https://doi.org/10.31891/2307-5732-2026-367-23
УДК 621.318:621.01

HRANIAK VALERII
Vinnytsia Mykhailo Kotsiubynskyi State Pedagogical University
https://orcid.org/0000-0001-6604-6157
e-mail: titanxp2000@ukr.net
TOKARCHUK OLEXII
Vinnytsia National Agrarian University
https://orcid.org/0000-0001-8036-1743
e-mail: tokarchyk08@ukr.net
KOLISNYK MYKOLA
Vinnytsia National Agrarian University
https://orcid.org/0000-0001-5502-6556
e-mail: kolisnik30@gmail.com

ENGINEERING DESIGN METHOD FOR DETERMINING THE INDUCTANCE OF HIGH-PASS FILTERS BASED ON STRUCTURAL PARAMETERS

The paper presents an engineering approach to the structural design of high-pass filter inductors based on analytical relationships between inductance and constructive parameters. The proposed methodology is intended to improve the efficiency of designing electromagnetic components used in inverter-based power converter systems.

A mathematical model has been developed that establishes analytical relationships between the inductance of a high-pass filter and its main structural parameters, including the geometric dimensions of the magnetic core, magnetic properties of materials, air gap characteristics, and winding configuration. The proposed model is based on classical electromagnetic theory and incorporates the effects of magnetic flux distribution, fringing in non-magnetic gaps, and nonlinear magnetization behavior.

On the basis of the developed model, a calculation methodology for determining the inductances of harmonic filters is proposed. This methodology allows simplifying engineering calculations, reducing the design time, and improving the accuracy of parameter determination. It also provides the possibility to optimize the electromagnetic characteristics of filters according to the specific operating conditions of inverter-based systems.

To verify the adequacy of the proposed model, computer simulations were carried out to analyze the dependence of inductance on key structural parameters, such as the number of turns, cross-sectional area of the magnetic core, and the size of the air gap. The obtained results demonstrate consistency with fundamental laws of electrical engineering and confirm the applicability of the developed approach for practical design tasks.

The proposed model and calculation technique can be effectively used in the development of high-performance harmonic filters for power systems with semiconductor converters, contributing to improved power quality and enhanced energy efficiency.

Keywords: *high-pass filter; structural design; inductance calculation; magnetic core; engineering calculation; power converter.*

ГРАНЯК ВАЛЕРІЙ
Вінницького державного педагогічного університету імені Михайла Коцюбинського
ТОКАРЧУК ОЛЕКСІЙ, КОЛІСНИК МИКОЛА
Вінницький національний аграрний університет

МЕТОД ІНЖЕНЕРНОГО ПРОЕКТУВАННЯ ДЛЯ ВИЗНАЧЕННЯ ІНДУКТИВНОСТІ ФІЛЬТРІВ ВИСОКИХ ЧАСТОТ НА ОСНОВІ СТРУКТУРНИХ ПАРАМЕТРІВ

У статті представлено інженерний підхід до структурного проектування індуктивностей високочастотних фільтрів, заснований на аналітичних залежностях між індуктивністю та конструктивними параметрами. Запропонована методологія спрямована на підвищення ефективності проектування електромагнітних компонентів, що використовуються в інверторних перетворювачах потужності. Застосування методики дозволяє зменшити кількість експериментальних ітерацій під час створення нових типів фільтрів та оптимізувати їх електромагнітні характеристики відповідно до умов роботи в системах із силовими напівпровідниковими пристроями. Для перевірки достовірності запропонованої моделі проведено комп'ютерне моделювання, у ході якого досліджено залежність індуктивностей фільтрів від зміни їх конструктивних параметрів. Отримані результати числових експериментів підтвердили адекватність побудованої математичної моделі та її придатність для використання у практичних інженерних розрахунках. Розроблена модель і методика розрахунку можуть бути використані при створенні високоефективних фільтрів вищих гармонік для систем електроживлення з інверторами та іншими типами силових перетворювачів.

Ключові слова: *фільтр високих частот; структурне проектування; розрахунок індуктивності; магнітопровод; інженерний розрахунок; перетворювач потужності.*

Стаття надійшла до редакції / Received 14.04.2026
Прийнята до друку / Accepted 17.07.2026
Опубліковано / Published 31.07.2026

Formulation of the problem

The most popular implementations of high-pass filters, which have found wide application, including as components of the solar overplant, are the T-type (Fig. 1) and L-type (Fig. 2) configurations [4, 5].

