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Thermal Losses of an Anisotropic Electrically Conductive Transformer

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ABSTRACT This paper presents the design and comprehensive analysis of an anisotropic electrically conductive transformer developed as an innovative component for modern infocommunication systems. The transformer is based on the use of materials with anisotropic electrical conductivity, opening new possibilities for improving device efficiency and integration. A detailed study of thermal losses is carried out under three main operating modes: no-load operation, short-circuit conditions, and optimal load performance, using numerical calculation methods without simplifications or assumptions. Special attention is paid to the influence of electrical conductivity anisotropy and the orientation of crystallographic axes on the overall efficiency and thermal behavior of the transformer. Unlike conventional transformers with magnetic cores, the proposed design eliminates hysteresis losses, significantly enhancing energy efficiency and minimizing unwanted heat generation. Equivalent electrical circuit models are developed for each operating mode, and analytical expressions for resistance and current are derived, allowing for precise evaluation of performance characteristics. Thermal losses due to Joule heating are quantitatively analyzed for different types of materials. Cadmium antimonide *(CdSb)*, zinc antimonide *(ZnSb)*, single-crystal bismuth *(Bi)*, and single-crystal tellurium *(Te)* are proposed as promising materials for anisotropic electrically conductive transformers. Numerical modeling results demonstrate a significant potential for minimizing energy losses and optimizing transformer design. The presented results confirm the suitability of the proposed transformer for use in microelectronic and telecommunication applications, where compactness, high efficiency, and thermal stability are critical. The relevance of this study is driven by the growing global demand for compact and energy-efficient components in infocommunication systems. The obtained results provide a foundation for further development of anisotropic electrically conductive transformers as effective matching elements and functional modules within modern telecommunication equipment.

KEYWORDS anisotropy, electrical conductivity, transformer, thermal losses, infocommunication system components.

I. INTRODUCTION

Modern infocommunication systems demand compact, energy-efficient, and multifunctional components capable of stable operation under high frequencies, variable loads, and constrained spatial conditions. Traditional electromagnetic transformers, while effective in high-power systems, face significant limitations due to the presence of a magnetic core, which introduces hysteresis losses and hinders miniaturization. In this context, anisotropic electrically conductive transformers (AECTs) present new opportunities, leveraging the unique properties of materials with anisotropic electrical conductivity, particularly in high-frequency (HF) and microwave (MW) applications. However, the challenge lies in the insufficient investigation of thermal losses in these devices, which directly affects their efficiency and longevity, thereby complicating their practical implementation in infocommunication systems.

The relevance of this study stems from the rapid advancement of telecommunication technologies, which increasingly require structural matching elements with high efficiency and low energy losses. AECTs, which eliminate the need for a magnetic core, have the potential to serve as the basis for compact transformers integrated into microelectronic circuits. Investigating thermal losses and optimizing the operating conditions of such devices are critical to enhancing their competitiveness compared to traditional counterparts. Furthermore, the use of anisotropic materials opens prospects for adaptive component design with tailored characteristics, aligning with the contemporary demands of electronic communications and radio engineering.

The objective of this paper is to analyze thermal losses in AECTs under various operating conditions and evaluate strategies for their minimization in infocommunication applications. The AECT design and its features were first introduced in [1-3], demonstrating the feasibility of electrodynamic transformation and its potential for novel energy conversion devices. However, the issue of thermal losses in such transformers has remained underexplored. The anisotropy of electrical conductivity and its impact on material properties have been actively studied in recent literature: for instance, [4] examines the anisotropic conductivity of thin films with aligned conductive rods, [5] analyzes the electrical properties of composites with aligned nanotubes, and [6] investigates the influence of anisotropy on the thermal and electrical characteristics of nanomaterials.

Contemporary research on materials for infocommunication system components, such as [7, 8], focuses on magnetics and conductors but does not address their application in the context of AECTs. Thus, the existing gaps in the analysis of AECT thermal characteristics necessitate a detailed study of their behavior under different operating conditions.

To address these gaps, this paper pursues the following objectives: to describe the AECT design and evaluate the impact of anisotropic electrical conductivity on its characteristics; to develop equivalent circuits and perform numerical calculations of thermal losses under idle, short-circuit, and optimal load conditions; to assess the use of promising materials for AECT fabrication; and to formulate practical recommendations for the design and application of AECTs.

