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Ensuring standardized parameters for the transmission of digital signals by twisted pairs at the technological stage of manufacturing cables for industrial operating technologies

***Introduction**. In production control and control systems, buildings use many simple devices - sensors to detect light, heat, movement, smoke, humidity and pressure, mechanisms for activation and control of switches, closing devices, alarm, etc. - «operating technologies» (OT). Different communication protocols and field tire technologies, such as Modbus for conditioning systems, Bacnet for access control and Lonworks for lighting, have been traditionally used and used for their connection. Network fragmentation leads to the need to use gateways to transform protocols when creating a single automation system, which complicates the implementation of complex control systems for any object. At the same time, information networks are unified, but the Ethernet protocol used in them for operating technologies for various reasons (technological, cost) has not been widespread. Due to its high bandwidth compared to existing field tire networks, industrial Ethernet is significantly capable of increasing flexibility in the implementation of additional functions in OT. Modern industrial Ethernet networks are based on non-shielded and shielded twisted pair category 5e cables. The presence of additional metal screens in the structure of twisted pair causes the increase in electrical resistance of conductors due to the effect of closeness, the electrical capacity, and the ratio of attenuation in the range of transmission of broadband signals. **Purpose.** Substantiation of the range of settings of technological equipment to ensure standardized values of the extinction coefficient and immunity based on the analysis of the results of measurements in a wide frequency range of electrical parameters of shielded and unshielded cables for industrial operating technologies. **Methodology.** Experimental studies have been performed for statistically averaged electrical parameters of the transmission of pairs for 10 and 85 samples of 305 m long and shielded cables of category 5e, respectively. It is determined that in the frequency range from 1 to 10 MHz, unshielded cables have less values of the attenuation coefficient. In the range of more than 30 MHz, the shielded cables have smaller values of the attenuation due to the influence of the alumopolymer tape screen. It is established that the coefficient of paired correlation between asymmetries of resistance and capacity of twisted pairs is 0,9735 - for unshielded and 0,9257 - for shielded cables. The impact has been proven to a greater extent asymmetry of resistance the pairs on the increasing noise immunity of cables. The influence noise interference on the deviation of the diameter and electrical capacity of the isolated conductor from the nominal values in the stochastic technological process is analyzed. The strategy of technological process settings to ensure the attenuation and the noise immunity in the high-frequency range is substantiated. **Practical value.** Multiplicative interference, caused by random changes in the stochastic technological process, can lead to a deviation of diameter 2 times from the nominal value at level of probability at 50 %. The equipment settings of the technological equipment must guarantee the coefficient of variation capacity of the insulated conductor at 0.3 % for high level of noise immunity.* References 36, figures 10.

Key words: **industrial Ethernet, twisted pair, ratio of attenuation, noise immunity, ohmic and capacitive asymmetry, stochastic technological process, additive and multiplicative interference, coefficient of variation**.

Сучасні мережі промислового Ethernet засновані на витих парах неекранованих та екранованих кабелів категорії 5e. Впровадження однопарного Ethernet стикається з проблемою забезпечення передачі цифрових сигналів на відстань до 1000 м зі швидкістю до 1 ГБіт/с. Виконано експериментальні дослідження статистично усереднених електричних параметрів передачі витих пар для 10 і 85 вибірок бухт довжиною 305 м неекранованих та екранованих кабелів категорії 5e відповідно. Визначено, що у діапазоні частоти від 1 до 10 МГц неекрановані кабелі мають менші значення коефіцієнту згасання. У діапазоні більше 30 МГц екрановані кабелі мають менші значення коефіцієнту згасання, що обумовлено впливом алюмополімерного екрану. Встановлено, що коефіцієнт парної кореляції між омічною та ємнісною асиметріями витих пар дорівнює 0,9735 – для неекранованого та 0,9257 – для екранованого кабелів. Доведено вплив у більшій мірі омічної асиметрії витих пар на завадостійкість кабелів. Проаналізовано вплив адитивної та мультиплікативної завад на відхилення діаметру та ємності ізольованого провідника від номінальних значень у стохастичному технологічному процесі. Обґрунтовано діапазони налаштувань технологічного процесу для забезпечення нормованих значень коефіцієнту згасання та завадостійкості витих пар у високочастотному діапазоні. Бібл. 36, рис. 10.

