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DEVELOPMENT OF MODELS OF THE ELECTROMAGNETIC ENVIRONMENT IN BUILDINGS AND URBANIZED AREAS

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A set of measures and means to control the electromagnetic situation of the environment in the territories of urban development, in buildings and individual premises has been substantiated and developed. The simulation tools show the ability to rationalize the parameters of overhead lines with voltages of 220 kV and below, which will reduce the electromagnetic load in the territories. Modeling the propagation of fields from underground high-voltage lines has established that the values of magnetic fields compared to overhead lines are lower up to 30 times. Models of propagation of electromagnetic fields of very high and ultrahigh frequency were built. Sources of electromagnetic fields of non-production origin in industrial buildings have been investigated. Uncompensated currents in power networks with nonlinear electric consumers generate magnetic fields by induction of 0.35–1.20 μT, which exceeds the maximum permissible levels of operation of computer equipment. Leakage currents on grounded metal structures generate magnetic fields with 1.52–6.75 μT.

Simulation of the propagation of electric and magnetic fields of components of personal computers of controlled ranges according to the MPRII standard was carried out. Models of propagation of the magnetic field of industrial frequency around electric motors and generators with their cross sections were built. On the basis of such models, design schemes for placing equipment in production areas are selected or places of safe stay and movement of personnel are selected. The expediency of using shielding to reduce field levels to safe values due to coating surfaces with liquid protective mixtures was shown. Metal-containing composition based on water-dispersion paint makes it possible to reduce the level of magnetic field of industrial frequency by 2.5–2.6 times, electric field by 1.6–1.7 times, electromagnetic field of industrial frequency – by 1.2–1.3 times

Keywords: electromagnetic field, electromagnetic situation, industrial frequency, power line, personal computer

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1. Introduction

The peculiarity of the formation of the electromagnetic situation in the territories of urban development, in individual buildings and premises is its variability and uneven distribution in space and time. This is due to the different load on the sources of electromagnetic fields of a wide frequency range (power supply networks, transformer substations, wireless communications, etc.) depending on the time of day, day of the week, and time of year. In addition, the electromagnetic situation is affected by the introduction of new electricity consumers, mobile base stations, etc. The need to control the electromagnetic situation is due to the implementation in the national regulatory bases of many countries, pan-European requirements for electromagnetic safety [1]. The mandatory annex to this document provides the maximum permissible levels of electromagnetic fields of all frequency ranges for the population and workers, which are usually tougher than national ones. In the context of the gradual transition of wireless communications to the 5G standard, the maximum permissible level of electromagnetic fields of mobile communication frequencies was increased to 100 $\mu W/cm^2$, which is a forced measure. But for a certain category of buildings, such as medical institutions, enterprises with sensitive electronic equipment, such levels are too large. Therefore, there is a need to introduce measures to reduce the levels of electromagnetic fields in individual buildings or premises with special means – electromagnetic screens. An effective toolkit for forecasting and choosing optimal electrical loads in territories and buildings is a preliminary simulation of the propagation of electrical, magnetic fields of industrial frequency, electromagnetic fields of ultrahigh frequencies. It can be used in assessing the safety of design solutions and to optimize the placement of electrical and electronic equipment in areas and in rooms with the maximum achievable level of electromagnetic safety in accordance with European requirements [2]. Thus, the levels of electromagnetic fields can be controlled taking into account the operating modes of electrical and electronic equipment located in certain territories and in individual buildings.

2. Literature review and problem statement

Regulation of the levels of electric and magnetic fields of industrial frequency in the territories of industrial and civil buildings is achieved mainly by placing overhead power lines at safe distances from buildings. The values of these fields are precalculated in accordance with [3]. In the cases where the field levels exceed the maximum permissible ones, it is proposed to use calibrated magnetic screens [4]. But this approach in an urbanized area is not always possible due to the limited free territory for the placement of overhead lines. An effective method of reducing the levels of magnetic and electric fields is to optimize the structure of wire suspension [5]. But this method is designed to accurately determine the levels of fields in close proximity to the wires for safe maintenance of lines. In places of permanent or temporary stay of people, the proposed method of calculation has no advantages compared to known and standard methods. In such a situation, the method of ensuring mutual shielding of the fields of individual wires of the overhead line is more acceptable [6]. But there is a problem with ensuring the safety of existing power lines, the modernization of which is impossible or impractical. Reducing the levels of magnetic and electric fields of transformer substations is carried out mainly by shielding fields with standard electrical steel protective materials [7]. But the authors did not provide spatial criteria for the safe placement of transformers. Currently, much attention is paid to the safety of mobile base stations for people [8]. Tasks related to the optimization of the location of base stations are well worked out [9]. The increase in the operating frequencies of the stations has the consequence of reducing the size of the cells since the spatial attenuation of electromagnetic waves increases, therefore, a protection system that simultaneously protects electronic equipment from electromagnetic influences [10] needs to be developed. At the same time, it is necessary to take into account all critical electromagnetic effects on people (low-frequency and high-frequency). This can be realized by modeling the propagation of magnetic, electrical, and electromagnetic fields of critical frequencies and choosing rational parameters of field sources and schemes for their location.

More complex is the electromagnetic situation inside industrial premises with a high density of placed electrical and electronic equipment [11]. Almost all studies concern only one factor influencing people, for example, one frequency of an electromagnetic field or the same type of technical means [12].

The results of studies of the dynamics of several physical factors in the workplaces of users in the premises for the operation of computer equipment are reported in [13]. But the disadvantage of this study is the practical impossibility of taking into account and separating external influences on the importance of physical factors in the workplaces of personal computer users. Work [14] provides recommendations for the normalization of the indoor microclimate through the use of a device for ionization and air purification but this is not enough to normalize the electromagnetic situation inside industrial premises. Under the conditions of combined exposure to electrical, magnetic fields of ultra-low frequencies and electromagnetic fields of ultrahigh frequencies, the most effective means of protecting people is shielding fields in buildings and individual rooms.

For technical and technological reasons, composite materials are promising [15]. The disadvantage of the proposed mixtures is their relatively low efficiency and the use of insufficiently common components. Elimination of these shortcomings is possible through the use of nanostructures that are added to standard inks [16]. To increase the efficiency of protection against man-made magnetic fields, it is possible to use, as a filler, a protective composition of ferrites obtained in the process of purification of process water [17]. To create an integrated system for controlling the electromagnetic situation in the territories of cities and in industrial and civil buildings, it is necessary to determine the critical factors of electromagnetic effects on people, their actual levels. This will make it possible to develop adequate methods and techniques for reducing the levels of electromagnetic fields in territories and buildings to the maximum permissible and technically achievable levels.