When designing such devices, considering the need for optimization under the inverter operating conditions and anticipated loads, there is typically a need to use non-standard values for the parameters of LCL and LC elements, respectively. It is worth noting that the values of the required inductance and capacitance are functionally dependent on each other, allowing for compensation of deviations in the parameter of one element by the other up to a certain limit [6, 7].

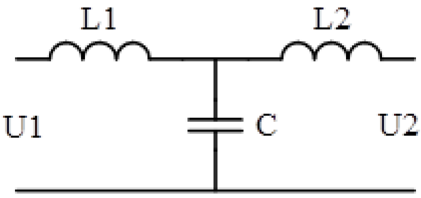

Fig. 1 Idealized equivalent circuit of a single-phase T-type high-pass filter

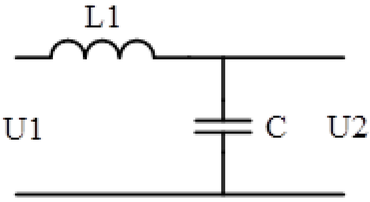

Fig. 2 Idealized equivalent circuit of a single-phase L-type high-pass filter

Considering the fact that in the construction of high-pass filters, it is the dimensions of the magnetic system and inductance coils that determine the form factor of the final product, and their structural design is less technologically complex compared to high-voltage capacitors, it is typical practice to use standard capacitors in conjunction with individually designed inductance coils. Therefore, based on the above, the development of a methodology for calculating the inductances of high-pass filters based on their constructive parameters is of significant theoretical and practical importance, aimed at simplifying the task of designing the final equipment.

Analysis of research and publications

The rapid technical development of recent decades has led to significant changes in the characteristics of electrical equipment used by various types of electricity consumers. The structure of generating capacities has also undergone substantial changes. One notable trend in the development of the power system, which is expected to continue in the future, is the rapid increase in decentralization of generating capacities, primarily through the use of renewable energy sources, including those involving semiconductor power converters (inverters) [1, 2]. It is well-known that when such converters are used, synchronization with the electrical grid becomes a known problem, accompanied by significant technical challenges [2, 3].

Figure 1 depicts the operation diagram of an inverter powered by a DC source and implementing pulse-width modulation of the output signal, realized using MATLAB Simulink.

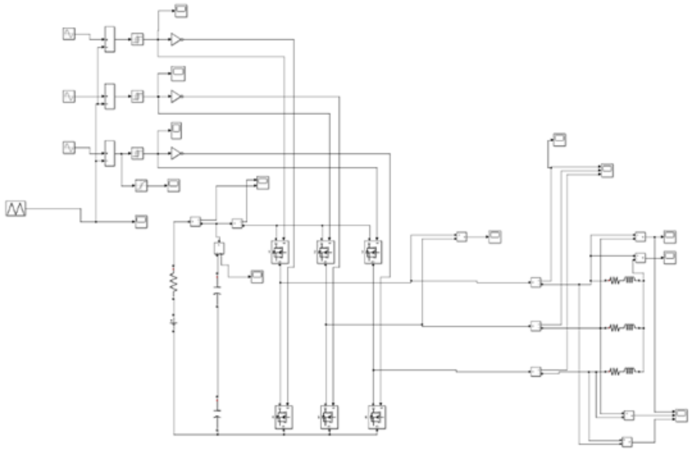

Fig. 3 Model of an inverter powered by a DC source and pulse-width modulation of the output signal

Based on the model depicted in Fig. 3, the parameters of the output voltage and current signals in inverters used in conjunction with photovoltaic power units were investigated. The simulation results of the linear voltage output of the inverter are shown in Fig. 4. The pulse-width modulation frequency was set to 200 kHz.

