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STUDY OF CURRENT TRANSFORMERS MAGNETIC FIELD BY METHOD FINAL ELEMENTS USING THE FEMM SOFTWARE COMPLEX

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ABSTRACT

The widespread use of current transformers both in relay protection systems and for measuring purposes makes the task of estimating their errors quite urgent. The permissible error levels of modern measuring current transformers should not exceed a fraction of a percent. Moreover, the errors of multi-range current transformers with incomplete filling of the magnetic circuit with secondary windings are determined distribution of the magnetic field in the magnetic system, depending on the scattering fluxes of the windings. The analysis of the capabilities of various software products that implement the finite element method for the calculation of electromagnetic systems. It has been established that, to the greatest extent, for the study of the magnetic field of current transformers by users without special training, is the FEMM software package. Using this program, we studied the distribution of the magnetic field of the current transformer when the magnetic system is not completely filled with turns of the secondary winding and with a different arrangement of the return wire of the multi-turn primary winding relative to the secondary winding for a current transformer with a toroidal magnetic system. For a transformer with a rectangular magnetic system, a magnetic field is simulated for one and two secondary coils. The characteristics of the distribution of the magnetic field in the magnetic system and the normal component of the scattering field of the transformer have been obtained. The diagrams of the magnetic field vectors are constructed for different sections of the transformer magnetic system. It is shown that when the magnetic system is incompletely filled with turns of the secondary winding, a significant uneven distribution of magnetic induction along the magnetic circuit occurs, which leads to an increase in the error of the current transformer. Studies have shown the effectiveness of the finite element method for modeling magnetic fields and error estimation of current transformers. The FEMM software environment used for research is a universal and accurate information technology for calculating current transformers, convenient for users without special training.

Keywords: Multiband Current Transformer; Finite Element Method; FEMM Software Package; Magnetic Field Distribution in the Magnetic Circuit; Error of Measuring Transformers

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INTRODUCTION

The accuracy of the calculation of processes in electromagnetic devices, including current transformers (CTs), can be significantly improved due to the widespread introduction of the finite element method (FEM) as the main computing base [3; 4]. Due to its versatility, adjustable accuracy, and a fairly simple computing organization, the FEM is currently the basis of numerous information technologies and software products that implement them. In this case, computer modelling and numerical analysis avoid expensive and lengthy field tests, which accelerates complements and clearly illustrates the design and development process, and promotes the development of engineering intuition [5]. On the other hand, the vast market for such software products based on FEM makes it difficult to choose ones for the right researcher and designer. The appropriateness of using a software product for a particular user-designer should be evaluated by the accuracy and speed of solving the field calculation problem, the convenience of working with the program, and the accuracy of finding the quantities of interest, in particular, errors.

The aim of the study is to investigate the magnetic field of a CT taking into account the effect of scattering fluxes and its influence on the measurement error using the most convenient for calculation information technology that implements the finite element method.

To achieve the goal of the study, a preliminary analysis of the software capabilities for modelling electromagnetic systems using FEM was performed.

The choice of the most affordable and easy-to-use software product allows you to go directly to research, in particular, to conduct a detailed analysis of the characteristics of a plane-parallel magnetic field in asymmetric structures of a CT:

– in a toroidal magnetic system (MS) of a multirange integrated CT with a single-turn primary winding while different filling of the MS with turns of the secondary winding;

– in a toroidal MS with a multi-turn primary winding while a different arrangement of its reverse wire relative to the part of the MS that is not filled with turns of the secondary winding;

– in a rectangular MS with a secondary winding.

OVERVIEW OF SOFTWARE TOOLS FOR MODELLING ELECTROMAGNETIC DEVICES BASED ON THE FEM

Today, the software market has a number of application systems designed to calculate electromagnetic fields using FEM. Software tools differ in the level of tasks to be solved, in the way discretization of the domain into finite elements, in the structure and content of the software product.

In the analysis of IT and software, we will use the comparison criteria formulated in [6]. The earliest FEM for the calculation of electromagnetic systems was implemented in universal computer mathematics systems such as MatLab, MathCAD, and Maple [7]. FEM-based software implemented in universal systems also has disadvantages that are characteristic of this method. They are manifested in a strong dependence of the accuracy of the obtained solution on the method of discretization of the spatial region of the simulated electromagnetic (EM) device. For example, a significant drawback of FEM-based EM field calculation programs is the use of a piecewise linear approximation of the desired function even in areas with linear characteristics of the medium, which is a source of additional error in determining the local and integral field characteristics and device parameters. In the general case, this disadvantage can be compensated for by an increase in the number of finite elements and by conducting additional numerical experiments. However, this requires serious modification of the program code.

Another universal IT simulation using FEM is the Femlab software package [8]. Femlab is essentially a toolbox of the Matlab package and runs under its control. This means that all programming features available in Matlab can be used in Femlab (for example, convenient graphical output and processing of calculation results). Another advantage of Femlab is the ability to export the finite element model to Simulink (a dynamic system-modelling tool built into Matlab). However, the use of Femlab requires knowledge of the Matlab programming language and a fairly expensive license, since Femlab is proprietary software and is distributed as a commercial program.

Let us consider specialized software for modelling electromagnetic devices based on FEM.

Universal software analysis system ANSYS [9; 10] is quite popular among specialists in the field of automated engineering calculations, including the calculation of CT.

As the shortcomings of the ANSYS program, users note it’s difficult to configure the graphical interface and a large number of settings that make it difficult to use. ANSYS is also a commercial product with a fairly expensive license.

The computer program ELCUT is intended for engineering analysis and two-dimensional modeling by the finite element method [12, 13], [14]. There are a number of limitations to the ELCUT program. Most of them are explained by the desire of the authors to create a simple and compact computer-modelling tool. The program requires a paid license. The English version of the ELCUT package is the QuickField package [15].