3. The aim and objectives of the study

The aim of our study is to develop models of electromagnetic situation in urbanized areas and in buildings for various purposes. This will provide an opportunity to reduce the electromagnetic load on the environment and indoors.

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

– to investigate the actual levels of electromagnetic fields of the most common sources in urbanized areas and to develop measures and means of reducing them to technically achievable values;

– to investigate the actual levels of electromagnetic fields in buildings, to determine the most critical sources of fields and to develop measures and means of their reduction to technically achievable values.

4. The study materials and methods

The object of our study is the dynamics of electromagnetic field levels of the most common radiation sources in urbanized areas and in buildings for various purposes.

The main hypothesis of the study assumes the negative influence of electromagnetic fields of a wide frequency range, located in certain territories and in individual buildings, on the formation of the electromagnetic situation.

Measurement of the levels of magnetic and electrical components of the electromagnetic field of industrial frequency and its harmonics in the territories and in buildings was carried out using the calibrated spectroanalyzer Spectran 5035 (Germany). The maximum basic measurement error did not exceed 1 dB.

Measurement of the levels of electromagnetic fields of the operating frequencies of wireless communication was carried out using the calibrated meter of electric and magnetic field strength PZ-31. The maximum basic measurement error did not exceed 2.7 dB. The measurement of the electric and magnetic fields of computer equipment in standard frequency bands (5 Hz–2 kHz, 2–400 kHz) was carried out by the Spectran 5035 device, which has a built-in function for measuring integral field levels in the specified frequency bands. Determining the effectiveness of materials for shielding electrical, magnetic, and electromagnetic fields was carried out using geometrically closed shielding structures with dimensions (0.2×0.2×0.2) m, covered with protective mixtures. The measuring antenna was placed in a protective structure through the technological hole. The shielding coefficient is the ratio of the field strength (energy flux density) in free space to this indicator in the protected zone.

5. Models of electromagnetic situation in buildings and urbanized areas

5. 1. The results of studies of the levels of electromagnetic fields in the territories of populated places and their normalization

Sources of electromagnetic fields of ultra-low frequencies in the territories of urban development and adjacent territories are power lines, transformer substations. Sources of electromagnetic fields of very high, ultra-high, and extremely high frequencies are mobile base stations and navigation equipment of airports located in the territories of cities and adjacent territories.

Full-scale measurements of field strengths and energy flux densities generated by all typical and most common sources were performed. The most common sources of industrial frequency fields are overhead power lines. At the same time, lines with voltages of 220 kV and below are allowed to be placed in the built-up areas without establishing a sanitary zone.

The results of measurements of the electrical and magnetic components of the electromagnetic field of industrial overhead power lines are given in Tables 1, 2.

Tables 1, 2 demonstrate that the field levels exceed the maximum permissible values for urban areas (1 kV/m and 1 μT). For the design of new and reconstruction of existing power lines and planning their location, preliminary modeling of the distribution of fields around overhead lines is expedient. It is known that the strengths of magnetic fields depend on instantaneous values of electric current and they are most critical for biological objects. Modeling the propagation of the magnetic component of electromagnetic fields was implemented on the basis of the fundamental law of Bio-Savar. The chosen software environment was Microsoft Visual Studio; the interface was implemented in the C# programming language; the algorithm was the MATLAB programming language. The results of modeling the propagation of the magnetic field of industrial frequency perpendicular to the longitudinal axis of the lines are shown in Fig. 1, 2, where point "0" is the projection on the ground of the central wire (overhead line axis).

Table 1

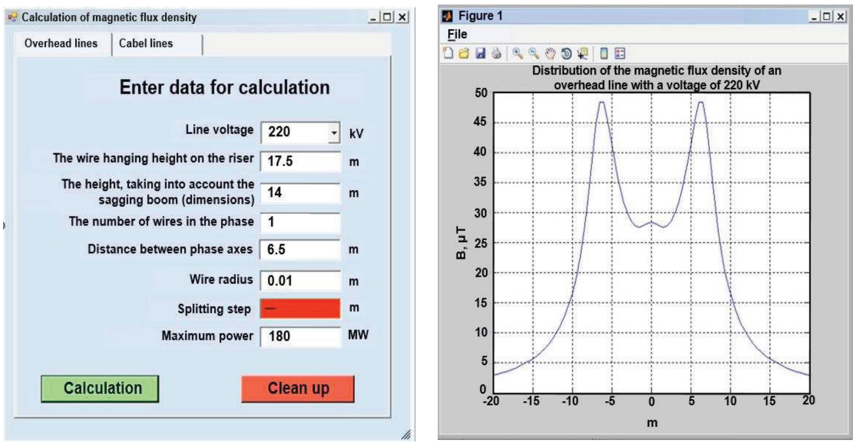
Electric field intensity and magnetic field induction of an overhead transmission line with a voltage of 220 kV

L, m	*E*, V/m	*B*, μT
5	4800...4900	13,8...14,2
10	2400...2600	9,0...12,0
15	680...720	4,2...5,0
20	450...470	2,5...3,7
50	100..120	0,3...0,5

Table 2

Electric field intensity and magnetic field induction of an overhead transmission line with a voltage of 110 kV

L, m	*E*, V/m	*B*, μT
5	420...460	5.6...5.8
10	240...250	5.2...5.4
15	230...240	3.4...3.6
20	190...220	2.8...3.0
50	130...140	1.4...1.6


Calculation of magnetic flux density

Enter data for calculation

Line voltage: 220 kV
The wire hanging height on the riser: 17.5 m
The height, taking into account the sagging boom (dimensions): 14 m
The number of wires in the phase: 1
Distance between phase axes: 6.5 m
Wire radius: 0.01 m
Splitting step: – m
Maximum power: 180 MW

a *b*

Fig. 1. Dependence of magnetic field induction (*B*) on the distance to the axis of the overhead power line with a voltage of 220 kV: *a* – initial data; *b* – plot of the dependence of *B* on the distance to the axis of the overhead power line with a voltage of 220 kV

It is possible to reduce the electromagnetic load on the territory by introducing a lower power of the overhead line in the design solution (Fig. 3).

Comparison of data in Fig. 2, 3 indicates that reducing the load by 2 times reduces the peak values of the magnetic field by 20 times.

Similarly, simulation of the propagation of the transformer's magnetic field was carried out (Fig. 4).

The presence of the resulting model makes it possible to choose its safe location and operating capacity.