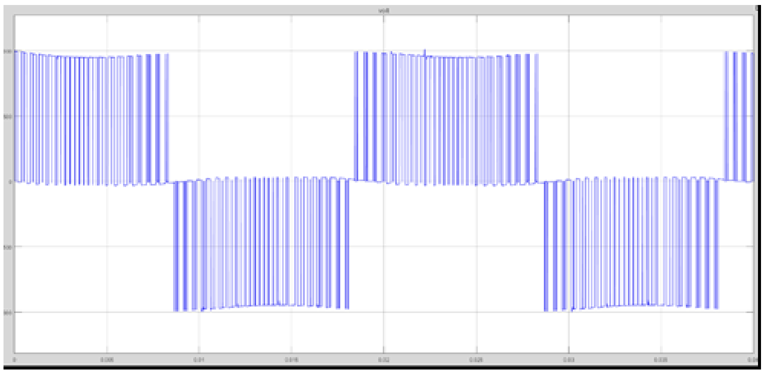

Fig. 4 Variation of the line-to-line voltage at the output of the inverter

The result of decomposing the line-to-line voltage signal into a Fourier series, limited to the first 50 harmonics, is shown in Figure 5.

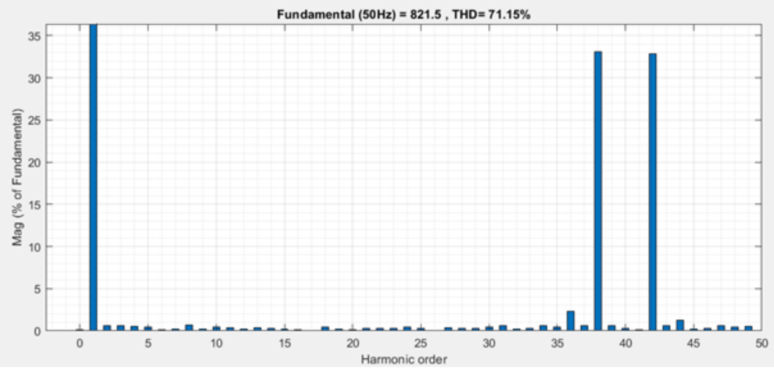

Fig. 5 Result of decomposing the line-to-line voltage signal at the output of the inverter into a Fourier series

Additionally, the current signal was also modeled, and it was established that the current waveform significantly depends on the type of load. Specifically, in the presence of an inductive component in the load, the non-sinusoidal of the current signal is much lower compared to the current signal in purely resistive or active-capacitive loads. It is noted that even significant inductance in the load (power factor 0.8-0.7) is insufficient to meet the specified DSTU EN 50160:2014 standard for the maximum allowable total harmonic distortion coefficient. A typical current signal at the output of the inverter is shown in Fig. 6.

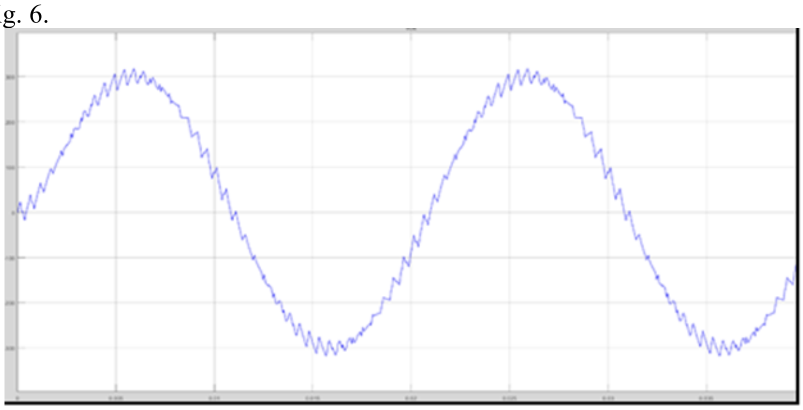

Fig. 6 Typical waveform of current in line at the output of the inverter

Therefore, as demonstrated above, a significant drawback of inverter technology is the considerable distortion of the current waveform at their output, necessitating the use of high-pass filters. The parameters of these filters need to be precisely tuned to match the operating mode and technical parameters of the inverter.

Development of a methodology for calculating the inductance of a high-pass filter coil based on its design parameters

Since the majority of power inverters operated in conjunction with solar powerplants are three-phase, a typical structural solution for implementing high-pass filters for such equipment involves constructing inductor coils on a combined magnetic core with the possibility of connecting to the midpoint of the coils for each phase (in the case of implementing a T-type high-frequency filter). The structural design scheme of such a magnetic system is shown in Fig. 7 [8].

