.687.2 : 004.94

ЧИСЕЛЬНЕ ДОСЛІДЖЕННЯ ЕЛЕКТРИЧНОГО ПОЛЯ У ВИСОКОВОЛЬТНІЙ КАБЕЛЬНІЙ МУФТІ З КОНУСОМ ВИРІВНЮВАННЯ ПОЛЯ

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

Шляхом комп'ютерного моделювання досліджується розподіл електричного поля поблизу конуса вирівнювання поля муфти високовольтного кабеля (110 кВ) зі зшито-поліетиленовою ізоляцією. Враховується залежність електропровідності ізоляції кабеля від напруженості електричного поля, а також положення конуса відносно зрізу елементів кабеля – зовнішнього напівпровідного шару ізоляції та мідного екрану. Розглядаються можливості виконання конуса у вигляді одного рефлектора і повного стрес-конуса (рефлектора з ізоляцією конуса). Аналізуються особливості розподілу поля залежно від форми конуса та нерівності його поверхні. Результати чисельного моделювання пропонується враховувати при проектуванні та удосконалюванні сучасних муфт кабелів на високу та надвисоку напругу. Бібл. 13, рис. 5, табл. 1.

***Ключові слова**:* кабель зі зшито-поліетиленовою ізоляцією, високовольтна кабельна муфта, конус вирівнювання поля, розташування конуса відносно елементів кабеля, нерівність поверхні конуса, комп'ютерне моделювання.

УДК 621.315.687.2 : 004.94

ЧИСЛЕННОЕ ИССЛЕДОВАНИЕ ЭЛЕКТРИЧЕСКОГО ПОЛЯ В ВЫСОКОВОЛЬТНОЙ КАБЕЛЬНОЙ МУФТЕ С ВЫРАВНИВАЮЩИМ КОНУСОМ

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

Путем компьютерного моделирования исследуется распределение электрического поля вблизи конуса выравнивания поля муфты высоковольтного кабеля (110 кВ) со сшито-полиэтиленовой изоляцией. Учитывается зависимость электропроводности изоляции кабеля от напряженности электрического поля, а также положение конуса относительно среза элементов кабеля – внешнего полупроводящего слоя изоляции и медного экрана. Рассматриваются возможности выполнения конуса в виде одного рефлектора и полного стресс-конуса (рефлектора с изоляцией конуса). Анализируются особенности распределения электрического поля в зависимости от формы конуса и неровности его поверхности. Результаты численного моделирования представляют интерес для проектирования и совершенствования современных муфт кабелей на высокое и сверхвысокое напряжение. Библ. 13, рис. 5, табл. 1.

***Ключевые слова**:* кабель со сшито-полиэтиленовой изоляцией, высоковольтная кабельная муфта, конус выравнивания поля, расположение конуса относительно элементов кабеля, неровность поверхности конуса, компьютерное моделирование.

1. *Berger L.I.* Dielectric strength of insulating materials. Handbook of Chemistry and Physics. – CRC Press/Taylor and Francis Group: Boca Raton, FL, 2006. – Pp. 42–46.

2. *Chen C., Liu G., Lu G., Jin W.* Influence of cable terminal stress cone install incorrectly // Proceedings of IEEE 9-th Internat. Conference on the Properties and Applications of Dielectric Materials, ICPADM 2009. – 19–23 July 2009. – Pp. 63–65.

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

4. *Donzel L., Greuter F., Christen T.* Nonlinear resistive electric field grading. Part 2: materials and applications // IEEE Electrical Insulation Magazine. – 2011. – Vol. 27. – No 2. – Pp. 18–29.

5. *Egiziano L., Tucci V., Petrarca C., Vitelli M.* Effect of thermal and mechanical stresses on the electrical properties of stress grading materials // IEEE Internat. Conference on Conduction and Breakdown in Solid Dielectries. – Sweden, June 22–25, 1998. – Pp. 553–556.

6. *Гук Д.А., Каменский М.К., Макаров Л.Е., Образцов Ю.В., Овсиенко В.Л., Шувалов М.Ю.* Новый высоковольтный испытательный центр ОАО "ВНИИКП". Опыт испытаний и исследований силовых кабелей, арматуры и материалов для их производства // Кабели и провода. – 2014. – № 5 (348). – С. 35–42.

7. *Гурин А.Г., Гонтарь Ю.Г.* Разрушение поверхностного слоя диэлектрика в концевых кабельных муфтах под действием грозовых перенапряжений // Вісник НТУ "ХПІ". – 2013. – № 59 (1032). – С. 53–60.

8. *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. – http://www.cdfi.gatech.edu/publications/3-HV-Issues-7_with-Copyright.pdf

9. *Котов Р.В.* Распределение электрического поля в кабельных муфтах холодной усадки // Электро. – 2006. – № 5. – С.40–44.

10. *Кучерявая И.Н.* Моделирование электрического поля в кабельной муфте с трубкой-регулятором // Технічна електродинаміка. – 2016. – № 6. – С. 3–9.

11. *Olsson C.O.* Modelling of thermal behaviour of polymer insulation at high electric dc field // Proceedings of the 5-th European Thermal-Sciences Conference. – The Netherlands, 18–22 May, 2008. – 8 p. – http://citeseerx.ist.psu.edu /viewdoc/download?doi=10.1.1.491.3890&rep=rep1&type=pdf

12. *Пиллинг Ю., Хайм К-Д., Бэрш Р.* Силикон для кабельной арматуры. Преимущества – в химических особенностях // Новости Электротехники. – 2004. – № 4 (28). – http://www.news.elteh. ru/arh/2004/28/11.php

13. *Зевеке Г.В., Ионкин П.А., Нетушил А.В., Страхов С.В.* Основы теории цепей. – М.: Энергоатомиздат, 1989. – 528 с.

Надійшла 23.06.2016
Остаточний варіант 05.07.2016