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ELECTRIC FIELD DISTRIBUTION IN MEDIUM-VOLTAGE XLPE CABLE TERMINATION TAKING INTO ACCOUNT OUTER SEMICONDUCTING LAYER

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The computer modeling of electric field in the termination of medium-voltage (10 kV) cross-linked polyethylene insulated power cable is carried out. The stress-control tube and mastic are used in the termination to reduce the field nonuniformity. The electric field distributions are examined at different stress control tube positions relative to the cutting ends of the cable outer semiconducting layer and copper wire shield. The properties of stress control tube and mastic are varied to determine their influence on maximum electric intensity in the cable insulation. The results and used approaches to the study of electric field can be applied to design the terminations allowing for the appropriate materials and arrangement of structural parts. References 11, figures 5, table 1.
Key words: cable termination, power cable, polyethylene insulation, outer semiconducting layer, field grading tube, stress control mastic, computer modeling.

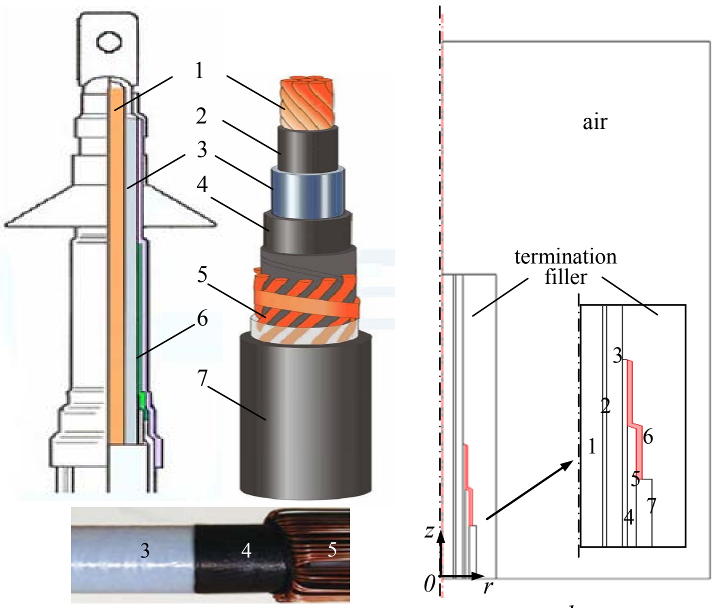
Introduction. The power cables are a component part of the electric power transmission and distribution systems. The reliability of power networks depends greatly on the reliability of power cables as well as on their connection to overhead transmission lines and electric apparatus by cable accessories.

All over the world during the last decades the developments of medium-voltage cable networks are related to application of power cables made with cross-linked polyethylene (XLPE) insulation [4], [5]. The cable terminations intended for connection of XLPE insulated power cables to the external electric apparatus and lines must be designed so as to reduce the electric field nonuniformity in termination space, provide there the electric intensity within permissible values, avoid both partial discharge initiation and insulation destruction, at the same time to attain long-term service life of the terminations [10].

The reduction in electric field nonuniformity inside cable termination is referred to as field grading or stress grading. This stipulates the special stress control methods in order to decrease the electric intensity in the active region of the termination and in particular at the cutting point of the cable shield to prevent the breakdown of cable insulation.

The basic field grading methods such as geometrical, refractive and impedance methods used for cable terminations are described and studied, for example, in works [2], [3]. The refractive field control is achieved with special field controlling materials integrated into terminations. The different polymer materials having high dielectric permittivity (higher than the permittivity of cable insulation) are utilized to produce the field grading tube and mastics for medium-voltage XLPE cable terminations [4].

The stress control tubes are set on the cutting end of cable constructive elements (copper wire shield and outer semiconducting layer) and envelop both the shield and polyethylene cable insulation. The arrangement of stress control tube and cable elements in cable end termination is shown in fig. 1, *a*. Here the cable conductor is marked by *1*; the inner and outer semiconducting layers are designated by *2* and *4*, respectively; the label *3* indicates the cable



a *b*

Fig. 1

insulation; the cable copper shield, stress control tube and cable jacket are denoted by *5*, *6* and *7*, respectively.

The cable termination with stress cone is studied in paper [6] by computer modeling and experiment. As shown in [6], the outer semiconducting layer of power cable should be taken into consideration and the proper installation of stress control means in the termination has to be provided for fail-safe operation of cable accessories.

