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CONSTRUCTING A MODEL OF THE INFLUENCE OF STRUCTURAL AND TECHNOLOGICAL INHOMOGENEITIES ON ELECTROMAGNETIC ENERGY LOSSES IN CABLES BASED ON A TWISTED PAIR

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The objects of research reported here were cables based on twisted pairs of various designs. The issue of the emergence of additional losses of electromagnetic energy is related to structural and technological inhomogeneities at the technological stage of cable production. The influence of the working capacitance of the twisted pair on the energy losses in the cables has been substantiated. A methodology was proposed for the numerical calculation of the electric field under the condition of ellipticity of the structural elements of the twisted pair. That has made it possible to determine the distortion of the electric field and the effect of inhomogeneities on the working capacitance of a twisted pair of different designs.

Specifically, it was shown that for shielded structures with continuous polymer insulation, the distortion of the electric field and the growth of the working capacitance are observed to a greater extent. The need to find technological solutions to reduce the effect of screen ellipticity on cable capacitance has been emphasized. The effectiveness of capacitance regulation in the presence of inhomogeneities has been confirmed, by using foamed insulation to reduce the loss of electromagnetic energy in the cable.

The effect of reducing the working capacitance and increasing additional losses under the simultaneous influence of the ellipticity of the electrical insulation and the protective polymer shell has been established, which necessitates the technological process adjustment in the manufacture of twisted pair.

An applied aspect of using the results is the possibility of improving the typical technological process of manufacturing twisted pairs to reduce additional losses of electromagnetic energy at the final technological stage of cable production.

The adequacy of the numerical studies was confirmed by experimental dependences of the attenuation coefficient and additional energy losses of the unshielded cable in the frequency range up to 100 MHz

Keywords: twisted pair, technological inhomogeneities, electric field, electromagnetic energy, foam insulation

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1. Introduction

Advanced technologies, including the Internet of Things (IoT), 5G, artificial intelligence, machine learning, cloud computing, lead to an increase in the number of intelligent devices and require the use of interference-resistant broadband cables with twisted pairs [1–4].

In the manufacturing sector, industrial automation is gaining momentum: cables with twisted pairs are also used to transmit data and signals in control systems and robotics [5]. The transition of industrial networks to Ethernet has given a noticeable increase in productivity and flexibility. At the same time, the approaches described in the concept of Industry 4.0 and IioT [1, 2] assume that wired data transmission is based on one-, two-, and four-pair cables based on a twisted pair of the corresponding category. Advancements are being implemented that provide data transmission and power supply via one twisted pair (PoE – Power over Ethernet) with a maximum transmission power of up to 50 W at a distance of up to 1000 meters [1, 2]. Increased demand in the field of power generation for applications of advanced digital signal transmission promotes the use of interference-resistant broadband cables based on shielded twisted pairs [5].

The increasing use of Ethernet networks in specialized organizations such as schools and colleges, medium and large enterprises and offices is also driving the further development of twisted pair cabling.

Overall, the global unshielded and shielded twisted pair cable market is expected to grow at an annual rate of 6.10 % during the period 2023 to 2028. At the same time, the world market for shielded twisted pair was estimated at 2.3 billion US dollars in 2021, and by 2030, according to forecasts, it will reach 2.8 billion US dollars with an average annual growth rate of 4.1 % [5].

5e category cables held the largest global market share in the telecommunications segment in 2020 due to growing demand for commercial applications and military devices [5]. The production of innovative cable and conductor products requires appropriate technology and technological process settings in the manufacture of twisted pairs to ensure standardized electrical transmission parameters in a wide frequency range. Research into the development of a model of the impact of structural and technological inhomogeneities on the loss of electromagnetic energy at the technological stage of cable production is relevant and has significant practical importance.

2. Literature review and problem statement

For cables based on a twisted pair, twisted with an appropriate pitch to increase interference immunity, depending on the category that determines the operating frequency range, a normalized electrical transmission parameter was established – the attenuation coefficient [6]. The attenuation coefficient is a frequency-dependent parameter that characterizes the upper limit of electromagnetic energy losses and the maximum distance of its transmission. The loss of electromagnetic energy is significantly affected by the working capacitance of the twisted pair. The working capacitance is determined by the applied materials and design: unshielded (without a metal screen in a polymer protective shell), shielded (shielded with aluminum foil or a two-layer screen in the form of an aluminum polymer tape) [7].

Research has proven that the presence of metal shields in the twisted pair structure leads to an increase in electrical working capacitance due to the appearance of additional partial capacitance of each of the insulated conductors on the metal shield [8]. However, it should be noted that the effect of fluctuations in the thickness of the electrical insulation on the electrical capacitance and attenuation coefficient of the twisted pair was not established in the cited work.

The authors of [9] theoretically, on the basis of numerical calculations, established a more significant influence of the working capacitance under the condition of fluctuation of the insulation thickness on the attenuation coefficient in comparison with the active resistance in the shielded cable design. But the issue of experimental confirmation of the conclusions was left unaddressed. The experimental studies reported in [10] proved the increase in the electric working capacitance of the shielded pair due to the appearance of additional partial capacitance of each of the insulated conductors on the metal screen [8]. Despite the practical significance of such results, the effect of reducing electromagnetic energy losses in shielded cable structures in the high-frequency range has not been considered.

It was experimentally proven in [11] that in the frequency range where the screen thickness is less than the depth of the skin layer, the inductance of the twisted shielded pair [12] increases. This leads to a decrease in the loss of electromagnetic energy in conductors [13, 14] and, in general, in a twisted pair, provided the thickness of the electrical insulation is increased [10]. These works do not take into account the stochastic nature of the twisting step and its effect on the electric capacitance of the cable.