Ключові слова: **промисловий Ethernet, вита пара, коефіцієнт згасання, завадостійкість, омічна та ємнісна асиметрії, стохастичний технологічний процес, адитивна та мультиплікативна завади, коефіцієнт варіації.**

Introduction. Many simple devices are used in control and management systems in production and buildings – sensors for detecting light, heat, movement, smoke, humidity and pressure, mechanisms for activating and controlling switches, locking devices, alarms, etc. The used controls, sensors, systems and devices are called Operational Technology (OT). Different communication protocols and fieldbus technologies have traditionally been used to connect them, such as Modbus for air conditioning [1-3], BACnet for access control [1-3] and LonWorks for lighting [1-3]. Network fragmentation leads to the need to use gateways to convert protocols when creating a single automation system, which makes it difficult to implement complex control systems for any objects. At the same time, information networks are unified, but the Ethernet protocol used in them, for operational technologies has not been widely used for various reasons (technological, cost) [4]. Due to its high bandwidth compared to existing fieldbus networks, Ethernet is able to significantly increase flexibility in the implementation of additional functions in OT.

Single-pair Ethernet (SPE) standards [5-10] became the solution to the implementation of the information protocol in OT.

Single-pair Ethernet is the latest technology to meet these new requirements, as it allows data to be transmitted over Ethernet using only one twisted pair, with signal transfer rates from 10 Mbit/s to 1 Gbit/s [10, 11]. For example, for comparison: Fast Ethernet with a signal transmission speed of 100 Mbit/s requires two, and Gigabit Ethernet requires four twisted pairs [12]. The advantage of single-pair Ethernet is also the ability to simultaneously supply power to end devices using Power over Data Line (PoDL) technology. With a transmission distance of up to 1000 m, single-pair Ethernet becomes a particularly interesting solution for use in the field of automation of any processes, including in the power industry [5, 6].

For example, single-pair Ethernet is already being implemented in new generations of cars instead of CAN and other buses [7-9]. In the future, control, communication and security functions will work in a unified way using Ethernet. This is a basic requirement for managing full network connectivity or autonomous transport in the future.

Single-pair Ethernet is also suitable for use in industrial automation. Single-pair cable connections are quick to install, save space, are inexpensive and easy to operate. Equipping simple sensors, cameras and similar devices with Ethernet interfaces makes SPE the driving force of integrated industry and the Industrial Internet of Things (IIoT) (Fig. 1) [5, 6]. In general, by 2025, the global market for Internet of Things technologies will be estimated at 6.2 trillion USD, of which 4.8 trillion USD will fall on the spheres of health care (2.5 trillion USD) and production (2.3 trillion USD), as the largest market segments [6]. To a greater extent, the growth will come from the connection between machines in production, processing industry, and the field of health care. The field level becomes intelligent, which simplifies and accelerates configuration, initialization and programming thanks to the use of cables based on a single twisted pair [6].

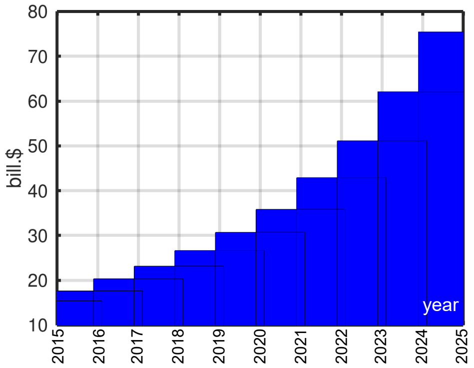

Fig. 1. Growth dynamics of the global Internet of Things market [5]

The cable, as an infrastructural foundation, is a direct transmission line. Depending on the required transmission rate and line length, two standard types of twisted pair are currently available for SPE.

For networks with signal transmission rate 10 Mbit/s for a distance of up to 1000 m, the cable design is regulated by the following Standards: IEC 61156-13 – SPE data transmission cable with bandwidth of up to 20 MHz for stationary installation [10] (a 10Base-T1L cable with a transmission distance of 1000 m in some cases is capable replace more expensive optical cables [12-15]); IEC 61156-14 – SPE data transmission cable with bandwidth up to 20 MHz for flexible installation [10].

Thanks to SPE technology, in which new data coding and scrambling technologies are applied, industrial and technological networks get better characteristics in terms of synchronization of devices connected to the communication line, the level of electromagnetic interference emitted to neighboring pairs is reduced, and higher data protection which are transmitted is ensured (Fig. 2).