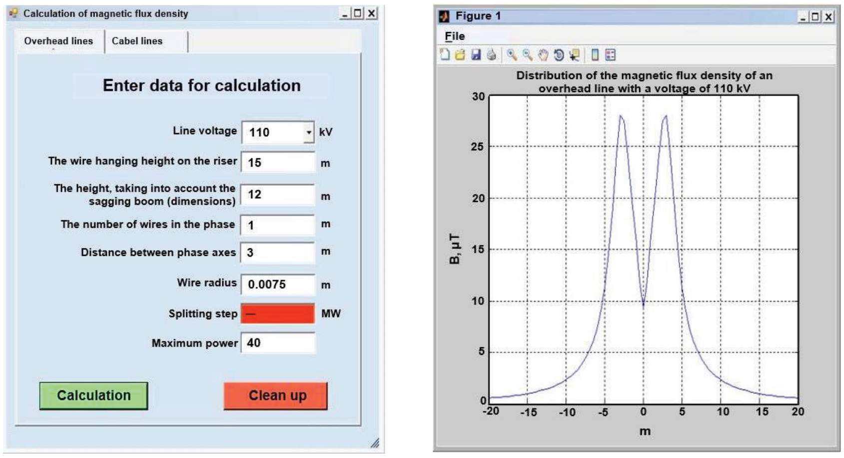
But in many cases, it is impossible or impractical to reduce working capacity. In such cases, it is advisable to use underground high-voltage cable lines.

The results of modeling the propagation of the magnetic field of cable lines above the earth's surface (0.5 m) are shown in Fig. 5, 6.

As can be seen from Fig. 5, 6, the impact of underground high-voltage power lines on the electromagnetic situation in the territory is much lower than the influence of overhead lines of similar voltages (up to 30 times).

It is advisable to regulate the electromagnetic load on the territory from the sources of electromagnetic fields of very high and ultrahigh frequencies by choosing the location of the emitters.

Zones of their influence are determined either by concentric circles or by sectors with calculations of distances exceeding the maximum permissible values of the stresses of the electrical components of electromagnetic fields and energy flux densities [18].

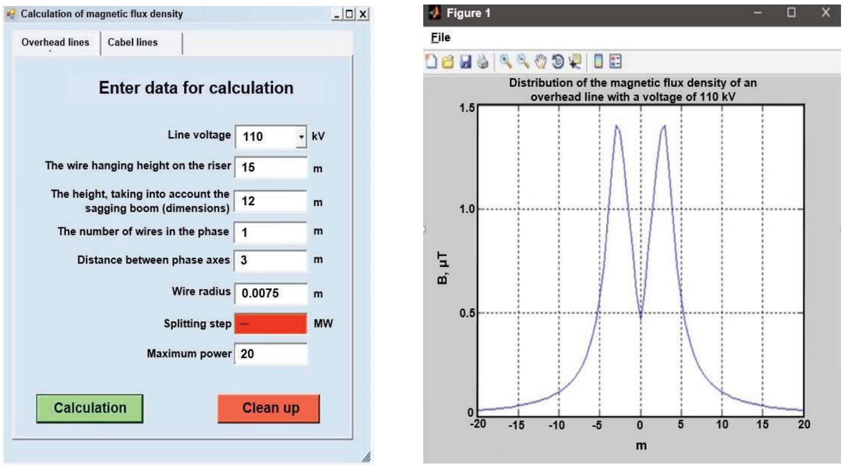


Enter data for calculation

Line voltage: 110 kV
The wire hanging height on the riser: 15 m
The height, taking into account the sagging boom (dimensions): 12 m
The number of wires in the phase: 1 m
Distance between phase axes: 3 m
Wire radius: 0.0075 m
Splitting step: — MW
Maximum power: 40

a *b*

Fig. 2. The dependence of magnetic field induction (B) on the distance to the axis of the overhead power line: *a* – initial data; *b* – plot of the dependence of B on the axis to the axis of the overhead transmission line with a voltage of 110 kV



Enter data for calculation

Line voltage: 110 kV
The wire hanging height on the riser: 15 m
The height, taking into account the sagging boom (dimensions): 12 m
The number of wires in the phase: 1 m
Distance between phase axes: 3 m
Wire radius: 0.0075 m
Splitting step: — MW
Maximum power: 20

a *b*

Fig. 3. Dependence of magnetic field induction (B) of an overhead transmission line with a voltage of 110 kV: *a* – initial data; *b* – plot of dependence of B of an overhead transmission line with a voltage of 110 kV, provided that its power is reduced from the distance to the axis of the overhead power line

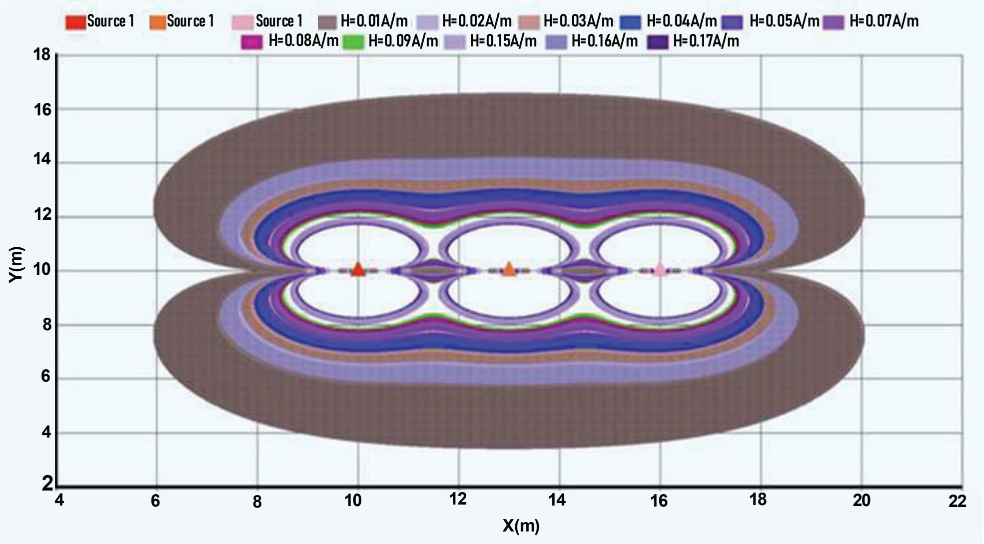
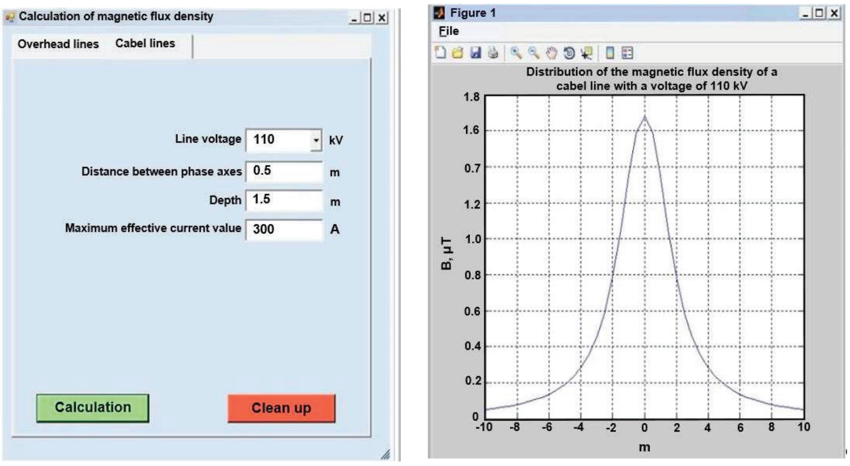