The most universal, simple and affordable for calculating electromagnetic devices and, in particular, current transformers, as the analysis shows, is the FEMM (Finite Element Method Magnetics) program [16; 17]. On the one hand, the FEMM program has a simple and affordable user-friendly interface, has sufficiently powerful tools for the calculation by the user with minimal special training, and on the other hand, FEMM makes it possible to improve the software built into the package by writing new software modules. For this, the FEMM system has a special and fairly easy to learn script compiled language Lua [18]. It should be especially noted that the FEMM program allows you to integrate Lua software modules into the Matlab system, as well as the fact that FEMM is a freeware. As a drawback of the FEMM program, it should be noted that the choice of measurement units for length in older versions of the program is inconvenient for the user [19].

The analysis makes it possible to assert that the FEMM software package is the most acceptable software tool for studying the distribution of the magnetic field in a CT. With its help, studies were further conducted, the results of which are presented in the article.

STATEMENT OF THE SIMULATION TASK

The errors of the measuring current transformer are determined by the magnetomotive force (m.m.f.) of the magnetization, which largely depends on the design of the MS, the secondary winding and the relative position of the primary and secondary windings.

When the MS is completely filled with turns of the secondary winding (the symmetrical structure of the CT – the angle of the turns of the secondary winding is $\alpha_2 = 360^{\text{o}}$, the scattering flux of the primary winding does not affect the magnetic field in the MS and the value of induction B is constant along the average length $B(L_{aver}) = const$ the existing equivalent circuit and errors calculation mathematical model give satisfactory design results.

An experimental study of integrated CTs (Fig. 1) shows that in the case when a part of the MS remains free of secondary turns with current (asymmetric structure of the CT, $\alpha_2 < 360^{\text{o}}$), the magnetic field of the scattering of the primary winding closes along this part of the MS, magnetizes it and significantly increases the induction in it. This leads to an increase in the m.m.f. of magnetization and errors in measuring the primary current of the CT in the process of monitoring and accounting for the consumed electricity. Therefore, the assumption $B(L_{aver}) = const$ is valid only for the symmetric structure of the CT. Note that due to the use of the FEMM 4.1 version in Fig. 1 and the following graphs, the linear dimensions are given in non-system units (centimetres).

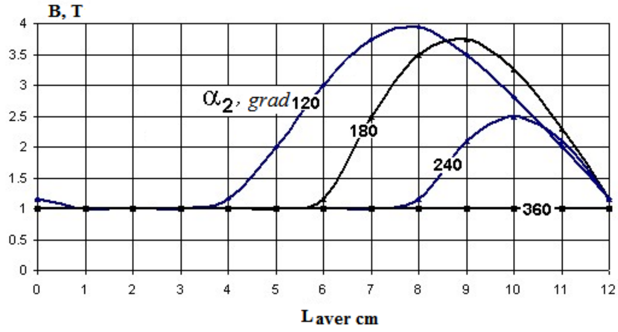


Fig. 1. **The dependence of the distribution of induction $B_{\text{c}} = \varphi\left(L_{\text{cp}}, \alpha_2\right)$ in MS with an asymmetric structure of CT**
***Source*: compiled by the author**

To obtain at the design stage adequate results for calculating CT errors, it is necessary to take into account the actual distribution of the magnetic field in the MS of the transformer.

In [20], the results of modelling using the FEMM program of the magnetic field distribution for various strengths of the MS unfilled part between the secondary winding sections of the built-in CT are presented.

To obtain at the design stage adequate results for calculating CT errors, it is necessary to take into account the actual distribution of the magnetic field in the MS of the transformer.

It will be shown below that the use of the FEMM program for research allows obtaining a qualitative picture of the distribution of the magnetic field in various regions of the constructional volume for various CT models with a minimum waste of time. It gets a large number of its characteristics and evaluates the effect of scattering fluxes on the magnetic field in the MS of CT. This allows you to take into account within the mathematical model the actual distribution of the magnetic field for calculating errors.

RESEARCH MATERIALS

The object of a detailed study is a current transformer with a toroidal magnetic system measuring 34.5 / 21.5 / 6 cm, made of cold-rolled electrical 3411 steel, and with a secondary winding of copper wire with a diameter of 2.1 mm.

The calculation model is shown in Fig. 2; it allows you to perform a study of the distribution of the magnetic field of the CT upon the following conditions:

– without a reverse wire of the primary winding and with angles of the secondary winding's turns $\alpha_2 = (90, 180, 270, 360)^{\text{o}}$;

– with the reverse wire of the primary winding located on the side of middle of the secondary winding (w_1');

– with the reverse wire of the primary winding located on the side of the middle of the free section of the MS (w_1'').

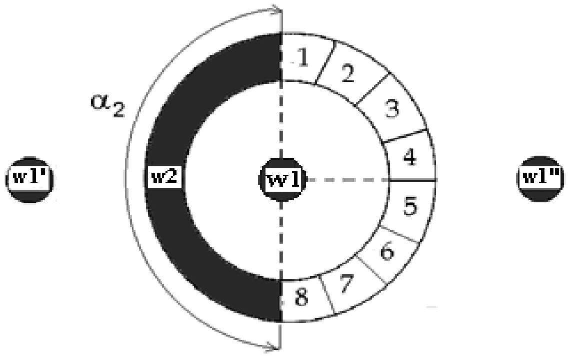


Fig. 2. **The calculation model of the toroidal CT**
***Source*: compiled by the author**

When designing a built-in CT, the calculation of the resulting magnetic field strength must be performed [21], taking into account the selection of an arbitrary number of sections on the part of MS which is free of the turns of secondary winding, and the determining of the conductivity of the total scattering flux, in view of the specific conductivity of the closure path of the scattering magnetic flux (Λ_σ^*),where the mentioned conductivity depends on filling the MS of transformer with the turns of the secondary winding ($\Lambda_\sigma^* = \varphi(\alpha_2)$).