II. DESIGN AND OPERATING PRINCIPLES OF ANISOTROPIC ELECTROCONDUCTIVE TRANSFORMERS

The design and operational features of AECTs have been discussed in [1-3]. The structure of such a transformer consists of a rectangular plate (denoted as component 1) with dimensions length a, height b, and width c, fabricated from a material characterized by anisotropic electrical conductivity, represented by the conductivity tensor $\hat{\sigma}$ (see Fig. 1). The top and bottom surfaces of the plate, each with an area of $a \times c$, are coated with dielectric layers (component 2) of thickness d_1. On the opposite side of these dielectric layers, conductive layers (component 3) of thickness d_2 are applied. Input electrical contacts (components 4 and 5) are fixed on the top and bottom conductive layers, while output electrical contacts (components 6 and 7) are placed on the opposite lateral faces of the plate, each with an area of $b \times c$.

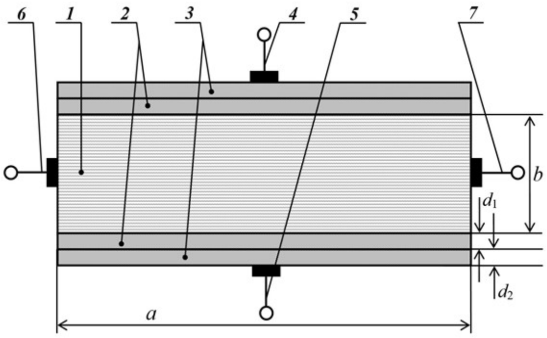

FIG. 1. Schematic design of the AECT (1 – anisotropic conductive plate, 2 – dielectric layers, 3 – conductive layers, 4, 5 – input electrical contacts, 6, 7 – output electrical contacts).

As is known, in the general case, the electrical conductivity tensor $\hat{\sigma}$ of the material of plate 1 is represented by a second-rank tensor, which, in the principal crystallographic axes Ox, Oy, Oz, takes the following form [9]

$$\hat{\sigma} = \begin{vmatrix} \sigma_{11} & 0 & 0 \\ 0 & \sigma_{22} & 0 \\ 0 & 0 & \sigma_{33} \end{vmatrix}. \quad (1)$$

If the chosen crystallographic axes OX and OY, with conductivity values σ_{11} and σ_{22} respectively, are located in the plane of the lateral face $a \times b$ of plate 1 such that the OX axis is oriented at a selected angle γ with respect to the Ox axis (see Fig. 2), then the conductivity tensor $\hat{\sigma}$ (1) takes the following form [10]

$$\hat{\sigma}' = \begin{vmatrix} \sigma_{11}\cos^2\gamma + \sigma_{22}\sin^2\gamma & (\sigma_{11}-\sigma_{22})\sin\gamma\cos\gamma & 0 \\ (\sigma_{11}-\sigma_{22})\sin\gamma\cos\gamma & \sigma_{11}\sin^2\gamma + \sigma_{22}\cos^2\gamma & 0 \\ 0 & 0 & \sigma_{33} \end{vmatrix}. \quad (2)$$

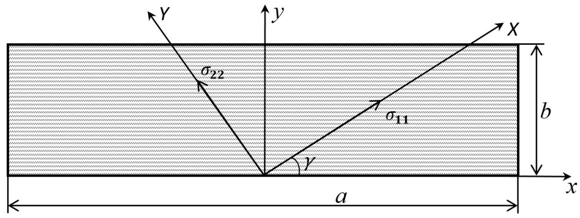

FIG. 2. Anisotropic conductive plate (the crystallographic axis OZ coincides with the laboratory axis Oz, both oriented perpendicular to the plane of the figure).

This results in the appearance of both longitudinal ($\sigma_\parallel$) and transverse ($\sigma_\perp$) components of the electrical conductivity tensor [11], as given by (3) and (4)

$$\sigma_\parallel = \sigma_{11}\cos^2\gamma + \sigma_{22}\sin^2\gamma, \quad (3)$$

$$\sigma_\perp = (\sigma_{11}-\sigma_{22})\sin\gamma\cos\gamma. \quad (4)$$

The transformation coefficient m of such a device is determined by the expression [1], as shown in (5)

$$m = \frac{(\sigma_{11}-\sigma_{22})\sin\gamma\cos\gamma}{\sigma_{11}\cos^2\gamma + \sigma_{22}\sin^2\gamma}\frac{a}{b}. \quad (5)$$