Fig. 4. Spatial distribution of the magnetic field around the transformer substation of three transformers (at a distance of 1 m from the wall, H_1=400 A/m, H_2=450 A/m, H_3=500 A/m)



Calculation of magnetic flux density

Overhead lines | Cabel lines

Line voltage 110 kV

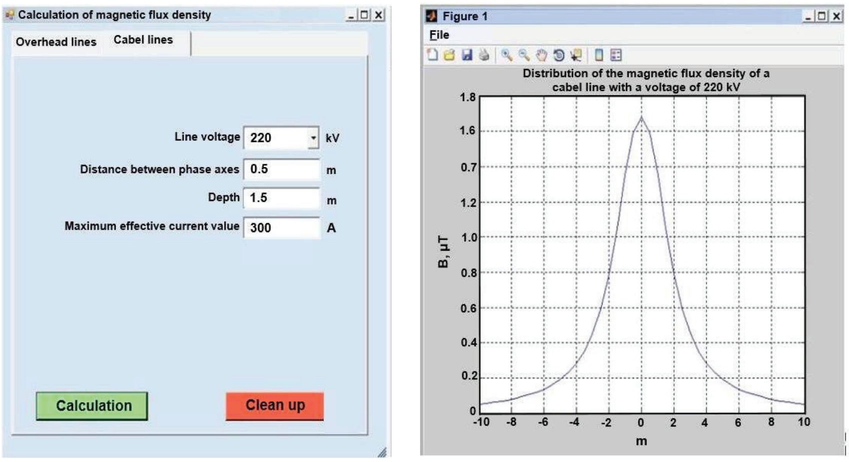
Distance between phase axes 0.5 m

Depth 1.5 m

Maximum effective current value 300 A

a *b*

Fig. 5. Dependence of magnetic field induction (*B*) of an underground cable line with a voltage of 110 kV on the distance to the longitudinal axis of the line (height above the ground surface – 0.5 m): *a* – initial data; *b* – plot of the dependence of *B* of an underground cable line with a voltage of 110 kV on the distance to the longitudinal axis of the line



Calculation of magnetic flux density

Overhead lines | Cabel lines

Line voltage 220 kV

Distance between phase axes 0.5 m

Depth 1.5 m

Maximum effective current value 300 A

a *b*

Fig. 6. Dependence of magnetic field induction (*B*) of an underground cable line with a voltage of 220 kV on the distance to the longitudinal axis of the line (height above the ground surface – 0.5 m): *a* – initial data; *b* – plot of the dependence of *B* of the underground cable line with a voltage of 220 kV on the distance to the longitudinal axis of the line

For very high frequencies, the radius of the zone of restriction of people's stay is determined from the ratio:

$$E=\frac{\sqrt{30PG\eta}}{R}KF(\theta)F(\varphi), \tag{1}$$

where E is the electric field strength (V/m) at a distance R (m),

P – emitter power (W),

G – antenna gain,

η – transmission coefficient of the antenna-feeder tract,

K – earth impact multiplier,

$F(\theta)$ – coefficient of consideration of the radiation pattern in the vertical plane,

$F(\varphi)$ – coefficient of consideration of the radiation pattern in the horizontal plane.

For ultrahigh and higher frequencies, the calculation is carried out from the ratio:

$$W=\frac{8PGKF^2(\theta)\eta}{R^2}, \tag{2}$$

where W is the radiation energy flux density μW/cm^2 at a distance of R (m),

P – emitter power (W),

G – antenna gain,

η – transmission coefficient of the antenna-feeder tract,

K – earth impact multiplier,

$F^2(\theta)$ – multiplier of the normalized radiation pattern in the direction of the radiation object.

The values of all parameters in the above ratios are taken from the technical documentation of radio engineering objects.

Zones of their influence (radiation patterns) can intersect, therefore, to obtain the total electromagnetic load in a certain area, the density of energy fluxes are added.

The use of the obtained models will make it possible to rationalize the placement of sources of electromagnetic fields in urbanized areas with the provision of at least standard field levels for each frequency range.

5. 2. The results of studies of the levels of electromagnetic fields in industrial premises and the development of measures and means of their reduction

The electromagnetic situation in buildings and individual premises is affected by electromagnetic fields generated by technological equipment involved in production processes, building life support equipment, and external fields.

Field strengths generated by common technical means (computer equipment, electric motors, etc.) are known or easily measured. The influence of external sources on the electromagnetic situation can be determined by full-scale measurements, provided that all electric consumers in the building are turned off. The most difficult is to determine the contribution of internal sources, mainly building power supply systems. Their peculiarity is the dispersion in space. Such sources are leakage currents. Even with the observance of the same electrical loads for individual phases, increased currents are observed in zero working conductors.

They are due to the generation of harmonics and interharmonics of industrial frequency by electric consumers with nonlinear volt-ampere characteristics. Such consumers are the majority of modern electronic devices – computer equipment, electric drive control systems, induction heating devices, etc. The results of measuring such electric current forces are given in Table 3.

The presence of currents uncompensated in the zero working conductor is the reason for the appearance in the surrounding space of magnetic fields of the corresponding frequencies. Their values are easily calculated from the Bio-Savara ratio for any segment of the conductor or are measured. In the surveyed premises, the induction values of magnetic fields generated by uncompensated currents were 0.35–1.20 μT. These values are lower than the maximum permissible for industrial frequency but exceed the limit values for computer equipment (0.25 μT in the frequency range of 5 Hz–2 kHz according to the European standard MPRII).