This approach allows us to calculate the distribution of induction in steel along the average MS length ($B_{aver}(L_{aver})$ and the real (X) and imaginary (Y) components of the vector of the resulting m.m.f. of magnetization taking into account the magnetic field strength in the section under the secondary winding (H_{i2x}, H_{i2y}) and sections (k) of the winding-free part of the MS

$$\left(\sum_{i=1}^{k} Hix, \sum_{i=1}^{k} H_{iy}\right).$$

$$F_x = \sum_{i=1}^{k} H_{ix} \cdot l_i + H_{i2x} \cdot l_2$$
$$,$$
$$F_y = \sum_{i=1}^{k} H_{ix} \cdot l_i + H_{i2y} \cdot l_2$$

where: k is the number of elements on the free part of the MS (k = 8 in Fig. 2) with length l_i;

l_2 is the average length of the MS under the secondary winding.

The error calculation algorithm is implemented in the FEMM package [20, 21], [22] and gives a satisfactory result for a toroidal CT with an arbitrary design of the secondary winding (angle α_2, number of layers, incomplete filling of the last layer with turns of the secondary winding).

However, the dependence $\Lambda_{\sigma}^{*}(\alpha_2)$ was obtained under a number of assumptions, which limits the scope of its application only for single-turn CTs with a toroidal MS and makes it necessary to simulate the magnetic field of the transformer when its structure changes.

Modeling in the FEMM program allows you:

– to visualize the distribution of magnetic field strength lines;

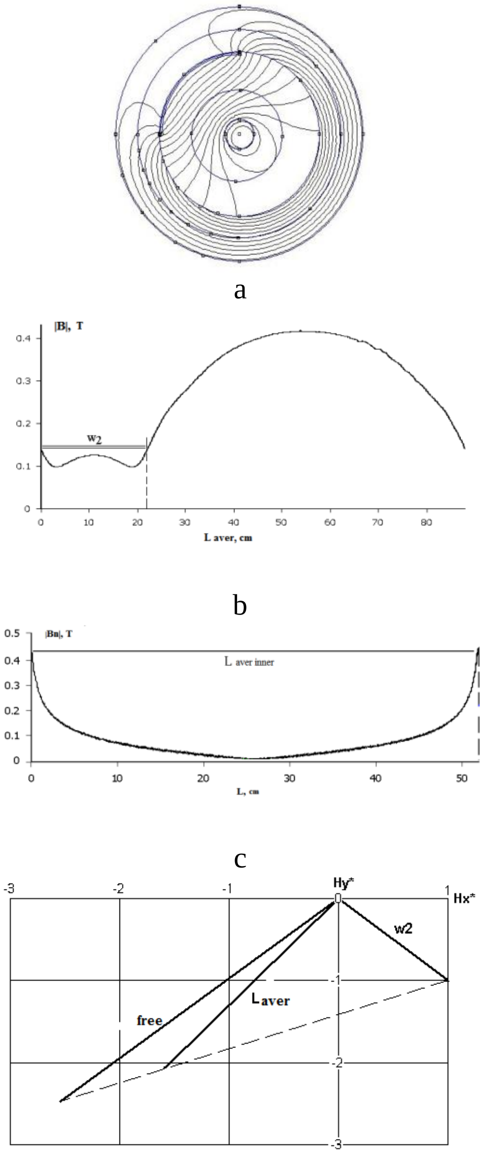
– to plot the diagrams of distribution of induction along the average length of the MS and the distribution of the normal component of the induction of the scattering field of the primary winding included in the MS;

– to plot a diagram of the vectors of the tangential component of the magnetic field strength in different sections of the MS; to determine the m.m.f. of magnetization without taking into account the allocation of sections on the free part of the MS and when dividing it into an arbitrary (1 ... 8) number of sections (Fig. 2).

Fig. 3, Fig. 4 and Fig. 5 show the results of modeling the CT magnetic field for various angles α_2 (a – distribution pattern of the magnetic field strength lines; b – distribution of induction along the average length of the MS; c – distribution of the normal component of the scattering field of the primary winding when field mentioned above closing through the inner surface of the MS; d – MP strength vectors).

In the absence of a primary winding reverese wire (single-turn CT), the distribution of magnetic field strength lines (Fig.3a, Fig. 4 and Fig. 5a) and a qualitative picture of the distribution of induction along the average MC length (Fig.3b, Fig.4b and Fig. 5b) correspond to the calculations given in [20; 21].

The presence of the normal component of the scattering field of the primary winding, which closes through the inner surface of MS (*L aver inner*) in the section free from the turns of the secondary winding (Fig. 3c, Fig. 4c and Fig. 5c), leads to a significant increase in the induction in the sections of the MS part, which has not winding (Fig. 3b, Fig.4b and Fig.5b).


a

b

c

d

Fig. 3. **The magnetic field at** $\alpha_2 = 90^{\text{o}}$

***Source*: compiled by the author**

With increasing sector α_2, the normal component of the scattering field of the primary winding, which closes along the inner surface of the MS, decreases (Fig. 3c, Fig.4c and Fig.5c), and this reduces the uneven distribution of induction along the length of the MS (Fig.3b, Fig.4b and Fig. 5b). This is confirmed by the diagram of the magnetic field vectors in the MS regions at $\alpha_2 = \text{var}$ (Fig. 6).

