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The complex influence of external and internal electricity networks on the magnetic field level in residential premises of buildings

*The **problem** of determining the complex influence of a group of electricity networks (external electricity networks, built-in transformer substations, cable electric heating systems, etc.) on the magnitude of the summary magnetic field (MF) in a residential premise of a building has not been sufficiently researched. This results in an overestimation of the assess the magnitude of the summary MF, generated by the group of electricity networks, as well as to the use of technical measures to reduce this MF, which have excessive efficiency and are accompanied by excessive expenses. The **goal** of the work is to investigate of the complex influence of external and internal electricity networks on the MF level in residential premises of buildings and definition of conditions, which provide the minimum necessary limitations on the MF flux density of individual electricity networks, at which the summary level of MF in residential premises, does not exceed the normative level of 0.5 μT. The **methodology** of determining the complex influence of the group of electricity networks on the level of MF in residential premises is based on the Biot-Savart's law and the principle of superposition and allows determining the functional dependence between the instantaneous values of currents in electricity networks, their geometrical and physical parameters, and the summary effective value of MF flux density in the premise. **Scientific novelty**. For the first time, the methodology for determining the complex influence of the group of external and internal electricity networks on the level of MF in residential premises is proposed. **Practical significance.** The implementation of the proposed methodology will allow to reduce the calculated coefficient of normalization of the MF of individual electricity networks by 25–50 %, which, in turn, will contribute to the reduction of economic costs for engineering means of normalizing the summary MF in residential premises, caused by the influence of the group of electricity networks.* References 56, tables 4, figures 8.
Key words: **magnetic field of a group of electricity networks, residential premises, high-voltage overhead power line, built-in transformer substations, cable electric heating system of the floors**.

***Проблема** визначення комплексного впливу групи електромереж (зовнішніх електромереж, вбудованих трансформаторних підстанцій, систем кабельного електрообігріву тощо) на величину сумарного магнітного поля (МП) в житловому приміщенні будинку не достатньо досліджена. Це призводить до завищеної оцінки величини сумарного МП, що створюється группою електромереж, а також до застосування технічних заходів зі зменшення цього МП, які мають надмірну ефективність і супроводжуються зайвими витратами. **Метою** роботи є дослідження комплексного впливу зовнішніх та внутрішніх електромереж на рівень МП в житлових приміщеннях будинків, та визначення умов, які забезпечують мінімально необхідні обмеження індукції МП окремих електромереж, за яких сумарний рівень МП в житлових приміщеннях не перевищує нормативний рівень 0,5 мкТл. **Методика** визначення комплексного впливу групи електромереж на рівень МП в житлових приміщеннях базується на законі Біо-Савара та принципі суперпозиції і дозволяє визначити функціональну залежність між миттєвими значеннями струмів в електромережах, їх геометричними і фізичними параметрами, та сумарним діючим значенням індукції МП в приміщенні. **Наукова новизна**. Вперше запропоновано методологію визначення комплексного впливу групи зовнішніх і внутрішніх електромереж на рівень МП в житлових приміщеннях. **Практична значимість**. Впровадження запропонованої методології дозволить зменшити розрахунковий коефіцієнт нормалізації МП окремих електромереж на 25–50 %, що, у свою чергу, сприятиме зменшенню економічних витрат на інженерні засоби нормалізації сумарного МП у житлових приміщеннях, зумовленого впливом групи електромереж.* Бібл. 56, табл. 4, рис. 8.
Ключові слова: **магнітне поле групи електромереж, житлові приміщення, високовольтні повітряні лінії електропередачі, вбудовані трансформаторні підстанції, кабельні системи електрообігріву підлог.**

Abbreviations

PL	power line	IPS	internal power supply system
TS	transformer substation	LVB	low-voltage busbar
CEHS	cable electric heating system	EN	electricity networks
MF	magnetic field		

Introduction. Reducing the MF of the industrial frequency of in residential buildings to a safe level is an important problem of protecting people's health from man-made electromagnetic impact [1–5]. The main sources of this impact are EN located near residential premises. As shown by the authors [6], unlike the electric field, the MF of EN penetrates through the walls in residential buildings with almost no attenuation.

In Ukraine, the maximum permissible level of power frequency MF flux density in residential premises is regulated by normative documents [7, 8]. According to them, the effective value of MF flux density should not exceed of 0.5 μT inside the premises and of 3 μT at a distance of 0.5 m from their walls. Therefore, when designing new or modernizing existing EN, technical measures are applied [9, 10], are aimed at limiting the MF flux density inside residential premises to the normative level of 0.5 μT. Now the measures are aimed at individually reducing the MF flux density of each EN to the normative level (0.5 μT).

The greatest impact on residential buildings according to MF is exerted by EN located closer than 100 m from them (Fig. 1). These high-voltage overhead PL of 0.4–330 kV [11], LVB of built-in TS of 6/(10)0.4 kV [12], CEHS of the floors [13], and IPS of residential premises [14, 15].

Many scientific researches have been devoted to the creation of effective methods for modeling, calculating and normalizing the MF of EN [10, 16–52]. However, still remains insufficiently researched the distribution of MF in residential premises of buildings under the condition of simultaneous the complex influence of several (n) different EN (Fig. 1).

Even if the influence of each of these EN will be limited by flux density $\widetilde{B}_{norm}$ = 0.5 μT (normalized), then with their complex influence, the summary MF flux density can significantly exceed the normative level of 0.5 μT. Since the level $\widetilde{B}_{\Sigma}$ depends on numerous parameters of the EN, its magnitude can vary within $\widetilde{B}_{\Sigma} \in \left(\widetilde{B}_{norm}(1...n)\right)$ and will approach the maximum boundary value $n\widetilde{B}_{norm}$.