The maximum transformation coefficient is observed at an optimal angle γ_{opt} = 45° and takes the following form [3], as given by (6)

$$m = \frac{\sigma_{11}-\sigma_{22}}{\sigma_{11}+\sigma_{22}}\frac{a}{b}. \quad (6)$$

The anisotropy of electrical conductivity (σ) affects the resistance in different operating modes of the AECT, which determines the thermal losses. Specifically, the values of $\sigma_\parallel$ and $\sigma_\perp$ influence the resistance of the plate depending on the orientation of the crystallographic axes, directly impacting the current and, consequently, the Joule losses in idle, short-circuit, and optimal load conditions. As is known, in the case of conventional classical transformers, their thermal losses are determined by the operating modes [12, 13]. These thermal losses are typically established experimentally for each mode. The thermal losses of the AECT under consideration can be expressed through analytical expressions and evaluated using numerical calculations, taking into account the specific features of their operation.

III. IDLE MODE OF THE ANISOTROPIC CONDUCTIVE TRANSFORMER

Let us connect the AECT to a power source without transferring energy to a load. The equivalent electrical circuit model of the AECT in idle mode is presented in Fig. 3.

In this case, the resistance of plate 1 with respect to contacts 4 and 5 is represented by the expression (7)

$$R_\parallel = \frac{1}{\sigma_\parallel}\frac{b}{ac} = \frac{1}{\sigma_{11}\cos^2\gamma + \sigma_{22}\sin^2\gamma}\frac{b}{ac}. \quad (7)$$

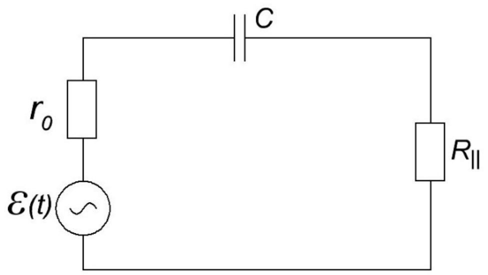

FIG. 3. Equivalent electrical circuit of the AECT in idle mode.

The resistance of plate 1 with respect to contacts 6 and 7 is given by the following expression (8)

$$R_{\perp} = \frac{1}{\sigma_{\perp}}\frac{a}{bc} = \frac{1}{(\sigma_{11}-\sigma_{22})\sin\gamma\cos\gamma}\frac{a}{bc}. \quad (8)$$

The AECT under consideration operates as follows: applying an electromotive force (EMF) $\varepsilon(t)=E_0 \sin(\omega t)$ to contacts 4 and 5 results in an electric current I_1, the magnitude of which is expressed as (9)

$$I_1 = E\Big/\sqrt{(r_0+R_{\parallel})^2 + 1/(\omega C)^2}, \quad (9)$$

where I_1 and E are the effective values of the current and EMF, respectively; r_0 is the internal resistance of the EMF source; and C is the capacitance of the transformer between contacts 4 and 5, determined by the expression (10)

$$C = \varepsilon_0\varepsilon_d\frac{ac}{2d_1}, \quad (10)$$

where ε_0 is the absolute dielectric permittivity, and ε_d is the dielectric permittivity coefficient of the dielectric material layer.

It should be noted that the load resistance R_n is disconnected. In this case, the thermal losses P_1 of the AECT are determined by the expression (11)

$$P_1 = I_1^2 R_{\parallel} = \frac{I_1^2}{\sigma_{11}\cos^2\gamma + \sigma_{22}\sin^2\gamma}\frac{b}{ac}. \quad (11)$$

IV. SHORT-CIRCUIT MODE OF THE ANISOTROPIC ELECTROCONDUCTIVE TRANSFORMER

Let us describe the operating parameters of the AECT in short-circuit mode. The equivalent electrical circuit of the AECT in this case is shown in Fig. 4. It should be noted that the resistances $R_{\parallel}$ and $R_{\perp}$ are connected in parallel.

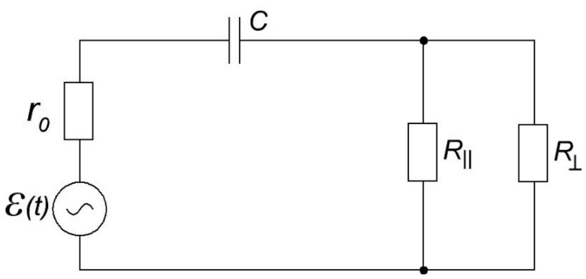

FIG. 4. Equivalent electrical circuit of the AECT in short-circuit mode (electrical contacts 6 and 7 are shorted together).