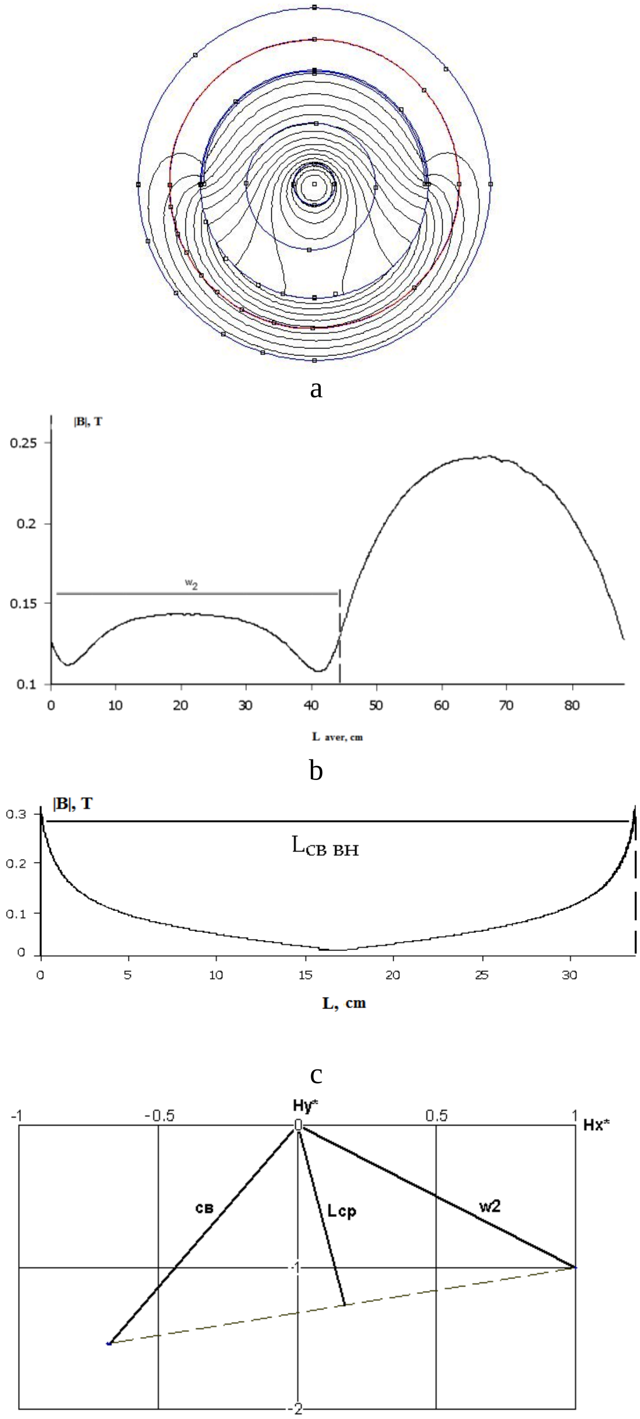


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Fig. 4. **The magnetic field at** $\alpha_2 = 180^{\text{o}}$

***Source*: compiled by the author**

When the MS is completely filled with turns of the secondary winding ($\alpha_2 = 360^{\text{o}}$), the CT structure becomes symmetrical and the distribution of the magnetic field along the average length of the MS does not change.

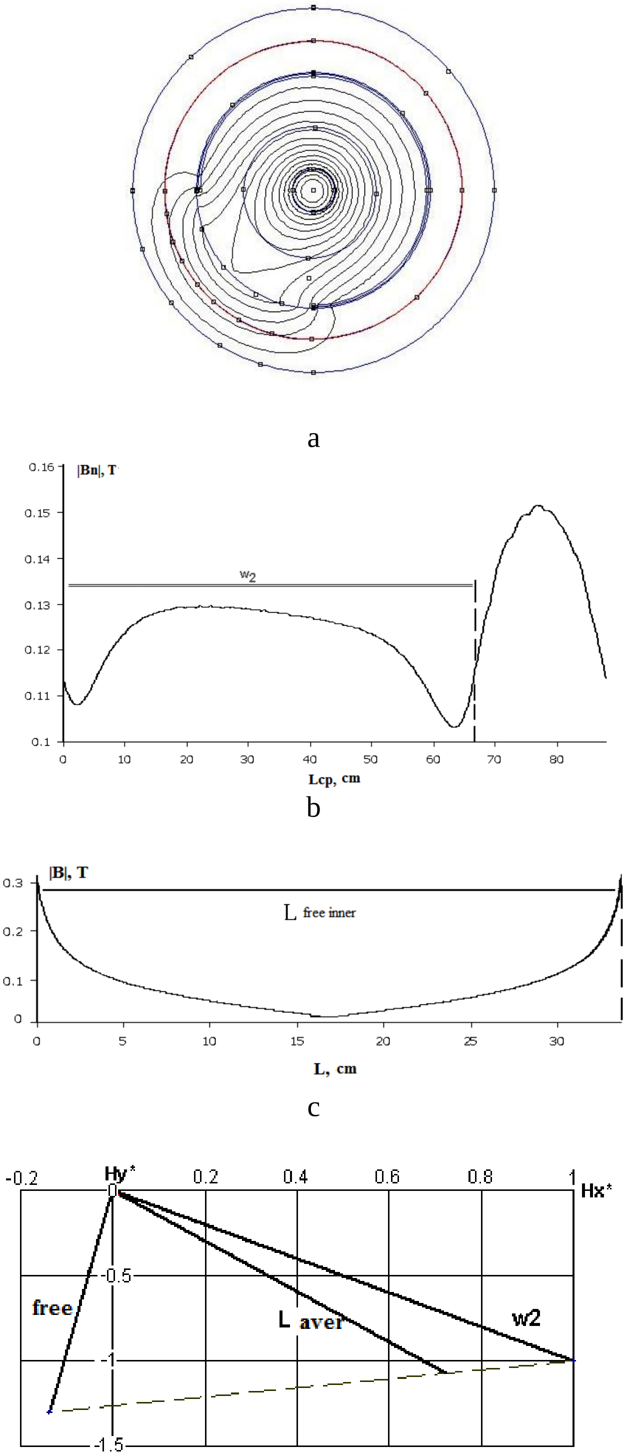

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Fig. 5. **The magnetic field at** $\alpha_2 = 270^{\text{o}}$

