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# COMPUTER STUDY OF DAMAGED CABLES WITH ELECTRIC FIELD DISTRIBUTION OUTSIDE THEM

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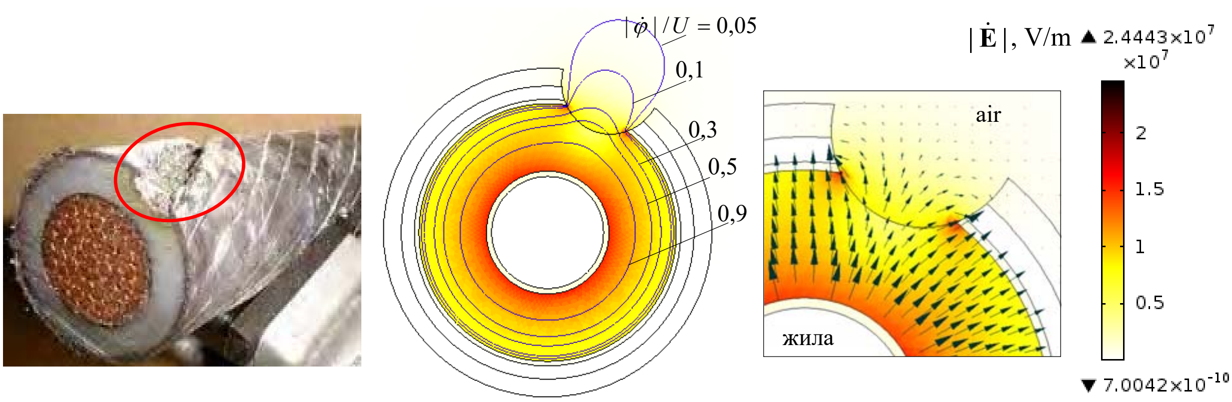
*The electric field distribution inside the polyethylene insulation of power cable and outside the cable with typical degradation of its jacket, metallic shield and a large part of the insulation is studied by computer modeling. The two- and three-dimensional problems are solved numerically to determine electric field strength. As shown, the interface between the main insulation and the defects is a weak site which is liable to further failure and deterioration of cable in service. For the damages under consideration the electric field is spread outside the cable at small distance, not more than 1.5 times larger than cable radius as the average.* References 11, figures 5.

***Key words:*** cross-linked polyethylene insulation, cable damages (damages of metallic shield / neutral, outer semiconducting layer, main insulation), electric filed outside the cable, two- and three-dimensional computer modeling.

**Introduction.** The study on the reliability of power cables and their failure mechanisms is a general topic in cable engineering. At present the different failure modes are studied extensively for cross-linked polyethylene (XLPE) insulated cables [1–4]. The underlying factors affecting the quality and reliability of power cables include presence of defects owing to manufacturing imperfections, non-proper working conditions, external mechanical damage associated with break in continuity of cable jacket, loss of its protective function, damage of the concentric neutral and / or metallic shield, poor contact between metallic shield and semiconducting layer, loss of contact between other cable components, corrosion, arcing damage at the interface between metallic shield and semiconducting layer which progresses into the insulation until failure arises [5–8]. In the general case, the detection of principal factors that give rise to cable breakdown needs the careful and complex study of operating conditions, aging of the insulation, environmental effects, resulting in water ingress in the cable, partial discharges, corrosion of metallic components and degradation of insulation [1, 6, 7].

The different ageing mechanisms and reliability factors are examined by experimental means in works [1, 7, 9]. The electric field enhancement in polyethylene insulation with various defects including the operating and manufacturing defects of cables are studied by computer modeling, e. g. in papers [8, 10].