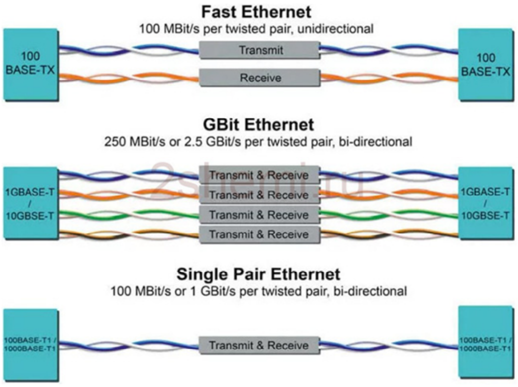

Fig. 2. Implementation of industrial Ethernet technology based on a cable of 4 twisted pairs of category 5e (upper two figures) and SPE (lower figure): when transmitting signals at rate 100 Mbit/s two pairs are used for reception and transmission, two ones – reserve; when transmitting signals at rate of 1 Gbit/s and more – four pairs for simultaneous reception and transmission with a complicated interface [6]

For a network with a signal transfer rate 1 Gbit/s for a distance of up to 40 m, the cable design is determined by the following Standards: IEC 61156-11 – SPE data transmission cable with bandwidth of up to 600 MHz for stationary installation [10]; IEC 61156-12 – SPE data transmission cable with bandwidth up to 600 MHz for flexible installation [10].

In comparison with traditional industrial cables of category 5e with four pairs for transmitting signals over a distance of 100 m at rate of up to 1 Gbit/s (Fig. 2), when implementing the technology of a single-pair cable based on a twisted pair, a reduction in the diameter and weight of the cable is observed, provided that standardized electrical transmission parameters in the frequency range up to 600 MHz: attenuation coefficient, impedance, reflection loss, and resistance to external electromagnetic interference, which determines the shielded design of the twisted pair [6, 13].

The goal of the paper is to substantiate the range of technological equipment settings to ensure standardized values of the attenuation coefficient and noise immunity based on the analysis of the results of measurements in a wide frequency range of electrical parameters of shielded and non-shielded cables for industrial operating technologies.

Review of publications and problem definition. The presence of additional metal shields in the design of a twisted pair leads to an increase in the electrical resistance of the conductors due to the effect of proximity and, to a greater extent, the electrical working capacity, and, in general, the attenuation coefficient, that is, the range of transmission of broadband signals with an increased level of cable immunity [6, 16-24].

Numerical calculation of the 2D model, under the condition that the partial capacity of each of the insulated conductors and the capacity of the shield to the ground of the twisted pair remain constant over the length, shows that the maximum surface energy density in the shielded cable is 1.62 times greater than in the non-shielded cable, and is mainly concentrated in insulation [25]. The simulation results are consistent with the experimental data on the efficiency of the foil-shielded and/or braided twisted pair compared to the non-shielded one in the frequency range up to 170 MHz [25, 26].

Based on the comparison of the capacity of non-shielded and shielded twisted pairs of category 5e, it was proved that the working capacity of shielded cables has increased values [27, 28]. The authors established that variations in the thickness of the insulation, i.e., the working capacity, have a greater influence on the attenuation coefficient compared to the active resistance, provided that the diameters of the conductors of the twisted shielded pair are the same [27]. Recommendations are given for increasing the insulation thickness of cable conductors to ensure the working capacity of twisted shielded pairs in the range of standardized values [25, 26].

It was shown in [29] that an increase in the insulation thickness by 50 % relative to the radius of the conductor leads to a decrease in the capacity of the insulated conductor by 20 %. Such a constructive solution leads to an increase in the mass and dimensional indicators of the twisted pair as a whole. The authors substantiated the methodology of the synthesis of design and technological solutions, including the effectiveness of the use of foam insulation, for regulating the capacity of the twisted pair of cables of industrial networks at the technological stage of the production of an insulated conductor.

Thus, the implementation of modern industrial Ethernet faces the problem of reaching a compromise between shielding and the effect of the shield on the working capacity to reduce the attenuation coefficient while ensuring the transmission of signals in a wide frequency band by shielded twisted pairs [30].

Experimental studies of the effect of the shield on the attenuation coefficient and interference resistance of twisted pairs. The attenuation coefficient α (dB/m) is the frequency-dependent parameter and depends on the active resistance R (the sum of the resistances of the forward and reverse conductors) and the inductance L, the working capacity C, the active conductivity of the insulation G (the electrophysical properties of the insulation – the tangent of the dielectric loss angle tgδ) of a twisted pair twisted with the appropriate step h to increase immunity [31]:

$$\alpha = 8{,}69\cdot\left(\frac{R}{2}\cdot\sqrt{\frac{C}{L}}+\frac{G}{2}\cdot\sqrt{\frac{L}{C}}\right)=$$
$$=8{,}69\cdot\sqrt{C}\cdot\left(\frac{R}{2}\cdot\sqrt{\frac{1}{L}}+\frac{\omega\cdot\mathrm{tg}\delta}{2}\cdot\sqrt{L}\right). \qquad (1)$$

Industrial Ethernet cables are usually made of copper wire with diameter of 24 AWG (0.511 mm) [32] and insulation based on a cable composition with high dielectric properties [33], including polyethylene [31].