***Source*: compiled by the author**

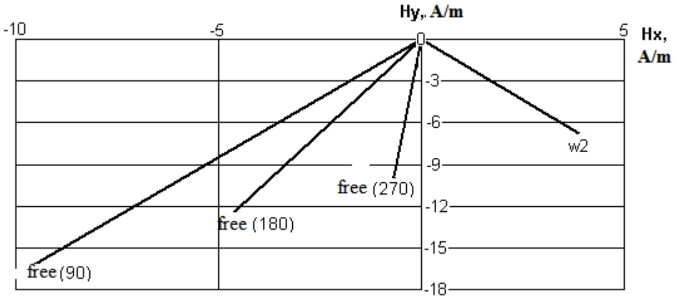


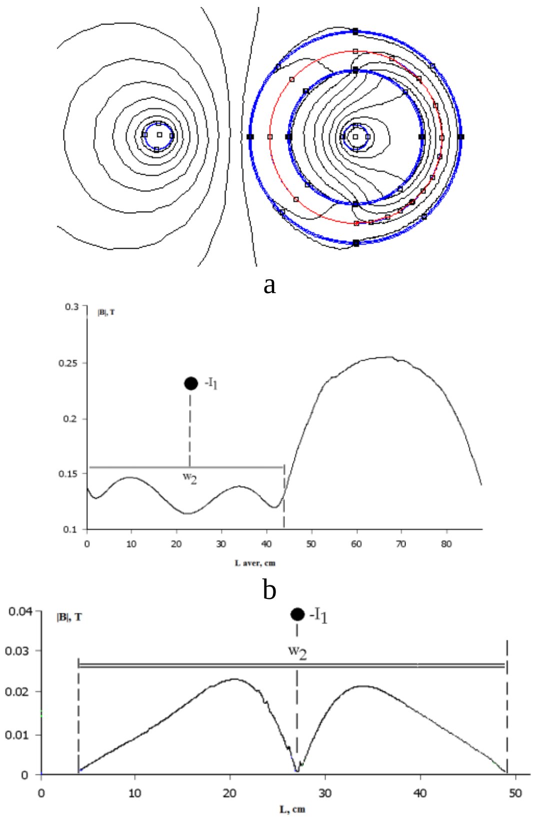
Fig. 6. **The components of the magnetic field at α_2 = var**

***Source*: compiled by the author**

A significant increase of induction on the free part of the MS (Fig.3b, Fig.4b and Fig.5b) leads to a significant error between the value of the m.m.f. of magnetization determined by induction on the MS section under the secondary winding (F_{w2}), the m.m.f. which is calculated by the value of induction along the average length of the MS (F_{aver}), and m.m.f. which determined taking into account the magnetic state of the sections of the winding-free part of the MS ($F_{w2}+\Sigma F_{free(i)}$) (Table, struct. No.1, No.2 and No.3). In this case, the calculation error increases with decreasing angle on the MS under the secondary winding (α_2 in Fig. 2).

In the table, the m.m.f. calculated by induction in the MS under the secondary winding (F_{w2}) was taken as the base value for each specific calculating structure.

The location of the reverse wire of primary winding (Fig. 7a) relative to the middle of the secondary winding (modelling was performed at $\alpha_2=180^{\circ}$) leads to a deformation of the induction distribution curve in the MS section under the secondary winding (Fig. 7b) due to the normal component of field of the primary winding which being a part of the outward surface of the MS (Fig. 7c). In this case, the non-uniformity of the distribution of induction $B(L_{aver})$ does not change (Fig.4b and Fig.7b) and the relative position of the magnetic field vectors in the MS sections (lines $l_1(w_2)$ and $l_1(w_2)$ in Fig. 9 and lines *free* and w_2 in Fig. 3d) is preserved. The calculated value of m.m.f. magnetization is also practically unchanged (Table, struct. No. 2 and struct. No. 4).



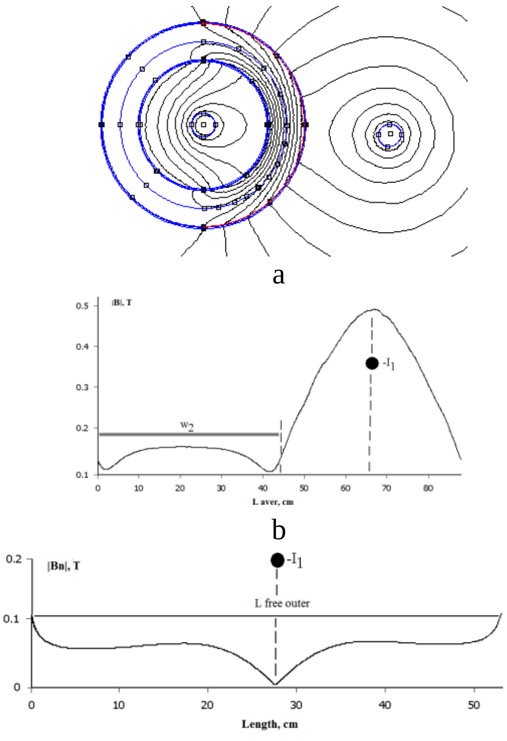
a

b

c

Fig. 7. **The distribution of the magnetic field with the location of the reverse wire from the secondary winding side**

***Source*: compiled by the author**



a

b

c

Fig. 8. **The distribution of the magnetic field with the location of the return wire from the free part of the MS**

***Source*: compiled by the author**

The location of the reverse wire of primary winding from the side of the free part of the MS (Fig. 8a) significantly increases the magnetic induction on the free part of the MS (Fig. 8b). This is due to the significant normal component of the magnetic field scattering flux of the reverse wire of the primary winding included in the outward surface of the MS (Fig. 8c) and the normal component of the scattering flux of the magnetic field of the direct wire of the primary winding which is part of the inner surface (Fig. 3c) of the free section of the MS. Their combined action leads to the magnetic bias of the free part of the MS of the CT (Fig. 8b) and an increase in the magnetizing force of the free section of the MS (line $l_1(free)$) in Fig. 9).

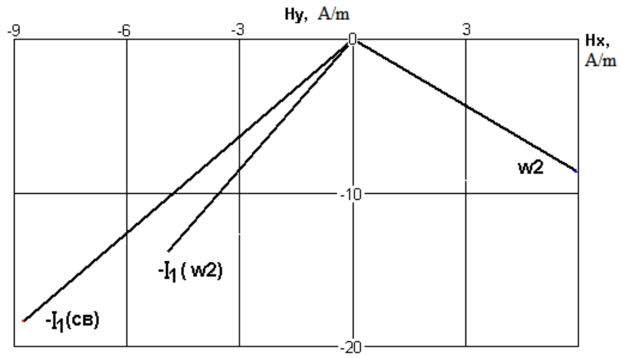


Fig. 9. **The magnetic field strength while different locations of the reverse wire**

***Source*: compiled by the author**

In all FEMM studies, the m.m.f. value (see Table) was calculated from the tangential component of the magnetic field strength along the average length of the sections of the magnetic system of the corresponding CT structure.