The defects of XLPE cables owing to corrosion and arcing can be developed in the form of deep destruction of cable jacket, outer semiconducting layer and main insulation (fig. 1, *a*, fig. 4, *a* [1, 2]) and as heavy degradation of metallic shield (fig. 2, *a* [6, 7])). As noted in [1], the corrosion phenomena are related to loss of contact (or poor contact) between semiconducting layer and metallic shield. That promotes the arcing damage at the interface and accelerated cable failure. Under certain conditions the corrosion phenomena along with breaks in the metallic shield, loss of its contact with semiconducting layer cause the arc progressing across semiconducting layer interface into cable insulation. As analyzed experimentally in papers [1, 2],




*a* *b* *c*

**Fig. 1**

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the sequence of cable destruction is initiated by discontinuity of jacket, loss of cable impermeability, corrosion of metallic shield due to water penetration from without, origin of partial discharges and arcing. These effects are typical for the cables having mechanical damages and operating in disadvantageous environment. The effects can result in complementary heating and degradation of XLPE insulation and even induce its large and deep destruction (figs. 1, *a* and 4, *a*).

The study of above-stated operating defects of XLPE insulated cables related with discontinuity of jacket and metallic shield and, as a result, with spread of electric field outside the cable is a topical task to understand more exactly and particularly the causes of cable failure with a view to provide their higher reliability. This task is the most relevant and significant for high and extra-high voltage cables.

*The purpose of the present work* is to reveal the distinctions of electric field distribution in XLPE insulation of high-voltage power cables and outside the cables at loss of protective function of their jacket and partial non-availability of metallic shield.

The specific and typical damages of copper shield, outer semiconducting layer and insulation of cable because of shield corrosion and arcing at the surface of the semiconducting layer (figs. 1, *a*; 2, *a*; 4, *a*) are considered. The study is carried out by numerical modeling in Comsol [11]. The two-dimensional models with computational domain containing circular cable cross-section (fig. 1, *a*) and with axial-symmetric representation of the cable (fig. 2, *a*) for damages along the large length of the cable are developed. The three-dimensional model is built for the deep destruction (in depth) of cable insulation (fig. 4, *a*).

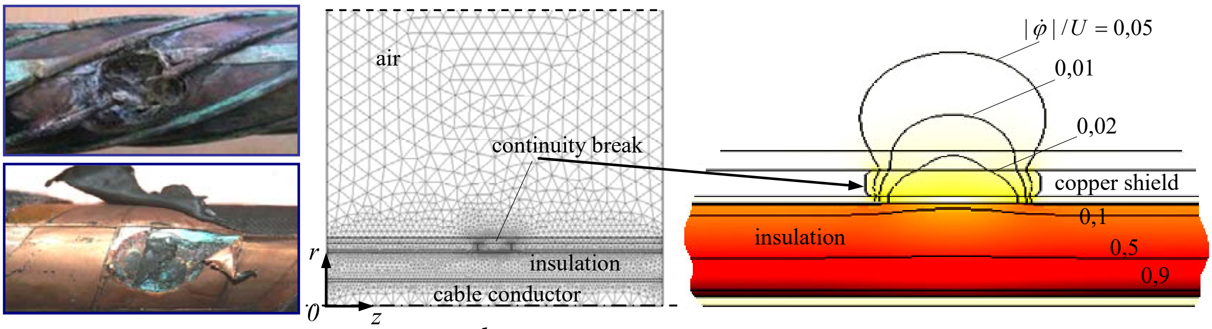



**Fig. 2**

**Model and computational domains.** The distribution of electric field $\dot{\mathbf{E}} = -\nabla\dot{\varphi}$ is determined by the equation solved for complex electric potential $\dot{\varphi}$:

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

Here: $\varepsilon_0$ and $\dot{\varepsilon}_r$ are the vacuum permittivity and the complex relative permittivity, respectively; $\sigma$ is the conductivity of material; $\omega = 2\pi f$ is the angular frequency ( $f$ = 50 Hz); $j$ is the imaginary unit; dots at the top denote the complex quantities.

The space charges injected from the surface of cable conductor and metallic shield into insulation are disregarded. The materials of cable are isotropic. The electric parameters $\dot{\varepsilon}_r$ and $\sigma$ can take the different values in the cable components.

The next boundary conditions are specified. The electric insulation condition (no current flows across the boundary – $\mathbf{n}\cdot\dot{\mathbf{J}}$ =0, where $\mathbf{n}$ is the unit external normal; $\dot{\mathbf{J}}$ is the total current density) is applied at the external boundaries of computational domains. The electric potential $\dot{\varphi}$ = 0 is defined on the surface of metallic shield. The potential $\dot{\varphi} = U$ (where $U$ is the peak value of phase voltage) is set on the surface of cable conductor.

