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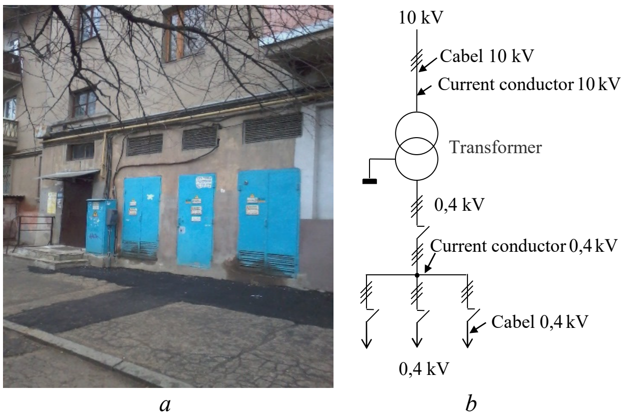
Simulation of the magnetic field in residential buildings with built-in substations based on a two-phase multi-dipole model of a three-phase current conductor

Problem. *Substations 10(6)/0.4 kV built into residential buildings create a magnetic field with magnetic flux density of more than 10 μT in nearby residential premises, which is a danger to the health of the population and makes the study of this magnetic field relevant for the development of methods for its protection. The main source of the substations external magnetic field is their low-voltage current conductor, the contribution of which to the total level of the magnetic field is more than 90 %. Multi-dipole mathematical models, which have a clear physical interpretation, are a promising method of modeling the substations magnetic field, which is important for the further development of methods of population protection. The* ***purpose*** *of the work is to modify the well-known multi-dipole model for calculation based on it with a limited error of the external magnetic field of current conductors of built-in substations that are close to residential buildings at a distance of up to one meter.* ***Methodology.*** *A modified two-phase multi-dipole mathematical model of the main source of the external magnetic field of substation – its three-phase low-voltage current conductors – is proposed, which, unlike the existing model, is based on a two- you to halve the distance to the area of calculation without increasing the error.* ***Verification***. *An experimental verification of the modified two-phase multi-dipole model of the magnetic field of a three-phase 100 kVA transformer substation on its full-scale physical model was carried out, and the results of the experiment were presented, confirming the coincidence of the calculation and the experiment with a spread of no more than 7 %.* References 37, tables 1, figures 10.
Key words: **built-in substation, residential building, current conductor, external magnetic field, multi-dipole mode**.

Вбудовані у житлові будинки трансформаторні підстанції (ТП) 10(6)/0,4 кВ створюють у сусідніх житлових приміщеннях магнітне поле з індукцією більш 10 мкТл, що складає небезпеку для здоров'я населення і робить актуальним дослідження цього магнітного поля для розробки методів від його захисту. Основним джерелом зовнішнього магнітного поля ТП є їх низьковольтні струмопроводи, вклад яких в загальний рівень магнітного поля складає більш 90 %. Перспективним методом моделювання магнітного поля ТП є мультидипольні математичні моделі, що мають чітку фізичну інтерпретацію, важливу для подальшої розробки методів захисту населення. Метою роботи є модифікація відомої мультидипольної моделі для розрахунку на її основі з обмеженою похибкою зовнішнього магнітного поля струмопроводів вбудованих трансформаторних підстанцій, що наближені до житлових приміщень на відстань до одного метра. Запропоновано модифіковану двофазну мультидипольну математичну модель основного джерела зовнішнього магнітного поля трансформаторної підстанції – його трифазного низьковольтного струмопроводу, яка на відміну від існуючої моделі ґрунтується на двофазній дипольній моделі трифазного електричного кола і дозволяє вдвічі наблизити розрахункову область без збільшення похибки. Здійснено експериментальну перевірку модифікованої двофазної мультидипольної моделі магнітного поля трифазного струмопроводу ТП 100 кВА на його повномасштабній фізичній моделі та наведені результати експерименту, що підтверджують співпадіння розрахунку і експерименту із розкидом не більш 7 %. Бібл. 37. табл. 1, рис. 10.
Ключові слова: **вбудована трансформаторна підстанція, житлове приміщення, струмопровід, зовнішнє магнітне поле, мультидипольна модель.**

Introduction. One of the main sources of magnetic field (MF) of power frequency, which pose a danger to the population, are transformer substations (TSs) 10(6)/0.4 kV (Fig. 1) built into residential buildings, which have power from 100 to 1260 kVA, and the study of MFs of which is receiving more and more attention in the world [1-26].



a *b*

Fig. 1. Built-in TS10/0.4 kV (*a*) and its simplified electrical circuit (*b*)

The magnetic flux density created by built-in TSs with power of 100 to 1260 kVA in neighboring residential premises located at a distance of 1-2 m above the TS can exceed 10 μT, which is confirmed as foreign (Fig. 2) [2, 3, 5, 21, 25, 26], as well as domestic (Fig. 3) studies [27]. This is more than an order of magnitude higher than the maximum permissible level of the magnetic flux density (0.5 μT) adopted in Ukraine [28], which requires its reduction. Therefore, the problem of modeling the MF of built-in TSs to determine their real level is relevant for the further development of means of its calculation and shielding on this basis [1, 4-15, 18, 27-31].