The results of the presented electrical parameters of the transmission of twisted pairs are averaged for 10 and 85 samples of 305 m long hanks of each non-shielded and shielded (in general, aluminum polyethylene foil shield) category 5e cables, respectively.

Figure 3 shows the correlation dependence between the working capacity C of twisted pairs of non-shielded $C_1$and shielded C_2 samples of 4-pair cables of category 5e: shielded cables have higher values of working capacity under the condition of the same insulation thickness. Here, the DC resistances of direct R_a and reverse R_b conductors of shielded cables *2* (Fig. 4) also have larger values compared to non-shielded ones *1* (Fig. 4). And, as a result, larger values of the attenuation coefficient α are observed in shielded structures (Fig. 5).

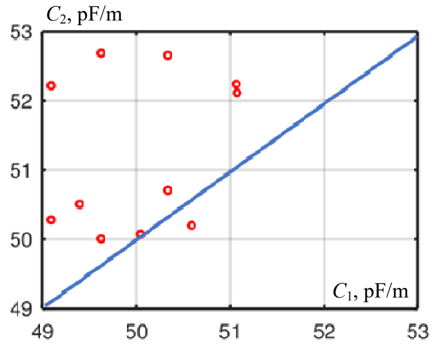

Fig. 3. The effect of the shield on the working capacity of non-shielded and shielded category 5e cables

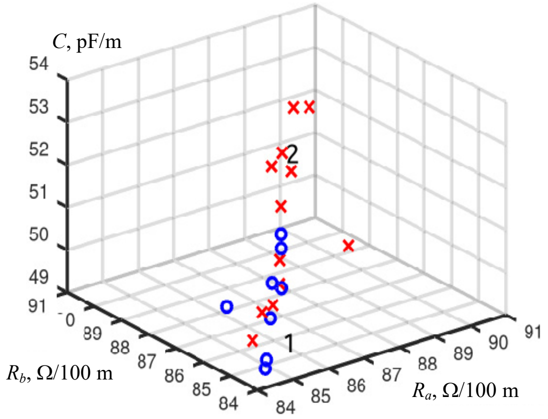

Fig. 4. Correlation dependence between the resistance of conductors and the working capacity of twisted pairs of samples of non-shielded (1) and shielded (2) cables

It turns out (Fig. 5) that the attenuation coefficient of non-shielded cables has smaller values only in the frequency range from 1 MHz to 10 MHz (compare Fig. 5,*a*,*b* and Fig. 6,*a*,*b*).

Shielded cable conductors have higher resistance values for the same diameters and diameter tolerances. This is due to the proximity effect of the shield, which leads to an increase in resistance even to DC.

Increased values of resistance and capacity of shielded network cable pairs lead to higher values of attenuation coefficient. However, this is true only for the frequency range for which the depth of the skin layer (Δ) is less than the thickness (h) of the shield. In the frequency range for which the skin layer and the shield thickness are of the same order, the attenuation coefficient of shielded cable pairs is equal to α of non-shielded cables (Fig. 4). For the given data, the effect of the shield on the attenuation coefficient begins to appear for frequency of more than 30 MHz: the shielded cable has lower values of the attenuation coefficient (Fig. 5,*b*). For the frequency from 10 MHz to 30 MHz, the values of attenuation coefficients of non-shielded and shielded cables practically do not differ.

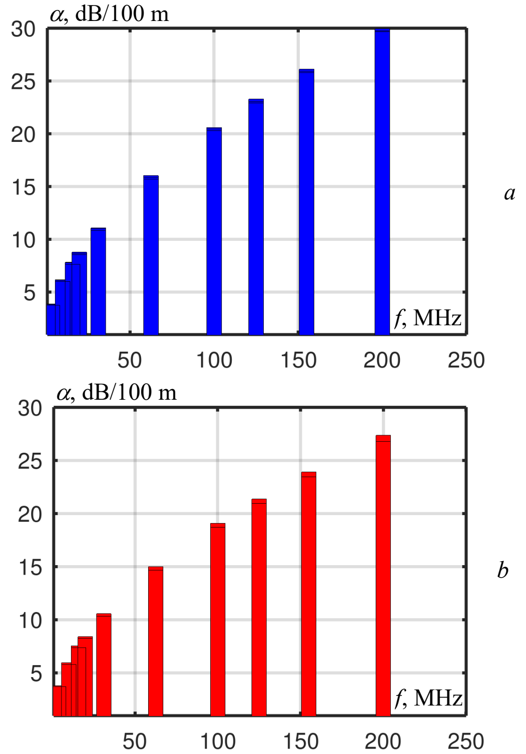

Fig. 5. Histograms of the frequency distribution of the attenuation coefficient of non-shielded (*a*) and shielded (*b*) cables with twisted pairs of category 5e