The computational domains contain environment (air) because the electric field is modeled outside the cable installed in open air. The dimensions of the domains are more than 4 times greater than cable diameter.

The two-dimensional problems are solved in Cartesian coordinates for the damages having a large length in the longitudinal direction of the cable. Then the computational domain includes the cable cross-section (fig. 1, *a*).

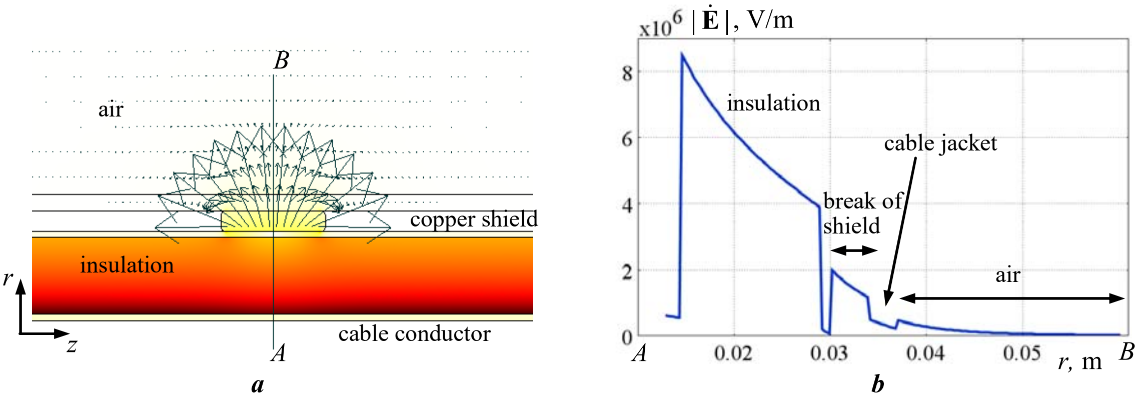



**Fig. 3**

The axially symmetric model (in cylindrical coordinates) is used for numerical computation of electric field and potential along the length of the cable (fig. 2, *a*) making an assumption that the damage of metallic shield has the same shape independently on angular coordinate. In other words, the damage is of the same shape in all axial sections of the cable.

In addition, the three-dimensional modeling is performed for the deep damage of cable components and the damage concentrated within a small area along the cable length (fig. 4, *a*).

**Initial data and numerical results.** The numerical simulation is carried out for 110 kV single-core XLPE insulated cable of АпвЭгаП 1x500/95 type (with conductor cross-section area of 500 mm$^2$, 16 mm insulation thickness and 4 mm shield thickness).

The conductivity of polyethylene 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 XLPE insulation and cable jacket is $\varepsilon_1 = \varepsilon_2 = 2.3$ .

The finite element mesh is generated as shown in fig. 2, *b*. The mesh is thickened near the damages, especially at the interfaces with cable elements.

Figs. 1, *b* and *c* show the electric field $|\dot{\mathbf{E}}|$ and isolines of $|\dot{\varphi}|$= const in the insulation and in the vicinity of the arcing damage due to discontinuity of cable jacket according to fig. 1, *a*. Here and below in fig. 2, *c* the values of ratio $|\dot{\varphi}|/U$ corresponding to displayed isolines are indicated. The distribution of electric field strength $|\dot{\mathbf{E}}|$ (in color and by arrows) near the damage is given in fig. 1, *c*. For the case under consideration and appropriate finite-element mesh resolution, the maximum electric field is equal to $|\dot{\mathbf{E}}|_{max}$ = 24 kV/mm and takes place at the corner areas of insulation adjacent to the damage. This value exceeds almost 2.8 times the field near the surface of cable conductor.

Fig. 2, *b* shows the computational domain of the problem with shield break and loss of concentric neutral in accordance with fig. 2, *a*. Then the electric field distribution and isolines of $|\dot{\varphi}|$ in the insulation and in the vicinity of the damage are presented in fig. 2, *c*.