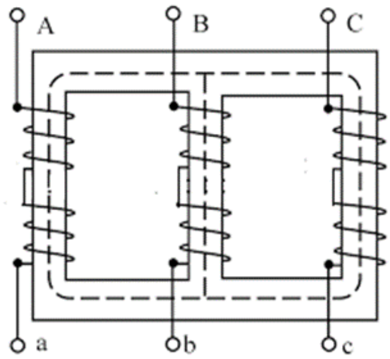

Fig. 7 Structural design scheme of the magnetic system of a three-phase high-pass filter

We set the value of induction B1 in the core and find the flux linkage [9-11].

$$\psi = B_1 S w, \quad (1)$$

where S – the cross-sectional area of the magnetic core;
w – the number of turns of the winding.

Based on the calculation of the magnetic circuit, we determine the required magnetomotive force of the winding:

$$F = I\,w, \tag{2}$$

where I – current in the winding.

We find the inductance [9, 10]:

$$L = \frac{\psi}{I}. \tag{3}$$

The voltage drops and the required magnetomotive force of the coil are determined by the second Kirchhoff's rule for the magnetic circuit as the sum of voltage drops across the respective sections of the magnetic circuit [10, 11]:

$$F = I\,w = \sum H_k L_k\,, \tag{4}$$

The magnetic field intensity in the ferromagnetic sections H1 in the central core and H2 in the side cores of the magnetic circuit, as well as in the yoke, is described by the magnetization curve B(H), which can be accurately approximated by a 7th-order polynomial in the following form:

$$H(B) = a_1 B + a_2 B^3 + a_3 B^5 + a_4 B^7\,, \tag{5}$$

The graphical relationship B(H) for steel 3407 ($H(B) = 2.117698963 \cdot B + 57.19874 \cdot B^3 - 50.3089 \cdot B^5 + 23.37212 \cdot B^7$) is provided in Fig. 8.

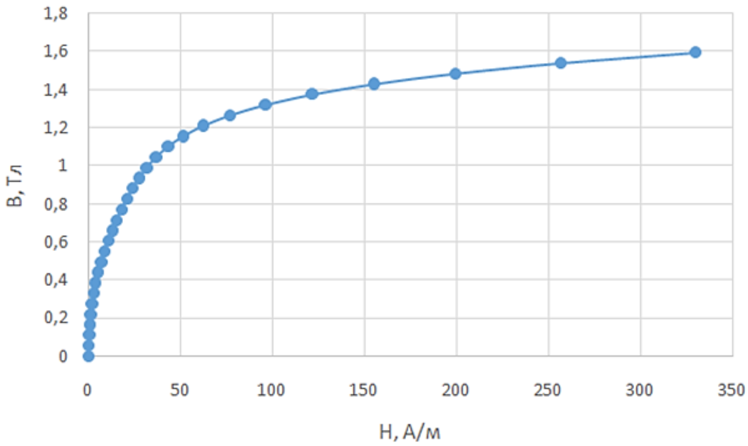

Fig. 8 Main magnetization curve B(H) for steel 3407

Then, the magnetic field intensity in the air gaps is found as [9, 11]:

$$H_k = \frac{B_k K_k}{\mu_0}\,, \tag{6}$$

where K_k – correction coefficient that accounts for the fringing of the magnetic flux in the non-magnetic gaps.

Calculation of K_1 and K_2 correction coefficients, which consider the fringing of the magnetic flux in the non-magnetic gaps.

The relative magnetic permeability of the rectangular gap (main):

$$G_0 = \frac{a\,b}{\delta}\,, \tag{7}$$

where a – depth of the core;

b – width of the core;

δ – gap between the core and the yoke.

The relative magnetic permeability of the quarter-cylindrical gap (end face of the central core):

$$G_{S1} = 0.52 \cdot a\,. \tag{8}$$

The relative magnetic permeability of the quarter-annular gap (end face of the central core):

$$G_{S2} = a \cdot \frac{\ln \dfrac{c}{\delta}}{\phi_1}\,, \tag{9}$$

where c – extension of the core beyond the winding;

$\varphi_1 = \pi/2$ – angle of deviation of scattered fluxes inside the magnetic cores.