The parameters of the AECT in this mode are characterized by the following expressions: (12), (13), and (14)

$$R_2 = R_{\parallel}R_{\perp}/(R_{\parallel}+R_{\perp}), \quad (12)$$

$$I_2 = E\Big/\sqrt{\left(r_0 + R_{\parallel}R_{\perp}/(R_{\parallel}+R_{\perp})\right)^2 + 1/(\omega C)^2}, \quad (13)$$

$$P_2 = I_2^2 R_2 = \frac{E^2 R_{\parallel}R_{\perp}(R_{\parallel}+R_{\perp})\omega^2C^2}{(R_{\parallel}+R_{\perp})^2 + \left(r_0(R_{\parallel}+R_{\perp})+R_{\parallel}R_{\perp}\right)^2\omega^2C^2}. \quad (14)$$

V. OPTIMAL LOAD MODE OF THE ANISOTROPIC ELECTROCONDUCTIVE TRANSFORMER

Let us consider the operating mode of the AECT in which an optimal balance is achieved between the useful power transferred to the load and the losses. The equivalent electrical circuit of the AECT for the optimal load mode is shown in Fig. 5. It should be noted that the resistances R_n and $R_{\perp}$ are connected in series.

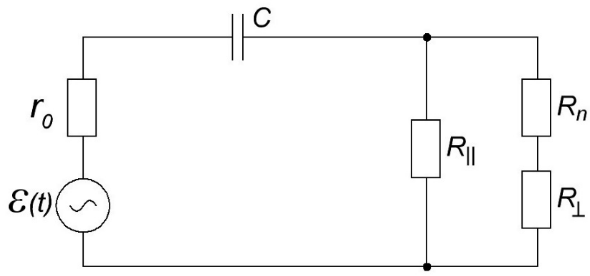

FIG. 5. Equivalent electrical circuit of the ACT in load mode.

$$R_3 = 2R_{\parallel}R_{\perp}/(R_{\parallel}+2R_{\perp}), \quad (15)$$

$$I_3 = E\Big/\sqrt{(r_0+R_3)^2 + 1/(\omega C)^2}, \quad (16)$$

$$P_3 = I_3^2 R_3 = \frac{2E^2R_{\parallel}R_{\perp}(R_{\parallel}+2R_{\perp})}{\left(r_0(R_{\parallel}+2R_{\perp})+2R_{\parallel}R_{\perp}\right)^2 + 1/\omega^2C^2}. \quad (17)$$

where $X_C = 1/\omega C$ is the capacitive reactance of the capacitor C.

Thus, the presented formulas for calculating the thermal losses of the AECT demonstrate the feasibility of performing numerical evaluations of heat dissipation under various transformer operating modes, which significantly simplifies their design and application.

VI. MATERIALS

As materials for the fabrication of the proposed AECT intended for operation at room temperature, both diamagnetic and paramagnetic anisotropic electrically conductive materials can be employed. These include cadmium antimonide doped with silver (*CdSb:Ag*), zinc antimonide (*ZnSb*), cadmium arsenide ($CdAs_2$), zinc arsenide ($ZnAs_2$), bismuth (*Bi*), tellurium (*Te*), and needle-like eutectics based on them.

The obtained Eqs. (11), (14), and (17) are used to perform numerical calculations of thermal losses for various AECT operating modes, based on two anisotropic electrically conductive structures: bismuth (*Bi*: σ_{11}=9×10^3 S/m, σ_{22}=4.5×10^3 S/m) and cadmium antimonide doped with silver (*CdSb:Ag*: σ_{11}=0.8 S/m, σ_{22}=0.3 S/m) [14–16].

For the calculations, the following parameters are used:

a = 0.1 m, $b \approx c$ = 0.02 m, d_1 = 0.2 mm, d_2 = 1 mm,
ε_0 = 8.854×10^{-12} F/m, ε_d = 2.23 (polyethylene),
r_0 = 5 Ω, γ = 45°,
E = {12 V, 48 V, 120 V, 220 V},
ω = {50 rad/s, 50×10^3 rad/s, 50×10^6 rad/s}.