Justification of the topic of the article. As shown by the results of research by European scientists [2, 4, 6, 9], as well as research by authors [27], the main source of TSs MF is a low-voltage current conductor of 0.4 kV (Fig. 1,*b*), the external magnetic field (EMF) of which at a distance of 2 m is more than 90 % of the total TS's MF (Fig. 4). Therefore, for engineering calculations, the EMF of built-in TSs can be replaced by the EMF of their low-voltage current conductors.

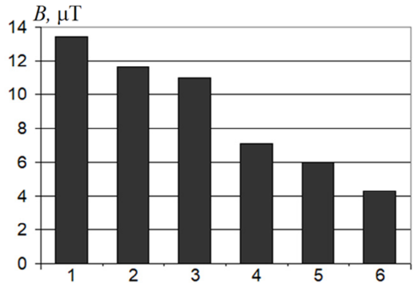


Fig. 2. Experimentally determined MFs in residential premises of buildings with built-in TSs of power of up to 1000 kVA in Europe (1 – Finland [21], 2 – Serbia [2], 3 – Hungary [3], 4 – Spain [25], 5 – Sweden [5], 6 – Switzerland [26])

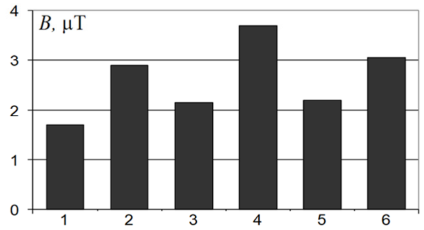


Fig. 3. Experimentally determined MFs in residential premises of houses with built-in TSs in the city of Kharkiv (1 – 360 kVA, 2 – 440 kVA, 3 – 630 kVA, 4 – 715 kVA, 5 – 565 kVA, 6 – 640 kVA)

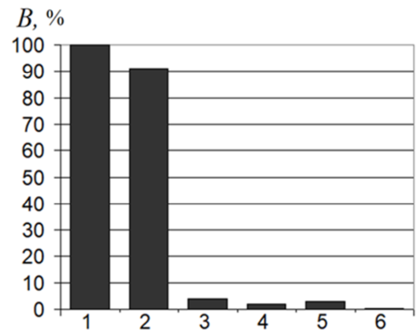


Fig. 4. The influence of individual sources of the TS's MF on the general level of the EMF at a distance of 2 m of them (1 – the total TS's MF; 2 – the MF of the low-voltage current conductor; 3 – the MF of the transformer; 4 – the MF of the low-voltage cable; 5 – the MF of the high-voltage current conductor; 6 – the MF of the high-voltage cable)

Three-phase current conductors of built-in TSs 10/04 kV 100 – 1260 kVA have straight sections located in horizontal (vertical) planes and are made of rigid aluminum (copper) busbars [28] with an interphase distance of up to 0.3 m.

A feature of the location of built-in TSs is the small distance between the surface of their current conductors and neighboring residential premises, which is from 1 to 2 m.

It is expedient to perform the modeling of the MF of the current conductors of the built-in TSs on the basis of the multi-dipole model (1) [27]. This model was developed to calculate the MF of power transmission lines (PTLs) [32]. It is suitable for modeling the three-dimensional MF of current conductors of any shape and has a clear physical interpretation, which simplifies the development of means of MF reduction based on it.

The multi-dipole model (1) is built on the basis of a system of dipole sources of the MF, which are characterized by magnetic moments $\vec{m}_i$ located in the geometric centers of independent rectangular microcircuits $d_i \times a$ with interphase current $\dot{I}_{AB}, \dot{I}_{BC}, \dot{I}_{CA}$ and areas $\vec{S}_{AB}, \vec{S}_{BC}, \vec{S}_{CA}$ into which all circuits of the interphase current of the current conductor are conventionally divided with length a:

$$\dot{\vec{H}}(P) = -\sum_{l=1}^{G} \sum_{\alpha=1}^{3} \sum_{c} \sum_{i=1}^{N} \nabla \left[\frac{\left(\dot{\vec{m}}_{l\alpha ci}, \vec{R}_{l\alpha ci} \right)}{4\pi R_{l\alpha ci}^{3}} \right]; \qquad (1)$$

$$\dot{\vec{m}}_{l\alpha ci} = \dot{I}_{l\alpha} \cdot \vec{S}_{l\alpha ci} = I_{l\alpha} \cdot e^{-j\varphi_\alpha} \cdot a \cdot d_{l\alpha ci} \cdot \vec{n}_{l\alpha ci},$$

where N is the number of microcircuits in each PTL circuit; $\vec{S}_i$ is the area vector of the i-th microcircuit; $\vec{n}_i$ is the unit vector normal to S_i; $\vec{R}_i$ is the radius vector from the geometric center of the i-th microcircuit to the observation point P; c are the parts of the PTL under investigation; α is the number of phases of the PTL; G is the number of split wires of each phase; $d_{l\alpha ci}$ is the current distance between the wires of different phases.

