Part 5

DECREASE IN PHYSICAL FACTORS IMPACT FROM POWER OBJECTS ON ENVIRONMENT

5.1. Decrease in impact of electric and magnetic fields of the industrial frequency on the person

5.1.3. Ensuring of the man safety from the adverse effect of electric and magnetic fields of industrial frequency

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The well-established approaches in our country to ensure the man safety from the adverse effect of EMFs, including the adverse effect of EMF IF, are based on 4 principles:

Time protection. It is applied when there is no any opportunity to reduce the EMF effect intensity up to the maximum permissible levels (MPLs). This principle is implemented in EMF IF hygienic specifications, as well as for the production conditions and for conditions of population affecting.

Distance protection. It is the most effective method. According to the industrial impact, it consists in withdrawal of the working personnel from a zone of the raised EMF effect. It is realized by means of mechanization, automation of production processes, usage of remote control, handlers, arrangement of the working places, considering a direction and properties of the radiator. In terms of affecting the population it is realized by the maximum distance from residential places (permanent staying) of population from the source of EMFs. Particularly, to ensure protection of population from EFs, created by ALs, sanitary and protective zones are formed (at present they are called as “sanitary ruptures”).

Protection using protection means. Protection means can be collective and individual. As collective protection means for production conditions, the devices which restrict supplying of electromagnetic energy to the working places are used (shielding). Protective screens and shielding suits are applied for individual protection from EF IF. The basic characteristic of any protection tool is an extent of EF reduction, is expressed in the screening factor.

Protection using self-compensation method of EMFs, created by the field source. In this case a configuration of EMF source is selected so that intensities of fields, created by their separate parts, could compensate each other in the space around the source or in the area of this space.

To support the health protection of people who are professionally connected with service and operation of EMF IF sources and of population, affected by EMFs, MPLs for electric and magnetic components of EMF IF are set. Traditionally hygienic specifications of EMFs are developed in Russia, as a rule, on the basis of complex hygienic, clinical-physiological, epidemiological and experimental investigations. Hygienic researches are aimed at estimation of intensities and time parameters of EMFs in real productive or non-productive conditions. Clinical-physiological studies are directed at estimation of abnormality of health and physiological functions of a person. Epidemiological investigations are conducted for estimation of distant consequences of the factor effect. Experimental researches are conducted for studying the peculiarities and character of biological EMF effect. However, experimental researches make the main contribution in explanation of EMF hygienic specifications.

At present several normative-methodological documents, regulating MPLs of EMF IF production effects, act in the territory of RF.

The main documents are:

- SanPiN 2.2.4.1191 – 03 “Electromagnetic fields in production conditions”, regulating conditions of EMF IF production effects.
- GOST 12.1.002 – 84 SSBT “Electric fields of industrial frequency. Permissible levels of intensity and requirements for conducting control at the working places”. It only regulates conditions of EF IF production effects.

According to SanPiN 2.2.4.1191 – 03 and GOST 12.1.002 – 84 the maximum permissible level of EF intensity is 5 kV/m at the working places during the whole working shift.

At EF intensity of 5 to 20 kV/m, the permissible time of staying in EFs is calculated by a formula:

$$T=50/E-2,$$

where E is EF intensity in the controlled zone, kV/m; T is permissible time of staying in EF at the applicable intensity level, h.

At the intensity of 20 to 25 kV/m, the permissible time of staying in EF is 10 min.

Staying in EF with intensity of 25 kV/m is not permitted without using of protection means.

According to normative-methodological documents, the permissible time of staying in EF can be single or partly during the workday. During the rest part of working time it is necessary to be out of a zone of EF effect or use protection means.

Maximum permissible levels of MF IF effects, created by electric network objects, are estimated for conditions of the overall (whole body) and local (limbs) effects (Table 5.12) by values of intensity and induction, accordingly.

But along with people who, professionally connected with service and operation of EMF IF sources, who work in electric power industry or other industries, hygienic specifications for population must be met at the working places of several work categories, according to existing sanitary-epidemiological regulations. But hygienic regulation of non-productive effects includes the population as a whole, that is, people who are not professionally connected with service and operation of EMF IF sources, but are affected by them during the productive activity.

Table 5.12. **Maximum permissible impact levels of periodic magnetic field with frequency of 50 Hz**

Time of staying, h	Permissible levels of MF *N/V*, (A/m)/µT at the following impact	
	general	local
1 h and less	1600/2000	6400/8000
2	800/1000	3200/4000
4	400/500	1600/2000
8	80/100	800/1000

EF of 50 Hz is regulated according to requirements of “Sanitary norms and rules of population protection from impact of electric field, created by A.C. air power lines of industrial frequency” № 2971 – 84; MSanPiN 001 – 96 “Sanitary norms of the permissible levels of physical factors at usage of national consumption products in life conditions” and SanPiN 2.1.2.1002 – 00 “Sanitary-epidemiological requirements for residential buildings and constructions”.

Until recently only EF levels of 50 Hz, created by ALs of 330 kV and higher, were regulated. By this, the set MPLs were differentiated, depending on probable staying time of population: from 0,5 kV/m inside residential buildings and constructions, 1 kV/m in territory of residential area to 20 kV/m in adverse terrain. In addition, this document includes the requirements for definition of APL sanitary and protection zone and the maximum level of EF intensity on their boundaries at 1 kV/m.

In SanPiN the MPLs of EF of 50 Hz were fixed, created only by national consumption products. In SanPiN 2.1.2.1002 – 00 the set MPLs refer to any type of living spaces and the territory of residential area and make 0,5 kV/m and 1 kV/m, accordingly, regardless of EMF source.

Up to 2000 there were no hygienic specifications for nonproductive effects of the magnetic component of 50 Hz EMFs. Presently there is a temporary normative, presented in SanPiN 2.1.2.1002 – 00 “Sanitary-epidemiological requirements for residential building and constructions”, where two normative values of 50 Hz MF are suggested: inside living spaces and in territory of residential area, which make 10 and 50 mcT, accordingly.

In 2002-2003 according to a task of the Moscow Committee on Science and Technology an activity on creation of scientifically substantiated MPLs of 50 Hz MFs for population was conducted. Based on the complex of hygienic, epidemiological and experimental researches, the draft normative-methodological document was developed. This document regulates MPLs of 50Hz MFs for population, created by the permanently acting sources, including MPLs of MFs inside living spaces of residential buildings and constructions (and equal with them), for the residential areas and also MPLs of 50 Hz MFs for people, who are not professionally connected with maintenance and operation of equipment, being the source of 50Hz MFs, but who are affected in process of productive activity. This document also establishes the principles and methods of 50 Hz MF level control and ensuring protection of population.

Hence, for living spaces inside residential and equal with them buildings, the suggested MPL is 5 μT. Outside the living spaces of residential buildings and in territory of residential area (also for MF impacts from the constant acting sources) considering not twenty-four-hour staying, the suggested MPL is 2 times higher, that is 10 μT. For conditions of temporary staying (including implementation of works by people, who are professionally not connected with operation of electric plants) particularly, under ALs and in zones of cable line passing, it is reasonable to fix a peak level of MPLs of 50 Hz MF equal to 20 μT. Further is necessary to approbate these normative values.

This way, in territory of RF the fundamental normative documentation has been developed by now. This documentation covers regulation of productive and nonproductive effects of EMF IF.