The calculation results are presented in Table 1. Here, $P1$, $P2$ and $P3$ represent the thermal losses of the AECT under idle, short-circuit, and optimal load conditions, respectively.

TABLE 1. Thermal Losses of the AECT in Different Operating Modes.

ω	*E* (V)	P_1 (W)	P_2 (W)	P_3 (W)
Bismuth (*Bi*)				
50 rad/s	12	2.050×10^{-10}	2.030×10^{-10}	2.040×10^{-10}
	48	3.280×10^{-9}	3.250×10^{-9}	3.260×10^{-9}
	120	2.050×10^{-8}	2.030×10^{-8}	2.040×10^{-8}
	220	6.890×10^{-8}	6.820×10^{-8}	6.860×10^{-8}
50×10^3 rad/s	12	2.047×10^{-4}	2.020×10^{-4}	2.032×10^{-4}
	48	3.275×10^{-3}	3.232×10^{-3}	3.251×10^{-3}
	120	2.047×10^{-2}	2.020×10^{-2}	2.032×10^{-2}
	220	6.880×10^{-2}	6.789×10^{-2}	6.830×10^{-2}
50×10^6 rad/s	12	8.520×10^{-3}	8.410×10^{-3}	8.462×10^{-3}
	48	1.363×10^{-1}	1.346×10^{-1}	1.354×10^{-1}
	120	8.520×10^{-1}	8.410×10^{-1}	8.462×10^{-1}
	220	2.8637	2.8267	2.843
Cadmium antimonide doped with silver (*CdSb:Ag*)				
50 rad/s	12	2.518×10^{-7}	2.473×10^{-7}	2.496×10^{-7}
	48	4.029×10^{-6}	3.957×10^{-6}	3.994×10^{-6}
	120	2.518×10^{-5}	2.473×10^{-5}	2.496×10^{-5}
	220	8.462×10^{-5}	8.312×10^{-5}	8.391×10^{-5}
50×10^3 rad/s	12	2.404×10^{-1}	2.365×10^{-1}	2.384×10^{-1}
	48	3.846	3.784	3.814
	120	2.404×10^{1}	2.365×10^{1}	2.384×10^{1}
	220	8.080×10^{1}	7.949×10^{1}	8.009×10^{1}
50×10^6 rad/s	12	5.631	5.587	5.607
	48	9.010×10^{1}	8.939×10^{1}	8.971×10^{1}
	120	5.631×10^{2}	5.587×10^{2}	5.607×10^{2}
	220	1.892×10^{3}	1.878×10^{3}	1.885×10^{3}

Analysis of the data presented in Table 1 reveals that bismuth (*Bi*), due to its high electrical conductivity, results in significantly lower thermal losses compared to silver-doped cadmium antimonide (*CdSb:Ag*). For instance, at $\omega = 50$ rad/s and $E = 12$ V, the losses for bismuth are approximately $P_1 \approx 2.050\times10^{-10}$ W, whereas for *CdSb:Ag* they reach $P_1 \approx 2.518\times10^{-7}$ W, which is three orders of magnitude higher. At a high frequency of 50×10^6 rad/s and $E = 220$ V, the difference is even more pronounced: $P_1 \approx 2.864$ W for bismuth versus 1.892×10^3 W for *CdSb:Ag*. The primary reason lies in the lower resistance of bismuth, which significantly reduces its contribution to thermal losses.

The conducted calculations highlight the necessity for further analysis and additional numerical studies involving other anisotropic structures to achieve an optimal balance between thermal efficiency and material cost. AECTs based on the proposed anisotropic electroconductive materials are expected to be implemented as structural matching elements in a wide range of modern telecommunication devices, with particular promise for coupling components such as amplifiers, oscillators, and antennas in HF and MW wavelength bands.

V. CONCLUSION

The proposed AECT enables both the increase and decrease of electric power in the low-frequency and MW wavelength ranges. Unlike conventional transformers that include a magnetic core –leading to hysteresis-related losses – the AECT eliminates this element, significantly reducing such losses. This work investigates the thermal losses of AECTs under various operating modes: no-load, short-circuit, and optimal load conditions. Numerical calculations reveal that the magnitude of thermal losses depends on the geometric dimensions of the conductive plate and the anisotropy of its electrical conductivity.