The error when using the multi-dipole model (1) also, like the dipole model [33], depends on the ratio of the maximum geometric size L of the object (microcircuit) and the distance R from its surface to the area of application, and is less than 10 % at $R/L \geq 3$. Therefore, for a guaranteed limitation of the error of model (1) at the level of 10 %, where $L = d_{\max}$, the following conditions must be met:

$$R \geq 3d_{\max} \text{ at } a_i \leq 2d, \qquad (2)$$

where $d_{\max}$ is the maximum interphase distance between the current conductors of the phases in the case of their location on the plane.

However, the use of the multi-dipole model (1) for the simulation of the TS's EMF has limitations. For example, this model with typical values of d = 0.3 m, $d_{\max}$ = 0.6 m allows to perform the calculation of the TS's EMF only at distances $R \geq 1.8$ m, since the interphase distance between the extreme phases, which determines the area S_{CA}, is $2d$ (Fig. 5,a). But the minimum value of R for built-in TSs is about 1 m, which limits the application of this model.

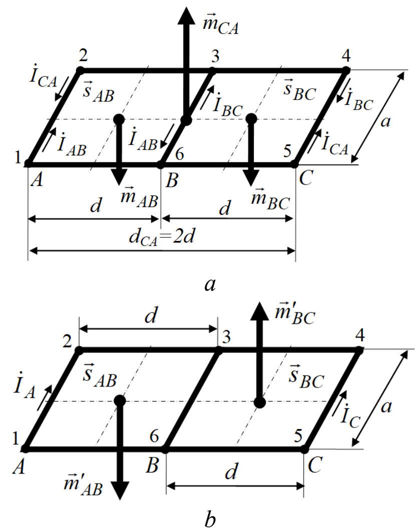


Fig. 5. Multi-dipole representation of an elementary three-phase circuit as a source of the MF: a) – traditional three-phase model; b) – two-phase model

Thus, the well-known multi-dipole model (1), which was developed for PTLs, needs modification to expand the scope of its application to built-in TSs with their typical minimum distances (from 1 m) from current conductors to residential premises.

The goal of the work is to modify the well-known multi-dipole model for calculation based on it with a limited error of the external magnetic field of current conductors of built-in transformer substations that are close to residential premises at a distance of up to 1 m.

A modified multi-dipole model of the current conductor of the built-in TS. When building a modified multi-dipole model of the TS's EMF, we believe that the walls of the TS, as well as the walls of buildings, practically do not shield the MF at frequency of 50 Hz [34, 35], and we accept the following assumptions:

- the premises of TS (except active elements of TS) and residential buildings do not have conductive and ferromagnetic elements and sources of MF;
- the currents of the current conductors are represented in the form of current filaments;
- the TS's MF is potential;
- all rectilinear parts of TS current conductors are flat and located either in a horizontal or in a vertical plane;
- the voltage of the TS power supply network is symmetrical and sinusoidal.

Let's transform the known multi-dipole model (1) for use on the TS, isolating the MF created by its interphase circuits with current:

$$\dot{\vec{B}}_S(P) = -\mu_0 \sum_{l=1}^{K}\sum_{i=1}^{N}\left[\nabla\left[\frac{\left(\dot{\vec{m}}_{ABli}, \vec{R}_{ABli}\right)}{4\pi R_{ABli}^3}\right] + \nabla\left[\frac{\left(\dot{\vec{m}}_{BCli}, \vec{R}_{BCli}\right)}{4\pi R_{BCli}^3}\right] + \nabla\left[\frac{\left(\dot{\vec{m}}_{CAli}, \vec{R}_{CAli}\right)}{4\pi R_{CAli}^3}\right]\right] \quad (3)$$

$$\dot{\vec{m}}_{ABli} = \dot{I}_{ABli}\cdot\vec{S}_{ABli},\ \dot{\vec{m}}_{BCli} = \dot{I}_{BCli}\cdot\vec{S}_{BCli},\ \dot{\vec{m}}_{CAli} = \dot{I}_{CAli}\cdot\vec{S}_{CAli}.$$

The condition for using model (3), which limits its error to 10 %, is relationship (2), which is not fulfilled at $R = 1$ m, since $d_{max} = 0.6$ m for it.

We will modify the known model (3). For this, we will use the two-phase model of the MF of the three-phase electric circuit (Fig. 5,*b*) proposed in [36], which is equivalent to the known three-phase model (Fig. 5,*a*) in terms of the space-time structure of the MF, but has half the maximum interphase distance. According to [36], the MF of an elementary three-phase current conductor with symmetry of the supply network voltages can be represented as a superposition of the MFs from 2 magnetic moments $\dot{\vec{m}}'_{AB}$, $\dot{\vec{m}}'_{BC}$, instead of three ones:

$$\dot{\vec{H}}(P) = -\nabla\frac{\left(\dot{\vec{m}}'_{AB}, \vec{R}_{AB}\right)}{4\pi R_{AB}^3} - \nabla\frac{\left(\dot{\vec{m}}'_{BC}, \vec{R}_{BC}\right)}{4\pi R_{BC}^3}, \quad (4)$$

$$\dot{\vec{m}}'_{AB} = \dot{I}_A\vec{s}_{AB},\ \ \dot{\vec{m}}'_{BC} = -\dot{I}_C\vec{s}_{BC}.$$

Here, the maximum overall size of the elementary microcircuit decreases from $2d$ (Fig. 5,*a*) to d (Fig. 5,*b*), which makes it possible to halve the distance to the area of application of the model – from $6d$ to $3d$ (up to 0.9 m at $d = 0.3$ m).