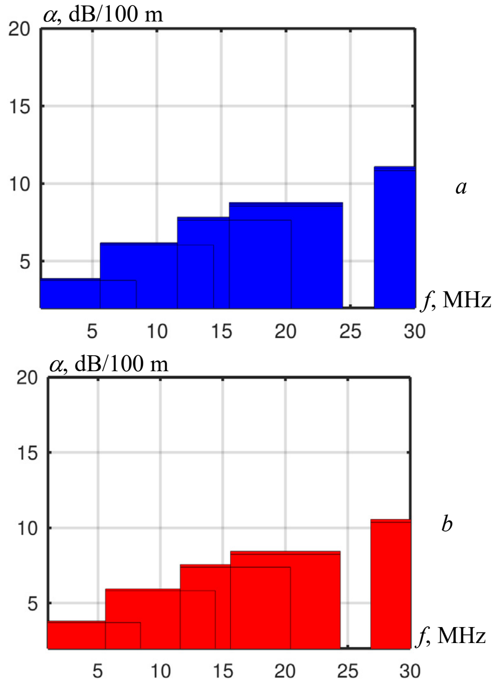

Fig. 6. Attenuation coefficient of non-shielded (*a*) and shielded (*b*) cables in the frequency spectrum from 1 to 30 MHz

External shields, which are placed on the cores from 4 pairs lengthwise, are made of a thin polymer film metallized with aluminum (aluminum polyethylene). A copper drainage conductor with silly with diameter of 0.5 mm is included in the film shield. It ensures the electrical continuity of the shield in case of accidental rupture of the metal foil shield during cable laying, installation and operation. Such a shield provides reliable shielding from the magnetic component of electromagnetic interference. This interference manifests itself in the high frequency range. It is possible to use an additional shield in the form of braiding. It provides protection of cable pairs from electrical interference that occurs in the low frequency range. The use of double-layer shields ensures reliable shielding in the entire operating frequency range of the network cable.

The frequency dependencies of transient attenuation at the near end (*NEXT*) of non-shielded and shielded cables are consistent with the results of the frequency dependence of the attenuation coefficient (Fig. 7):

$$NEXT = 20\lg\left|\pi\left(h_i/h_j+1\right)/\gamma_i h_i\left[1+k\left(h_i/h_j+1\right)/\left(h_i/h_j-1\right)\right]\right|, \quad (2)$$

where h_i, h_j are the twisting steps; γ_i is the propagation coefficient of electromagnetic waves in twisted pair *i* with a smaller twisting step h_i, which is determined ($\gamma = \alpha + j\beta$) by electrical parameters at the corresponding circular frequency ω $|\gamma| = \sqrt[4]{\left(R^2+\omega^2\cdot L^2\right)\cdot\left(G^2+\omega^2\cdot C^2\right)}$ – module, 1/m; *b* is the phase coefficient, rad/m); $k = 0.2 - 0.8$ is the coefficient that depends on the cable design and the location of the interacting circuits.

Electromagnetic coupling and influence parameters are determined by the mutual arrangement of pair conductors in the cable, the twisting step, the degree of structural homogeneity, and the quality of the insulation materials [34-36]. Here, the electrical component of the electromagnetic influence is related to the change along the length of the thickness and dielectric permeability of the insulation, the mutual location of the pairs in the cable. Magnetic one – to the change in the diameter of the conductors of the pair along the length of the cable, deviations in the diameters of the forward and reverse conductors (ohmic asymmetry), fluctuations in the twisting step of pairs of conductors along the length, unequal distance between the pairs.