Another dispersed source of industrial frequency magnetic fields is leakage electric currents on grounded metal structures of buildings. These are metal engineering networks, reinforcement of reinforced concrete panels, bearing metal frames (Table 4).

Table 3

The value of electric currents in individual phases and zero working conductor in an industrial building

Phase A, A	Phase B, A	Phase C, A	Neutral N, A
58	66	69	106
56	57	72	108
61	56	69	104
28	31	26	38
34	26	32	41

Table 4

The value of electric currents in metal grounded structures of an industrial building

No.	Electric current in the power supply network, A	Electrical leakage current in a grounded structure, A
1	27–31	2–4
2	23–24	1–3
3	38–39	6–7
4	27–28	3–4
5	35–38	4–6

As can be seen from the data in Table 4, there is no direct relationship between the electrical load in the power network and the leakage electric currents. Obviously, the values of leakage currents depend on abnormal phenomena in the power grid. Inspection of pipelines (more than 2000 measurements) made it possible to determine the distribution of the values of leakage currents by their number (Fig. 7).

The values of these fields at a distance of up to 5 m from the linear structure are 1.52–6.75 mT, which exceeds the standard levels (Low ALs) according to Directive 2013/35/EU (Annex II) [1].

Inspection of the electromagnetic situation in the administrative, educational, and industrial premises of buildings of different service life allowed us to summarize the contribution of sources of different origin in the level of the magnetic field (Fig. 8).

From the data in Fig. 7, 8, one can conclude that a preliminary condition for the implementation of electromagnetic safety measures is to minimize leakage currents in cable networks and metal structures.

Reduction of unbalanced currents in the power grid is achieved by the use of modern harmonic suppression systems and industrial frequency interharmonics with feedback [19]. Reducing the values of leakage currents on metal structures can be achieved through a complete revision of the power network and the elimination of galvanic contacts and induction guidance from the regular current-carrying networks. The use of polymer engineering networks or the rupture of grounding of existing metal structures completely stops the leakage of electric current.

To further reduce the levels of magnetic fields, it is advisable to shield the built-in transformers of switchboards with metal or composite protective structures. Almost complete shielding of the magnetic fields of these objects is achieved by using electrical steel of any brand.

Reducing the levels of external electromagnetic fields is achieved by shielding the walls of a building or individual rooms using special materials. The most acceptable are liquid protective compositions [15]. Their advantages are the adjustability of shielding coefficients depending on the actual electromagnetic situation outside the building. Adjustability of protective properties is needed to reduce the levels of low-frequency electromagnetic fields while ensuring the stable functioning of wireless communication.

Testing of composite protective mixture based on water-dispersion paint with the addition of 45 % magnetite (by weight) was carried out. It was established that the level of magnetic field of industrial frequency decreased by 2.5–2.6 times, the electric field of industrial frequency 1.6–1.7 times, and the electromagnetic field of the mobile frequency (2.6 GHz) by 1.2–1.3 times. Given that mobile communication is stable with energy flux densities of 0.1 μW/cm^2, and in urbanized areas signal levels are almost never lower than 0.3 μW/cm^2, this result is acceptable.

After normalization of the levels of external electromagnetic fields and fields of non-production origin, the main task is to reduce the levels of fields generated by the equipment used in production, educational processes, etc.

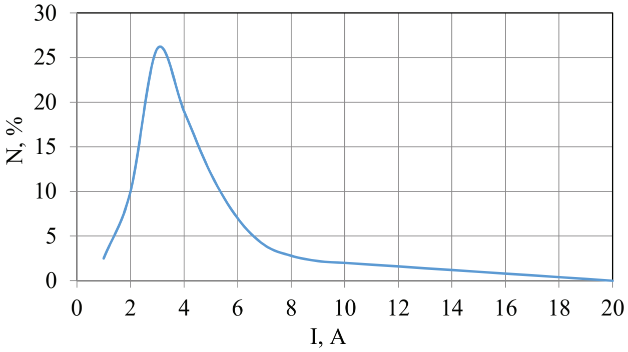


Fig. 7. Distribution of registered electric currents by internal grounded metal structures

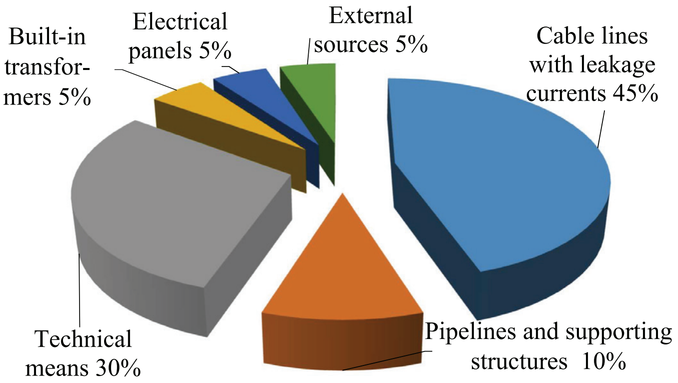


Fig. 8. Distribution of sources of magnetic field of industrial frequency by specific weight (%), its harmonics and interharmonics in buildings for various purposes

The most common equipment is personal computers. The levels of electric and magnetic fields generated by their components in controlled frequency bands at fixed distances and propagation patterns are known. Modeling the spatial structures of the fields of computer components will make it possible to create safe workplaces and accommodate many computers in the premises.

Modern liquid crystal monitors generate dipole-shaped electric fields, and system units generate dipole-shaped magnetic fields [18]. Models of these fields in the plane of the user's stay are shown in Fig. 9.