Then, on the basis of (4), we will obtain a modified two-phase multi-dipole mathematical model of the MF of the three-phase TS current conductor, consisting of K rectilinear circuits, which have N two-phase microcircuits:

$$\dot{\vec{B}}_S(P) = -\mu_0 \sum_{l=1}^{K}\sum_{i=1}^{N}\left[\nabla\left[\frac{\left(\dot{\vec{m}}_{ABli}, \vec{R}_{ABli}\right)}{4\pi R_{ABli}^3}\right] + \nabla\left[\frac{\left(\dot{\vec{m}}_{BCli}, \vec{R}_{BCli}\right)}{4\pi R_{BCli}^3}\right]\right], \quad (5)$$

$$\dot{\vec{m}}_{ABli} = \dot{I}_{Ali}\cdot\vec{S}_{ABli} = \dot{I}_{Ali}\cdot a_i\cdot d_l\cdot\vec{n}_{li},$$

$$\dot{\vec{m}}_{BCli} = -\dot{I}_{Cli}\cdot\vec{S}_{BCli} = -\dot{I}_{Cli}\cdot a_i\cdot d_l\cdot\vec{n}_{li},$$

where l is the number of the rectilinear circuit of the TS ($l = 1,\ldots, K$); N is the number of elementary microcircuits in the rectilinear contour l.

The condition for using model (5) with a limited error of 10 % is

$$R \geq 3d \ \text{ at } \ a_i \geq d\,;\ d_{\max} = d\,. \quad (6)$$

Figure 6,*b* presents a diagram of the distribution of magnetic moments of a low-voltage current conductor of a TS 100 kVA (Fig. 6,*a*) when implementing the proposed modified two-phase multi-dipole model (5).

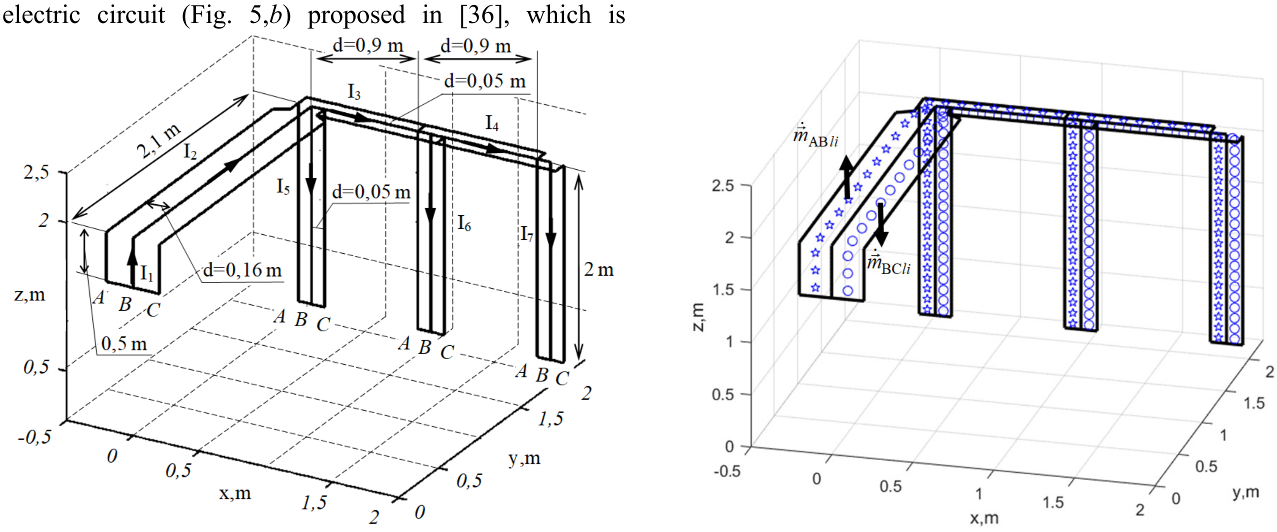


Fig. 6. Low-voltage current conductor of the TS 10/0,4 kV, 100 kVA (I_n = 150 A (0.4 кВ); $I_1 = I_2 = I_n$; $I_3 = 2/3I_n$; $I_4 = I_5 = I_6 = I_7 = 1/3I_n$) (*a*) and the distribution of magnetic moments of microcircuits when using the two-phase multi-dipole mathematical model of the MF (*b*)

Thus, the modified two-phase multi-dipole mathematical model of the TS's MF proposed by the authors (5) allows to zoom in twice as close the calculation area due to the reduction of the minimum overall size of its microcircuit – from double the interphase distance 2*d* to the interphase distance *d*, which makes it possible to model the EMF for all built-in TSs at distances from 1 m to their current conductors. In addition, the modified model (5) allows to reduce the volume of calculations due to the corresponding decrease in the number of magnetic moments in comparison with the known model (3).

Verification of the modified multi-dipole model of the TS current conductor. We perform experimental verification of the proposed model of the TS's EMF (5) on the basis of a comparison of the results of the calculation of the EMF magnetic flux density of the 100 kVA TS current conductor (Fig. 6) and the measurements of the magnetic flux density of a full-scale laboratory model of this current conductor (Fig. 9).