However, ensuring of the normative values of EMF IF at the working places and at place of population living is not always possible. Protection of working personnel from EF IF at OSG of ultra high voltage (UHV) is reached due to application of constructions, reducing EF levels by using the compensative action of dissimilar phases of live parts and screening effect of high bays for equipment, as well as implementation of bus bars with a minimal number of multiple conductors in phase and with their minimal possible sag and other activities. By that, means of protection from EFs of 50 Hz should correspond to the following:

- stationary screening devices - to requirements of GOST 12.4.154 – 85 SSBT “Screening device for protection from electric fields of industrial frequency. General technical requirements, basic parameters and dimensions”.
- screening kits - to requirements of GOST 12.4.172 – 87 SSBT “Individual screening kit for protection from electric fields of industrial frequency. General technical requirements and methods of control”.

The accumulated experience of solving a problem on ensuring of personnel protection from EF impact shows that application of a complex of special constructions and combinations of electric plants, protection means, and grounding of the isolated conductors, rational methods of repair-exploitation service and organizational activities is the most preferable.

A practice of UHV objects operation shows that frequently it’s impossible to implement protective actions of technical and organizational character. It is connected with insufficient effectiveness and rather restricted zone of stationary shields application. A question concerning application, as a method of protection of substation personnel from EF effect, of special design-layout solutions, which ensure meeting the hygienic norms at the minimal shielding capacity, is far from its solution. Rationalization of repair-exploitation service methods is aimed, mainly, at shortening of works in conditions of EF (usage of “sectional” principle of equipment repair, prolongation of overhaul periods, decrease in equipment inspection periodicity, introduction of remote control, etc.) and it isn’t applied in all cases and is of a sporadic character.

Long-term experience of operation of UHV plants shows that in Russia and abroad the most universal and effective mean of personnel protection from EF adverse effect is an individual shielding kits (SKs) of the work clothes.

The modern SK is a high technical product, creating the closed electroconductive space around the human body (the individual “Faraday cage”), excluding penetration of EF even of a very high intensity inside the shielding space. Possessing a high electroconductivity, the suits bypass the human body, excluding the bias and impulse currents flowing through it.

Beside this, kits for working under voltage protect the respiratory organs of the user against hazardous air-ions, formed as a result of air ionization under high voltage effect. The shielding kits of the best world producers combine high protective indices with the required sanitary-hygienic ones. Today such kits are designed and produced in the USA, Japan and Germany. Its production is mastered in some other countries. The kits are widely applied all over the world at repair and operation of UHV plants, particularly, at performing some works at ALs under voltage. In Russia using the individual SKs is obligatory at repair and maintenance of equipment in a zone of UHV plant effect. It is regulated by a number of documents of industrial and federal levels.

Personnel of RAO “UES of Russia”, Federal Grid Company, enterprises of “Rosenergoatom” and other Russian organizations, maintaining substations and ALs of UHV, is now equipped with domestic SKs, developed and serially delivered by the Moscow Close JSC “NPO “Energoform”. These SKs correspond to all requirements of the Russian and international standards, certified by a body on individual protection means certification of the State Standard of RF. These SKs have a sanitary-epidemiological decision.

Using in process of kits production of the most modern, high efficient materials (including of the Russian design), original constructive solutions, a big number of special additional accessories and wide model range brought SKs into one line with the best world analogs. It should be mentioned that by a variety of important specification figures, the Russian SKs significantly excel the best foreign samples (Table 5.13).

As it was mentioned above, testing of the shielding properties of kits is conducted by means of a model of vertically standing person (MVSP), designed and implemented in 1986 – 2000 by PEO “Long distance power transmission”. MVSP were applied for estimating the capacitive currents values in a human body (MVSP-1 and MVSP-3) and EF intensity levels over the human body surface, being on the ground potential (MVSP -2 and MVSP -3); capacitive and air-ionic current values (MVSP-4 and MVSP-6), and also EF intensity (MVSP-5 and MVSP-6) over the body surface of a person, who works under voltage. Nowadays the devices are used for EF qualification tests of EF-1 and EF-3 types at the stands of the State Institution the Research Institute of Occupational Health of RAMS, carried on by employees of NPO “Technoservis-Elektro” and a branch of the JSC “FGC UES” of the Intersystem Electric Grids of Center. MVSP-5(6) is placed horizontally inside the stand of high AC voltage, firstly, by face to the upper plate – a source of EF and then by back.

Table 5.13. **Technical data (shielding properties) of the screening kits of Ep-4 (l) type**

A factor of the fabric shielding, dB, not less:	
at frequency of 50 Hz	90
to 10 MHz	90
10…500 MHz	80
500…20 000 MHz	60
A factor of shielding the kit as a whole at frequency of 50 Hz, dB, not less	60
Resistance of the shielding clothes, Ohm, not more	10
Resistance of the shielding gloves, Ohm, not more	30
Resistance of the shielding footwear, Ohm, not more	500
A factor of aero-ion concentration reduction in the inhaled air, ref. units, not less:	
light	3
heavy (aerosols)	12

In these positions measurements of the capacitive current, flowing through a body of MVSP at different intensity E of the undistorted EF between the plates of a high voltage stand, are conducted. Such measurements of current are carried on for a MVSP without SK named I_1 and with SK named I_2. A factor of the shielding kit $K_{s.k.}$ is estimated by a ratio of currents I_1/I_2. In Fig. 5.23 a process of measuring the capacitive current, flowing through MVSP-5(6) with SK, is shown. This current passes through MVSP-5(6) that is uniformed by SK. Table 5.14 contains testing results of the shielding properties of SK of EF-1 type by means of MVSP-5(6), placed by face to the source of EF and in Table 5.15 - by back to the source.

According to GOST 12.4.172 – 87 SSBT “Individual shielding kit for protection from electric fields of industrial frequency. Main technical requirements and methods of control” a factor of SK shielding should be not less than 100. So, EF-1 shielding kit tests confirm a high efficiency of EF IF shielding.

The shielding kit protects a person from EF effect and accompanying factors. As opposed to EF IF, protection of the working staff from the adverse effect of MF IF can be ensured only by means of time protection and distance protection; application of protection means is limited. It is explained by the fact that for MF any mean, shielding from EF, including the screening kit, is transparent, it means that such kit does not protect a person from MF.

Table 5.14. **Efficiency of the shielding kit EF-1 at position of MVSHP-5(6) by face to EF source**

E, kV/m	I_1, μA	I_2, μA	$K_{s.k}$, ref.units
6,25	55,0	0,2	275
12,50	108	0,4	270
18,75	160	0,6	267
25,00	212	0,8	265
31,25	267	1,0	267
37,50	319	1,2	266
50,00	425	1,6	266
56,25	480	1,8	267
62,50	542	2,0	271

For population the main sources of EMF IF of high intensity are high-voltage ALs, passing through the habitable territory as well as cable lines, passing through residential area and residential buildings, laid over the outside walls, in floors, under ceiling of in-built transformer substations, etc. In this connection one of the primary goals is a necessity of reduction of MF levels, created by constant acting sources, placed in or out of residential and social buildings, including habitable territories. It is also necessary to mention that solving a question on screening the sources of MF IF or residential places is practically impossible by traditional methods (using the materials with high magnetic conductivity) for extended sources, such as air and cable lines. In this connection it is necessary to develop the principally new methods of MF reduction (shielding) for ALs in habitable territory.