Practical conclusions are provided based on frequency ranges:

– Low frequencies (50 rad/s): both materials exhibit negligible losses, making them suitable for low-frequency applications with minimal heating;

– Medium frequencies (50×10^3 rad/s): losses increase but remain manageable (within $10^{-12} – 10^{-5}$ W), and anisotropic electroconductive materials with higher conductivity are preferable to minimize losses;

– High frequencies (50×10^6 rad/s): thermal losses rise significantly for materials with lower conductivity, potentially requiring cooling in certain operating conditions.

The obtained results demonstrate the potential of AECTs for improving energy efficiency. Implementing such transformers opens broad prospects for miniaturization and integration into microelectronic devices, thereby enhancing the practical capabilities of structural elements used in modern switching, measurement, and other equipment within infocommunication systems.

AUTHOR CONTRIBUTIONS

A.A., M.D., M.R. – conceptualization, writing-review and editing, supervision; M.D., D.L. – methodology, software, resources, writing-original draft preparation, visualization, validation, investigation.

COMPETING INTERESTS

The authors declare that they have no conflict of interest.

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АНОТАЦІЯ У статті розглянуто конструкцію анізотропного електропровідного трансформатора як інноваційного компонента інфокомунікаційних пристроїв, що функціонують на основі використання властивостей матеріалів з анізотропією електропровідності. Запропоновано теоретичну модель такого трансформатора, побудовану з урахуванням особливостей розподілу електричного поля, напрямків струму та орієнтації кристалографічних осей у провідному анізотропному середовищі. Проведено комплексне дослідження теплових втрат трансформатора в трьох характерних режимах роботи: холостого ходу, короткого замикання та оптимального навантаження. Для кількісної оцінки втрат використано чисельні методи розрахунку, що враховують взаємодію струмів з анізотропним середовищем. Особливу увагу приділено впливу орієнтації анізотропії електропровідності на розподіл струмів та величину теплових втрат. Представлено еквівалентні електричні схеми кожного з режимів роботи та виведено відповідні аналітичні вирази для опору, струму й потужності, які враховують як геометричні параметри пристрою, так і електрофізичні характеристики обраного матеріалу. На відміну від класичних трансформаторів із магнітним осердям, у яких виникають втрати, пов'язані з гістерезисом та вихровими струмами в феромагнітних матеріалах, анізотропний електропровідний трансформатор функціонує без магнітного осердя, що дозволяє уникнути втрат, зумовлених перемагнічуванням. Такий підхід відкриває нові перспективи для створення високочастотних, енергоефективних та компактних компонентів, придатних для інтеграції в мікроелектроніку, сенсорні системи та телекомунікаційне обладнання. Як потенційно придатні матеріали для виготовлення анізотропних електропровідних трансформаторів запропоновано низку діамагнітних і парамагнітних кристалів із вираженою електропровідною анізотропією. Серед них розглянуто монокристали бісмуту (*Bi*), телуру (*Te*), сполуки типу кадмій-стибій (*CdSb*), цинк-стибій (*ZnSb*), а також штучно-структуровані матеріали з інженерно заданою анізотропією. Показано, що такі матеріали забезпечують ефективне електричне перетворення енергії без застосування магнітних елементів, з високим коефіцієнтом трансформації та низькими втратами. Проведено чисельні розрахунки теплових втрат в таких трансформаторах для різних частот (від 50 рад/с до 50×106 рад/с) і різних рівнів напруги (від 12 В до 220 В) на прикладі бісмуту (*Bi*) та сполуки кадмій-стибію, легованої сріблом (*CdSb:Ag*). Результати показали значне зростання втрат зі збільшенням частоти, що необхідно враховувати під час проєктування високочастотних пристроїв. Описано фізичні механізми виникнення втрат у різних режимах та вплив параметрів матеріалу на їхню величину. Запропоновані підходи та отримані результати можуть бути використані для оптимізації геометричних розмірів і параметрів анізотропних матеріалів з метою підвищення ефективності анізотропних електропровідних трансформаторів. Такі пристрої мають потенціал застосування як узгоджувальні елементи, перетворювачі сигналів або енергетичні ланки у складі сучасної телекомунікаційної апаратури, особливо в умовах мініатюризації.

КЛЮЧОВІ СЛОВА анізотропія, електропровідність, трансформатор, теплові втрати, компоненти інфокомунікаційної системи.