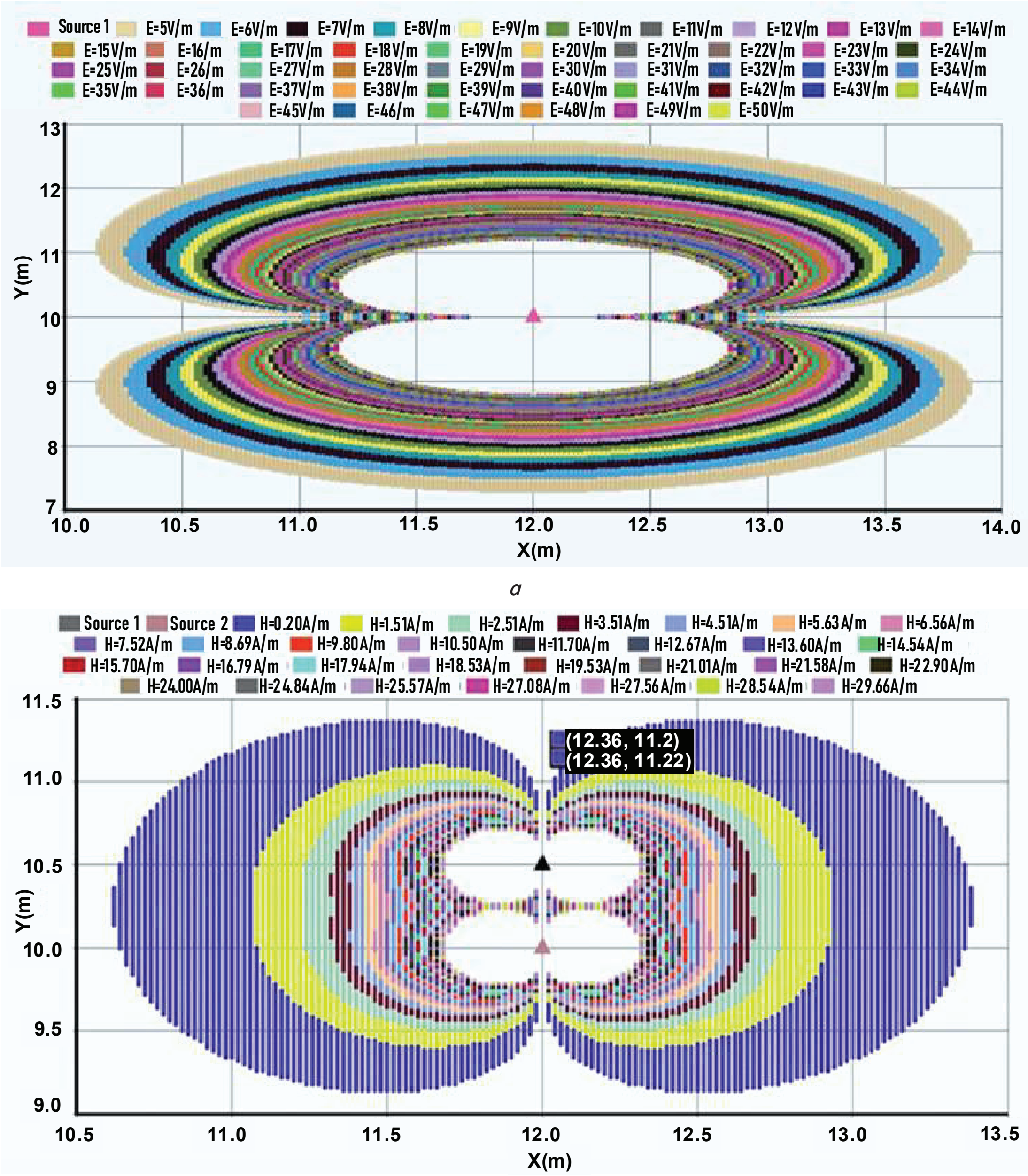
The obtained model makes it possible to form the relative location of several computerized workplaces with normative levels of electric and magnetic fields (Fig. 10).

The presence of the model will help optimize the location of equipment in the premises in terms of electromagnetic safety of workers and electromagnetic compatibility of electronic equipment.

Common production equipment are electric motors for various purposes and capacities. The electric field of these devices is blocked by metal housings, and a magnetic field propagates in the surrounding space. To obtain the correct model of its distribution, it is enough to measure the field strength near the equipment housings. The distribution of the magnetic field of two electric motors is shown in Fig. 11.

A similar model was obtained for three electric generators in the turbogenerator hall of the power plant.

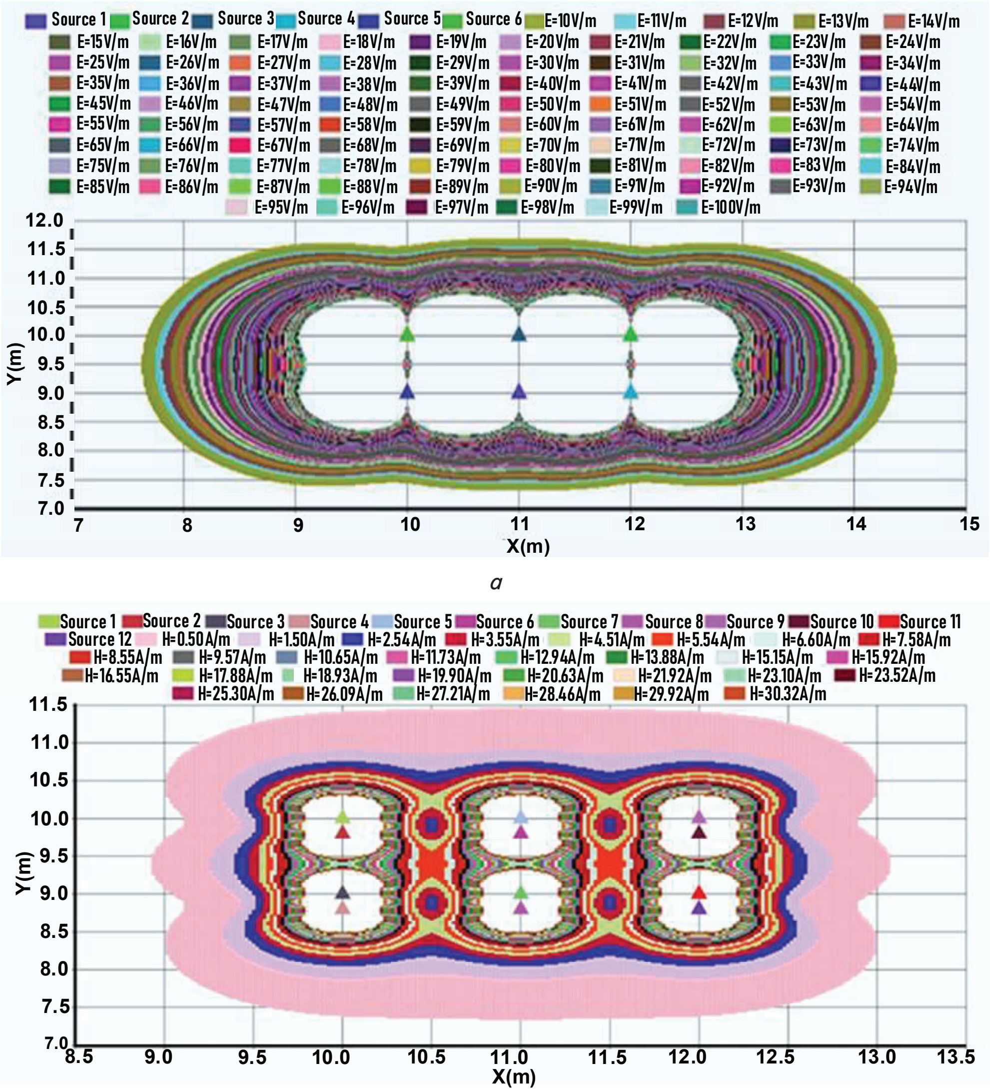
Taking into account the simulation results may be a necessary but insufficient condition for the normalization of the electromagnetic situation. It is known that the intensity of the electrical component of the electromagnetic field depends solely on the operating voltage. But the presence of equipment with nonlinear volt-ampere characteristics (for example, induction steelmaking furnaces) can cause harmonics of industrial frequency even in high-voltage power lines, which increases the total electric field strength (Fig. 13).