The ratio between the electric and magnetic components of electromagnetic coupling is determined by the operating frequency range of the cable. In the low frequency range (up to 10 kHz), the electrical component of electromagnetic influence prevails. This effect is significant only between closely spaced pairs. For frequency of more than 100 kHz, the influence is caused by both electric and magnetic components, to reduce which different twisting steps of twisted pairs in the cable are used. In a twisted cable, the transient attenuation of pairs will be different due to ohmic and capacitive asymmetries. Twisting pairs with different coordinated steps leads to the fact that the working capacities and resistances of the loops of twisted pairs differ from each other. Capacitive asymmetry arises – the difference in the working capacity of twisted pairs and ohmic one arises –

the difference in the resistances of loops R_s of twisted pairs with different twisting steps and different diameters:

$$\Delta C = \left(C_i - C_j\right) / \left(C_i + C_j\right); \tag{3}$$

$$\Delta R = \left(R_{si} - R_{sj}\right) \cdot \left(R_{si} + R_{sj}\right), \tag{4}$$

where $R_s = R_a + R_b$ is the resistance of the pair loop, which is equal to the sum of the resistances of the direct R_a and the reverse R_b conductors.

The resistances R_a and R_b are also different from each other. The difference between them is that the ohmic asymmetry within the pair is caused only by the different diameters of the conductors.

It was established (Fig. 4) that a positive correlation is characteristic for the direct and reverse conductors of twisted pairs of non-shielded and shielded network cables. Only in this case, the normalized value of the ohmic asymmetry of no more than 1 % of the loop resistance is ensured, which guarantees the protection of the cable from external and internal (between pairs) interferences.

Figure 7 shows the lines of the transient attenuation level for frequency of 10 MHz as a function of ohmic and capacitive asymmetry of twisted pairs of non-shielded (Fig. 7,*a*) and shielded (Fig. 7,*b*) cables, respectively. Figure 8 – for the frequency of 20 (*a*), 62.5 (*b*) and 100 (*c*) MHz of non-shielded (*1*) and shielded (*2*) samples, respectively.

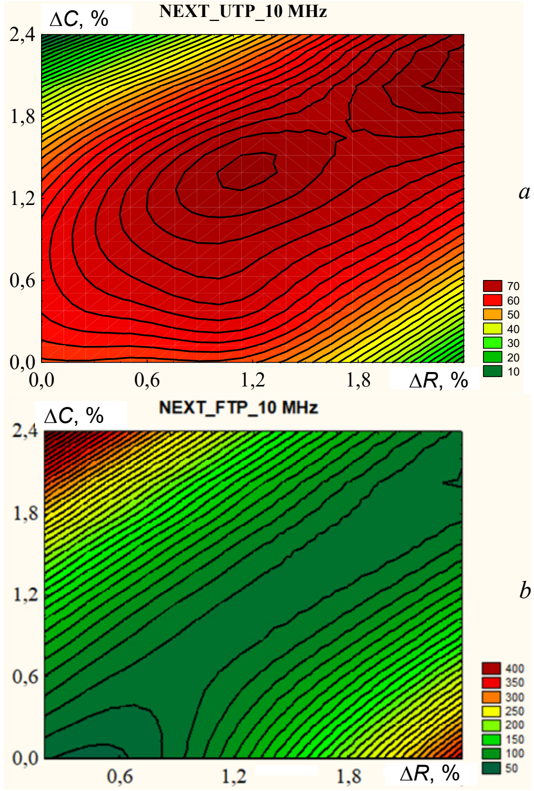

Fig. 7. Transient attenuation at the near end for frequency of 10 MHz depending on ohmic and capacitive asymmetries of twisted pairs of non-shielded (*a*) and shielded (*b*) cables

The use of a shield leads to a smaller spread and an increase in transient attenuation in shielded cable designs (compare curves *1* and *2* in Fig. 8).

The results of experimental studies prove that there is a significant positive correlation between ohmic and capacitive asymmetries. So, the pair correlation coefficient is: **0.9735** – for a non-shielded cable; **0.9257** – for shielded cable. The value of the pairwise correlation coefficient between asymmetry and near-end transient attenuation varies for different hanks (cable length in each hank is 305 m) (as an example, selectively, see below).

For non-shielded cable:

- between ohmic asymmetry and NEXT: **0.6683** – for the first; **0.9058** – for the second; **0.7871** – for the third; **0.4990** – for the fourth;
- between capacitive asymmetry and NEXT: **0.6683** – for the first; **0.7256** – for the second; **0.5567** – for the third; **0.2689** – for the fourth.

For shielded cable:

- between ohmic asymmetry and NEXT: **0.9257**;
- between capacitive asymmetry and NEXT: **0.5868**.