However, the distribution induction along the radial cross-section of the toroidal MS of transformer is uneven (Fig. 10).

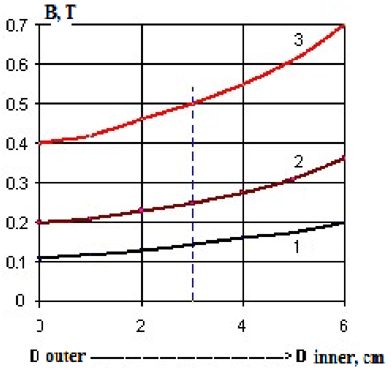


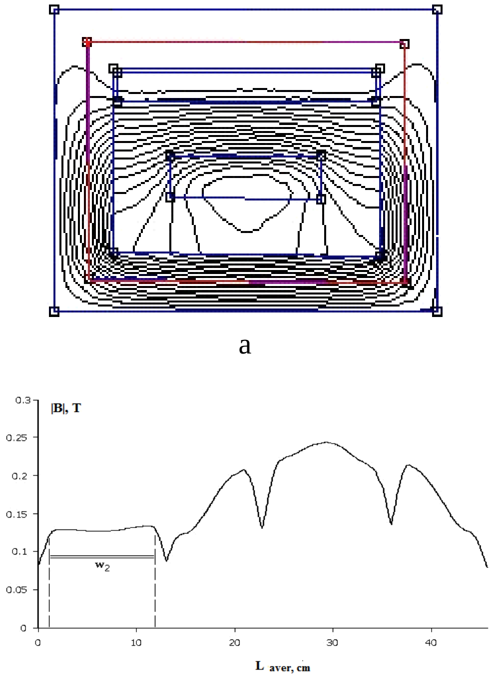
Fig. 10. **The distribution of induction by radial cross-section of a toroidal MS**

***Source*: compiled by the author**

In this case, the non-uniformity turned out to be greater on the unfilled part of the MS both in the presence of the primary conductor of reverse wire from the free part of the MS (line 3) and in the absence of the reverse wire (line 2) compared to the portion of the magnetic system under the secondary winding (line 1). This leads to a slight increase in the resulting m.m.f. calculated by the value of induction along the average length of the MS.

To assess the influence of the design of the CT magnetic system on the distribution of the magnetic field, a magnetic field was simulated for a rectangular magnetic system of a transformer (Fig. 11 and Fig. 12) made of 3411 steel with dimensions: window width – 7 cm, window height – 11 cm, average length of the magnetic circuit - 45.6 cm, the width of the magnetic circuit – 2.4 cm. To assess the influence of the design of the CT magnetic system on the distribution of the magnetic field, a magnetic field was simulated for a rectangular magnetic system of a transformer (Fig. 11 and Fig. 12) made of 3411 steel with dimensions: window width – 7 cm, window height – 11 cm, average length of the magnetic circuit – 45.6 cm, the width of the magnetic circuit – 2.4 cm.

The calculation showed that for this CT structure, a similar effect of the scattering field on the distribution of the magnetic field in the MS is observed, regardless of the location of the secondary winding coil on one rod (Fig. 11a) or on two lateral rods of the MS (Fig. 12a).



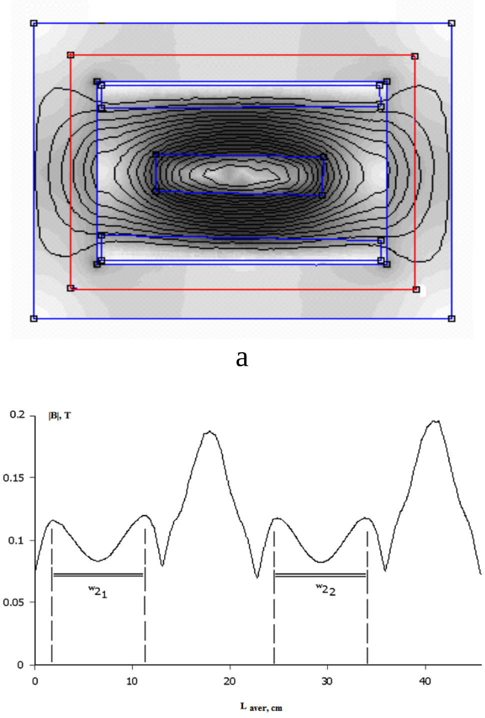
a

b

Fig. 11. **The distribution of the magnetic field in the MS of CT with one secondary coil**

***Source*: compiled by the author**

The greatest degree of non-uniformity in the distribution of induction occurs for MSs with one coil of secondary winding (Fig. 11b) due to the larger normal component of the scattering field of the primary winding closing through the inner surface of the free section of the MS (similar to the toroidal CT an $\alpha_2 = 90^o$ in Fig. 3c)



a

b

Fig. 12. **The distribution of the magnetic field in MS of CT with two secondary coils**
***Source*: compiled by the author**

The ratio of the magnetic field vectors in the free part of the magnetic circuit (L_{free}) and along the average length (L_{aver}) for one (index 1) and two (index 2) secondary winding coils (Fig. 13) shows a significant increase of MMF under the decreasing of the filling of the MS with turns of the secondary winding.