The further improvement of the cable terminations and joints is associated with detailed analysis of effective ways for using the field grading facilities and with study of electric processes inside cable terminations taking into account the properties of materials in insulation structure, the location of stress control means and their electrophysical characteristics. That defines topicality of the article.

This work is devoted to computer modeling of electric field distribution in cable end termination (fig. 1). The termination of 10 kV XLPE insulated power cable is examined. The stress control tube and special field grading mastic which is applied to the cutting end of cable outer semiconducting layer [1] (see insertion in fig. 4 below) are used to smooth the electric field within the cable termination. The computations are carried out by finite-element method in professional code Comsol [7].

The purpose and distinction of the present work are to define the influence of both stress tube position relative to cable outer semiconducting layer and the physical properties of the tube and stress control mastic on electric field homogeneity inside cable end termination. The study is aimed at the results as applied to choosing the materials and rational location of stress control means in the cable termination.

Model. The following simplifying assumptions are made in the computational model:

– the cable termination construction is characterized by symmetry about an axis Oz, therefore the model is presented as two-dimensional and axially symmetric one (fig. 1, *b*);

– the cable structural elements such as two semiconducting layers, outer sheath are considered, although the sheath and inner semiconducting layer have a slight effect on electric field distribution in the active region of cable termination;

– the insulation materials of the cable and termination are isotropic, they are characterized by their invariable conductivity and dielectric permittivity (note that in the general case these parameters depend on electric intensity, in addition the conductivity is a function of temperature [9]);

– the electric field varies slowly with time; the problem is stated for quasi-static approach at frequency f = 50 Hz.

The field problem is formulated in terms of complex electric potential $\dot{\varphi}$ that satisfies the following equation:

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

where σ – is the conductivity; j – is the unit imaginary number; $\omega = 2\pi f$ – is the angular frequency; ε_r – is the complex relative permittivity; $\varepsilon_0 = 8.85 \cdot 10^{-12}$ F/m – is the permittivity of free space.

The conductivity σ and permittivity ε_r can take different values in the insulation materials of power cable and cable termination.

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

The numerical solution of differential equation (1) by Comsol model provides the electric potential $\dot{\varphi}$ and electric field $\dot{\mathbf{E}} = -\nabla \dot{\varphi}$ at all points of computational region.

Results and discussion. The distributions of electric intensity and equipotential lines are computed in the cable end termination with stress control tube (sct) and field grading mastic. The electric field variation along the external surface of base polyethylene cable insulation is determined too.

The computer modeling is realized for 10 kV XLPE insulated cable with conductor cross-section area of 120 mm^2 (conductor diameter of 6.2 mm) and 6.2 mm insulation thickness. The cross-section area of cable copper shield is 16 mm^2 (the shield thickness is equal to 2.3 mm), the external diameter of the cable is 33 mm [5].