Table 5.15. **Efficiency of the shielding kit EF-1 at position of MVSP-5(6) by back to EF source**

E, kV/m	I_1, μA	I_2, μA	$K_{s.k}$, ref.units
6,25	65	B.i.s*	—
12,50	129	the same	—
18,75	191	»	—
25,00	258	»	—
31,25	321	»	—
37,50	386	0,1	3860
50,00	515	0,1	5150
56,25	580	0,1	5800
62,50	644	0,2	3220

* B.i.s. — below the instrument sensitivity.

For population protection from EF IF, created by high-voltage ALs, constructions of passive, active and resonance cable shields were developed by the branch of the JSC “FGC of UES” - Intersystem Electric Grids of Center. These shields allow reducing EF intensity up to 5 kV/m (MPLs for residential territory) under power lines and as well as reducing 1,5…2,0 times a zone width, in which EF intensity exceeds 1 kV/m (MPLs for residential area).

The designed constructions of passive, active and resonance vertical and directed contour shields (DCSs) solve a problem on MF IF levels reduction at residential places. In Fig. 5.24 the DCSs construction is showed at ALs of 500 kV. In Fig. 5.25 one can see the distribution of H_{max} intensity (the acting value for the greater axle of an ellipse) of MF at the level of 1,8 m above the ground in cross-section of 500 kV AL with the minimal sizes “phase wire - ground wire” of 10 m, equipped with DCSs. All parameters of DCSs are estimated, considering the sag in the run of wires of AL phases and DCSs.

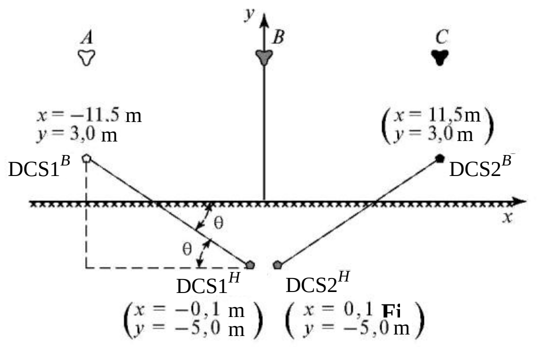


Fig. 5.24. Directed contour shield, intended for reducing the intensitv level of MF from ALs of 500 kV

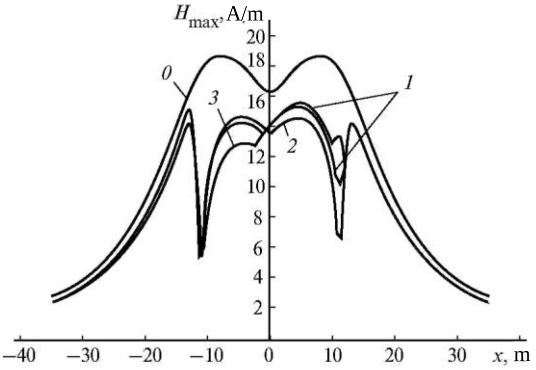


Fig. 5.25. Distribution at the level of 1,8 m above the ground of MF intensity in AL cross-section of 500 kV with minimal sizes “wire-ground” of 10 m: curve 0 - not screened AL; curve 1 – screening by passive (short-circuit) DCSs; curve 2 – screening by active DCSs (the screen chain includes the sources of EMF (electromotive force); curve 3 - screening by resonance DCS (the screen chain condensers)

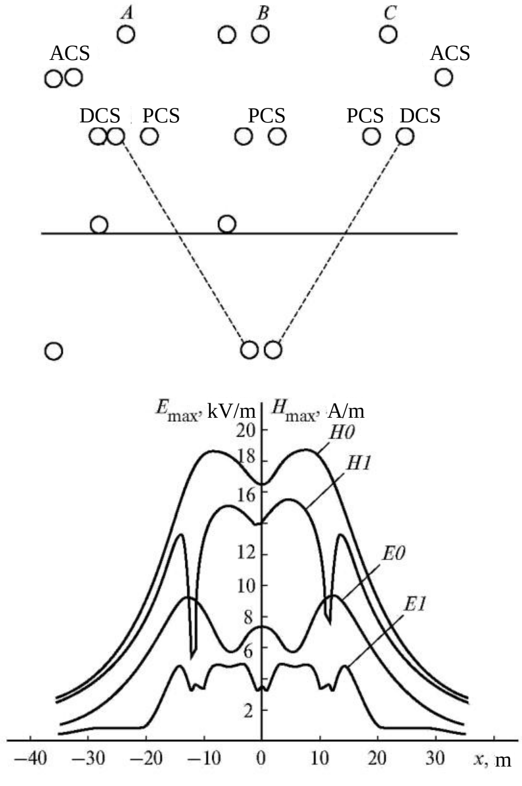


Fig. 5.26. Arrangement of phases of ALs, ACSs, PCSs and DCSs, and distribution of E_{max} and H_{max} at a level of 1,8 m above the ground in AL cross-section of 500 kV with the size of 10 m at horizontal position of upper wires of DCSs and wires of PCSs

Using of contour shields allows reducing the level of MF intensity under ALs to 16 A/m (MPLs for populated area) as well as reducing the zone of MF intensity, exceeding 8 A/m (MPLs for a zone of residential area according to the draft new normative document).

In Fig. 26 the distribution of EMF intensity at the level of 1,8 m above the ground in AL cross-section of 500 kV with the minimal sizes of 10 m, equipped with passive DCSs, and also with active and passive cable shields, combined with DCSs (ACS and PCS), is given: not screened EF – the curve *E0*; EF, screened by two ACSs, three PCSs and upper wires of two DCSs — the curve *E1*; non screened MF — the curve *H0*; MF, screened by two passive DCSs, — the curve *H1*.

In productive conditions the main sources of MF IF are power lines with their commutation equipment and reactors without the closed ferromagnetic iron circuit. At that, cable lines (CLs) play a very important role because recently they were not considered to be potential sources of MF IF, having an adverse effect on the person.

To solve the questions on person’s safety ensuring in conditions of MF IF effect, the branch of the JSC “FGC of UES” - Intersystem Electric Grids of Center together with the State Institution the Research Institute of Occupational Health of RAMS developed a principle of CL arrangement by the approaching method of cable phase axis and neutral conductor axis, being a part of CLs or a bunched cable, as well as of virtual axis of these cables [11, 12].

In Fig. 5.27 schemes of traditional component arrangement of 0,4 kV CLs, laid to the transformer substation (TS) of 10/0,4 kV, in-built into the apartment house, is shown.

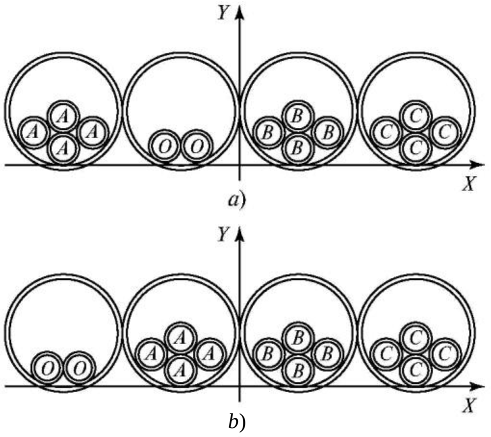


Fig. 5.27. Schemes of traditional component arrangement of 0,4 kV CLs in asbestos-cement pipes

A surface of the living space floor is over CLs at a distance of 965 mm. In this space the MF intensity should not exceed 4 A/m (MPLs for the living spaces). At maximum load, the design value of phase current in CLs in bilateral mode is 1800 A.