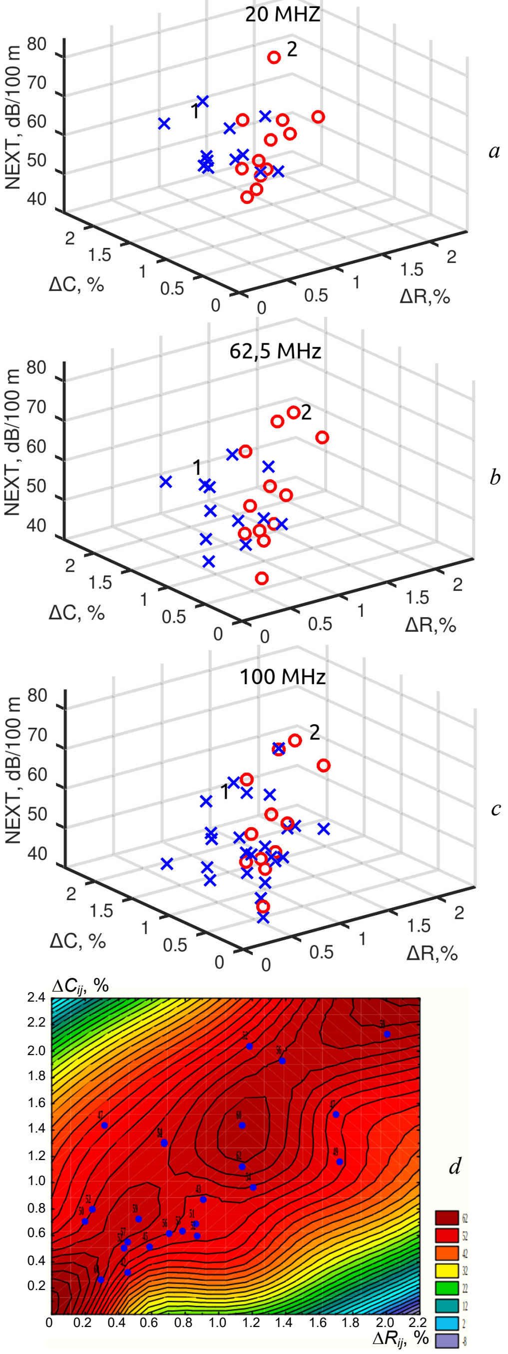

Fig. 8 Transient attenuation of twisted pairs of non-shielded and shielded cables (*a-c*) and non-shielded cable for frequency 100 MHz (*d*)

Thus, the guarantee of the transmission parameters (attenuation coefficient and interference immunity) is determined by the technological process settings to ensure the geometric parameters and homogeneity, first of all, of the twisted pair conductors.

Ranges of technological equipment settings in the manufacture of twisted pairs with standardized transmission parameters. Cables are manufactured on technological equipment that can be affected by random disturbing influences. The cable is a long-dimension product that is made «per pass», in connection with which its geometric parameters have non-constant length values, that is, they are irregular.

This leads to a change in the electrical parameters of the transmission, which requires the introduction of a system of automatic control of the manufacturing process, first of all, the diameter of the conductor to reduce the dispersion of this parameter.

The stochastic model of the technological process takes into account the additive (4) (Fig. 9,*a*,*b*, curves *1* and *2*) and multiplicative (5) (Fig. 9,*a*,*b*, curve *3*) characteristics of the change in the diameter d of the conductor from the nominal d_n (radius r_n)) values in the process of applying insulation

$$d = d_n \cdot \tilde{e}\,; \tag{4}$$

$$d = d_n \cdot \left(1 + \tilde{e}\right), \tag{5}$$

where $\tilde{e}$ is the random number with a normal distribution law.

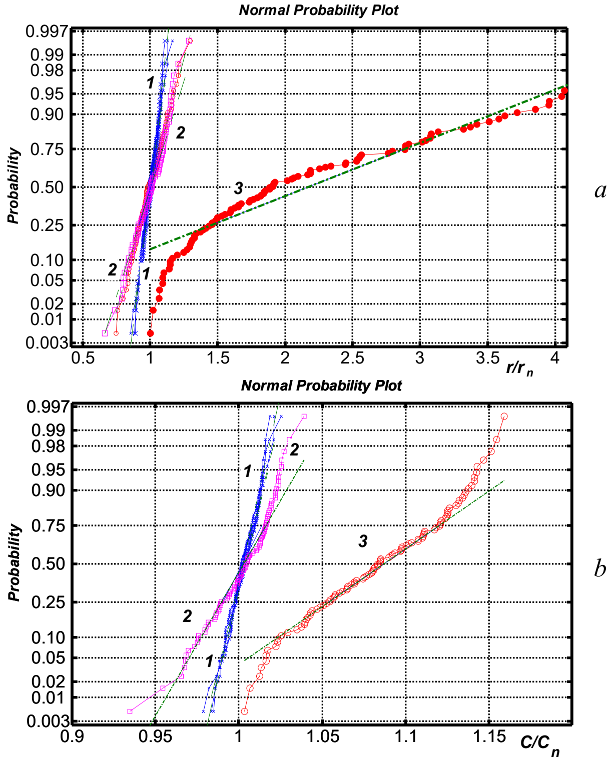

Fig. 9. Integral functions of the distribution of deviations from the nominal values of the diameter (radius) and electric capacity of the insulated conductor in the case of multiplicative and additive nature of variations in the geometric dimensions of the twisted pair of category 5e