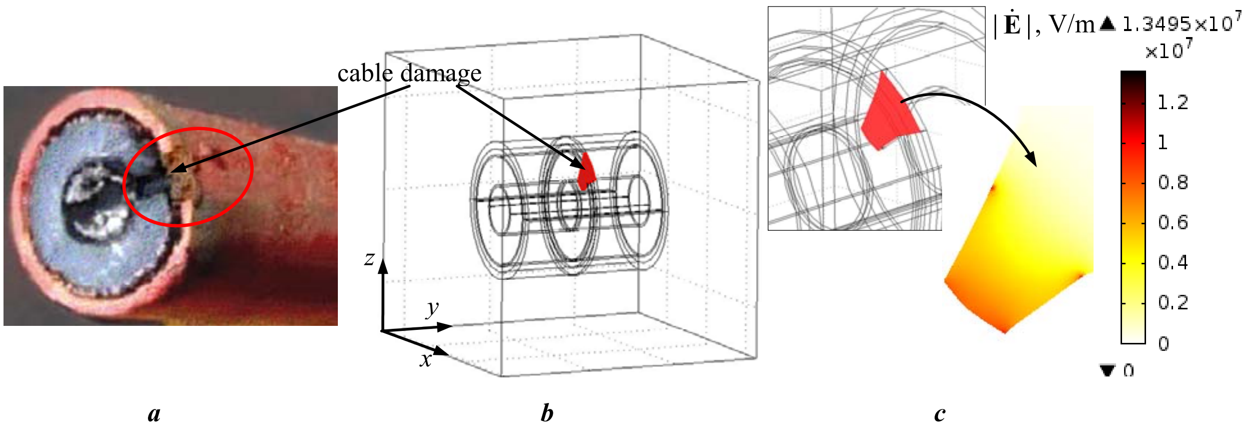
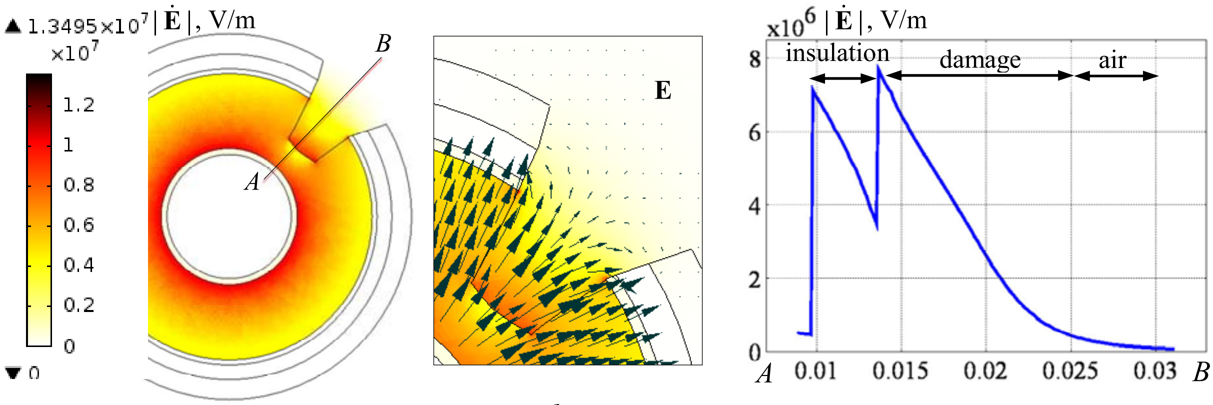



**Fig. 4**




*a* *b* *c*

**Fig. 5**

In addition to that, the field pattern near the shield break is given in fig. 3, *a* by arrows. The variation of electric field strength along the line *AB* passing across the center of the shield damage is plotted in fig. 3, *b*. The electric field strength is equal to up to 2 kV/mm in the region of shield break filled by air. The field spreads slightly outside the cable and decays completely at the distance of about 1.5–1.7 times of cable radius.