In Fig. 5.28 distribution of intensity H_{max} over the surface of the living space floor over TS in bilateral load mode is given for CLs according to the scheme shown in Fig. 5.27, *a* is a curve *1* and according to the scheme presented in Fig.5.27, *b* is a curve 2.

For component arrangement (Fig. 5.27, *a*) H_{max} for living spaces is 25 times as much as MPL making 4 A/m, and H_{max} for component arrangement (Fig. 5.27, *b*) is 16 as much as MPL.

In traditional constructions of CLs, the phase component arrangement of the bunched cables with their horizontal position, is used.

As an example let’s consider two constructions of CLs: the first one consists of a single phase cable and a neutral conductor, placed horizontally at a distance of 20 cm between the axis of the nearest cables (Fig. 5.29, *a*) and the second one consists of the same cables, put in corners of a square with the minimum distance between the cable axis (Fig. 5.29, *b*). A radius of each cable is 2 cm, a modul of the phase current at bilateral load I_{ph}=1800 A.

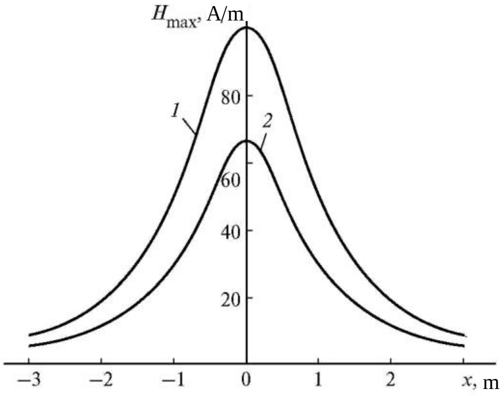


Fig. 28. Distribution of intensity H_{max} of MF, created at the floor surface of living space (y=965 mm)

At D point, located over the axis of CL middle phase of horizontal arrangement (phase B in Fig. 5.29, *a*), intensity vector $\dot{\vec{H}}_A$, $\dot{\vec{H}}_B$ и $\dot{\vec{H}}_C$ have absolutely different modules and are shifted in space at a significant angles.

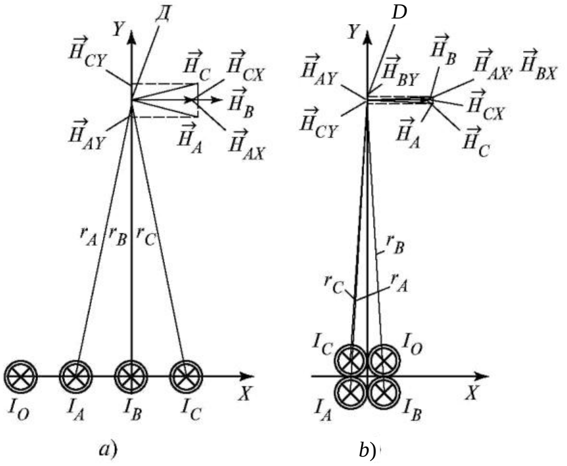


Fig. 5.29. Components of intensity of MF, created by CLs of horizontal arrangement (a) and CLs with cabling in the corners of a square (b) at bilateral load

The components $\dot{\vec{H}}_{AX}$, $\dot{\vec{H}}_{BX} = \dot{\vec{H}}_B$ и $\dot{\vec{H}}_{CX}$ are of the same direction and at estimation of the resulting vector module in *OX*-direction, their complex values are added: $\dot{H}_X = \dot{H}_{AX} + \dot{H}_{BX} + \dot{H}_{CX}$, compensating each other (Fig.5.30, *a*).

The components $\dot{\vec{H}}_{AY}, \dot{\vec{H}}_{BY} = \dot{\vec{H}}_B$ *and* $\dot{\vec{H}}_{CY}$ are of the opposite-direction and at estimation of the resulting vector module in OY-direction, the complex values are subtracted: $\dot{H}_Y = \dot{H}_{AY} + \dot{H}_{BY} + \dot{H}_{CY}$,) that leads to increase in H_y value (Fig. 5.30, *b*).

Therefore, the resulting component of full vector $\dot{\vec{H}}$ of MF intensity is, mainly, estimated by a component $\dot{\vec{H}}_Y$ in OX-direction.

For CLs with cable arrangement in corners of a square, the components of intensity are significantly less in OY-direction at the same D point (Fig. 5.29, *b*) than components in OX-direction, because vectors $\dot{\vec{H}}_A$, $\dot{\vec{H}}_B$ и $\dot{\vec{H}}_C$ have small angles of divergence and their modules are similar. It leads to greater compensation degree of intensity of MF, created by this CL.

In Fig. 5.31 distribution of MF intensity, created by CLs of horizontal arrangement is shown by a curve *1* and created by CLs with cable arrangement in corners of a square is shown by a curve *2* at the floor surface of living space (*y*=965 mm) at bilateral load (I_{ph}= 1800 A).

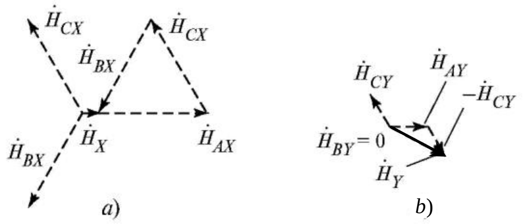


Fig. 5.30. To estimation in OX-direction (*a*) and OY-direction (*b*) of a module of the resulting vector intensity of MF, created by CLs of horizontal arrangement

Rearrangement of CLs of horizontal cable position into CLs with cable arrangement in corners of a square led to approach of cable axes, that resulted in reducing the MF intensity H_{max} of 98 A/m to 16 A/m at a level of *y*=965 mm.

One of the options of the bunched cable (BC) CL arrangement, considered earlier with in-built arrangement of TS of 10/0,4 kV in corners of a square, is shown in Fig. 5.32.

Curves of H_{max} distribution at the floor surface of living space over TS for the considered option of CL BC arrangement in corners of a square, are shown in Fig. 5.33: *y*= 965 mm, curve *1* - a bilateral mode, curve *1*′ - unilateral mode; *y*= 1065 mm, curve *2* - bilateral mode and curve 2′ - unilateral mode. For unilateral mode of phase current values and neutral conductor the following values are accepted: $\dot{I}_A = 1800$ A, $\dot{I}_B = 900e^{-j120}$ A, $\dot{I}_C = 900e^{j120}$ A, $\dot{I}_0 = 900e^{j180}$ A.

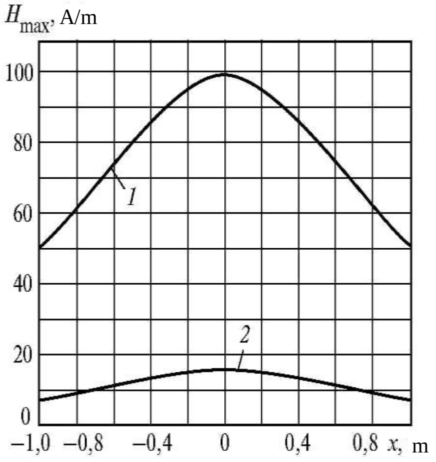


Fig. 5.31. Distribution of intensity of MF, created by CLs of horizontal arrangement and CLs with arrangement of cables at the corners of a square at the floor surface of living space (y = 965 mm) at bilateral load (Iph = 1800 A)

At such component arrangement of the bunched cables of CLs H_{max} in unilateral mode is always less than in bilateral.