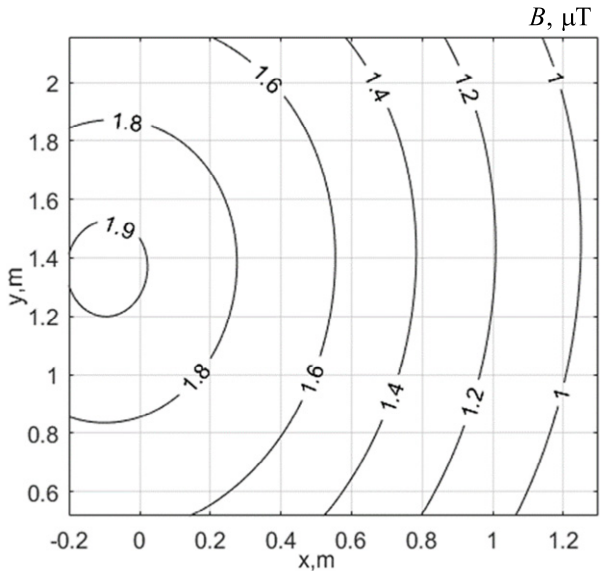
The results of calculating the magnetic flux density of the current conductor in the horizontal plane, located at a height of 1.85 m above the current conductor of the TS (at a height of 0.5 m above the floor of the premise), were performed in accordance with (5) on the basis of the original computer code of the authors in the MATLAB software package and presented in Fig. 7,*a* and Fig. 8.

Experimental studies of the TS's EMF were performed on a full-scale laboratory model of the TS 100 kVA (Fig. 9) with nominal current of 150 A, where a low-voltage current conductor is a source of the MF (Fig. 6,*b*).

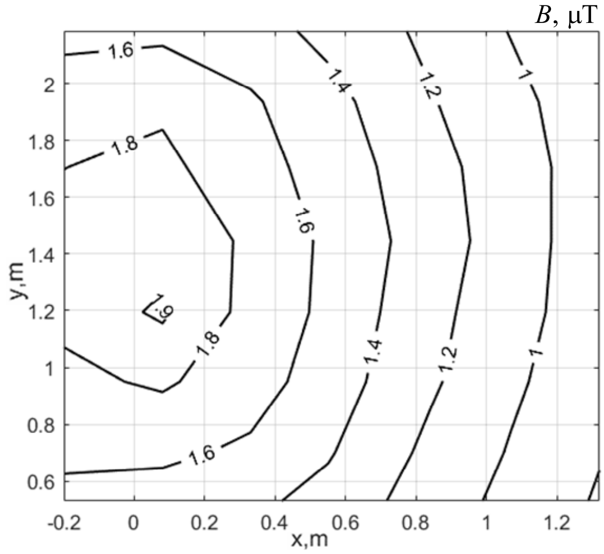
The layout of the current conductor (Fig. 9) is made of wooden rails and a PVC wire with a cross-section of 30 mm^2 and is mounted on the working site of the magnetic measuring stand of the unique magnetodynamic complex of the IPMach of the National Academy of Sciences of Ukraine [37]. The laboratory installation (Fig. 10) includes a layout of the current conductor (Fig. 9), which is fed through an induction regulator of the IR 59/32 type with the ability to adjust the three-phase current in the range of 0-220 A. Measurements of the current values of the magnetic flux density were performed at the nodes of the coordinate mesh with a step 0.25 m by EMF-828, Magnetoscop 1.069 type magnetometers on a control plane 1.85 m away from the current conductor.

To simplify measurements, the TS layout (Fig. 9) is placed on its side. Here, the measurements were performed on a vertical plane 1.85 m away from the current conductor, which is similar to the conditions of the performed calculation.

The results of the measurements are presented in Fig. 7,*b* and Table 1. A comparison of the calculation results with the experimental results shows that the calculated value of the magnetic flux density of the TS's EMF with a spread of less than 7 % coincides with the experimental results. This confirms the correctness of the modified two-phase multi-dipole model of the TS's EMF proposed by the authors and the assumptions made above.



a



b

Fig. 7. Distribution of the EMF of the TS 100 kVA in the horizontal plane above the TS at a height of 1.85 m at nominal load: *a* – calculation; *b* – experiment

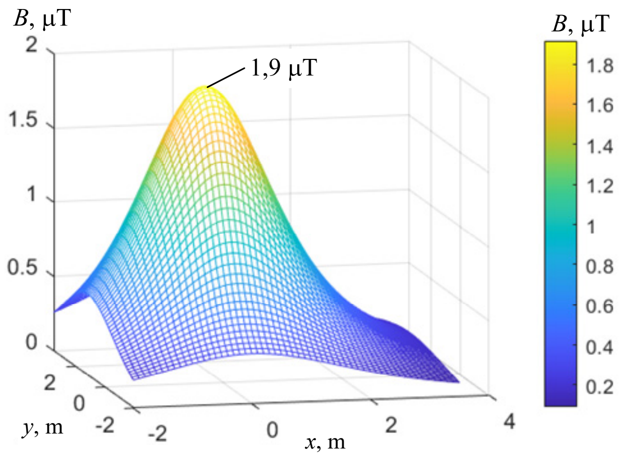


Fig. 8. Calculated values of the distribution of the EMF of the low-voltage current conductor of the TS 100 kVA at a height of 1.85 m above the current conductor at nominal load