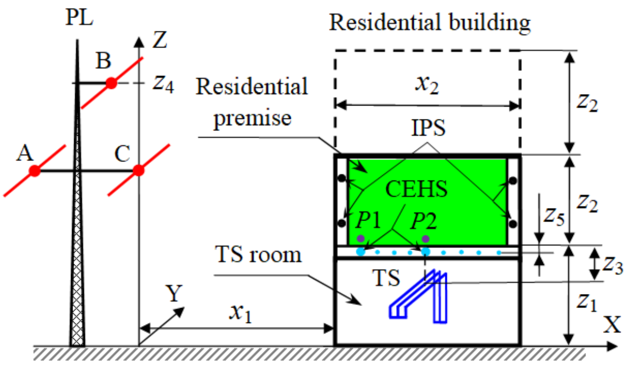


Fig. 1. The residential building with the built-in transformer substation (TS), which is an element of the electrical complex consisting of the external (PL) and internal (TS, CEHS, IPS) electricity networks

There is no possibility to determine the real level of the summary MF $\widetilde{B}_{\Sigma}$ forces us to take into account its maximum limit value $n\widetilde{B}_{norm}$. This leads to its excessive reduction ($\widetilde{B}_{\Sigma}$<0.5 μT), as well as to the unjustified increase in the cost of engineering means of the MF normalizing.

Therefore, it is relevant to study the complex influence of a group of EN at the MF level in residential premises in order to determine cost-effective limitation of the MF flux density for individual EN, at which the summary value of the MF in residential premises corresponds to the normative level $\widetilde{B}_{norm}$ = 0.5 μT.

The goal of the work is to investigate the complex influence of external and internal electricity networks on the MF level in residential premises of buildings and definition of conditions, which provide the minimum necessary limitations on the MF flux density of individual electricity networks, at which the summary level of MF in residential premises, does not exceed the normative level of 0.5 μT.

Assumptions adopted during the analysis.

1) The effective value of the MF flux density and its spatial components are investigated.

2) The supply voltages of the EN are synchronized, have a frequency of 50 Hz, and cosφ = 1.

3) The current conductors of all EN are oriented parallel to the coordinate axes.

4) The currents in EN are sinusoidal, symmetrical, and modeled by current filaments with different directions of power transfer.

5) There are no ferromagnetic and electrically conductive elements and the additional sources of MF in the studied area.

6) The MF flux density of each of the n EN is independent on the MF of other EN and depends linearly on its current.

7) The PL MF is three-phase two-dimensional, the TS MF is three-phase three-dimensional and is modeled by its LVB, the CEHS MF characterized by the vertical z component and is modeled by straight sections of two-wire heating cables, powered by a voltage of 220 V.

8) The IPS is powered by a voltage of 220 V, modeled by standard two-wire cables with a current of up to 30 A, which are mounted in the walls of a residential premises.

The adopted assumptions do not introduce a significant error in the analysis and allow us to take into account the worst cases when the impact of EN on magnetic field of premise is maximized.

Determination of the complex influence of the EN group. The complex influence of n different EN (PL, TS, CEHS, IPS) on the MF flux density distribution in a residential premise can be determined by summing the instantaneous values of spatial components $b_x(t)$, $b_y(t)$, $b_z(t)$ of MF flux density of each of these EN according to relations:

$$b_{\Sigma i,\lambda,x}(P,t)=\sum_{i=1}^{n}\beta^{i}b_{\lambda,x}(P,t); \quad (1)$$

$$b_{\Sigma i,\lambda,y}(P,t)=\sum_{i=1}^{n}\beta^{i}b_{\lambda,y}(P,t); \quad (2)$$

$$b_{\Sigma i,\lambda,z}(P,t)=\sum_{i=1}^{n}\beta^{i}b_{\lambda,z}(P,t). \quad (3)$$

In this case, the parameters of the studied EN are determined by the relations:

$$\beta^{i} \in (-1,+1),\ \omega = 2pf,\ f = 50 \text{ Hz}; \quad (4)$$

$$\lambda = A,B,C;\ i = 1 \equiv \text{PL},\ i = 2 \equiv \text{TS},\ i = 3 \equiv \text{CEHS}, \quad (5)$$

$$A^{i} \sim \sin(\omega t - \varphi_i), \quad (6)$$

$$B^{i} \sim \sin(\omega t + 2\pi/3 - \varphi_i), \quad (7)$$

$$C^{i} \sim \sin(\omega t - 2\pi/3 - \varphi_i), \quad (8)$$

where A, B, C are the phases of EN; i, n are the number and quantity of EN; β^{i} is the current direction coefficient; φ_i is the current shift angle respectively to voltage; x, y, z are the coordinate axes; P is the observation point.