To overcome this problem, the authors of [15, 16] performed a statistical analysis of the effect of fluctuations in the pitch of twisting the pair on the capacitance of unshielded and shielded cables. The impact of the stochastic nature of the change in capacitance on the attenuation coefficient and electromagnetic interference between twisted pairs has made it possible to substantiate the requirements for the density of the structure and the settings of the technological process of manufacturing shielded cables with twisted pairs [17]. But there are objective difficulties in determining the capacitance of a twisted pair based on the numerical calculation of the electric field, taking into account structural inhomogeneities depending on the design of the cable.

In this area, the research carried out in [18] proves that an increase in the insulation thickness of the twisted pair conductors ensures the attenuation coefficient of shielded cables in the range of normalized values. At the same time, the authors showed [9] that an increase in insulation thickness by 50 % leads to a decrease in capacitance by 20 % with a simultaneous increase in the mass and dimensions of the twisted pair. The use of foam insulation at the technological stage of manufacturing insulated cable conductors is substantiated as an option for overcoming the relevant difficulties in [19]. Despite the practical orientation of such theoretical results, the issue of the influence of insulation foaming on electromagnetic energy losses has not been considered.

It should be noted that modern technological control systems provide continuous control over electrical capacitance at the stage of manufacturing an insulated conductor along its entire length [20, 21]. This makes it possible to make timely decisions regarding the adjustment of the technological process with a capacitance deviation of (±0.1–±0.3) % [20, 21]. It is compliance with the settings of the technological process with the specified deviation of the electric capacitance of the insulated conductor that ensures the attenuation coefficient of the twisted pair within the normalized values in the entire frequency range.

At the same time, the performed experimental studies prove that the limit value of the attenuation coefficient of the twisted pair cable is exceeded. This situation reflects the appearance of structural inhomogeneities at the final technological stage of twisted pair production. One of the most likely inhomogeneities at the final stage of the technological process at high speeds of extrusion of the protective polymer shell, application of aluminum polymer or solid metal screens is non-roundness (ellipticity) of the structural elements of the cable. Uncertainty is observed in clarifying the reasons for the increase in electromagnetic energy losses in twisted pairs precisely at the final technological stage of cable production. All this allows us to assert the feasibility of conducting research into the correlation between structural and technological inhomogeneities and the electrical capacitance of the twisted pair, i.e., electromagnetic energy losses, at the final technological stage of cable production.

3. The aim and objectives of the study

Our research was aimed at establishing the influence of structural and technological inhomogeneities on the working capacitance and loss of electromagnetic energy in a twisted pair. This could make it possible to ensure the attenuation coefficient of electromagnetic energy within the normalized values in a wide frequency range with the appropriate adjustment of the technological process at the final stage of cable production.

To accomplish the aim, the following tasks have been set:

– to justify the methodology of numerical calculation of the electric field in the presence of structural and technological inhomogeneities of cables based on twisted pairs;

– to determine the effect of the ellipticity of the structural elements on the structure of the electric field and the working capacitance and to substantiate ways of reducing their influence on the loss of electromagnetic energy, depending on the design of the cable and electrical insulation materials;

– to prove the adequacy of numerical studies to the experimental investigation.

4. The study materials and methods

4. 1. The object and hypothesis of the study

The object of our study was the loss of electromagnetic energy in cables based on twisted pair. The hypothesis of the study assumed the impact of structural and technological inhomogeneities on the loss of electromagnetic energy at the final technological stage of manufacturing unshielded and shielded cables. A simplification was adopted regarding inhomogeneities in the form of ellipticity of the structural elements of the cable. The assumption concerned the substantiation of electromagnetic energy losses based on the numerical determination of the electric field and electric capacitance of a twisted pair with an elliptical polymer sheath and screen in the cable design.

4. 2. Materials and structures of twisted pairs

The study was conducted for three options for the design of a single twisted pair:

1) an unshielded pair in a protective polymer shell;

2) a screened pair with a combined two-layer screen consisting of a dielectric and a metal foil (aluminum polymer);

3) a shielded pair with a single-layer metal screen.

The structural dimensions of the twisted pair of all three calculation models were chosen to be the same. The diameter of the conductors was 0.64 mm and 0.511 mm. The thickness of the insulation was 0.32 mm and 0.275 mm, respectively. Dielectric permeability of solid polyethylene insulation ε_2=2.1 for three types of twisted pair designs. Additionally, for a structure shielded with a single-layer metal screen, the value of dielectric constant was assumed to be equal to ε_2=1.55 (foamed insulation). Protective polymer shell based on polyvinyl chloride plastic with a dielectric constant of ε_3=4.5, 0.125 mm thick. A two-layer aluminum polymer screen with a total thickness of 0.125 mm, wrapped with a non-polar polymer film to a twisted pair [7] with a dielectric constant of ε_4=2.5 with a thickness of 0.025 mm. Metal single-layer screen with a thickness of 0.125 mm. The free space in the cable structure was filled with air with a dielectric constant of ε_1=1.0. The voltage applied to the cable was equal to 100 V.

4. 3. Method for determining the working capacitance of twisted pair

The working capacitance of the twisted pair was based on the calculation of the electric field by the method of secondary sources [22, 23] with the following assumptions:

1. Neglecting the helical surface of the twisted pair: the twisting step and the bending radius are 8–10 times greater than the transverse dimensions of the pair. Accordingly, the electric field was considered the same in each cross-section, that is, it is plane-parallel.