Fig. 9. Full-scale laboratory layout of a low-voltage current conductor of the TS 10/0.4 kV, 100 kVA on the magnetic measuring stand

Table 1

Results of comparison of calculation and measurements of the EMF of the TS 100 kVA

x, m	*y*, m	Calculation *B*, μT	Experiment *B*, μT	Error, %
–0,1	0,33	1,622	1,526	5,92
0,43	0,75	1,506	1,443	4,22
0,94	1,25	1,159	1,098	5,25
1,42	1,74	0,821	0,779	5,14
0,18	0,5	1,698	1,640	3,43
0,65	1	1,445	1,418	1,91
1,17	1,51	1,038	0,984	5,21
–0,1	0,33	1,822	1,757	3,57
0,94	1,25	1,289	1,230	4,58
0,18	0,5	1,869	1,914	2,43
0,65	1	1,586	1,546	2,51
–0,1	0,33	1,900	1,863	1,93
0,43	0,75	1,766	1,785	1,04
0,94	1,25	1,349	1,302	3,47
1,42	1,74	0,946	0,886	6,31
0,18	0,5	1,848	1,847	0,04
0,65	1	1,579	1,524	3,49
–0,1	0,33	1,773	1,700	4,16
0,43	0,75	1,666	1,625	2,45
0,94	1,25	1,291	1,214	5,97
1,42	1,74	0,920	0,876	4,78
0,18	0,5	1,628	1,556	4,40
0,65	1	1,417	1,345	5,08
1,17	1,51	1,047	0,990	5,39

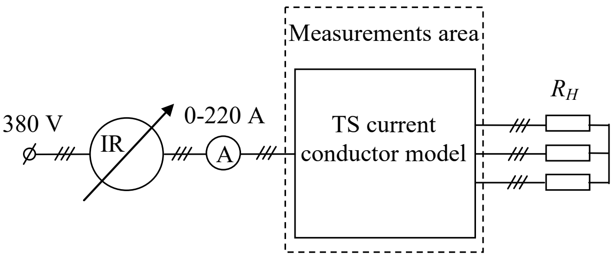


Fig. 10. Diagram of the laboratory installation for the study of the EMF of the layout of the TS 100 kVA current conductor

Thus, a modified two-phase multi-dipole mathematical model (5) was proposed for calculating the EMF of the TS current conductors and its experimental verification was performed on a full-scale laboratory model of a 100 kVA TS low-voltage current conductor. A comparison of the calculation and experimental results confirms the correctness of the proposed modified mathematical model and the calculation relations based on it.

It is promising to use the proposed modified two-phase multi-dipole mathematical model for calculating the MF of curvilinear (flexible) current conductors.

Conclusions.

1. It has been confirmed that the main source of the MF of built-in TSs is their low-voltage current conductor, the contribution of which to the total level of the magnetic field at a distance of 2 m is more than 90 %, which allows engineering calculations to ignore other sources of the TS's MF.

2. On the basis of the analysis of the results of research by foreign authors, as well as own research of the MF in residential buildings with built-in TSs in Ukraine, it is shown that the magnetic flux density level of built-in TSs with power of 100-1260 kVA, located in residential premises above the TSs, is from 1.5 to 13 μT, which significantly exceeds the maximum permissible level adopted in Ukraine (0.5 μT), constitutes a danger to the health of the population and confirms the urgency of reducing the TS's MF.

3. A modified two-phase multi-dipole mathematical model of the external MF is proposed for the main source of the magnetic field of the TS – its three-phase current conductor, which is based on the two-phase dipole model of a three-phase electric circuit and, compared with the known multi-dipole model, allows to approximate the calculation area twice without increasing the error and ensure the calculation of the external MF from the built-in TS in all residential premises of the building, including those located at a distance of one meter from the TS.

4. An experimental test of the modified two-phase multi-dipole model of the three-phase current conductor was carried out on a full-scale physical model of the TS 100 kVA current conductor, performed on the magnetic measuring stand of the unique magnetodynamic complex of the IPMach of the National Academy of Sciences of Ukraine, which confirmed the coincidence of the calculation and experimental results with a spread of less than 7 %.

5. The use of the proposed two-phase multi-dipole model of the three-phase current conductor of built-in TSs will allow the calculation of the MFs based on it to be extended to all neighboring residential premises, including those close to a distance of up to 1 m, which will contribute to solving the problem of protecting the population from the negative effects of the power frequency magnetic field.

Conflict of interest. The authors of the article declare that there is no conflict of interest.

REFERENCES

1. Leung S.W., Chan K.H., Fung L.C. Investigation of power frequency magnetic field radiation in typical high-rise building.