We also take into account additional conditions caused by the above assumptions:

$$\varphi_{PL} = 0;\ \varphi_{TS} = 0;\ \varphi_{CEHS} = p/6, \quad (9)$$

$$b_{PL\ y}(P) = b_{CEHS\ x}(P) = b_{CEHS\ y}(P) = 0. \quad (10)$$

The magnitude of the influence of the EN group on the population through the MF is determined by calculating the effective value of the MF flux density, which is subject to sanitary regulation [7, 8] and physical measurements. The MF flux density effective values are defined as [17, 49]:

$$\tilde{B}_i(P)=\sqrt{\frac{1}{T}\int_0^T [b_i(P,t)]^2 \mathrm{d}t}\ ,\ T=2\pi/\omega\ . \qquad (11)$$

Then, using (1–3) and (11), we get:

$$\tilde{B}_{\Sigma i,\lambda,x}(P,t)=\sqrt{\frac{1}{T}\int_0^T \left(b_{\Sigma i,\lambda,x}(P,t)\right)^2 \mathrm{d}t}\ , \qquad (12)$$

$$\tilde{B}_{\Sigma i,\lambda,y}(P,t)=\sqrt{\frac{1}{T}\int_0^T \left(b_{\Sigma i,\lambda,y}(P,t)\right)^2 \mathrm{d}t}\ , \qquad (13)$$

$$\tilde{B}_{\Sigma i,\lambda,z}(P,t)=\sqrt{\frac{1}{T}\int_0^T \left(b_{\Sigma i,\lambda,z}(P,t)\right)^2 \mathrm{d}t}\ . \qquad (14)$$

The integration operation in the ratios (12–14) according to (11) can be carried out by numerical methods, based on specialized computer programs, or analytically.

The searched effective value of the MF flux density module for n the group of EN $\tilde{B}_{\Sigma}(P)$ is defined as rms sum of effective values of the spatial components x, y, z of (12–14):

$$\tilde{B}_{\Sigma}(P)=\sqrt{\left[\tilde{B}_{\Sigma i,\lambda,x}(P)\right]^2+\left[\tilde{B}_{\Sigma i,\lambda,y}(P)\right]^2+\left[\tilde{B}_{\Sigma i,\lambda,z}(P)\right]^2}\ . \qquad (15)$$

In accordance with current normative [7, 8], effective value of the MF flux density $\tilde{B}_{\Sigma}(P)$, given by (15), should not exceed the normative $\tilde{B}_{norm}$ = 0.5 μT value inside the residential premise.

Research of the impact of individual EN. Based on the obtained relations of (1–15), we will determine the individual influence of the PL, TS, and CEHS on the MF level in a residential premise (Fig. 1). To do this, we will determine the instantaneous values of the spatial components x, y, z the MF flux density of the individual EN under consideration.

For overhead power line the instantaneous values of the spatial components, their MF flux density are determined according to the results obtained by the authors in [12, 22, 25] relations:

$$b_{A,x}(P)=\frac{\mu_0 I_A}{2\pi}\cdot\frac{z-z_A}{r_A^2}\sin(\omega t-\varphi), \qquad (16)$$

$$b_{A,z}(P)=\frac{\mu_0 I_A}{2\pi}\cdot\frac{x-x_A}{r_A^2}\sin(\omega t-\varphi), \qquad (17)$$

$$b_{B,x}(P)=\frac{\mu_0 I_B}{2\pi}\cdot\frac{z-z_B}{r_B^2}\sin\left(\omega t+\frac{2\pi}{3}-\varphi\right), \qquad (18)$$

$$b_{B,z}(P)=\frac{\mu_0 I_B}{2\pi}\cdot\frac{x-x_B}{r_B^2}\sin\left(\omega t+\frac{2\pi}{3}-\varphi\right), \qquad (19)$$

$$b_{C,x}(P)=\frac{\mu_0 I_C}{2\pi}\cdot\frac{z-z_C}{r_C^2}\sin\left(\omega t-\frac{2\pi}{3}-\varphi\right), \qquad (20)$$

$$b_{C,z}(P)=\frac{\mu_0 I_C}{2\pi}\cdot\frac{x-x_C}{r_C^2}\sin\left(\omega t-\frac{2\pi}{3}-\varphi\right), \qquad (21)$$

$$r_A^2=(x-x_A)^2+(z-z_A)^2,$$
$$r_B^2=(x-x_B)^2+(z-z_B)^2,$$
$$r_C^2=(x-x_C)^2+(z-z_C)^2. \qquad (22)$$

For the built-in TS, the instantaneous values of the spatial components are determined according to [13] based on the Biot-Savart's law and the superposition principle [53, 54]. They are obtained by summing the components of the MF flux density, which is created by each of the straight-line sections $L1$–$L5$ (Fig. 2) of LVB TS. For example, the components of the MF flux density for the A phase are defined as [13]:

$$b_{A,x}(P)=\sum_n^N b_{zx}\left(I_{A,z,n}, x_{0,n}, y_{0,n}, z_{1,2,n}\right)\sin(\omega t+\varphi)+$$
$$+\sum_k^K b_{yx}\left(I_{A,x,k}, x_{0,k}, y_{1,2,k}, z_{0,k}\right)\sin(\omega t+\varphi), \qquad (23)$$

$$b_{A,y}(P)=\sum_n^N b_{zy}\left(I_{A,z,n}, x_{0,n}, y_{0,n}, z_{1,2,n}\right)\sin(\omega t+\varphi)+$$
$$+\sum_v^V b_{xy}\left(I_{A,x,v}, x_{1,2,v}, y_{0,v}, z_{0,v}\right)\sin(\omega t+\varphi), \qquad (24)$$

$$b_{A,z}(P)=\sum_v^V b_{xz}\left(I_{C,x,v}, x_{1,2,v}, y_{0,v}, z_{0,v}\right)\sin(\omega t+\varphi)+$$
$$+\sum_k^K b_{yz}\left(I_{C,y,k}, x_{0,k}, y_{1,2,k}, z_{0,k}\right)\sin(\omega t+\varphi), \qquad (25)$$

where $I_{A,z,n}$, $x_{0,n}$, $y_{0,n}$, $z_{1,2,n}$ are the current and coordinates of the ends of the n-th straight-line section of the parallel Z-axis; $I_{A,y,k}$, $x_{0,k}$, $y_{1,2,k}$, $z_{0,k}$ are the current and coordinates of the ends of the k-th straight-line section of the parallel Y-axis; $I_{C,x,v}$, $x_{1,2,v}$, $y_{0,v}$, $z_{0,v}$ are the current and coordinates of the ends of the v-th straight-line section of the parallel X-axis; N, K, V are the number of straight-line sections parallel to the axis Z, Y, X respectively.