2. The surfaces of conductors and insulation were assumed to be circular and cylindrical.

3. The third assumption related to the features of field calculation in models containing dielectric wedges. Between the insulated conductors that collided, wedge-shaped sections were formed, on which an important assumption was violated in the construction of numerical models: the length of the section with a surface charge should be shorter than the distance to the field observation point. To ensure this condition, air gaps of about 10 μm thickness were introduced between the insulated conductors. These gaps practically did not affect the integral characteristics – the capacities of the gaps, but they made it possible to avoid the overlap of nodes, which can cause a sharp increase in the local error of numerical calculations.

Numerical calculations were performed in the free Octave software environment [24].

5. Results of studies of the effect of ellipticity of elements on the working capacitance and energy loss in the cable

5. 1. Methodology of numerical calculation of the electric field in the presence of structural and technological inhomogeneities

The methodology of the numerical calculation of the electric field under the condition of the presence of structural and technological inhomogeneities consisted in the transition from the calculations of the electric field in the primary problem to the calculation of the field in a vacuum [9]. The calculated model contained surfaces coinciding with the boundaries of the separation of the environments of the original task. Secondary charges were placed on them, the calculated density σ of which was selected so that two conditions were met:

a) on the surfaces describing the electrodes (pair conductors, metal screen), the given potentials U_i were reached according to the Fredholm integral equation of the first kind:

$$\frac{1}{2\pi\varepsilon_0}\int \sigma_j \cdot \ln\left(\frac{r_{0j}}{r_{ij}}\right) \cdot dl_j = U_i, \tag{1}$$

where i is the number of the node in which the characteristics of the field are sought; j is the node number in which the charge is located; r_{ij} is the distance between sections i and j; r_{0j} is the distance from site j to point O, the potential of which can be taken as zero; σ_j is the secondary charge density at point j; dl_j is the length of an infinitesimal section centered at point j; $\varepsilon_0=8.85\cdot10^{-12}$ F/m – electrical constant;

b) the conditions of equality of the normal components of the electric displacement vector were fulfilled on the surfaces describing the boundaries of separation of dielectric media:

$$\varepsilon_2 \cdot \left(E_n - \frac{\sigma_i}{2\varepsilon_0}\right) = \varepsilon_1 \cdot \left(E_n + \frac{\sigma_i}{2\varepsilon_0}\right), \tag{2}$$

where E_n is the normal component of the field strength at point i, created by all charges except for the one located at this point; $\sigma_i/(2\varepsilon_0)$ is the normal component of the field strength at point i, created by the charge located at this point.

Condition (2) was written as Fredholm's integral equation of the second kind:

$$\frac{\sigma_i}{2\varepsilon_0} - \frac{\varepsilon_2-\varepsilon_1}{\varepsilon_2+\varepsilon_1} \cdot \frac{1}{2\pi\varepsilon_0}\int \sigma_j \cdot \frac{\cos\left(\overline{r_{ij}}, \overline{n_i}\right)}{r_{ij}} \cdot dl_j = 0. \tag{3}$$

The solution to the Fredholm integral equations of the first kind for the potentials on the electrode surfaces and of the second kind for the jumps of the normal component of the field strength at the boundary of the separation of dielectric media involved reducing to a component system of linear algebraic equations (SLAE) in matrix form [9]:

$$\bar{A}\cdot\bar{\sigma}=\bar{U}_{\cdot}, \tag{4}$$

where σ is a matrix-column of unknown values of the density of secondary charges, Kl/m^2; in the total number of nodes N (SLAE order), U is a matrix-column, the first N_e terms of which reflect the given potentials of the nodes lying on the electrodes, the others (N–N_e) – at the border of separation of dielectric media and equal to zero; A is a square matrix of coefficients, the elements of which are a_{ij} [9]:

$$a_{ij}=\begin{cases}\begin{pmatrix}\dfrac{1}{2\pi\varepsilon_0}\ln\dfrac{r_{0j}}{r_{ij}}\cdot\Delta l_j & \forall i\neq j\\ \dfrac{1}{2\pi\varepsilon_0}\ln\dfrac{r_{0j}}{\Delta l_j/(2e)}\cdot\Delta l_j & \forall i=j\end{pmatrix} i=1\div N_e\\ \begin{pmatrix}\dfrac{1}{2\varepsilon_0} & \forall i=j\\ -\alpha\cdot\dfrac{1}{2\pi\varepsilon_0}\ln\dfrac{\cos(\bar{r}_{ij},\bar{n}_j)}{r_{ij}}\cdot\Delta l_j & \forall i\neq j\end{pmatrix} i=N_e+1\div N\end{cases}, \tag{5}$$

where Δl_j is the length of the line segment centered at point j; e is the base of the natural logarithm ($e\approx2.71828$).

The calculated density of secondary charges and field strength (in a vacuum) were found on the basis of the numerical solution to SLAE (4):

a) for electrode surfaces:

$$E_i=\frac{\sigma_i}{\varepsilon_0}; \tag{6}$$

b) for the separation limit of dielectric media (normal component of field strength):

$$E_i=\frac{\sigma_i}{2\varepsilon_0}\left(1+\frac{1}{\alpha}\right), \tag{7}$$

where α is a parameter related to the dielectric constants of adjacent media. Thus, when the normal vector was oriented from medium ε_2 to medium ε_1, parameter α was equal to:

$$\alpha=\frac{\varepsilon_2-\varepsilon_1}{\varepsilon_2+\varepsilon_1}.$$

According to (7), the normal component of the electric field intensity at the boundary of separation of dielectric media from the side of the positive direction of the normal was determined.