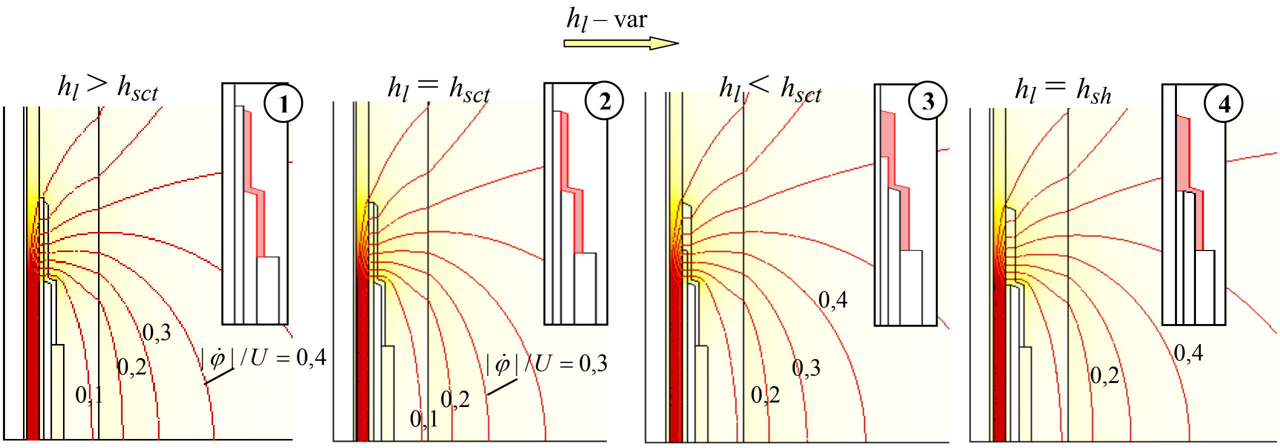


Fig. 2

Components of computational region	Properties	
	ε_r	σ, S/m
Polyethylene insulation of cable	2,3	10^{-15}
Inner semiconducting layer of cable	2,3	10^{-7}
Outer semiconducting layer of cable	2,3	10^{-7}
Cable outer sheath (jacket)	2,2	10^{-14}
Silicone filling of termination	3,0	10^{-15}
Stress control tube	4	10^{-7}
Stress control mastic	15	10^{-8}
Air	1	10^{-18}

The computational region of the problem is presented in fig. 1, *b*. Its dimensions are nearly twice as much than the termination length (along an axis Oz).

The properties of components in the computational region are given in table [8], [11].

The various positions of stress control tube relative to the cutting ends of the outer semiconducting layer and copper wire shield of the power cable are studied. In particular, the alternative designs when the semiconducting layer length h_l is greater than the tube length h_{sct} ($h_l > h_{sct}$), when these components are of the same height ($h_l = h_{sct}$) and when $h_l < h_{sct}$ are examined. Moreover, the case subject to the condition that the outer semiconducting layer of cable insulation is cut on the equal level with cable shield ($h_l = h_{sh}$) is considered. These design modifications correspond to variants 1–4 in fig. 2.

As taken into account in the work, the stress control tube and mastic can be made from materials possessing different physical properties (σ, ε_r).

Fig. 2 gives the distribution of electric field and equipotential lines in the vicinity of stress control tube depending on the height of outer semiconducting layer h_l. Here and below in fig. 4, the values of ratio $|\dot{\varphi}|/U$ corresponding to displayed lines are indicated, the cable termination has no stress control mastic. As illustrated, the field distribution inside the termination is strongly nonuniform. The equipotential lines are the densest within polyethylene insulation and the electric field is also higher. The field lines and equipotential lines are concentrated near the end of copper shield of the cable. Here electric field is sufficiently high. Generally and particularly the shield end is the weak point of the termination.

The electric field variation along the interface between the cable insulation and outer semiconducting layer is presented in fig. 3 for four variants in accordance with fig. 2. The elec-