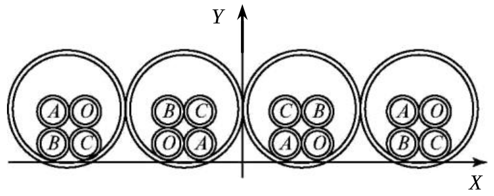


Fig. 5.32. Option of arranging the bunched cables of CLs in corners of a square

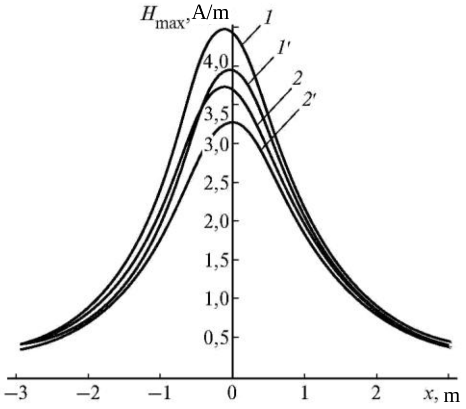


Fig. 5.33. Distribution of intensity $H_{\max}$ of MF at a floor surface of living space over TS for arranging CL BC in corners of a square

For a level of y=965 mm H_{max1}= 4,481 A/m, $H_{max1'}$= 3,914 A/m, i.e. in order the considered CL meets MPL for living spaces ($H \le 4$ A/m), it should be shifted from the floor surface of living space by 10 cm, then for a level of y=1065 mm H_{max2} = 3,710 A/m and $H_{max'}$ = 3,244A/m.

Arrangement of BCs, consisting of phase cables and neutral conductor in asbestos-cement pipes in corner of a square, result in significant reduction of intensity of MF, created by CLs at y≈1 m from axes of CL BC. However, at passing of CLs through the outside walls of residential buildings or floors, when a distance from axis of BC to the surface of inside wall or a floor of living space is 30…70 cm. such an arrangement of BCs and CLs will not meet a condition of $H \le 4$ A/m, i.e. MPLs of MF intensity for living spaces will not be satisfied.

The best option of intensity compensation of MF, created by currents of cables, included in BC, is an option of full alignment of cable axes. Then intensities of MF, created by current of each cable in any point of space around the cable, will have the same direction, and the resulting value of intensity $H=H_{max}$ will be estimated by the equation.

$$\dot{H} = \frac{\dot{I}_A}{2\pi r_A} + \frac{\dot{I}_B}{2\pi r_B} + \frac{\dot{I}_C}{2\pi r_C} + \frac{\dot{I}_0}{2\pi r_0}, \qquad (5.1)$$

and since in case of coincidence of cable axes in BC $r_A = r_B = r_C = r_0 = r$, the equation (5.1) will be as follows:

$$\dot{H} = \frac{1}{2\pi r}\,(\dot{I}_A + \dot{I}_B + \dot{I}_C + \dot{I}_A) = 0\,, \qquad (5.2)$$

because a sum of all currents is always a zero. But, actually, physical sizes of the cable (diameter) prevent from implementation of this BC arrangement.

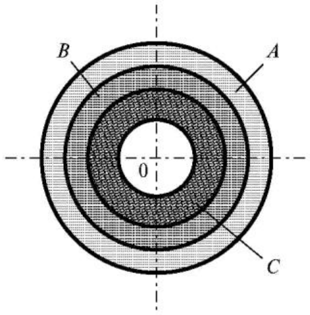


Fig. 5.34. Coaxial arrangement of phase wire and neutral conductor in the bunched cable

Only coaxial cable arrangement in BC can meet a condition (5.2), as it is shown in Fig. 5.34. Alternation of phase wire and neutral conductor has no sense and can be free.

Lets' consider two parallel cables *A1* and *A2* with current $\dot{I}$ in each one, being at a distance of 2R from each other. From a centre of the distance between the cables, we draw a circle with a radius R and in a centre of this circle we place coordinate axis XOY, so that OX-axis will be direct, connecting cable axes at an angle of α (Fig.5.35).

В точке *Д,* расположенной на расстоянии *h* от центра окружности по оси *OY*, токами кабелей создается МП, составляющие напряженности которого по осям *OX* и *OY* для каждого кабеля определяются выражениями:

At *D* point, located at a distance *h* from a centre of the circle in *OY*-direction, MF is created by current of cables, which intensity components in *OX* and *OY*-directions are estimated for each cable by the following equations:

$$\left.\begin{aligned}
\vec{\dot{H}}_{A1X} &= \vec{x}^{\,0}\,\frac{\dot{I}}{2\pi}\,\frac{h - R\sin\alpha}{R^2\cos^2\alpha + (h - R\sin\alpha)^2}\,;\\
\vec{\dot{H}}_{A1X} &= \vec{y}^{\,0}\,\frac{\dot{I}}{2\pi}\,\frac{R\cos\alpha}{R^2\cos^2\alpha + (h - R\sin\alpha)^2}\,;\\
\vec{\dot{H}}_{A2X} &= \vec{x}^{\,0}\,\frac{\dot{I}}{2\pi}\,\frac{h - R\sin(\alpha + 180)}{R^2\cos^2(\alpha + 180) + [h - R\sin(\alpha + 180)]^2}\,;\\
\vec{\dot{H}}_{A2Y} &= \vec{y}^{\,0}\,\frac{\dot{I}}{2\pi}\,\frac{R\cos(\alpha + 180^\circ)}{R^2\cos^2(\alpha + 180) + [h - R\sin(\alpha + 180)]^2},
\end{aligned}\right\} \qquad (5.3)$$

where $\vec{x}^{\,o}$ and $\vec{y}^{\,o}$ are unit vectors in OX and OY-directions.

Since all components of MF intensity have the similar phase angles, because they are created by the same phase current, an arrangement of the resulting vector is estimated in space by the following expression:

$$\dot{\vec{H}}_A = \dot{\vec{H}}_{A1X} + \dot{\vec{H}}_{A1Y} + \dot{\vec{H}}_{A2X} + \dot{\vec{H}}_{A2Y},$$

and its module is calculated be the equation:

$$H_A = \sqrt{(H_{A1X} + H_{A2X})^2 + (H_{A1Y} + H_{A2Y})^2}, \quad (5.4)$$

Where $H_{AX} = H_{A1X} + H_{A2X}; \; H_{AY} = H_{A1Y} + H_{A2Y}$ — are actual values of the resulting vector components in coordinate axis.

Flip angle $\dot{\vec{H}}_A$ to *OX*- axis is estimated by the equation:

$$\beta = \operatorname{arctg} \frac{\dot{H}_{AY}}{\dot{H}_{AX}}. \quad (5.5)$$

From D point we draw a perpendicular to vector $\dot{\vec{H}}_A$ in *XOY*-direction (Fig.5.35). Then at a distance of:

$$r_A = \frac{2\dot{I}}{2\pi \dot{H}_A} \quad (5.6)$$

from *D* point at the drawn perpendicular, the axis of A cable can be placed. This axis is a virtual analog of *A1* and *A2* cables, creating MF by its current of $2\dot{I}$ in the considered D point, intensity vector of which is equal to $\dot{\vec{H}}_A$.