The relative magnetic permeability of the quarte-cylindrical gap (end of the central core):

$$G_{S3} = 0.26 \cdot b. \tag{10}$$

The relative magnetic permeability of the quarter-tubular gap (end of the central core):

$$G_{S4} = b \cdot \frac{\ln \frac{c}{\delta}}{\phi_2}. \tag{11}$$

where $\varphi_2 = \pi$ – angle of deviation of scattered fluxes from the external parts of the magnetic cores.
The relative magnetic permeability of the quarter-spherical gap:

$$\mathrm{G}_{S7} = 0.144 \cdot c. \tag{12}$$

The total permeability for the central core is determined:

$$G_1 = G_0 + 2 \cdot G_{S1} + 2 \cdot G_{S2} + 2 \cdot G_{S3} + 2 \cdot G_{S4} + 4 \cdot G_{S7}. \tag{13}$$

The relative coefficient that accounts for the fringing of the magnetic field:

$$K_1 = \frac{G_0}{G_1} \tag{14}$$

The relative magnetic permeability of a half-cylindrical gap (outer end face of the lateral core):

$$\mathrm{G}_{S5} = 0.26 \cdot a. \tag{15}$$

The relative magnetic permeability of a half-annular gap (outer end face of the lateral core):

$$G_{S6} = b \cdot \frac{\ln \frac{c}{\delta}}{\phi_2}. \tag{16}$$

The total relative permeability for the side cores:

$$G_2 = G_0 + G_{S1} + G_{S2} + 2 \cdot G_{S3} + 2 \cdot G_{S4} + \mathrm{G}_{S5} + G_{S6} + 4 \cdot G_{S7} \tag{17}$$

The coefficient of fringing of the magnetic field for the side cores is determined:

$$\mathrm{K}_2 = \frac{G_0}{G_2}. \tag{18}$$

We determine the magnetic voltage drop and the required magnetomotive force of the coil:

$$F = H_1 L_1 + H_2 L_2 + 2 H_2 L_я + 2 \cdot \frac{B_1 K_1 \delta}{\mu_0} + 2 \cdot \frac{B_2 K_2 \delta}{\mu_0} = I \cdot w, \tag{19}$$

where $L_я$ – length of half the yoke of the magnetic core;
$L_1 = L_2$ – length of the magnetic core;
μ0 – the magnetic constant ($4\pi \cdot 10^{-7}$);
B_1 – magnetic induction in the central core;
B_2 – magnetic induction in the side cores of the magnetic circuit.
The current of the winding is determined for the given magnetic field induction:

$$I = \frac{F}{w}. \tag{20}$$

We calculate the flux linkage as:

$$\psi = B_1 S w = B_1 a b w. \tag{21}$$

The inductance of the winding equals:

$$\mathrm{L} = \frac{\psi}{\mathrm{I}}. \tag{22}$$

The modeling results of the dependence of inductance on the structural parameters of the filter

To confirm the adequacy of the obtained results, we will conduct modeling of the corresponding dependencies, having predetermined the following approximate structural parameters of the coil and the magnetic system: the depth of the core, a = 0,135 m, the width of the core b = 0.095 m, the gap between the core and the yoke δ = 0,012 m, the length of the magnetic core $L_1 = L_2$ = 0,34 m, the number of turns of the coil w = 11, the cross-sectional area of the magnetic core S = 0.012 m^2.

The modeling results are presented in Fig. 9 – Fig. 11.

As inferred from the theoretical analysis of the dependencies presented in Figures 9 to 11, the obtained mathematical model fully satisfies the fundamental rules of electrical engineering, confirming its adequacy.