For the phases B and C of the busbar, the MF flux density components are determined similarly [13].

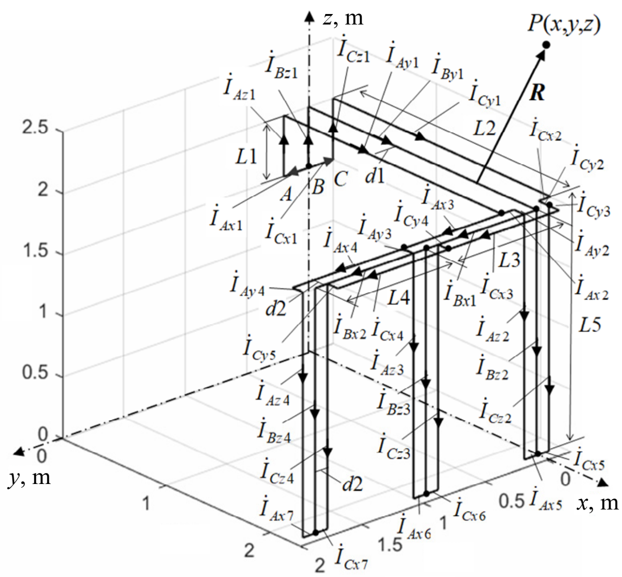


Fig. 2. The investigated low-voltage busbar TS 100 kVA 6(10)/0.4 kV

The cable electric heating system. In order to simplify the analysis and consider the worst case with maximum of the MF [10]. The CEHS is replaced by two straight sections of two-core heating cables (Fig. 1), laid under the floor of the premise, which are parallel to the y-axis: the first section is located at a distance of 0.5 m from the wall (point $P1$), and the x coordinate of the second segment axis (point $P2$) coincides with the x coordinate of the middle phase of the LVB TS (Fig. 2). If the CEHS is made of a two-wire heating cable with current I_{CEHS} then instantaneous maximum value of the CEHS MF flux density is determined by its spatial component z [12].

When powered from a single-phase EN of 220 V, this flux density will be:

$$b_{A,z}(r,P)=\frac{\mu_0}{2\pi}\frac{\sqrt{2}\cdot I_{\text{CEHS}}\cdot d}{\left[r^2+(0{,}5d)^2\right]}\sin(\omega t-\varphi), \qquad (26)$$

where $\mu_0 = 4\pi\cdot 10^{-7}$ H/m; d is the distance between the axes of the cable cores; r is the distance from the cable axis to the observation point P, $\varphi = \pi/6$ is the phase shift between the linear current of phase A of the PL (TS) and the corresponding phase current of the CEHS.

The internal EN IPS has the current of up to 30 A and powered by one of the 220 V phase of the EN of building. The IPS is executed from standard two-wire cables laid in the walls with a distance between the cores of no more than 4 mm. At the same time, according to (26), the maximum value of the MF flux density generated by the cable at the current of 30 A at the distance of 0.5 m from the wall of the dwelling will not exceed of 0.1 μT. Therefore, in further analysis, the influence of IPS can be neglected due to the insignificant level of flux density of their MF.

Investigation on the complex influence of EN. The above analysis and obtained relations of (1–21) allow us to investigate the distribution of the effective value of the MF of PL, TS, CEHS in residential premise (Fig. 1). When studying, the complex influence of MF from the group of n EN, the most likely is the occurrence of this influence from the pair PL+CEHS EN. Less likely is the influence of the combination TS+PL or TS+CEHS, as well as from three EN PL+TS+CEHS. However, from the point of view of ensuring the safety of the population's health, it is expedient to study all the mentioned variants of complex influence.

Parameters of the investigated EN. As an external EN, we consider the typical overhead of the 110 kV PL, 250 A with a triangular suspension of phase wires oriented parallel to the y-axis (Fig. 1). The wires coordinates are: A (–6.3 m; 7 m), B (–2.1 m; 13 m), C (0 m; 7 m), $x1$ = 20 m.

We consider the TS with the 100 kVA power as, an example of the built-in TS (Fig. 1), which is modeled by the LVB (Fig. 2) in accordance with [10]. The LVB parameters: $d1$ = 0.16 m, $d2$ = 0.05 m, $L1$ = 0.5 m, $L2$ = 2.2 m, $L3$ = $L4$ = 0.9 m, $L5$ = 2 m, the nominal current of I = 150 A, the currents of straight-line sections of the busbar ($L1$ – $L5$): $I1 = I2 = I$, $I3 = I\cdot 2/3$, $I4 = I5 = I/3$.

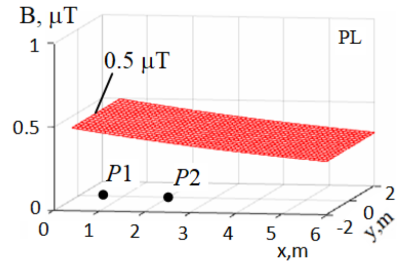
The CEHS is executed from standard two-wire heating cables oriented parallel to the y-axis with the distance between the wires 2.2 mm, has a nominal current of 10 A, $z5$ = 0.05 m, powered by the phase voltage of one of the phases (a, b, c) of the apartment EN of 220 V. The CEHS cables is represented as straight-line segments oriented parallel to the y-axis that according to [10] allows modeling the maximum CEHS MF in the place of laying the cable. The observation points $P1$, $P2$ (Fig. 1) are located between current conductors PL and busbar TS, CEHS. The residential building (Fig. 1) has the TS room located on the 1st floor, and the residential premise on the 2nd floor above the TS, $z1$ = 3.5 m, $z2$ = 2.5 m, $z3$ = 2.5 m, $z4$ = 13 m. When calculating the summary MF it is taken into account that the observation points $P1$, $P2$ (Fig. 1) are located between current conductor PL and busbars TS.