Coordinates of A cable axis are estimated by the formula:

$$x_A = r_A \sin\beta; \quad y_A = h - r_A \cos\beta. \quad (5.7)$$

For any *k* phase wire or neutral conductor, including N_k cables with their centers being uniformly placed along the perimeter of a circle with radius R_k, formulas (5.3) for components of MF intensity in *OX*- and *OY*-directions are as follows:

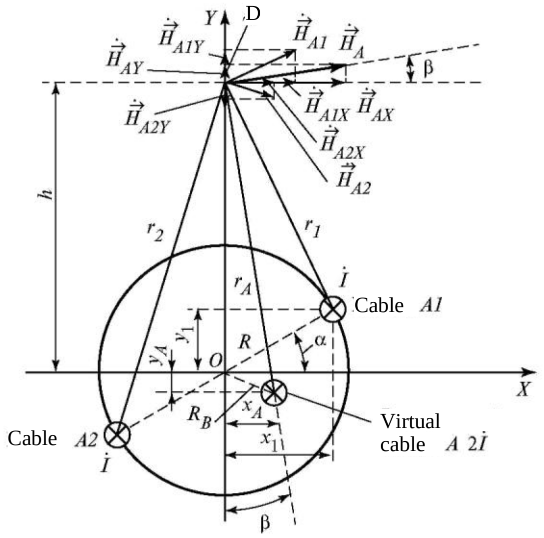


Fig. 5.35. To estimation of coordinates of the virtual cable *A* with the current $2\dot{I}$, creating MF intensity in *D* point, equal to intensity of MF, created be real parallel cables *A1* and *A2* with the current $\dot{I}$

$$\dot{\vec{H}}_{kX} = \vec{x}^{\,0} \frac{\dot{I}_k}{2\pi} \sum_{i=0}^{N_k - 1} \frac{h - R_k \sin\left(\alpha + \alpha_k + i\,\frac{2\pi}{N_k}\right)}{R_k^2 \cos^2\left(\alpha + \alpha_k + i\,\frac{2\pi}{N_k}\right) + \left[h - R_k \sin\left(\alpha + \alpha_k + i\,\frac{2\pi}{N_k}\right)\right]^2};$$

$$\dot{\vec{H}}_{kY} = \vec{y}^{\,0} \frac{\dot{I}}{2\pi} \sum_{i=0}^{N_k - 1} \frac{R_k \cos\left(\alpha + \alpha_k + i\,\frac{2\pi}{N_k}\right)}{R_k^2 \cos^2\left(\alpha + \alpha_k + i\,\frac{2\pi}{N_k}\right) + \left[h - R_k \sin\left(\alpha + \alpha_k + i\,\frac{2\pi}{N_k}\right)\right]^2},$$

where α_k — is a slope of the first wire of *k* phase or neutral conductor to *OX* axis.

Formulas (5.4 and 5.6) also change, which for a common with N_k and R_k case are for a phase *k* or a neutral conductor, will be the following:

$$H_k = \sqrt{H_{kX}^2 + H_{kY}^2}; \qquad r_k = \frac{N_k I_k}{2\pi H_k}.$$

An axis of the virtual cable is located inside the circle at a distance from centre of $R_B < R$. At increase in N_k number of cable components and at the permanent value of $N_k I_k$, H_{kY} module reduces as a result of mutual compensation and the module of component H_{kx} increases. According to formulas (5.5.) and (5.7) this leads to reduction of β angle as well as of x_a and y_a coordinates, i.e. a centre of the virtual cable tends to the centre of the circle.

Placing the phase cable and neutral conductor uniformly along the perimeter of circles with one centre, we'll receive AL with axes of virtual phase cables and neutral conductor, being at a distance significantly less than diameters of real cables.

Applying a principle of the maximum approach of virtual cables axes, different constructions of CLs are obtained and some of them are shown in Fig. 5.36.

CL, shown in Fig. 5.36, *a*, has one bunched cable and consists of $N_A = N_B = N_0 = 4$ phase cables - *A*, *B* and neutral conductor with cross-section of 240 mm^2 each, diameters of cables $D_A = D_B = D_0 = 3$ cm, and also $N_B = 8$ of *C* phase cables with cross-section of 120 mm^2 and diameter of $D_C = 2$ cm each. Axes of the neutral conductor are over a perimeter of the circle with radius $R_0 = 2{,}12$ cm with a slope $\alpha_0 = 45^0$ to *OX*-axis. For phase *A*: $R_a = 4{,}1$ cm, $\alpha_A = 0$. For phase *B*: $R_b = 5{,}1$ cm, $\alpha_B = 45^0$. For 4 half-phase cables *C1*: $R_{C1} = 5{,}75$cm, $\alpha_{C1} = 20^0$, but for half-phase cable *C2*: $R_{C2} = 5{,}75$ cm, $\alpha_{C2} = -20^0$.

Arrangement of CL BC, shown in Fig.5.36, *b* is notable for changing the names of phase cables, being a part of BC: zero for *A*, *A* for *B*, *B* for *C*, *C* for zero.

CL, presented in Fig. 5.36, *c* contains one BC, one neutral conductor cable (N_0=1) with diameter D_0=5 cm, located in the centre of bunch, and 4 phase cables *A*, *B*, and *C* (N_A=N_B=N_C=4) with diameter D_A=D_B=D_c=3 each. R_A = 0,04 m, R_B = R_C = 0,07 m, α_A = =α_C = 0, α_B = 45°.

Bunched beam of CL, shown in fig.5.36, *d*, contains 14 cables with equal diameters D=3 cm. Neutral conductor contains two cables with R_0=15 cm, α_0= 45^0. Each phase is divided into two half-phases, consists of four cables. Parameters of half-phase are: *A1*—R_{A1} = 2,5 cm, α_{A1} = 90°; *A2*—R_{A2} = 4,5 cm, α_{A2} = 0; *B1*—R_{B1} = 3,9 cm, α_{B1} = 39,8°; *B2*— R_{B2} = 3,9 cm, α_{B2} = −39,8°; *C1*—R_{C1} = 7,0 cm, α_{C1} = 39,8°; *C2*—R_{C2} = 7,0 cm, α_{C2} = −39,8°.

In fig.5.36,e the example of CPL arrangement is shown, and it contains three phase cables A and B (N_A = N_B = 3, D_A = =D_B= 3 см, R_A = R_B = 4 см, α_A = −30°, α_B = 30°) six C phase cables (N_C =6, D_C = 1,5 см, R_C = = 4,5 см, α_C = 0) and one cable of neutral conductor (N_0 = 1, D_0 = *5* см, R_0 = 0, α_0 = 0).

In Fig. 5.36, *f* the bunched cable of CL is shown; it contains two cables in each phase and one neutral conductor: $N_A = N_B = N_c = 2, N_0 = 1, D_A = D_B = D_C = D_0 = =5$ cm, R_A = R_B = R_C = *5* cm, α_A = 90°, α_B = −30°, α_C = 30°.