Fig. 4, *b* presents the 3D computational domain for sufficiently deep destruction of the cable including the destruction of its jacket, outer semiconducting layer and a large part of insulation as seen in fig. 4, *a*. The electric field distribution directly in the damage is displayed in fig. 4, *c*. In such case, the field $|\dot{\mathbf{E}}|$ is given in the insulation and damage in fig. 5, *a* and near the damage in fig. 5, *b* by arrows. The change of $|\dot{\mathbf{E}}|$ along the line *AB* in radial direction (fig. 5, *a*) is shown in fig. 5, *c*. As seen, the electric field spreads weakly beyond the cable. The field in the area of damage contiguous with main insulation exceeds the maximum value of electric field strength for defectless insulation. According to color legend in fig. 5, *a*, the greatest value of $|\dot{\mathbf{E}}|$ increases 1.54 times for the available damage in comparison with the insulation without the damage when the field can be determined analytically. The edge areas of the insulation along or near the boundary with the outer semiconducting layer (figs. 4, *c* and 5, *a*) are subject to destruction.

Note that the sharp changes of electric field in figs. 3, *b* and 5, *c* are explained by the transition from one material to another when the materials of cable components have different values of dielectric permittivity and conductivity.

**Summary.** The numerical simulation of electric field distribution in XLPE insulation and outside the high-voltage power cable with loss of its impermeability, partial break of metallic shield and damage of main insulation is carried out by using finite-element method. As shown, the electric field enhancement near the damage site can reduce the dielectric strength or accelerate the aging of the insulation. The maximum values of electric field strength at external boundary of the insulation in the vicinity of the contact with the damage are revealed. In the cases under consideration, the electric field spreads weakly outside the cable, over a distance of not more than 1.5–1.7 times of cable radius.

The study of electric field in the insulation and outside the power cables with the loss of protective function of jacket and the partial destruction of metallic shield gives a possibility to assess the potential power cable failure risks by comparison of the maximum electric field strength with the dielectric strength of insulating material and to use the results for new approaches to cable test and diagnostics.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**КОМП'ЮТЕРНЕ ВИВЧЕННЯ ЕЛЕКТРИЧНОГО ПОЛЯ КАБЕЛІВ З УШКОДЖЕННЯМ МЕТАЛЕВОГО ЕКРАНА**

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*На основі комп'ютерного моделювання досліджено розподіл електричного поля в поліетиленовій ізоляції та поза кабелями з характерними ушкодженнями зовнішньої оболонки, металевого екрана, значної частини ізоляції. Чисельне розв'язання задачі розрахунку електричного поля виконано у двовимірному і тривимірному випадках. Показано ослаблення основної ізоляції на границі з ушкодженнями, і за рахунок цього можливість її подальшої деградації. Для розглянутих ушкоджень електричне поле поширюється за межі кабеля на незначну відстань – у середньому не більше 1,5 радіуса кабеля.* Бібл. 11, рис. 5.

***Ключові слова***: зшито-поліетиленова ізоляція, ушкодження кабелів (металевого екрана, зовнішнього напівпровідного шару, основної ізоляції), електричне поле поза кабелем, дво- та тривимірне комп'ютерне моделювання.

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**КОМПЬЮТЕРНОЕ ИЗУЧЕНИЕ ЭЛЕКТРИЧЕСКОГО ПОЛЯ КАБЕЛЕЙ С ПОВРЕЖДЕНИЕМ МЕТАЛЛИЧЕСКОГО ЭКРАНА**

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*На основе компьютерного моделирования исследовано распределение электрического поля в полиэтиленовой изоляции и вне кабелей с характерными повреждениями внешней оболочки, металлического экрана, значительной части изоляции. Численное решение задачи расчета электрического поля выполнено в двумерном и трехмерном случаях. Показано ослабление основной изоляции на границе с повреждениями, и за счет этого возможность ее дальнейшей деградации. Для рассмотренных повреждений электрическое поле распространяется за пределы кабеля на незначительное расстояние – в среднем не более 1,5 радиуса кабеля.* Библ. 11, рис. 5.

***Ключевые слова***: сшито-полиэтиленовая изоляция, повреждения кабелей (металлического экрана, внешнего полупроводящего слоя, основной изоляции), электрическое поле вне кабеля, дву- и трехмерное компьютерное моделирование.

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