Complex influence investigate methodology. The investigation of the complex influence is carried out by the relations (1–26) applying computer modeling in the MATLAB software environment [55].

1. We set the initial values of the currents (I_{in}) of PL, TS, CEHS, at which each of these EN separately creates the MF in the premises (Fig. 3), flux density which is equal to the normative level of 0.5 μT:

$$\widetilde{B}_{PL}=\widetilde{B}_{TS}=\widetilde{B}_{\text{CEHS}}=\widetilde{B}_{norm}\,. \qquad (27)$$

At the same time, the control point for the PL is the closest point to it $P1$ (Fig. 1), and for the TS and CEHS this is a point $P2$ (Fig. 1), the x coordinate which coincides with the x coordinate middle phase of the busbar $L2$ of TS (Fig. 2). At these points the summary MF flux density will be maximum.



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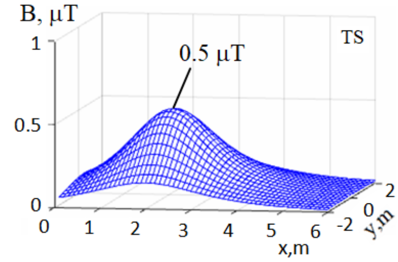

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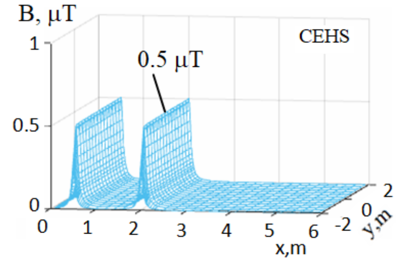

c

Fig. 3. Distribution of the MF flux density in the residential building under the individual influence of different EN, the flux density of which corresponds to the normative level (a – PL, b – TS, c – CEHS)

2. Calculate the summary MF $\widetilde{B}_{\Sigma}$, created by the PL, TS, CEHS when the condition (27) are fulfilled. The results obtained for different combinations of EN parameters are included in Table 1.

3. We reduce the current proportionally I_{in}, of each EN according to point 1 of the methodology to the level, when their summary value $\widetilde{B}_{\Sigma 1}$ decreases to the level $\widetilde{B}_{norm} = 0.5$ μT for each item in Table 1. At the same time, the MF flux density each of the EN $\widetilde{B}_{\Sigma norm}$ is the same in accordance with (27):

$$\widetilde{B}_{\Sigma norm} = \widetilde{B}_{PL} = \widetilde{B}_{TS} = \widetilde{B}_{CEHS}. \quad (28)$$

Next, we determine and enter into Table 1 the MF flux density value $\widetilde{B}_{\Sigma}$ subject to (27) and $\widetilde{B}_{\Sigma norm}$ each of the EN. Also we determine and fixate in Table 1 the values of the normalization coefficient K_m

$$K_m = \widetilde{B}_{\Sigma} / \widetilde{B}_{norm},\ K_m \in (1 \div n),\ \widetilde{B}_{\Sigma norm} = \widetilde{B}_{norm} / K_m. \quad (29)$$

It defines the necessary amount of reduction of the summary MF flux density $\widetilde{B}_{\Sigma}$ to achieve the normative level. Also we define the normalized summary MF flux density $\widetilde{B}_{\Sigma norm}$ of each of the EN, when reaching which their summary level is reduced to 0.5 μT.

4. Similar actions under p. 1–3 are carried out when studying the complex influence of two different EN in combination PL–TS, PL–CEHS, TS–CEHS. The calculation results are entered in Tables 2–4.

The most characteristic investigate results are presented in the form of graphs in Fig. 5–8.

Analysis of result. For the TS–PL pair (Table 2, Fig. 5) the maximum value $\widetilde{B}_{\Sigma}$ reaches 0.85 μT with opposite signs of currents EN and requires reduction of the MF flux density each of these sources to 1.7 times (from 0.5 μT to 0.29 μT), and the minimum value $\widetilde{B}_{\Sigma}$ is 0.7 μT occurs when the direction of the TS and PL. For the TS–CEHS pair (Table 3, Fig. 6) the maximum value $\widetilde{B}_{\Sigma}$ reaches 0.86 μT at supply of CEHS from phase +A (+B) and minimal (0.57 μT) at supply of CEHS from phase +C (–B). For the PL–CEHS pair (Table 4, Fig. 7) the maximum value $\widetilde{B}_{\Sigma}$ is 0.89 μT at supply of CEHS from phase +A (–A) and minimal (0.59 μT) at supply of CEHS from phase –C. Thus, for groups of two considered EN, the maximum value $\widetilde{B}_{\Sigma}$ is 0.89 μT, and minimal is 0.57 μT. At the same time, for the normalization of MF of these EN, the necessary normalization coefficient K_m will be from 1.06 to 1.96 units and at $n = 2$ approaches the limit values – 1 or 2 units.