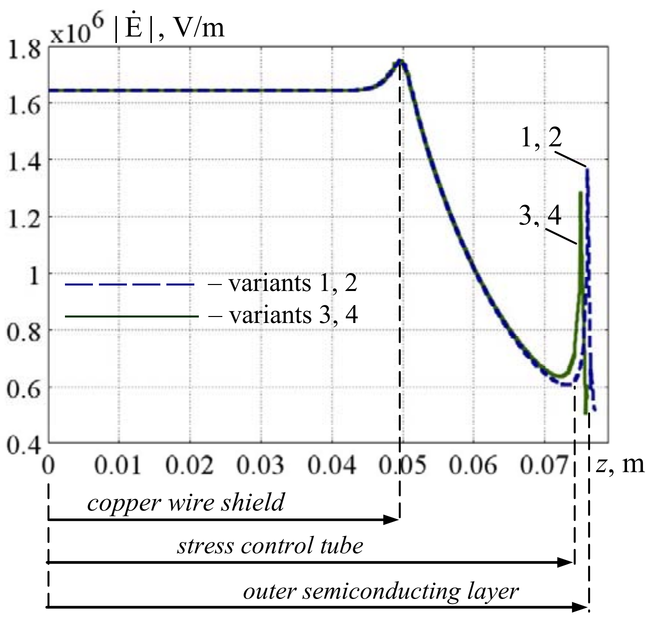


Fig. 3

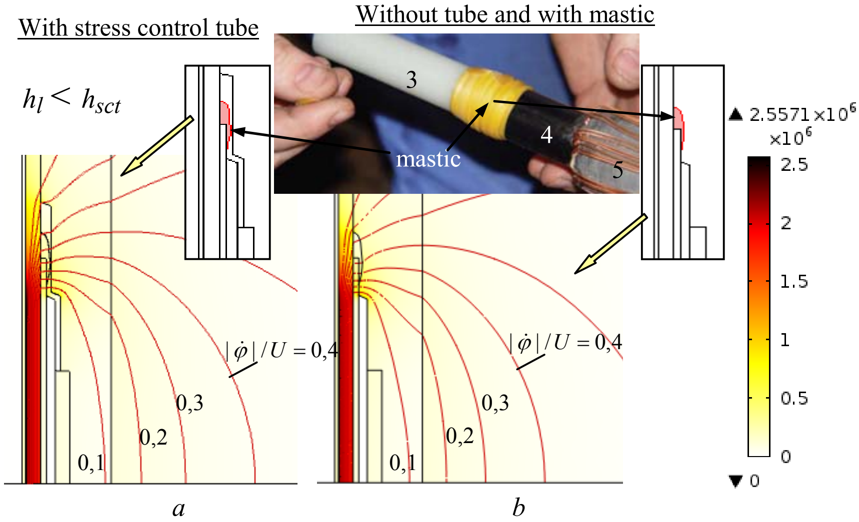


Fig. 4

tric field strength $|\dot{\mathbf{E}}|_{max} \approx \approx 1{,}76$ kV/mm and is within the admissible limits of operating electric intensity given in [4] for polyethylene insulated cables.

The electric field simulations are implemented at different values of tube permittivity ε_r for the most realistic construction when the stress control tube covers copper shield and semiconducting layer (variant 3 in fig. 2). As revealed, the variation of the tube permittivity from 2.3 to 40 has a weak influence on the value of $|\dot{\mathbf{E}}|_{max}$ in the cable insulation.

The distributions of electric field and equipotential lines in close proximity to the semiconducting layer of cable insulation and with application of stress control mastic are shown in fig. 4, *a* in the case with field grading tube and in fig. 4, *b* without the tube. The photo of XLPE insulated cable with mastic [1] is presented in the insertion into the figure. Here the designations correspond to the labels explained above and specified in fig. 1.

The electric field along the insulation surface is plotted in fig. 5 for cable termination without stress control tube and mastic (curve *1*), with mastic and without tube (curve *2*), with tube and mastic (curve *3*). The numerical results give the greatest value of electric intensity $|\dot{\mathbf{E}}|_{max} \approx 2{,}7$ kV/mm at the end of outer semiconducting layer without any field grading means (dependence 1 in fig. 5). The least value of $|\dot{\mathbf{E}}|_{max} \approx \approx 1$ kV/mm takes place when both stress control tube and mastic are used in the cable termination (curve *3* in fig. 5 and pattern in fig. 4, *a*). The weakest areas of cable insulation for different termination designs under consideration can be determined by depicted component lengths below an axis Oz in fig. 5. The identical line segments are given in fig. 3.

As found by numerical simulations, provided that the conductivity of mastic cover is $\sigma = 10^{-8}$ S/m = const and the mastic permittivity is varied from 2.3 to 40, the electric intensity $|\dot{\mathbf{E}}|_{max}$ in the cable insulation decreases only by 1.2%. At the same time, when the permittivity of stress control mastic is invariable and equal to $\varepsilon_r = 15$, the variation of mastic conductivity within the range of $\sigma = 10^{-6} - 10^{-2}$ S/m (or the intensification of conductive properties of mastic material) leads to more than 35% increase of $|\dot{\mathbf{E}}|_{max}$.