As an example, let's consider CL, shown in Fig.5.36, *c*. We'll estimate MF intensities (created by bilateral load of phase currents of CLs in D point, located at a distance *h*=0,5 m in OY-direction from its centre). A module of the phase current is 1000 A. Table 5.16 contains the estimating results of coordinate axes of virtual similar cables (CAVSC), components $\dot{H}_{ix}$, $\dot{H}_{iy}$ and the resulting $\dot{H}_i$ of MF intensity, created by each phase, the resulting components $\dot{H}_{X\Sigma}$ and $\dot{H}_{Y\Sigma}$ and also intensity H_{max} along the greater axle of an ellipse, obtained by a formula [36]:

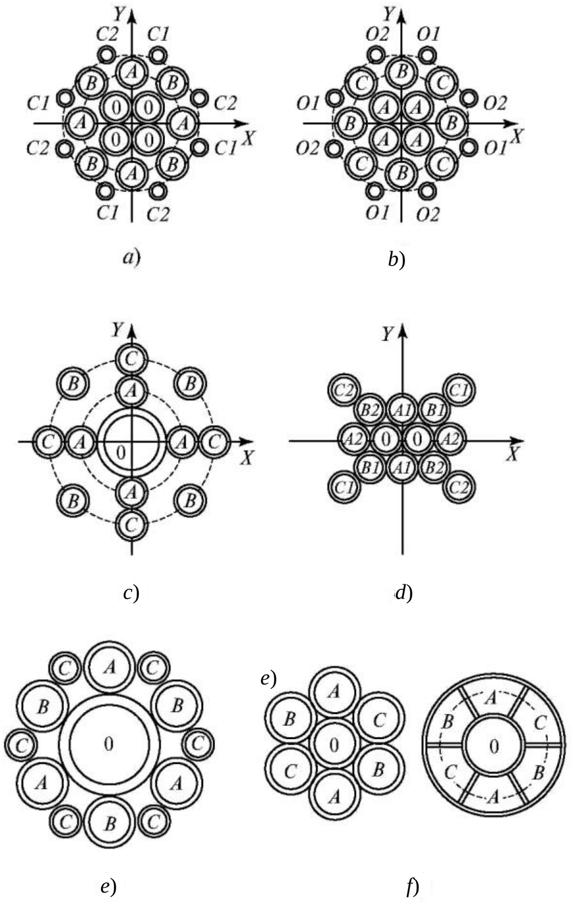


Fig. 5.36. Some constructions of CLs, developed by a method of the maximum approach of the virtual cable axes

$$H_{\max} = \sqrt{\frac{1}{2}\,(H_{Y\Sigma}^2 + H_{X\Sigma}^2) + \frac{1}{2}\,\sqrt{(H_{Y\Sigma}^2 + H_{X\Sigma}^2)^2 - 4H_{Y\Sigma}^2 H_{X\Sigma}^2 \sin^2(\psi_{Y\Sigma} - \psi_{X\Sigma})}}\ .$$

Table 5.16. **Coordinate axes of the virtual cables $\vec{H}_{ix}$, $\vec{H}_{iy}$, $\vec{H}_i$, $\vec{H}_{X\Sigma}$, $\vec{H}_{Y\Sigma}$ and $\vec{H}_{\max}$ in D point with A=0,5 m in OY-direction for CLs, shown in Fig. 5.36, c**

Phase	CAVSC, *x*/*y*, mm	$\dot{H}_{ix}$	$\dot{H}_{iy}$	$\dot{H}_i$	$\dot{H}_{X\Sigma}$	$\dot{H}_{Y\Sigma}$	$H_{\max}$
		A/m					
A	0/0,020	318,32	0	318,32	$0{,}2122e^{j\,120}$	0	0,2122 (0,2122)*
B	0/0,192	$318{,}19e^{-j\,120}$	0	$318{,}19e^{-j\,120}$			
C	0/−0,192	$318{,}43e^{j\,120}$	0	$318{,}43e^{j\,120}$			
0	0/0	0	0	0			

* In brackets it is intensity of MF, created in D point by phase currents (*I*=1000 A), flowing in virtual phase cables.

At a module of phase currents of 1000 A at a distance of 0,5 m from the centre of CLs in OY-direction, H_{max} makes only 0,2 A/m.

If to rotate a cable bunch of CLs, shown in Fig. 5.36, *c* around its axis, the coordinates of axes of virtual analog cables and H_{max} intensity will change in D point. In Fig. 5.37 curves of the changing coordinates of virtual cable axis are shown at changing the angle α of cable bunch rotation around its centre from null to π/2.

As one can see from Fig. 5.37, a distances between the axes of virtual analog cables *A, B, C* and a neutral one (for cable of a neutral conductor x_0=y_0=0) doesn't exceed 0,4 mm (between the axes of virtual analog cables *B* and *C* the maximum distance is 2×0,19 mm).

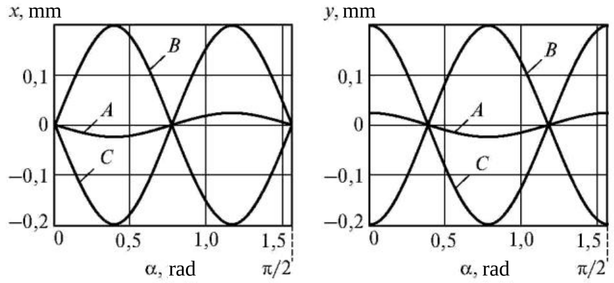


Fig. 5.37. The curves of changing of virtual cable axis coordinates at a changing angle α of the bunched cable rotation around its center from zero to π/2

Modules of components $\dot{H}_{ix}$ vary in a range of 318,3±0,122 A/m, and components $\dot{H}_{iy}$ change from -0,122 to +0,122 A/m (Fig. 5.38). Distances between the axes of virtual cables are very small, that leads to sharp decrease in $\dot{H}_{ix}$ components and to a high degree of $\dot{H}_{iy}$ components compensation, whereby the resulting intensity H_{max} changes in a very narrow range: from 0,2121904 to 0,2121965 A/m (Fig. 5.39).

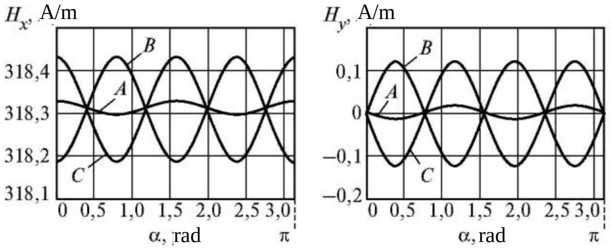


Fig. 5.38. The curves of changing the modules of components $\dot{H}_{ix}$ and $\dot{H}_{iy}$ at a changing angle α of the bunched cable rotation (Fig. 5.36, c) around its center from zero to π

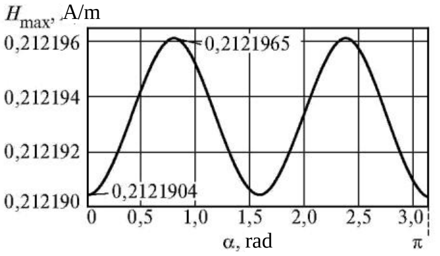


Fig. 5.39. Changing of intensity H_{max} at a changing angle α of the bunched cable rotation (Fig. 5.36, *c*) around its center from zero to π

With reduction of a number of phase cables (neutral conductor), included in the cable bunch, distances between the axes of virtual analog cables increase, that in other equal conditions leads to increase in a value of the resulting intensity of MF H_{max}, created by currents of the cable bunch.

Let's replace one by one CLs, coming out from transformer of 10/0,4 kV, for CLs, containing of one BC each, with arrangements, showed in Fig.5.36.