The tangential component of the field strength at the points on the boundary of separation of dielectric media was determined on the basis of (8):

$$E_\tau=\frac{1}{2\pi\varepsilon_0}\int\sigma_j\frac{\sin(\bar{r}_{ij},\bar{n}_i)}{r_{ij}}\cdot dl_j\approx$$
$$\approx\frac{1}{2\pi\varepsilon_0}\sum_{j=1}^{j=N}\sigma_j\frac{\sin(\bar{r}_{ij},\bar{n}_i)}{r_{ij}}\cdot\Delta l_j, \tag{8}$$

where $\sin(r_{ij}, n_j)$ is the sine of the angle between vectors r_{ij} and n_j.

Formulas (1) to (8) were used to determine the plane-parallel electric field of the twisted pair model. The true density σ′ of charges on the surfaces of conductors isolated by a dielectric with a dielectric constant ε is ε times greater than the density of charges σ in a vacuum, and was taken into account when calculating the partial capacitance:

$$\sigma'=\varepsilon\cdot\sigma. \tag{9}$$

Taking into account the heterogeneity of the twisted pair design in the form of an elliptical protective sheath or cable screen was carried out based on the application of the ellipse equation in a parametric form to describe the shape of the structural elements:

$$\{x=a\cdot\cos(t)\},\{y=b\cdot\sin(t)\}, \tag{10}$$

where a and b are semi-axes (major and minor) of the ellipse; t is a parameter that varied from −π to +π.

Next, the major semi-axis of the ellipse did not change because it was determined by the given values of the thickness of the insulation and structural elements. The value of the minor semi-axis decreased.

To calculate the electric field, in addition to the parametric equations of the ellipse, the following were determined:

– the length dl of the ellipse section:

$$dl=\sqrt{dx^2+dy^2}=\sqrt{(a\cdot\sin(t))^2+(b\cdot\cos(t))^2}\cdot dt; \tag{11}$$

– angular coefficient of tangent:

$$k=\frac{dy}{dx}=\frac{dy/dt}{dx/dt}=\frac{b\cdot\cos(t)}{-a\cdot\sin(t)}=\frac{-b}{a}\mathrm{ctg}(t); \tag{12}$$

– angular coefficient of normal:

$$k_n=\frac{-1}{k}=\frac{a}{b}\mathrm{tg}(t). \tag{13}$$

On the basis of (1) to (8) and taking into account (9) and (10) to (13), numerical modeling of the electric field was carried out and values of the working capacitance of the twisted pair were determined, taking into account the presence of ellipticity of structural elements.

Fig. 1, 2 show calculation models with circular and elliptical configurations of the shape of structural elements for determining the electric field at nodes N of a twisted pair with a conductor diameter of 0.64 *mm*. The calculation models in Fig. 1 in the absence of ellipticity and the presence of ellipticity at the ratio of the semi-axes b/a=0.70.

A model with the simultaneous presence of the ellipticity of the insulation of one of the conductors (located on the left) and the protective polymer shell of an unshielded twisted pair is presented in Fig. 2: a – ratio of semi-axes for insulation and shell b/a=0.70; b – ratio of semi-axes for insulation a/b=0.70 and shell b/a=0.70, respectively. For the specified models, depending on the design of the twisted pair, the electric field strength was determined according to (1) to (13), the partial capacitances ($C_{1\text{-}1}$) of the insulating gap between the two conductors, the self-capacitance of the conductors (we assumed that (C_1) and (C_1) were the same) and the working effective capacitance C of the twisted pair:

$$C=C_{1\text{-}1}+\frac{C_1\cdot C_1}{C_1+C_1}=C_{1\text{-}1}+\frac{1}{2}C_1. \tag{14}$$