For the group of TS, PL, CEHS (Table 1, Fig. 8) maximum value $\widetilde{B}_{\Sigma}$ is 1.32 μT and occurs with opposite currents of TS and PL and supply of CEHS from the –C phase, and the minimum value is 0.66 μT at the direction of the currents coincides of TS and PL and supply of CEHS from the +B phase. At the same time, for the normalization MF these three *(n* = 3) EN, the necessary normalization coefficient K_m consists of 1.32 to 2.64 units. Changing the order of phase alternation does not significantly affect the MF level.

Additional studies also show that changing the geometry of the 110 kV PL wire suspension from triangular (Fig. 1) to horizontal or vertical does not fundamentally affect the value $\widetilde{B}_{\Sigma}$.

For all groups of EN, the values and K_m significantly depend on the CEHS supply parameters (current sign and supply phase), which creates conditions for minimizing the MF value in the premise by the consumer.

The results of modeling using the developed methodology of (1–29) were confirmed by experimental tests (Fig. 4), carried out at the magnetic measuring stand Anatolii Pidhornyi Institute of Power Machines and Systems of NAS of Ukraine (IEMS of NAS of Ukraine) [56]. The deviation between the results of modeling and experiment did not exceed 10 %.

Thus, to normalize the complex influence of two normalized MF EN, it is necessary to reduce the MF flux density of each of them from 1.06 to 1.96 times, and for three normalized EN – reduction from 1.32 to 2.64 times. The implementation of the proposed methodology will reduce normalization coefficient K_m their MF from maximum values of 3 (2) units to minimum values of 1.32 (1.06) units, what provides reduction of this coefficient by 25–50 % and accordingly reduces economic losses on the MF normalization.

Peculiarities of normalization of the complex influence of the EN group on MF. To normalize the complex influence of the group of *n* already pre-normalized EN, the MF which does not exceed 0.5 μT, the use the above research methodology. For this, such well-known engineering methods of reducing the MF of EN can be introduced [9, 10]. They include: protection by distance, active and passive shielding, constructive-technological measures.

The choice of these methods is based of the technical and economic analysis.

Obviously, the smaller normalization coefficient K_m, the lower the economic costs of practical implementation of the normalization will be needed.

Therefore, the minimization of the K_m is the important task of MF normalization, which, first of all, it is advisable to implement by means of the proposed methodology based on the determination of all actual parameters of the group of EN given in Tables 1–4. Significant reduction K_m also possible through the implementation of an optimal power supply regime CEHS.

More difficult will be the normalization of the complex influence for the EN group, the each of which have not yet been normalized and have an excess of the MF above the normative level of 0.5 μT. In this case, the required initial normalization coefficient of the MF $K_{m,n,i} = \widetilde{B}_i / \widetilde{B}_{norm}$ for the each *i*-th EN is first determined. At the second stage, the final normalization coefficient $K_{m,i}$ is calculated:

$$K_{m,i} = K_{m,n,i} K_m. \quad (30)$$

a b

Fig. 4. Laboratory installation for the study of the complex effect of PL+TS, created on the magnetic measuring stand of the IEMS NAS of Ukraine (a – physical model of a low-voltage busbar of the TS, 150 A; b – physical model of the PL 150 A)

Table 1

The effective value of flux density of the summary MF TS+PL+CEHS $\tilde{B}_{\sum}$, value $\tilde{B}_{\sum norm}$ and coefficient K_m when changing the currents signs, the order of phase alternation (ABC–ACB) and the power supply phases of CEHS

№	TS β^n, ABC	PL β^n, ABC	CEHS β^n, phase	$\tilde{B}_{\sum}$ μT	$\tilde{B}_{\sum norm}$ μT	K_m
1	+	+	+, a	0.84	0.3	1.68
2	+	+	–, a	0.84	0.3	1.68
3	+	–	+, a	1.14	0.22	2.28
4	+	–	– , a	0.97	0.26	1.94
5	+	+	+ , b	0.66	0.38	1.32
6	+	+	– , b	0.69	0.36	1.38
7	+	–	+ , b	1.22	0.2	2.44
8	+	–	– , b	0.94	0.27	1.88
9	+	+	+ , c	0.93	0.27	1.86
10	+	+	– , c	0.79	0.32	1.58
11	+	–	+ , c	0.91	0.28	1.82
12	+	–	– , c	1.32	0.19	2.64
13	+	+	+ , a	1.09	0.23	2.18
14	+	+	–, a	0.91	0.28	1.82
15	+	–	+, a	1.12	0.22	2.24
16	+	–	– , a	0.79	0.32	1.58
17	+	+	+ , b	0.77	0.33	1.54
18	+	+	– , b	1.09	0.23	2.18
19	+	–	+ , b	0.87	0.29	1.74
20	+	–	– , b	0.87	0.29	1.74
21	+	+	+ , c	0.96	0.26	1.92
22	+	+	– , c	0.81	0.31	1.62
23	+	–	+ , c	0.74	0.34	1.48
24	+	–	– , c	1.11	0.23	2.22

Thus, proposed by the authors the methodology for determining the complex influence of the EN group on the level of MF in residential premises is based on (1–30) and includes analytical methods, calculation and assessment of the impact of external and internal EN (PL, TS, CEHS). It allows to identify and implement conditions for economically feasible limitation of the MF flux density of individual EN, at which the summary level of MF in residential premises does not exceed the normative level of 0.5 μT.