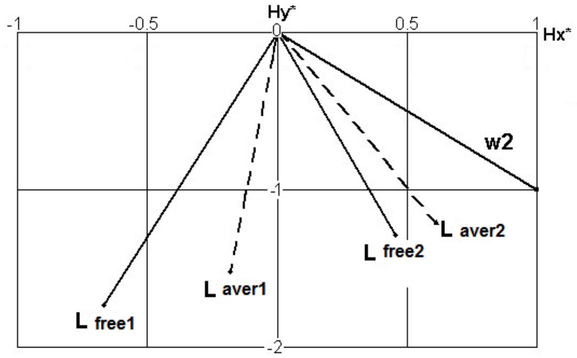


Fig. 13. **The ratio of magnetic field strength vectors**
***Source*: compiled by the author**

The error in calculating the MMF without taking into account the sections of the free part of the MS is up to 40 % (see Table; struct. No. 6).

The distribution of induction along the cross-sections of a rectangular MS is similar to the distribution in Fig. 10 for a toroidal MS.

Table. **The value of the m.m.f. for calculated models of CT**

No. of calculated structure	m.f.f.	F_{w2}	F_{aver}	$F_{w2} + \Sigma F_{free(8)}$
1	Fig. 3a	1	1,521	1,63
2	Fig. 4a	1	1,029	1,16
3	Fig. 5a	1	1,025	1,054
4	Fig. 7a	1	1.026	1,17
5	Fig. 8a	1	1,3	1,48
6	Fig. 11a	1	1,21	1,38
7	Fig. 12a	1	1,035	1,098

***Source*: compiled by the author**

CONCLUSIONS

1. The study of magnetic fields and CT errors is most expedient to be carried out by the finite element method using the FEMM software package.

2. The calculation of m.m.f., performed by the value of induction in the MS under the secondary winding, gives a significant (up to 20 %) error in comparison with the calculation obtained when taking into account the values of induction in individual sections of the free part of the MS. The magnitude of the error is determined by the structure of the CT and increases with the reduction of the angle of filling of the MS with the turns of the secondary winding.

3. The scattering field of the reverse wire of the primary winding increases the resulting m.m.f. of magnetization up to 30 % when it is located on the side of the unfilled part of the MS and depends on the angle of filling of the MS with the turns of the secondary winding.

4. The number of sections of the free part of the MS, ensuring the convergence of the iteration

process of calculating the m.m.f., must be at least eight.

5. For accurate calculation of CT errors, it is necessary to take into account the uneven distribution of induction over the transverse cross-section of the transformer MS.

6. The uneven distribution of induction in the MS of the transformer with a coiling secondary winding is greater than in a toroidal MS with a distributed secondary winding.

7. The results of the analysis of the magnetic field show the need to adjust the equivalent circuit and the mathematical model for calculating errors for asymmetric CT structures.

REFERENCES

1. Zocholl, S. E. “Analyzing and Applying Current Transformers”. N.-Y.: *Schweitzer Engineering Laboratories*. 2004. 105 p.

2. Rathore, B. & Dadhich, A. A. “Review Paper on Current Transformer”. *An International Journal of Jaipur National University*. 2016; Vol. 5: 112–143. DOI: https://doi.org/10.5958/2277-4912.2016.00028.X.

3. Kwon, Y. W. & Bang, H. “The Finite Element Method Using MATLAB”. N.-Y.: *CRC Press, Inc*. 59. 2000. 9 p.

4. Bianchi, N. “Electrical Machine Analysis Using Finite Elements”, London: *Taylor & Francis.* 2005. 304 p. DOI: https://doi.org/10.1201/9781315219295.

5. Sule, I. “Simulation Model for Assessing Operational Performance of Current Transformers”. *Advanced Materials Research.* 2007; Vol.18-19: 71–77. DOI: https://doi.org/10.4028/www.scientific.net/amr.18-19.71.

6. Bul’, O. B. “Comparison of Engineering Methods for Calculation of Magnetic Circuits and Fields of Electromagnets”. *Russian Electrical Engineering.* 2007; Vol.78 No.7: 374–379. DOI: https://doi.org/10.3103/S1068371207070085.

7. Romaniuk, F., Novash, I. , Rumiantsev, Y. & Węgierek, P. “Wye-connected Current Transformers Simplified Model Validation in MATLAB-Simulink”. *Przegląd Elektrotechniczny. Procedia Engineering.* 2015; No.202: 312–318. DOI: https://doi.org/10.15199/48.2015.11.67.

8. “System of Finite Element Calculations” EMLAB 3.x. – Available from: http://matlab.exponenta.ru/femlab/book6 /1.php. – Active link: 02.11.2019.

9. “ANSYS”. [Electronic resource]. – Access mode: https://www.ansys.com/ – Active link: 02.02.2019.

10. Basov, K. A. “ANSYS for Designers”. Moscow: Russian Federation. *DMK Press.* 2009. 248 p.

11. “ANSYS”. – Available from: https://www.ansys.com/ – Active link: 02.02.2019.

12. “ELCUT. A new Approach to Modeling Fields”. – Available from: https://elcut.ru/ – Active link: October 12. 2019.

13. “ELCUT ® Modeling of two-dimensional Fields by the Finite Element Method”. – Available from: http://old.exponenta.ru/soft/others/elcut/Manual.pdf/. – Active link: September 17, 2019.

14. Chemeris, V. & Marinchenko, G. “Zastosuvannja modeljujuchoї programi “ELCUT” dlja doslidzhennja elektromagnitnih harakteristik induktornih sistem”. [Establishing model-based ELCUT Programs for Achieving the Electromagnet Characteristics of Inductor Systems] (in Ukrainian). *Science and Technology.* 2011; Vol.9 No.1: 116–123. DOI: https://doi.org/10.18372 / 2310-5461.9.5036.

15. “QuickField. A new Approach to Field Modelling”. – Available from: 9http://quickfield.com/. – Active link: 15.07.2019.

16. Baltzis, K. B. “The FEMM Package: A Simple, Fast, and Accurate Open Source Electromagnetic Tool in Science and Engineering”. *Journal of Engineering Science and Technology Review.* 2008; Vol.1: 83–89. DOI: https://doi.org/10.25103/jestr.011.18.