Fluctuations in the diameter d also lead to a change in the capacity C from the nominal values C_n of the insulated conductor (Fig. 9,*b*).

Additive interference (Fig. 9,*a*,*b*, curves *1* and *2*, Fig. 10, curves *2* and *4*) is due to external factors affecting the technological process, in particular, a transtient process in the power supply network. Multiplicative (Fig. 9,*a*,*b*, curve *3*, Fig. 10, curves *1* and *3*) – due to random changes in the technological process itself.

Figure 10 shows the effect of variations in the capacity of an insulated conductor on transient attenuation at the near end between adjacent pairs. The curves correspond to: *1*, *2* – σ/C = 0.1 % for multiplicative and additive nature; *3*, multiplicative – σ/C = 1 %; *4*, additive – σ/C =1 % (σ is the root mean square deviation).

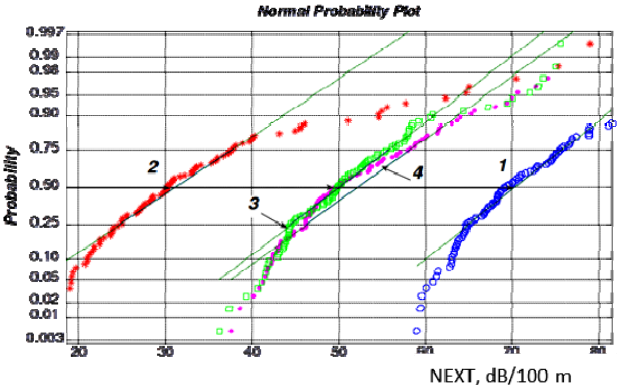

Fig. 10. Integral distribution functions of transient attenuation at the near end between adjacent twisted pairs in the case of additive (curves *2*, *4*) and multiplicative (curves *1*, *3*) character of variations in the capacity of an insulated conductor

With the same coefficients of variation σ/C = 0.1 %, the capacity spread is 0.101 % and 10.1 % in the case of multiplicative (curve *1*) and additive (curve *2*) nature of its change (Fig. 10), respectively. As a result, transient attenuation at the level of 50 % of probability is 2.33 times less, that is, the level of mutual influence between neighboring pairs is greater (Fig. 10, curves *1* and *2*), with the additive nature of the interference.

For the same capacity variations (curves *3* and *4*, Fig. 10) the nature of their change practically does not affect the transient attenuation.

Transient attenuation value for frequency 20 MHz – at the level of 70 dB (Fig. 8,*a*), in the frequency range from 62.5 MHz to 100 MHz – at the level of 60 dB (Fig. 8,*b*,*c*).

Conclusions.

The correlation between the resistance of the conductors and the working capacity of the twisted pairs proves the greater values of the electrical parameters of the shielded compared to the non-shielded ones, provided that the insulation thickness of the conductors of the 4-pair category 5e cables is the same.

It was found that the attenuation coefficient of non-shielded cables has lower values in the frequency range from 1 MHz to 10 MHz. At higher frequency values, the opposite is true: shielded cables have lower attenuation values. For frequency of 200 MHz – by 12 %, which can ensure the transmission of signals over a longer distance.

On the basis of the determined strong positive correlation between ohmic and capacitive asymmetries, it is proved that the transient attenuation at the near end is most affected by the homogeneity of the geometric dimensions of the twisted pair conductors. Larger values of the pair correlation coefficient between ohmic asymmetry and interference immunity for a shielded cable determine the appropriate settings of the technological process when applying the shield.

It is shown that the multiplicative interference caused by random changes in the stochastic technological process, at the level of 50 % probability, can lead to a deviation of the diameter by 2 times from the nominal value.

To ensure normalized values of interference immunity of twisted pairs in the high-frequency range, the technological equipment settings must guarantee the coefficient of variation of the capacity of the insulated conductor at the level of 0.3 %.

Conflict of interest. The authors declare about absence of conflict of interest.

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