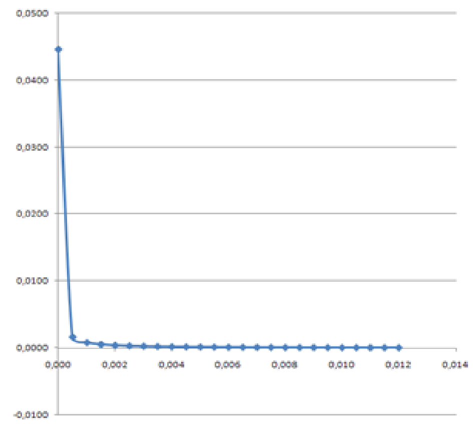

Fig. 9 Dependency of inductance L on the value of the non-magnetic gap δ

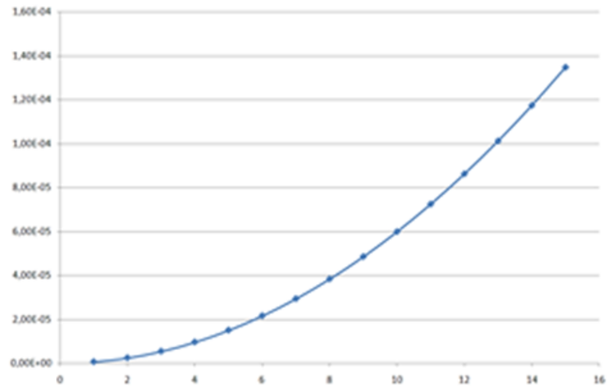

Fig. 10 Dependency of inductance L on the number of turns of the coil w

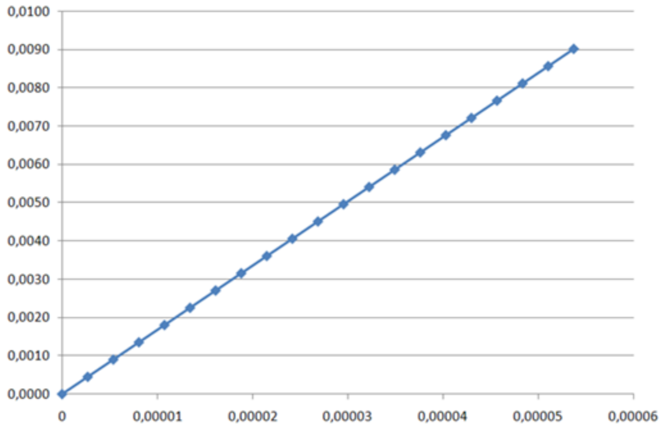

Fig. 11 Dependency of inductance L1 on the cross-sectional area S

Conclusions

1. The mathematical model and calculation methodology for the inductances of high-pass filters have been developed based on their structural parameters. This will simplify and expedite the process of designing high-pass filters suitable for operation in conjunction with semiconductor power converters (inverters).

2. Computer simulation of the obtained mathematical model depicting the dependence of the inductances of higher harmonic filters on their structural parameters has been conducted, confirming its adequacy.

References

1. Cao J., Yang Y., Qu N., Xi Y. et al. A low-carbon economic dispatch method for regional integrated energy system based on multi-objective chaotic artificial hummingbird algorithm // Scientific Reports. 2024. Vol. 14. Article number: 4129. DOI: 10.1038/s41598-024-54733-2.

2. Horbachuk V. M., Dunaievskyi M. S., Syrku A. A. Modern issues of electricity generation and storage in the power system of Ukraine // Eastern Europe: Economy, Business and Management. 2020. No. 1 (24). P. 260–268.

3. Kukharchuk V. V., Katsyv S. Sh., Hraniak V. F., Madyarov V. G. et al. Analysis of dependency current harmonics on load and filter parameters for asymmetrical network models // Przegląd Elektrotechniczny. 2020. Vol. 96, No. 9. P. 103–107. DOI: 10.15199/48.2020.09.22.

4. Kozlov V. S., Peresunko I. I., Antonenko A. O. Aspects of implementation of power active filters at industrial facilities // Bulletin of Vinnytsia Polytechnic Institute. 2016. No. 3. P. 46–50.

5. Zill D. Z., Glover J. D. Power System Analysis and Design. India: Cengage, 2011. 828 p.

6. Owusu P. A., Asumadu-Sarkodie S. A review of renewable energy sources, sustainability issues and climate change mitigation // Cogent Engineering. 2016. Vol. 3. Article number: 1167990. DOI: 10.1080/23311916.2016.1167990.

7. Vedmitskyi Y. G., Kukharchuk V. V., Hraniak V. F., Vishtak I. V. et al. Newton binomial in the generalized Cauchy problem as exemplified by electrical systems // Proc. SPIE 10808, Photonics Applications in Astronomy, Communications, Industry, and High-Energy Physics Experiments. 2018. 7 p. DOI: 10.1117/12.2501600.

8. Guru B. S., Hiziroglu H. R. Instructor's Manual for Electric Machinery and Transformers. Oxford: Oxford University Press, 2000. 222 p.

9. Karpov Yu. O., Katsyv S. Sh., Kukharchuk V. V., Vedmitskyi Yu. H. Theoretical foundations of electrical engineering. Steady-state regimes of linear electric circuits with lumped and distributed parameters. Vinnytsia: VNTU, 2011. 377 p.

10. Ida N., Bastos J. P. A. Electromagnetics and Calculation of Fields. 2nd ed. Berlin: Springer-Verlag, 1997. 583 p.