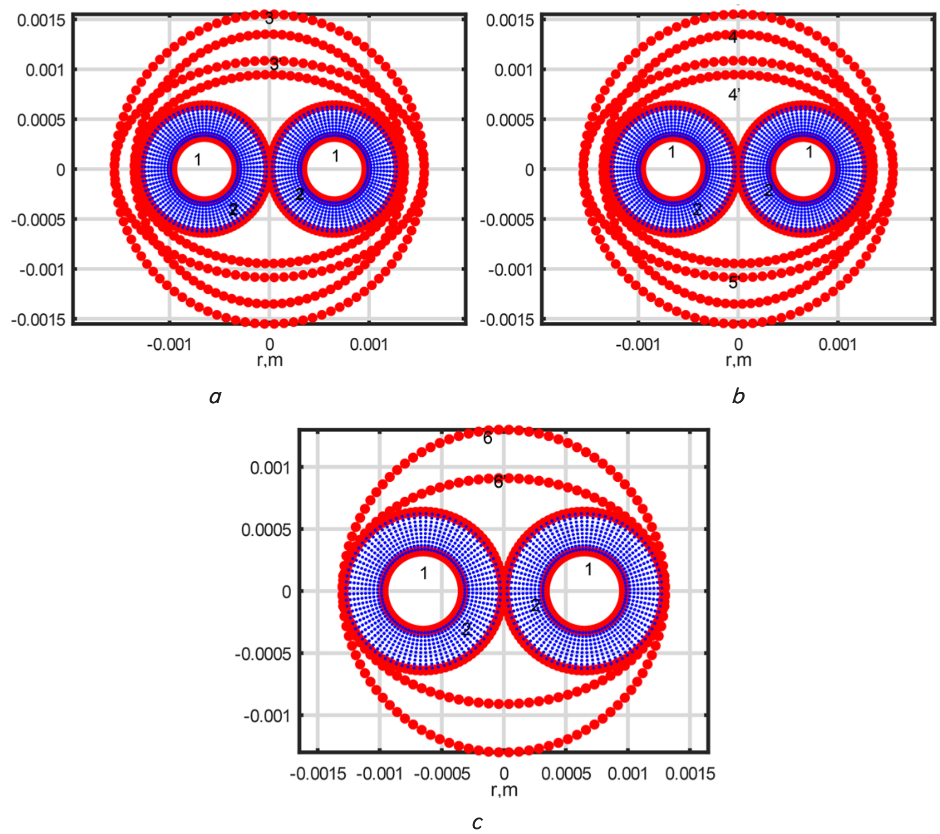

Fig. 1. Calculation models of a twisted pair: *a* – unshielded: 1 – conductors, 2 – polymer insulation, 3, 3' – protective polymer shell in the absence and presence of ellipticity of the shell; *b* – shielded with a two-layer screen: 1 – conductors, 2 – polymer insulation, 4, 4' – polymer layer of the screen in the absence and presence of ellipticity of the screen, 5, 5' – aluminum foil of the screen in the absence and presence of ellipticity of the screen; *c* – shielded with a single-layer screen: 1 – conductors, 2 – insulation, 6, 6' – metal screen in the absence and presence of ellipticity of the screen

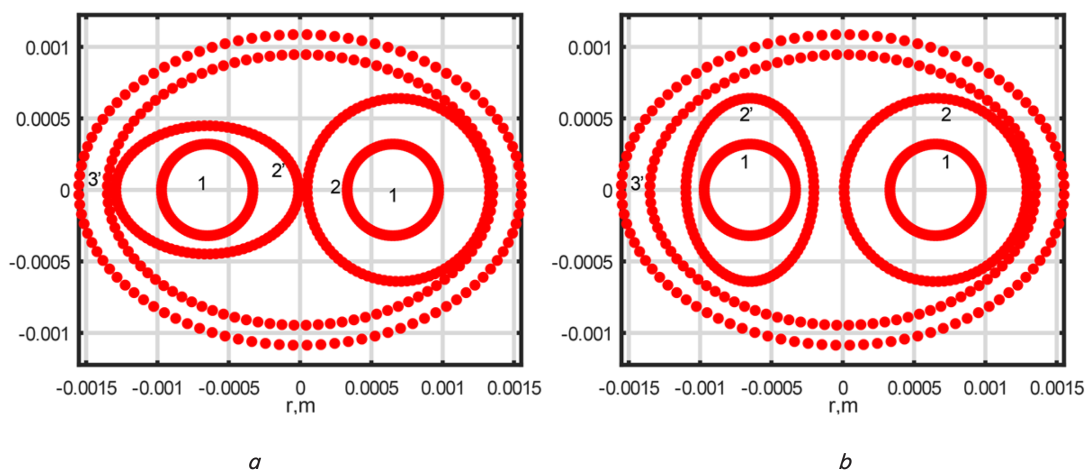

Fig. 2. Calculation model in the presence of ellipticity of insulation and protective polymer shell: a – b/a=0.70; b – for insulation a/b=0.70, for the shell b/a=0.70: 1 – conductors, 2'; 2 – polymer insulation; 3' – protective polymer shell

Dots show nodes where the density of surface charges, i.e., the intensity of the electric field, was determined. Visual control of the location of nodes (Fig. 1, 2) was used to qualitatively check the correctness of the model geometry task. The potential was applied to the conductor located on the left in the calculation models in Fig. 1, 2.

5. 2. The effect of the ellipticity of structural elements on the structure of the electric field and the working effective capacitance of the cable

Fig. 3, 4 show the structure of the electric field in the presence of technological inhomogeneities in the form of ellipticity of structural elements of cables with twisted pairs.