Distribution of MF intensity H_{max} is shown in Fig. 5.40. This intensity is created at the floor surface of living space over TS (y=965 mm) by CL currents with BC arrangement according to configurations, shown if Fig.5.36, *a* and *b*: curves *A1* and *B1* – bilateral (I_{ph} = 1800 A) and curves *A1*′ and *B1*′- unilateral loading mode, accordingly. For arrangements according to configurations, given in Fig.5.36, *a* and *b*, H_{max} doesn't exceed 0,0043 and 0,0040 A/m at bilateral mode and 0,0027 and 0,0020 A/m at unilateral mode of loading, accordingly.

In comparison with CL, showed in Fig.5.32, CL from Fig. 5.36, *a* and *b* in bilateral mode creates (Fig. 5.33, curve 1) H_{max} values being more than 1000 times less.

Distribution of MF intensity H_{max} is shown in Fig.5.41, *a*. This MF is created at the floor surface of living space by CL currents, arranged according to schemes, shown in Fig. 5.36, *c*, in Fig. 5.41, *b* - by scheme of Fig. 5.36, *d*, in Fig. 5.42, *a* - by scheme of Fig.5.36, *e*, and in Fig. 5.42, *b* - by scheme of Fig. 5.36, *f*, in bilateral mode (curves *1*) and unilateral mode (curves *1*′). In fig. 5.41, *b* the curves *X1* and *X1*′ correspond to perpendicular position of the floor surface of living space in *OX*-direction, and the curves *Y1* and *Y1*′ – in OX-direction of the bunched cable (Fig 5.36, *d*).

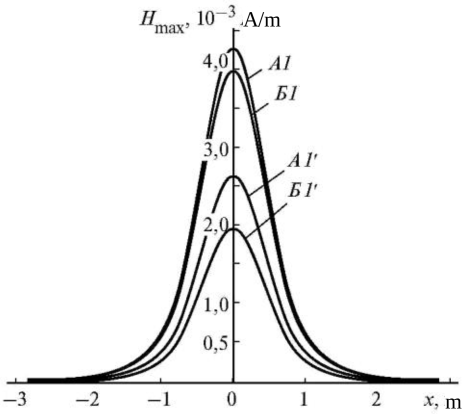


Fig. 5.40. Distribution of intensity H_{max} of MF, created by CL currents at the floor surface of living space over TS, arranged according to schemes, shown in Fig. 5.36, *a* and *b*: curves *A1 and B1* — bilateral loading mode and curves *A1′* and *B1′* — unilateral loading mode

At decrease in a number of cables, composing phases and a neutral conductor of CLs, MF intensity increases from (4,0 … 4,3) 10^{-3} A/m (Fig. 5.40, bilateral loading mode) to 1,53 A/m (Fig. 5.42, bilateral loading mode).

As opposed to CLs, arranged by a principle of maximum approach of cables axes of phase wires and a neutral conductor, CLs constructed by a principle of maximum approach of virtual cable axes, can pass through external walls and inside floors.

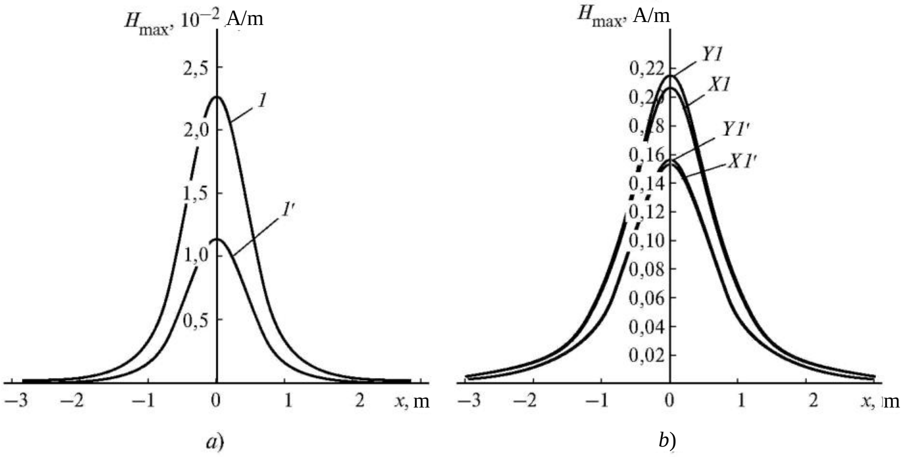
In 2006 the branch of the JSC "FGC of UES" - Intersystem Electric Grids of Center together with the State Institution the Research Institute of Occupational Health of RAMS developed the principles of creation and construction of electromagnetic shields for reactors without ferromagnetic core and also construction of a reactor without ferromagnetic core, containing the shielding winding, resulting in 5…50 times reduction of the intensity of MF, created by reactors.

Configuration of CLs with placing the axes of cables in cable bunches on the square sides (Fig. 5.32) is introduced at designing and building TS of 10/0,4 kV for the inhabited complex.

A patent of the Russian Federation from April, 10, 2006 for invention № 2273934 on CLs, which cable bunches are grouped by a principle of approaching of the axes of virtual cables is received [11].

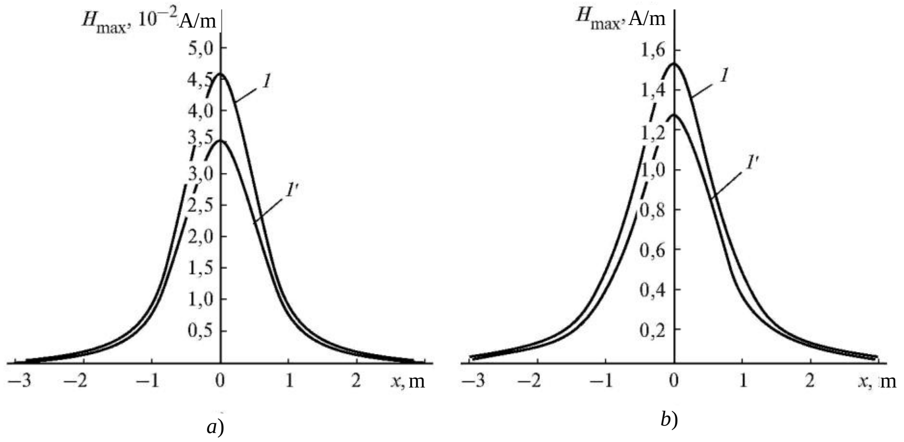
Patent applications of the Russian Federation on a design of electromagnetic screens for reactors without the ferromagnetic core, and also on a design of reactors without the ferromagnetic core, containing the shielding windings, are submitted.

Algorithms are developed, programs are made and certificates on official registration of programs on estimation of EFs of transmission lines, electromagnetic parameters of ALs of UHV and MFs, created by multi-layer and multi-row reactors without the ferromagnetic core [37, 38], are received.



a) *b*)

Fig. 5.41. Distribution of intensity of MF H_{max}, created at floor surface of living space by currents of CLs, arranged according to schemes from Fig. 5.36, *c* (*a*) and Fig. 5.36, *d* (*b*)



a) *b*)

Fig. 5.42. Distribution of intensity of MF H_{max}, created at floor surface of living space by currents of CLs, arranged according to schemes from Fig. 5.36, *d* (*a*) and Fig. 5.36, *e* (*b*)