17. Baltzis, K. B. “The Finite Element Method Magnetics (FEMM) Freeware Package: May it Serve as an Educational Tool in Teaching Electromagnetics?” *Education and Information Technologies.* 2010; Vol. 15(1): 19–36. DOI: https://doi.org/ 10.1007/s10639-008-9082-8.

18. Cute, V. I. “System of Automated Formation of Calculating Models of Electric Machines for FEMM Software Environment”. *Technical Electrodynamics.* 2018; No.4: 74–78. DOI: https://doi.org/ 10.15407 / techned2018.04.074.

19.“Finite Element Method Magnetics: OldVersions. FEMM 4.2”. – Available from: http://www.femm.info/wiki/Old333Versions /. – Active link: 17.09.2019.

20. Shevchenko, V. P. & Babiychuk, O. B. “Issledovanie magnitnogo polja transformatora toka”. [Investigation of the Magnetic Field of a Current Transformer] (in Russian). “Jelektromashi-nostroenie i jelektrooborudovanie, Electrical”. *Engineering and Electrical Equipment*. 2008; No.70: 91–94.

21. Shevchenko, V. P. “Proektirovanie transformatorov toka”. [Designing Current Transformers] (in Russian). “Jelektronnoe uchebnoe posobie”. *Electronic textbook*. 2014. 138 p. - Available from: www.twirpx.com. – Active link: 10.14.2019.

22. Shevchenko, V. P. “Paket programm proektirovanija i analiza transformatorov toka” [Package of Design and Analysis of Current Transformers] (in Russian). – Available from: Www.twirpx.com. – Active link: 10.14.2019.

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ДОСЛІДЖЕННЯ МАГНІТНОГО ПОЛЯ ТРАНСФОРМАТОРІВ СТРУМУ МЕТОДОМ КІНЦЕВИХ ЕЛЕМЕНТІВ З ВИКОРИСТАННЯМ ПРОГРАМНОГО КОМПЛЕКСУ FEMM

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АНОТАЦІЯ

Широке застосування трансформаторів струму як в системах релейного захисту, так і в вимірювальних цілях робить досить актуальною задачу оцінки їх похибок. При цьому похибки багатодіпазонних трансформаторів струму з неповним заповненням магнітопроводу витками вторинної обмотки визначаються розподілом магнітного поля в магнітній системі, що залежать від потоків розсіювання обмоток. Проведено аналіз можливостей різних програмних продуктів, що реалізують метод кінцевих елементів для розрахунку електромагнітних систем. За допомогою програмного комплексу FEMM, виконано дослідження розподілу магнітного поля трансформатора струму при неповному заповненні магнітної системи витками вторинної обмотки і при різному розташуванні зворотного проводу багатовиткової первинної обмотки щодо вторинної обмотки для трансформатора струму з тороідальною магнітною системою Для трансформатора з прямокутною магнітною системою виконано моделювання магнітного поля при одній і двох котушках вторинної обмотки. Отримано характеристики розподілу магнітного поля в магнітній системі і нормальної складової поля розсіювання трансформатора. Побудовано діаграми векторів напруженості магнітного поля для різних ділянок магнітної системи трансформатора. Показано, що при неповному заповненні магнітної системи витками вторинної обмотки виникає значна нерівномірність розподілу магнітної індукції вздовж магнітопроводу,, що призводить до збільшення похибки трансформатора струму. Проведені дослідження показують ефективність застосування методу скінченних елементів для моделювання магнітних полів і оцінки похибок трансформаторів струму. Програмне середовище FEMM, використане для дослідження, є універсальною і точною інформаційною технологією аналізу магнітного поля трансформаторів струму, зручною для користувачів без спеціальної підготовки.

Ключові слова: багатодіапазонний трансформатор струму, метод кінцевих елементів, програма FEMM; розподіл магнітного поля в магнітопроводі; похибка вимірювальних трансформаторів

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ИССЛЕДОВАНИЕ МАГНИТНОГО ПОЛЯ ТРАНСФОРМАТОРОВ ТОКА МЕТОДОМ КОНЕЧНЫХ ЭЛЕМЕНТОВ С ПРИМЕНЕНИЕМ ПРОГРАММНОГО КОМПЛЕКСА FEMM

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АННОТАЦИЯ

Широкое применение трансформаторов тока, как в системах релейной защиты, так и в измерительных целях определяет задачу оценки их погрешностей достаточно актуальной. При этом погрешности многодиапазонных трансформаторов тока с неполным заполнением магнитопровода витками вторичной обмотки в значительной мере определяются распределением магнитного поля в магнитной системе, зависящим от потоков рассеяния обмоток. Проведен анализ возможностей различных программных продуктов, реализующих метод конечных элементов, для расчета электромагнитных систем. С помощью программного комплекса FEMM, выполнено исследование распределения магнитного поля трансформатора тока при неполном заполнении магнитной системы витками вторичной обмотки и при различном расположении обратного провода многовитковой первичной обмотки относительно вторичной обмотки для трансформатора тока с тороидальной магнитной системой. Для трансформатора с прямоугольной магнитной системой выполнено моделирование магнитного поля при одной и двух катушках вторичной обмотки. Получены характеристики распределения магнитного поля в магнитной системе и нормальной составляющей поля рассеяния трансформатора. Построены диаграммы векторов напряженности магнитного поля для разных участков магнитной системы. Показано, что при неполном заполнении магнитной системы витками вторичной обмотки возникает значительная неравномерность распределения магнитной индукции вдоль магнитопровода, что приводит к увеличению погрешности трансформатора тока. Проведенные исследования показывают эффективность применения метода конечных элементов для моделирования магнитных полей и оценки погрешностей трансформаторов тока. Программная среда FEMM, использованная для исследования, является универсальной и точной информационной технологией для анализа магнитного поля трансформаторов тока, удобной для пользователей без специальной подготовки.

Ключевые слова: многодиапазонный трансформатор тока; метод конечных элементов; программный комплекс FEMM; распределение магнитного поля в магнитопроводе; погрешность измерительных трансформаторов

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