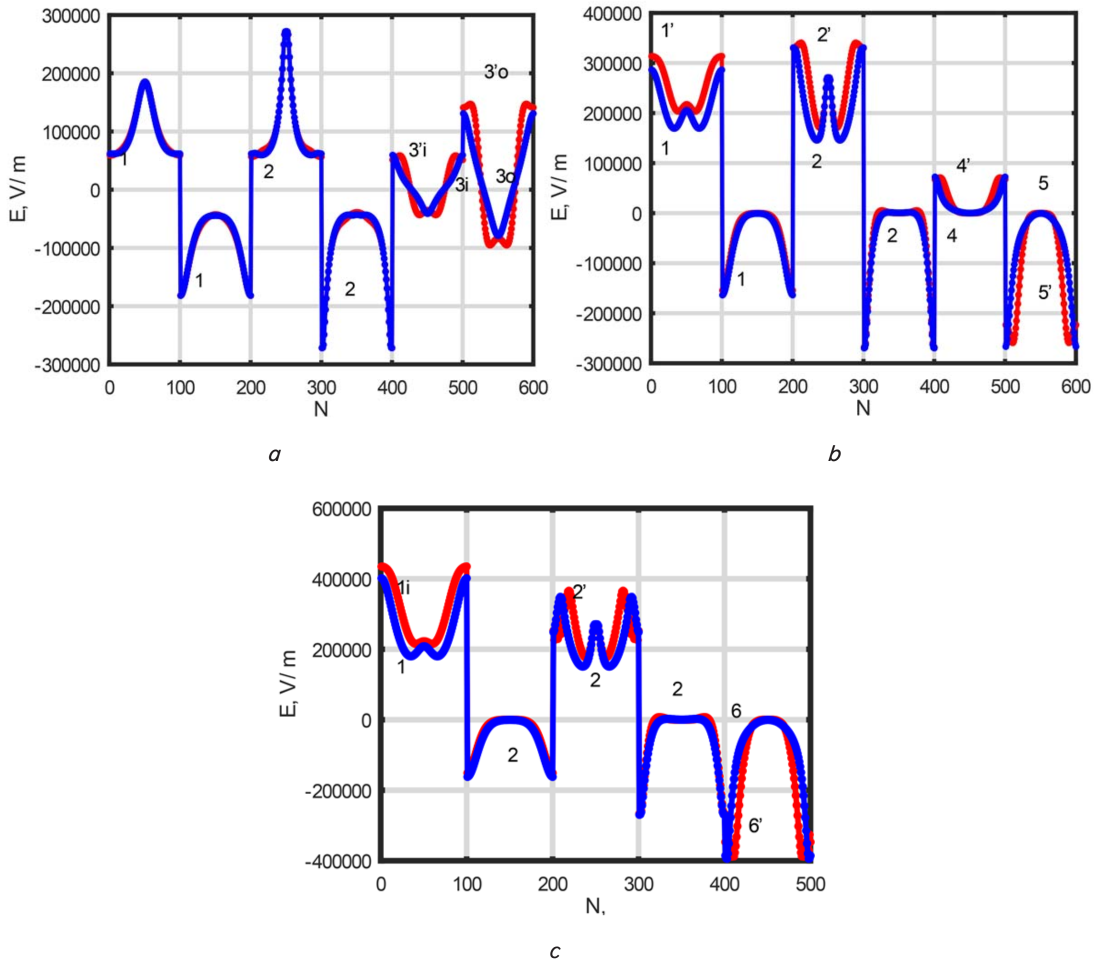

Fig. 3. Distribution of the electric field strength on the surfaces (nodes *N*) of the structural elements of the twisted pair: *a* — unshielded: 1 — conductors; 2 — polymer insulation, 3i 3'i — internal and 3o, 3'o — external surfaces of the protective polymer shell in the absence and presence of ellipticity of the shell; *b* — shielded with a two-layer screen: 1 — conductors; 2 — polymer insulation; 4, 4' — polymer interlayer of the screen in the absence and presence of ellipticity of the screen; 5, 5' — aluminum foil of the screen in the absence and presence of ellipticity of the screen; *c* — shielded with a single-layer screen: 1 — conductors; 2 — insulation; 6, 6' — metal screen in the absence and presence of ellipticity of the screen

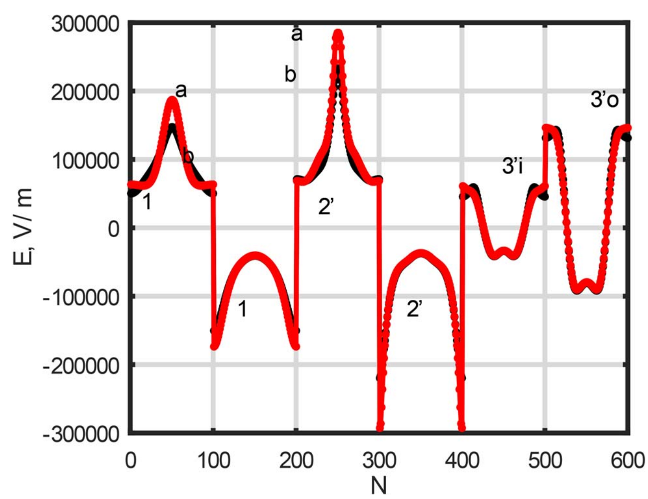

Fig. 4. Distribution of the electric field strength on the surfaces (nodes *N*) of the structural elements of the unshielded twisted pair in the presence of ellipticity of the insulation and the protective polymer shell: 1 — conductors; 2' — polymer insulation; 3'i, 3'o — the inner and outer surfaces of the protective polymer shell: *a* — *b* / *a*=0.70 for insulation and shell; *b* — *a* / *b*=0.70 for insulation and *b* / *a*=0.70 for the shell

Based on the calculation of the electric field, the values of the working effective capacitance and its components, depending on the ratio of the axes and the insulation material (solid and foam) of the twisted pair with different conductor diameters, are given in Tables 1, 2. For twisted pairs with conductor diameters of 0.64 mm (Table 1) and 0.511 mm (Table 2), the influence of the ellipticity (*b/a*) of the structural elements of the calculation models and the dielectric permittivity of the electrical insulation (ε_2) under the condition of continuous (ε_2=2.1) and foamed (ε_2=1.55) polyethylene insulation on the working effective capacitance of twisted pairs is presented.

Table 1

The influence of the ellipticity of the structural elements on the components and the working effective capacitance of a twisted pair with a conductor diameter of 0.64 mm

Half-axes ratio b/a	Mutual capacitance $C_{1\text{-}1}$, 10^{-12}, F/m	Natural capacitance C_1, 10^{-12}, F/m	Working capacitance C, 10^{-12}, F/m	Ratio of working capacitance to natural capacitance C/C_1	Ratio of working capacitance with ellipticity to capacitance without ellipticity $C_{b/a}/C$
Unshielded twisted pair					
1	32.845	36.966	51.328	1.389	1.000
0.9	32.972	37.082	51.513	1.389	1.004
0.8	33.148	37.249	51.772	1.389	1.009
0.7	33.420	37.521	52.181	1.391	1.017
Shielded with a two-layer aluminum polymer screen					
1	19.257	75.361	56.938	1.324	1
0.9	18.614	78.120	57.674	1.355	1.013
0.8	17.762	82.413	58.968	1.398	1.036
0.7	16.611	89.637	61.429	1.459	1.079
Shielded with a single-layer metal shield (dielectric permeability of insulation ε_2=2.1)					
1	18.398	93.821	65.309	1.437	1
0.9	17.687	97.866	66.120	1.480	1.012
0.8	16.740	104.42	68.948	1.514	1.056
0.7	15.448	116.19	73.545	1.580	1.126
Shielded with a single-layer metal screen (dielectric permeability of foam insulation ε_2=1.55)					
1	13.827	74.979	51.32	1.46	1
0.9	13.218	77.885	52.161	1.493	1.016
0.8	12.421	82.418	53.630	1.537	1.045
0.7	11.367	90.08	56.406	1.597	1.099