European Transactions on Electrical Power, 2011, vol. 21, no. 5, pp. 1711-1718. doi: https://doi.org/10.1002/etep.517.
2. Grbic M., Canova A., Giaccone L. Magnetic field in an apartment located above 10/0.4 kV substation: levels and mitigation techniques. *CIRED – Open Access Proceedings Journal*, 2017, no. 1, pp. 752-756. doi: https://doi.org/10.1049/oap-cired.2017.1230.
3. Thuroczy G., Janossy G., Nagy N., Bakos J., Szabo J., Mezei G. Exposure to 50 Hz magnetic field in apartment buildings with built-in transformer stations in Hungary. *Radiation Protection Dosimetry*, 2008, vol. 131, no. 4, pp. 469-473. doi: https://doi.org/10.1093/rpd/ncn199.
4. Geri A., Veca G. M. Power-frequency magnetic field calculation around an indoor transformer substation. *WIT Transactions on Modelling and Simulation*, 2005, vol. 39, pp. 695-704. doi: https://doi.org/10.2495/BE050641.
5. Salinas E., Aspemyr L., Daalder J., Hamnerius Y., Luomi J. Power Frequency Magnetic Fields from In-house Secondary Substations. *CIRED'99, 15th Conference on Electricity Distribution, Technical Reports*, session 2. 1999, pp. 161-164.
6. Burnett J., Du Yaping P. Mitigation of extremely low frequency magnetic fields from electrical installations in high-rise buildings. *Building and Environment*, 2002, vol. 37, no. 8-9. pp. 769-775. doi: https://doi.org/10.1016/S0360-1323(02)00043-4.
7. Bravo-Rodriguez J., Del-Pino-Lopez J., Cruz-Romero P.A Survey on optimization techniques applied to magnetic field mitigation in power systems. *Energies*, 2019, vol. 12, no. 7, art. no. 1332. doi: https://doi.org/10.3390/en12071332.
8. Alotto P., Guarnieri M., Moro F., Turri R. Mitigation of residential magnetic fields generated by MV/LV substations. *42nd International Universities Power Engineering Conference*. Brighton, UK, 2007, pp. 832-836. doi: https://doi.org/10.1109/UPEC.2007.4469057.
9. Buccella C., Feliziani M., Prudenzi A. Active shielding design for a MV/LV distribution transformer substation. *2002 3rd International Symposium on Electromagnetic Compatibility*. Beijing, China, 2002, pp. 350-353. doi: https://doi.org/10.1109/ELMAGC.2002.1177442.
10. Canova A., Giaccone L. Real-time optimization of active loops for the magnetic field minimization. *International Journal of Applied Electromagnetics and Mechanics*, 2018, vol. 56, no. S1, pp. 97-106. doi: https://doi.org/10.3233/JAE-172286.
11. Del-Pino-Lopez J.C., Giaccone L., Canova A., Cruz-Romero P. Ga-based active loop optimization for magnetic field mitigation of MV/LV substations. *IEEE Latin America Transactions*, 2014, vol. 12, no. 6, pp. 1055-1061. doi: https://doi.org/10.1109/TLA.2014.6894000.
12. Del-Pino-Lopez J., Giaccone L., Canova A., Cruz-Romero P. Design of active loops for magnetic field mitigation in MV/LV substation surroundings. *Electric Power Systems Research*, 2015, vol. 119. pp. 337-344. doi: https://doi.org/10.1016/j.epsr.2014.10.019.
13. Garzia F., Geri A. Active shielding design in full 3D space of indoor MV/LV substations using genetic algorithm optimization. *IEEE Symposium on Electromagnetic Compatibility*. Boston, MA, USA, 2003, vol. 1. pp. 197-202. doi: https://doi.org/10.1109/ISEMC.2003.1236591.
14. Garzia F., Geri A. Reduction of magnetic pollution in urban areas by an active field cancellation. *WIT Transactions on Ecology and the Environment*, 2004, vol. 72, pp. 569-579. doi: https://doi.org/10.2495/SC040561.
15. Celozzi S., Garzia F. Active shielding for power-frequency magnetic field reduction using genetic algorithms optimization. *IEE Proceedings – Science, Measurement and Technology*, 2004, vol. 151, no. 1, pp. 2-7. doi: https://doi.org/10.1049/ip-smt:20040002.
16. Shenkman A., Sonkin N., Kamensky V. Active protection from electromagnetic field hazards of a high voltage power line. *HAIT Journal of Science and Engineering*, 2005, vol. 2, no. 2, pp. 254-265.
17. Celozzi S. Active compensation and partial shields for the power- frequency magnetic field reduction. *2002 IEEE International Symposium on Electromagnetic Compatibility*, Minneapolis. MN, USA, 2002, vol. 1, pp. 222-226. doi: https://doi.org/10.1109/isemc.2002.1032478.
18. Canova A., del-Pino-Lopez J.C., Giaccone L., Manca M. Active Shielding System for ELF Magnetic Fields. *IEEE Transactions on Magnetics*. March 2015, vol. 51, no. 3, pp. 1-4. doi: https://doi.org/10.1109/tmag.2014.2354515.
19. Szabo J., Janossy G., Thuroczy G. Survey of residential 50 Hz EMF exposure from transformer stations. *Bioelectromagnetics*, 2007, vol. 28, no. 1, pp. 48-52. doi: https://doi.org/10.1002/bem.20264.
20. Ilonen K., Markkanen A., Mezei G., Juutilainen J. Indoor transformer stations as predictors of residential ELF magnetic field exposure. *Bioelectromagnetics*, 2008, vol. 29, no. 3, pp. 213-218. doi: https://doi.org/10.1002/bem.20385.
21. Okokon E. O., Roivainen P., Kheifets L., Mezei G., Juutilainen J.. Indoor transformer stations and ELF magnetic field exposure: use of transformer structural characteristics to improve exposure assessment. *Journal of Exposure Science & Environmental Epidemiology*, 2014, vol. 24, no. 1, pp. 100-104. doi: https://doi.org/10.1038/jes.2013.54.
22. Grbic M., Canova A., Giaccone L. Levels of magnetic field in an apartment near 110/35 kV substation and proposal of mitigation techniques. *Mediterranean Conference on Power Generation, Transmission, Distribution and Energy Conversion*. Belgrade, 2016, pp. 1-8. doi: https://doi.org/10.1049/cp.2016.1025.
23. Rahman N.A., Rashid N.A., Mahadi W.N., Rasol Z. Magnetic Field Exposure Assessment of Electric Power Substation in High Rise Building. *Journal of Applied Sciences*, 2011, vol. 11, pp. 953-961. doi: https://doi.org/10.3923/jas.2011.953.961.
24. Izagirre J., Del Rio L., Gilbert I.P., Rodriguez-Seco J.E., Güemes J.A., Iralagoitia A.M. Application of a new IEC magnetic field assessment methodology to promote transformer substation sustainable development. *IEEE 2011 EnergyTech*. Cleveland, OH, USA, 2011, pp. 1-6. doi: https://doi.org/10.1109/EnergyTech.2011.5948529.
25. Navarro-Camba E.A., Segura-García J., Gomez-Perretta C. Exposure to 50 Hz Magnetic Fields in Homes and Areas Surrounding Urban Transformer Stations in Silla (Spain): Environmental Impact Assessment. *Sustainability,* 2018, vol. 10, no. 8, art. no. 2641. doi: https://doi.org/10.3390/su10082641.
26. Röösli M., Jenni D., Kheifets L., Mezei G. Extremely low frequency magnetic field measurements in buildings with transformer stations in Switzerland. *Science of the Total Environment*, 2011, vol. 409, no. 18, pp. 3364-3369. doi: https://doi.org/10.1016/j.scitotenv.2011.05.041.
27. Rozov V.Y., Pelevin D.Y., Pielievina K.D. External magnetic field of urban transformer substations and methods of its normalization. *Electrical Engineering & Electromechanics*, 2017, no. 5, pp. 60-66. doi: https://doi.org/10.20998/2074-272X.2017.5.10.
28. *Electrical installation regulations*. Kharkiv, Fort Publ., 2017. 760 p. (Ukr).
29. Kuznetsov. B.I., Nikitina T.B., Bovdui I.V. Method of adjustment of three-circuit system of active shielding of magnetic field in multi-storey buildings from overhead power lines with wires triangular arrangement. *Electrical Engineering & Electromechanics*, 2022, no. 1, pp. 21-28. doi: https://doi.org/10.20998/2074-272X.2022.1.03.
30. Kuznetsov. B.I., Nikitina T.B., Bovdui I.V. Comparison of the effectiveness of thriple-loop and double-loop systems of active shielding of a magnetic field in a multi-storey old buildings *Electrical Engineering & Electromechanics*, 2022, no. 3, pp. 21-27. doi: https://doi.org/10.20998/2074-272X.2022.3.04.