a

b

Fig. 9. The propagation of the electromagnetic field around one personal computer: *a* – electric field; *b* – magnetic field



a

b

Fig. 10. Spatial distribution of the electromagnetic field around six computerized workplaces: *a* – electric field; *b* – magnetic field

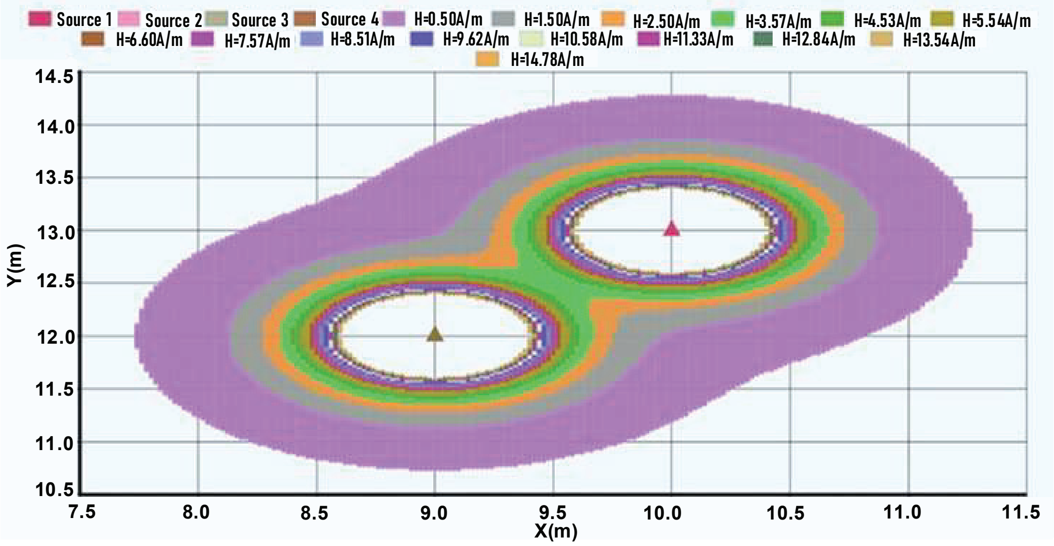


Fig. 11. Spatial propagation around two electric motors of the magnetic field of industrial frequency

Reducing the levels of such fields is possible due to their shielding. For effective shielding of the electric field, it is advisable to add a conductive substance, for example, graphite, to shielding liquid mixtures [15]. Such a mixture is technological and reduces the electric field strength by at least half (Fig. 14).

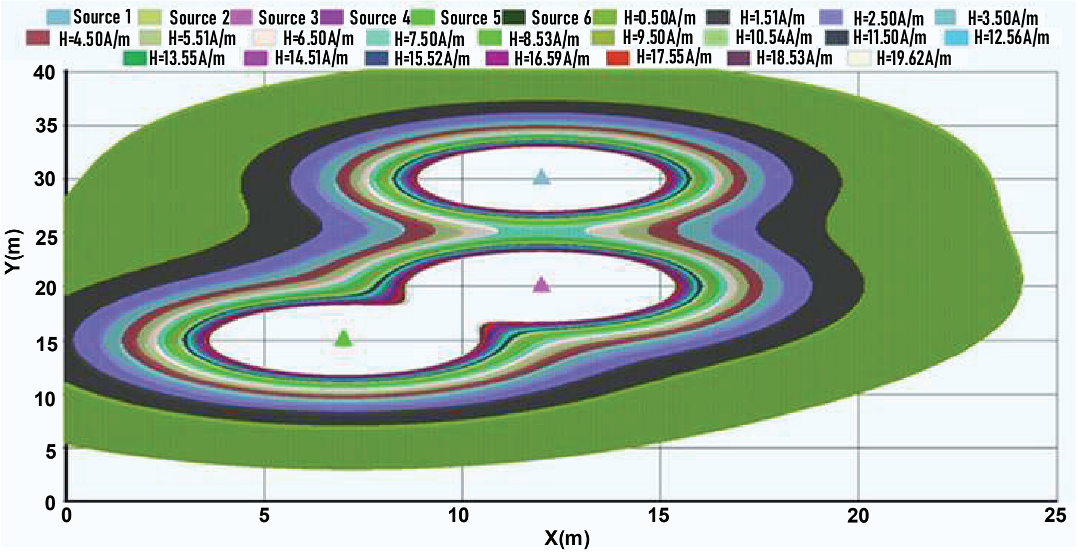


Fig. 12. The spread of a magnetic field around three electric generators in the plane of human presence

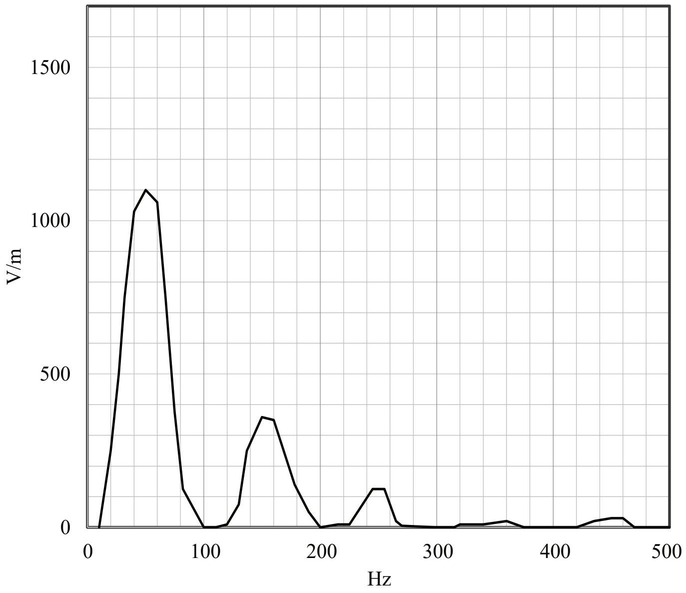


Fig. 13. Spectrum of electric field strength of an overhead transmission line with a voltage of 220 kV