Table 2

The influence of the ellipticity of the structural elements on the components and the working effective capacitance of a twisted pair with a conductor diameter of 0.511 mm

Half-axes ratio b/a	Mutual capacitance $C_{1\text{-}1}$, 10^{-12}, F/m	Natural capacitance C_1, 10^{-12}, F/m	Working capacitance C, 10^{-12}, F/m	Ratio of working capacitance to natural capacitance C/C_1	Ratio of working capacitance with ellipticity to capacitance without ellipticity $C_{b/a}/C$
Unshielded twisted pair					
1	32.940	36.931	51.406	1.392	1.000
0.9	33.097	37.082	51.638	1.392	1.004
0.8	33.316	37.299	51.965	1.393	1.011
0.7	33.632	37.613	52.448	1.394	1.020
Shielded with a two-layer aluminum polymer screen					
1	19.230	72.228	55.344	1.305	1
0.9	18.605	74.801	56.005	1.336	1.012
0.8	17.778	78.777	57.166	1.378	1.033
0.7	16.664	85.331	59.329	1.438	1.072
Shielded with a single-layer metal shield (dielectric permeability of insulation ε_2=2.1)					
1	18.194	93.055	64.722	1.438	1
0.9	17.487	97.046	66.010	1.470	1.020
0.8	16.546	103.50	68.298	1.515	1.055
0.7	15.265	115.13	72.732	1.583	1.234
Shielded with a single-layer metal screen (dielectric permeability of foam insulation ε_2=1.55)					
1	13.845	75.080	51.385	1.461	1
0.9	13.236	77.989	52.230	1.493	1.016
0.8	12.438	82.529	53.702	1.537	1.045
0.7	11.382	90.221	56.492	1.597	1.099

5. 3. Adequacy of numerical studies to experimental investigation

Experimental frequency dependences of the attenuation coefficient of an unshielded cable in a protective polymer sheath with 4 twisted pairs in the absence and presence of structural and technological inhomogeneities are shown in Fig. 5. Curve 2 indicates the presence of inhomogeneities in the pair: the attenuation coefficient exceeds the limit value (curve 1).

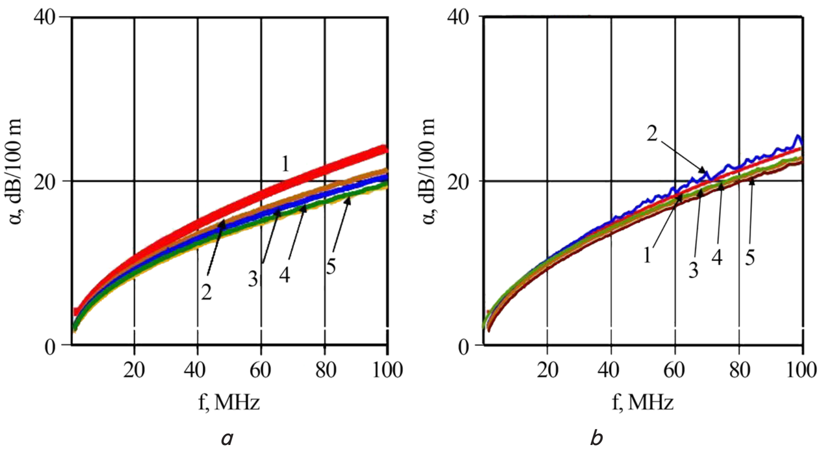

Fig. 5. Experimental frequency dependences of the attenuation coefficient of an unshielded cable: *a* – in the absence; *b* – in the presence of structural and technological inhomogeneities: 1 – the limiting value of the attenuation coefficient; 2 –5 – value of the attenuation coefficient of each twisted pair in the cable

Fig. 6 shows additional losses of electromagnetic energy depending on the frequency in a four-pair unshielded cable caused by structural and technological inhomogeneities due to imperfection of technological process settings.

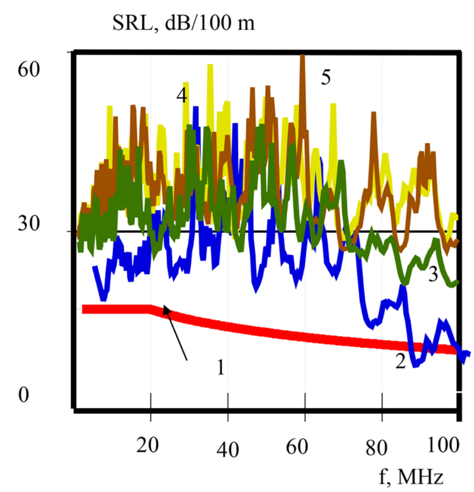

Fig. 6. Experimental frequency dependences of structural-reverse losses of electromagnetic energy of an unshielded 4-pair cable: 1 – limit value of SRL; 2–5 – SRL value of each twisted pair in the cable

As can be seen from Fig. 6, the presence of inhomogeneities of structural elements leads to the appearance of additional losses of electromagnetic energy on the experimental frequency dependence of structural return losses (SRL) and going beyond the limit value (curve 1) for one of the twisted pairs (curve 2) in the cable of category 5e.