Table 2

The effective value of flux density of the summary MF TS+PL $\tilde{B}_{\sum}$, value $\tilde{B}_{\sum norm}$ and coefficient K_m at changing the order of phase alternation and current signs

№	TS β^n	PL β^n	$\tilde{B}_{\sum}$, μT	$\tilde{B}_{\sum norm}$ μT	K_m
1	+ ABC	+ ABC	0.53	0.47	1.06
2	+ ABC	–ABC	0.85	0.29	1.7
3	+ ABC	+ ACB	0.7	0.36	1.4
4	+ABC	– ACB	0.7	0.36	1.4

Table 3

The effective value of flux density of the summary MF TS+CEHS $\tilde{B}_{\sum}$, value $\tilde{B}_{\sum norm}$ and coefficient K_m at changing current sign and power supply phase CEHS

№	TS β^n, ABC	CEHS β^n, phase	$\tilde{B}_{\sum}$, μT	$\tilde{B}_{\sum norm}$ μT	K_m
1	+	+ , a	0.87	0.29	1.74
2	+	– , a	0.56	0.45	1.12
3	+	+ , b	0.86	0.29	1.72
4	+	– , b	0.57	0.44	1.14
5	+	+ , c	0.57	0.44	1.14
6	+	– , c	0.98	0.26	1.96

Table 4

The effective value of flux density of the summary MF PL+CEHS $\tilde{B}_{\sum}$, value $\tilde{B}_{\sum norm}$ and coefficient K_m at chan ging current sign and power supply phase CEHS

№	PL β^n, ABC	CEHS β^n, phase	$\tilde{B}_{\sum}$, μT	$\tilde{B}_{\sum norm}$ μT	K_m
1	+	+ , a	0.77	0.33	1.54
2	+	– , a	0.79	0.32	1.58
3	+	+ , b	0.64	0.39	1.28
4	+	– , b	0.9	0.28	1.8
5	+	+ . c	0.89	0.28	1.78
6	+	– , c	0.59	0.42	1.18

Taking into account the importance of the practical implementation of the proposed methodology to reduce the complex influence of external and internal EN on the MF level in residential premises of buildings, it is necessary to consider the draft amendments to the regulatory documents of the Ministry of Energy [7, 8, 22], and State Building Standards [15].

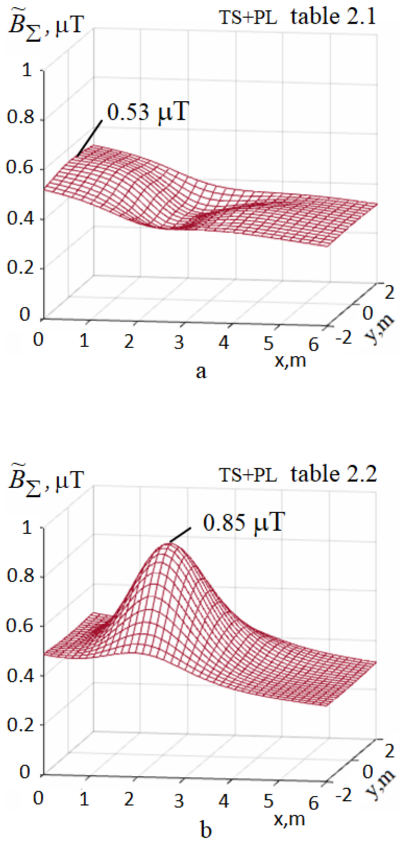

Fig. 5. Total minimum (a) and maximum (b) influences of the PL+TS to the level $\tilde{B}_{\Sigma}$

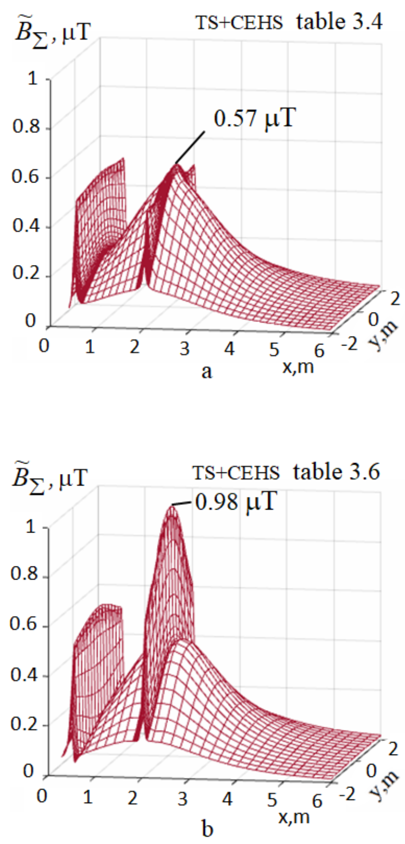

Fig. 6. Total minimum (a) and maximum (b) influences of the TS + CEHS to the level $\tilde{B}_{\Sigma}$

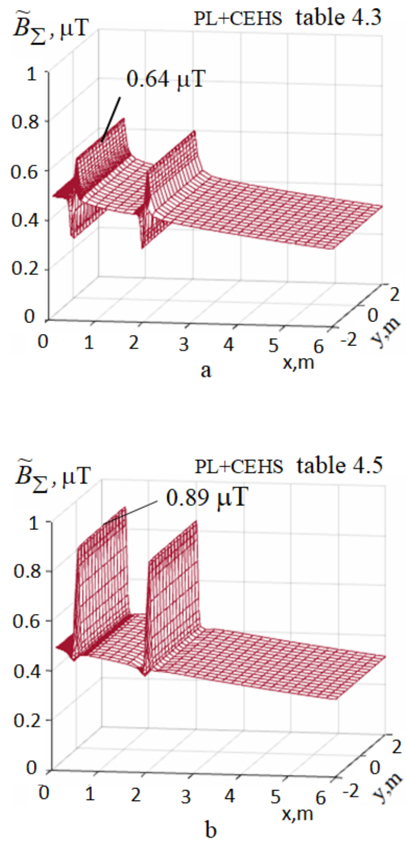

Fig. 7. Total minimum (a) and maximum (b) influences of the PL + CEHS to the level $\tilde{B}_{\Sigma}$