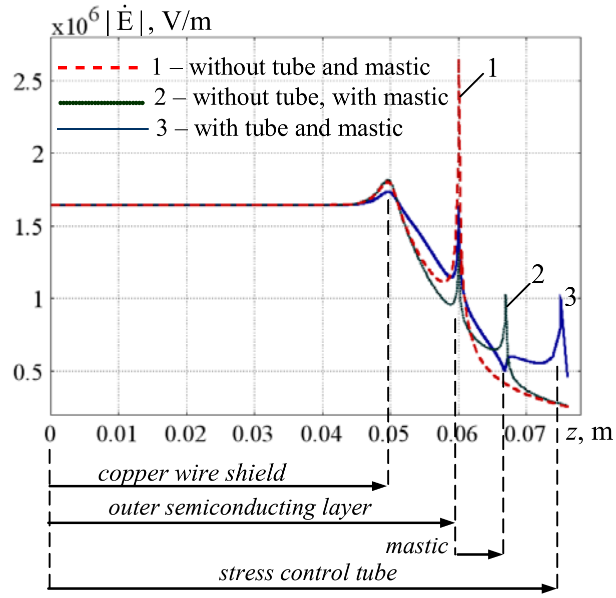


Fig. 5

Conclusion. The computer modeling of electric field distribution in medium-voltage cable end termination is performed taking into account the outer semiconducting layer of cable insulation system and the position of stress control tube relative to the cutting ends of the layer and copper shield of XLPE power cable. As shown, under the given conditions the length of semiconducting layer has an insignificant influence on the field distribution in active region of the termination.

The combined application of the stress control tube and mastic gives a possibility to attain the smallest values of electric intensity in the cable insulation as compared with the use of alone mastic.

The increase of mastic conductivity (above 10^{-6} S/m in the case under examination) causes the higher electric intensity in the polyethylene insulation of power cable. At specified data, the optimal values of the conductivity are over the range from 10^{-9} to 10^{-7} S/m.

The developed approaches to computer study of electric field in refractive modeled cable termination can assist in designing of the termination to improve the field distribution, keep the electric intensity within acceptable values and allow for both arrangement of structural components and properties of their feasible materials.

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РОЗПОДІЛ ЕЛЕКТРИЧНОГО ПОЛЯ В МУФТІ СИЛОВОГО КАБЕЛЯ СЕРЕДНЬОЇ НАПРУГИ З УРАХУВАННЯМ ЗОВНІШНЬОГО НАПІВПРОВІДНОГО ПОКРИТТЯ ЙОГО ПОЛІЕТИЛЕНОВОЇ ІЗОЛЯЦІЇ

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Виконано комп'ютерне моделювання електричного поля в кінцевій муфті силового кабеля з ізоляцією зі зшитого поліетилену на середню напругу (10 кВ). У муфті для зниження нерівномірності поля застосовується трубка-регулятор та мастика. Досліджено розподіл електричного поля при різних розташуваннях трубки відносно зрізу напівпровідного шару поліетиленової ізоляції та мідного екрану кабеля. Проварійовано електричні властивості матеріалів регулюючої трубки і мастики, визначено їхній вплив на максимальні значення напруженості електричного поля в ізоляції кабеля. Результати та застосовані підходи до дослідження електричного поля можуть використовуватися при проектуванні муфт із урахуванням вибору матеріалів і взаємного розташування конструктивних елементів. Бібл. 11, рис. 5, табл. 1.

Ключові слова: кабельна муфта, силовий кабель, поліетиленова ізоляція, напівпровідне покриття ізоляції, трубка вирівнювання поля, мастика, комп'ютерне моделювання.

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РАСПРЕДЕЛЕНИЕ ЭЛЕКТРИЧЕСКОГО ПОЛЯ В МУФТЕ СИЛОВОГО КАБЕЛЯ СРЕДНЕГО НАПРЯЖЕНИЯ С УЧЕТОМ ВНЕШНЕГО ПОЛУПРОВОДЯЩЕГО ПОКРЫТИЯ ЕГО ПОЛИЭТИЛЕНОВОЙ ИЗОЛЯЦИИ

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Выполнено компьютерное моделирование электрического поля в концевой муфте силового кабеля с изоляцией из сшитого полиэтилена на среднее напряжение (10 кВ), в которой в качестве средств снижения неравномерности поля применены трубка-регулятор и выравнивающая мастика. Исследовано распределение электрического поля при различных расположениях трубки относительно среза полупроводящего слоя полиэтиленовой изоляции и медного экрана кабеля. Проварьированы электрические свойства материалов регулирующей трубки и мастики, определено их влияние на максимальные значения напряженности электрического поля в изоляции кабеля. Результаты и использованные подходы к исследованию электрического поля могут быть применены при проектировании муфт с учетом выбора материалов и взаимного расположения конструктивных элементов. Библ. 11, рис. 5, табл. 1.

Ключевые слова: кабельная муфта, силовой кабель, полиэтиленовая изоляция, полупроводящее покрытие изоляции, трубка выравнивания поля, мастика, компьютерное моделирование.

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