6. Discussion of results of investigating the influence of technological inhomogeneities on the loss of electromagnetic energy in the cable

For the considered models (Fig. 1, *a–c*, 2, *a*, *b*), there is a distortion of the electric field (Fig. 3, *a–c*, 4), which is due to the presence of ellipticity of the structural elements. In contrast to [7], the proposed methodology for the numerical calculation of the electric field allows taking into account technological inhomogeneities in cables. This ensures the determination of structures with a greater disturbance of the electric field and the need for technological process settings at the final stage of cable production. In the design of the cable with a metal screen, the electric field strength has higher values on the surface of the conductor (Fig. 2, *c*, curve 1'). At the same time, for this design, there is a greater distortion of the field on the surface of the insulation (Fig. 3, *c*, curve 2') compared to others (Fig. 3, *a*, *b*, curves 2'). As a result, this leads to a greater impact on the working effective capacitance (Tables 1, 2) in such a design compared to others.

For all three calculation models, the growth of the natural capacitance C_1 of the conductors is determined when the ratio of the semi-axes of the ellipses b/a decreases (Tables 1, 2) due to the decrease in the length of the insulating gaps. At the same time, for shielded structures, there is a decrease in the partial capacitance between the conductors due to pulling part of the power lines onto the shield (Table 1). Based on these results, it can be stated that the effective capacitance of the shielded cable exceeds that of the shielded cable by 40.9 % and 38.97 % of the unshielded and double-layer shield with a conductor diameter of 064 mm (Table 1). The capacitance excess is 19.7 % and 22.6 % with a conductor diameter of 0.511 (Table 2) in the case of solid polyethylene insulation with a dielectric constant of ε_2=2.1 and a ratio of the semi-axes of the ellipses b/a=0.70, respectively. This allows us to assert the need to find technological solutions to reduce the effect of the ellipticity of the screen on the working capacitance of the twisted pair.

In this sense, the use of insulation with a reduced dielectric constant (ε_2=1.55) (Tables 1, 2), for example, nitrogen-foamed polyethylene insulation [19], is of particular interest in the shielded design. The mechanism of influence of foam insulation is an effective factor in regulating the working capacitance. In contrast to [7, 9, 19], in our research, even in the presence of ellipticity of the shield (b/a=0.70), electromagnetic energy losses are reduced by 14.4 % and 13.5 % in a shielded twisted pair with conductor diameters of 0,64 mm and 0.511 mm, respectively.

The simultaneous presence of the ellipticity of the insulation and the protective polymer shell in the unshielded cable design (Fig. 2) leads to additional distortion of the electric field (Fig. 4, curves *a*, *b*). But, as a not obvious consequence, there is a decrease in working capacitance by 5.5 % at b/a=0.70 for insulation and shell and by 11.8 % at a/b=0.70 for insulation and b/a=0.70 for the shell compared to the case of only ellipticity (Table 1). This is due to a decrease in the volume of solid polymer insulation and an increase in air in the cable. The obtained data on the reduction of the working capacitance allow us to assert the reduction of the attenuation coefficient, which is a limitation of this theoretical study. At the same time, the disadvantage of the proposed methodology for calculating the electric field under the condition of the presence of structural and technological inhomogeneities is the impossibility of taking into account the morphological inhomogeneity of the polymer insulation and protective sheath of the cable.

It is impossible not to note that the distortion of the electric field in the presence of ellipticity of structural elements (Fig. 5) leads to the appearance of additional losses of electrical energy in the cable. Determination of additional losses arising from the simultaneous influence of technological inhomogeneities of the insulation and the protective sheath requires a more precise adjustment of the technological process of manufacturing insulated twisted pair conductors.

The consistency of theoretical studies on the distortion of the electric field (Fig. 3, 4) and the growth of the working capacitance (Tables 1, 2) in the cable with inhomogeneities is confirmed by the experimental dependences of the attenuation coefficient (Fig. 5, curve 2).

Our experimental studies of additional losses of electromagnetic energy (Fig. 6) prove the need to improve the typical technological process of manufacturing twisted pairs to reduce the influence of structural and technological inhomogeneities at the final technological stage of cable production.

However, it is impossible not to note that the distortion of the structure of the electric field in the presence of ellipticity of the structural elements also leads to an increase in the electromagnetic influence between the twisted pairs in the cable, which gives rise to a potentially interesting direction of further research. In particular, it may involve establishing the impact of structural and technological heterogeneities on the attenuation coefficient to cross disturbances, which determines the overall performance of cables.

7. Conclusions

1. Our research substantiates the methodology of numerical determination of the electric field, which is based on the method of secondary sources and allows taking into account the presence of structural and technological inhomogeneities in the form of ellipticity of structural elements of cables based on twisted pairs.

2. It was established that with an increase in the ellipticity of the screen due to the distortion of the electric field, the capacitance of the pair increases by 40.9 % and 19.7 % compared to the unshielded one with conductor diameters of 0.64 and 0.511 mm. This made it possible to emphasize the effectiveness of using foamed polymer insulation at the technological stage of cable production to regulate the working capacitance and reduce its impact on the loss of electromagnetic energy in the shielded pair.

3. There is a correlation between the performed theoretical and experimental studies on the influence of structural and technological inhomogeneities on the attenuation coefficient and additional losses of electromagnetic energy in unshielded twisted pairs. This is an indirect evidence of the adequacy of the conducted numerical studies and allows justifying the technological process settings to reduce the effect of ellipticity on the loss of electromagnetic energy in cables, depending on the design. The use of foam insulation causes a decrease in electrical capacitance by 27 % and 12 % and electromagnetic energy losses by 13 % and 6.0 % in a shielded twisted pair with conductor diameters of 0.64 and 0.511 mm. The improvement of the typical manufacturing process of twisted pairs ensures normalized values of additional losses of electromagnetic energy and the attenuation coefficient of the twisted pair in the working frequency range of the cable.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study and the results reported in this paper.

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Data availability

All data are available in the main text of the manuscript.

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