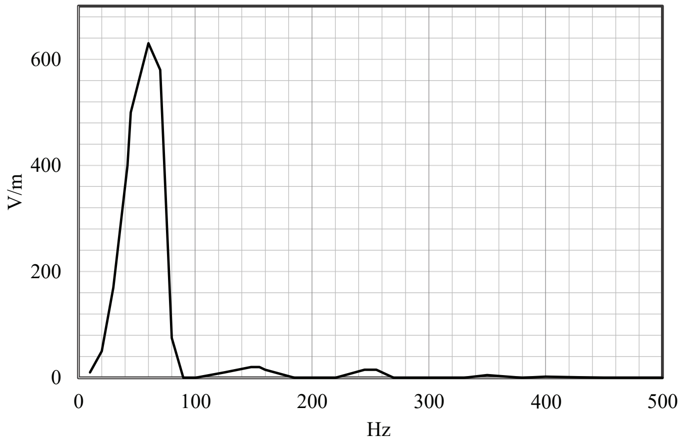


Fig. 14. The spectrum of the shielded electric field strength of the overhead transmission line with a voltage of 220 kV

The electric and magnetic fields of most sources localized in space can be considered as a combination of electric and magnetic dipoles [20]. For example, the fields of video monitors are electric dipoles, and system units and uninterruptible power supplies are magnetic dipoles. Magnetic fields of electric motors – quadrupole and octupole type. This makes it possible to obtain with the use of well-known mathematical functions integral models of the propagation of electric and magnetic fields in rooms for any purpose.

6. Discussion of results of research on electromagnetic control in buildings and urbanized areas

Analysis of the results of measurements of levels of electromagnetic fields of industrial frequency in urban areas indicates that the maximum permissible levels in areas of temporary or permanent stay of people are exceeded. The developed models of distribution of the magnetic component of such fields (Fig. 9–12) make it possible to choose the most rational parameters of overhead power lines, the routes of their laying to reduce electromagnetic effects, taking into account the dependence of the intensity of magnetic fields on the instantaneous value of electric current.

The results of modeling and propagation of electromagnetic fields indicate that it is advisable to gradually switch to underground high-voltage cable power lines. The magnetic fields generated by them are much lower than the fields of overhead lines, and the electric field is completely blocked in the soil layer.

The study and development of electromagnetic safety measures in buildings showed that the prerequisite for the introduction of technical solutions is determining the sources of electromagnetic fields of non-production origin – leakage currents on grounded structures and unbalanced currents in power grids. At the same time, it is mandatory to observe the uniformity of the load on individual phases of the three-phase network. In buildings, consumers with nonlinear volt-ampere characteristics contribute more than 20 % of the total electrical load. Therefore, the presence of systems for compensating reactive power and suppression of harmonics and interharmonics of industrial frequency is mandatory.

The obtained models of propagation of electromagnetic fields of typical sources (Fig. 9–12) make it possible to rationalize the placement of equipment in buildings and individual premises. At the same time, it is necessary to take into account different values of the maximum permissible levels for various equipment and activities. This is especially true of the operation of computer equipment in control systems for technological processes – air traffic, electricity generation, etc., where side electromagnetic effects are significant.

The study has certain limitations. Under real conditions of operation of sources of electromagnetic fields, it is possible to increase their real values. For example, with safe calculated locations of mobile base stations in certain areas, it is possible to increase the density of energy flows due to the reflection of electromagnetic waves from the surfaces of buildings, metal decorative facing structures, roofs of buildings, etc. The introduction of electromagnetic safety measures requires instrumental surveys in places of possible spatial redistribution of fields.

The disadvantage of the study is the lack of actual data on the level of electromagnetic fields of ultrahigh frequencies in rooms and the patterns of their propagation, depending on the design features of buildings. The main reason for the increase in the electromagnetic background in buildings may not be taken into account the sources of electromagnetic fields, especially those operating periodically. This requires electromagnetic monitoring for a time sufficient to detect all critical sources. Therefore, the developed approach to the normalization of the electromagnetic situation in buildings and in the territories of urban development should be considered as basic, which requires clarification under real conditions of implementation.

7. Conclusions

1. The electromagnetic fields of overhead power lines permitted for use in urban areas (220 kV and below) exceed the maximum permissible levels in areas of permanent or temporary stay of people (up to 2.6 times for the electrical component and 12 times for the magnetic component at a distance of 10 m). Modeling the propagation of fields makes it possible to reduce the predicted field levels by changing the parameters of the suspension or electrical load. This makes it possible to choose a safe location of the designed lines and choose a rational way to modernize existing lines. The fields of cable lines of similar voltages are lower than the fields of overhead lines up to 30 times. Reducing the impact on people of electromagnetic fields of very high and higher frequencies is achieved by a rational arrangement of emitters. Modeling the propagation of electromagnetic fields of mobile base stations in the intersection areas of radiation patterns makes it possible to avoid exceeding the maximum permissible levels.

2. The formation of the electromagnetic situation in buildings and structures is due to the influence of electromagnetic fields of technological electrical and electronic equipment and fields of uncompensated electric currents. Uncompensated currents in the power grid are due to the presence of electric consumers with nonlinear volt-ampere characteristics. The magnetic fields generated by them are 0.35–1.20 μT, which exceeds the permissible values for the operation of computer equipment (0.25 μT). A dispersed source of magnetic fields is the leakage current on the grounding of metal structures. Their values at a distance of 5 m are 1.52–6.75 mT, which exceeds the permissible values for domestic and industrial conditions. Reducing the levels of fields of non-production origin is achieved by the use of harmonic suppression systems and interharmonics of electric current of industrial frequency and the elimination of current flow by metal structures. The developed models of distribution of electric and magnetic fields of the most common sources (components of personal computers, electric motors and generators) make it possible to rationalize the placement of equipment in terms of electromagnetic safety and determine the zones of safe stay and movement of people. If necessary, reducing the level of electrical, magnetic and electromagnetic fields is achieved by using shielding. Liquid metal-containing composition for covering surfaces makes it possible to reduce the level of magnetic field of industrial frequency by 2.5–2.6 times, electric field by 1.6–1.7 times, electromagnetic field with a frequency of 2.6 GHz – by 1.2–1.3 times.

Conflicts of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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Data availability

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

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