31. Kuznetsov. B.I., Nikitina T.B., Bovdui I.V. Synthesis of an effective system of active shielding of the magnetic field of a power transmission line with a horizontal arrangement of wires using a single compensation winding. *Electrical Engineering & Electromechanics*, 2022, no. 6, p. 15-21. doi: https://doi.org/10.20998/2074-272X.2022.6.03.
32. Rozov V.Yu., Reutskyi S.Yu., Pelevin D.Ye., Pyliugina O.Yu. The magnetic field of power transmission lines and the methods of its mitigation to a safe level. *Technical Electrodynamics*, 2013, no. 2, pp. 3-9. (Rus).
33. Rozov V.Yu. *External magnetic fields of power electrical equipment and methods for reducing them*. Kyiv, the Institute of Electrodynamics Publ., 1995, no. 772, 42 p. (Rus).
34. Pelevin D.Y. Screening magnetic fields of the power frequency by the walls of houses. *Electrical Engineering & Electromechanics*, 2015, no. 4, pp. 53-55. (Rus). doi: https://doi.org/10.20998/2074-272X.2015.4.10.
35. Rozov V.Yu., Grinchenko V.S., Pelevin D.Ye., Chunikhin K.V. Simulation of electromagnetic field in residential buildings located near overhead lines. *Technical Electrodynamics*, 2016, no. 3, pp. 6-8. (Rus).
36. Rozov V.Yu., Pelevin D.Ye. The dipole model of magnetic field of three-phase electric circuit. *Technical Electrodynamics*, 2012. no. 4. pp. 3-7. (Rus).
37. Baranov M.I., Rozov V.Y., Sokol Y.I. To the 100th anniversary of the national academy of sciences of Ukraine – the cradle of domestic science and technology. *Electrical Engineering & Electromechanics*, 2018, no. 5, pp. 3-11. doi: https://doi.org/10.20998/2074-272X.2018.5.01.

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