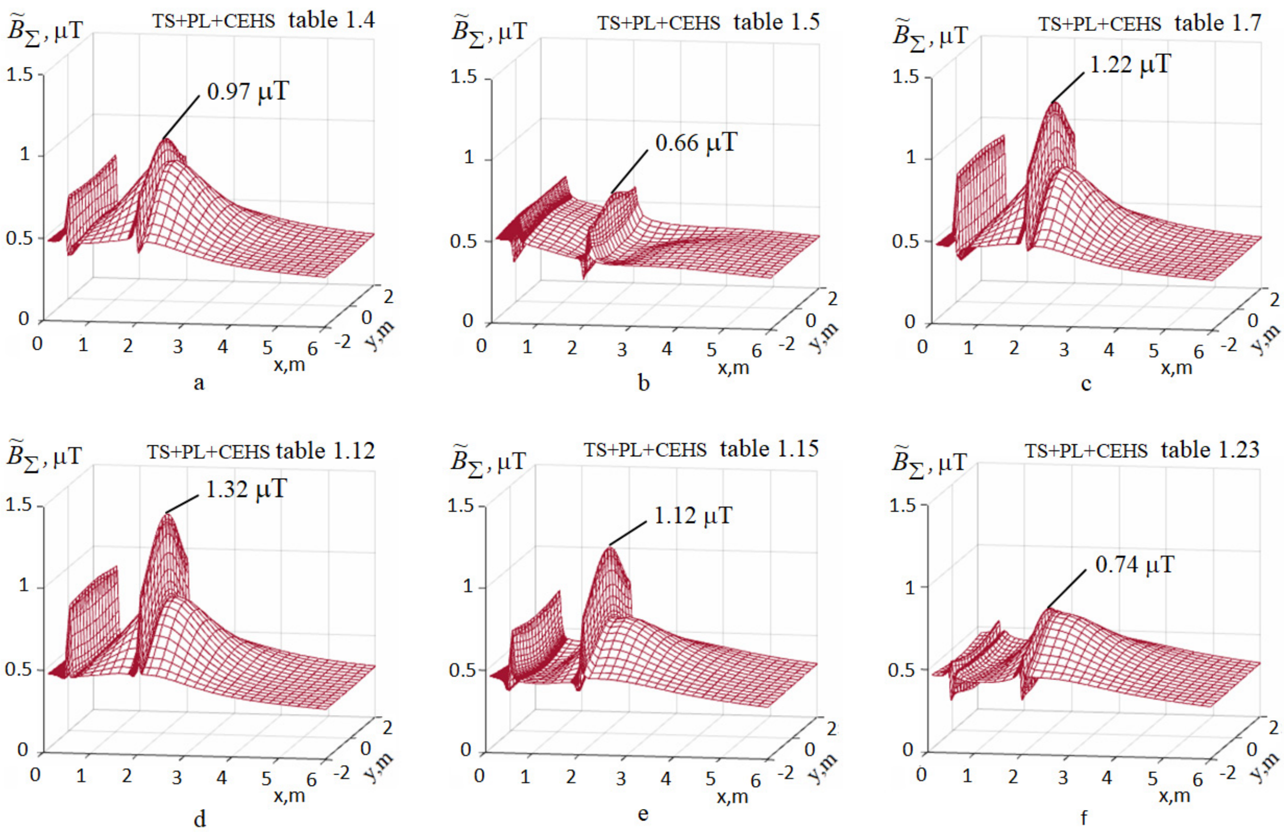

Fig. 8. Characteristic total influences of the PL + TS + CEHS on the level $\tilde{B}_{\Sigma}$

Conclusions.

1. Uncertainty of the processes of complex influence of the magnetic field of the group with *n* electricity networks on the level of the magnetic field in residential premises may lead to the usage of methods to reduce the induction of their magnetic field with overefficiency, and cause irrational economic losses.

2. The methodology for determining the complex influence of the group of electricity networks on the level of the magnetic field in residential premises is proposed. This approach is based on Biot-Savart's law and the principle of superposition. At the same time, the functional dependence between the instantaneous values of currents in electricity networks, their geometric and physical parameters, as well as the total effective value of the magnetic field flux density in the premise is taken into account. The technique makes it possible to establish the minimum necessary limits of the magnetic field flux density for individual electricity networks to normalize the summary magnetic field in the premise.

3. The method for normalizing the summary magnetic field is proposed, which is formed by the group of electricity networks in the residential premise, based on the above methodology. This method allows you to determine the actual level of the summary magnetic field in the premise and, on this basis, develop cost-effective measures to normalize the magnetic field in the premise.

4. It is theoretically substantiated and experimentally confirmed that the implementation of the proposed methodology for determining the complex influence of real electricity networks (overhead PL of 110 kV, built-in TS of 6/10 kV, cable electric heating system of 2.2 kW) allows reduction of the normalization coefficient K_m of magnetic field of individual electricity networks on 25 – 50 %, which allows to reduce the economic costs of normalizing the magnetic field in the premise accordingly.

5. Taking into account the importance of the practical implementation of the proposed methodology for cost-effective reduction of the impact of the group of electricity networks on the magnetic field level in residential premises to values that are safe for the population, it is planned to prepare draft amendments to the regulatory documents of the Ministry of Energy and the State Construction Standards.

Conflict of interest. The authors declare that they have no conflicts of interest.

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