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EXPANDING THE FUNCTIONAL CAPABILITIES OF AN ELECTROMAGNETIC CONVERTER WITH A SPATIALLY PERIODIC MAGNETIC FIELD STRUCTURE

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This study investigates the process of interaction between the non-uniform electromagnetic field of a primary transducer and a metallic cylindrical article in order to obtain multiparametric information.

The study tackles the scientific and technical task of expanding the functional capabilities of an electromagnetic transducer by increasing the number of controllable parameters for an article at a single excitation frequency using the same transducer.

The method is based on extracting the amplitude and phase of the spatial harmonics of the non-uniform probing field. The advantage of such transducers is in the fact that, while operating at a single fixed excitation frequency, they enable multiparametric inspection of metal articles.

The results have practical significance for the instrumentation industry when designing and manufacturing primary transducers with a spatially periodic structure of the excitation magnetic field. This makes it possible to perform contactless monitoring of the electrical, magnetic, and geometric parameters of cylindrical articles of various sizes and types.

For a transducer having two poles with currents in opposite directions, at $\gamma = 36°$ and $d/a = 0.5$, the influence of the 5th spatial harmonic on the extracted 1st and 3rd harmonics is zero, while the influence of the 7th harmonic on the 1st and 3rd harmonics amounts to 0.36% and 2.7%, respectively. The influence of the 7th harmonic on the 3rd can be reduced to 1% by choosing $d/a = 0.4$.

An algorithm for monitoring three parameters of a cylindrical article has been developed, based on the normalized amplitudes of the 1st and 3rd harmonics and the phase of the 1st harmonic, thereby expanding the functional capabilities of the method. It has been established that the influence of higher spatial harmonics on the measurement results is insignificant, and the total error does not exceed 1.5% without higher harmonics, in contrast to single-frequency methods where the error exceeds 5%

Keywords: nondestructive testing, spatial harmonic, magnetic permeability, electrical conductivity, amplitude, phase, sensitivity

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1. Introduction

Of particular scientific and practical interest are multiparameter methods of non-destructive testing (NDT), which make it possible to obtain the most complete information about an object under study. It is continuous quality control over the material at the stage of supply, during technological operations in the manufacture of parts, as well as during their subsequent operation, that ensures reliability and safety.

The most common materials used for the manufacture of articles in industry, energy, and transport are magnetic and non-magnetic materials of various chemical composition. Most often it is necessary to evaluate the chemical composition of electrically conductive objects, recognize the grade of steel, evaluate the hardness, strength, depth, and quality of mechanical, thermal, and chemical-thermal treatments, determine the degree of mechanical stress, control the quality of surface layers, detect intergranular corrosion.

Compared to unproductive and expensive destructive testing methods, the electromagnetic method is most effective in the study of metal articles and structures. Such advantages of the electromagnetic method as high productivity, speed, multiparameter, electrical form of the output signal, as well weak dependence on temperature, pressure, humidity, and contamination of the surface of objects, open up wide possibilities of its application in quality control systems for materials and articles.

Further advancement of multiparameter electromagnetic methods and devices is aimed at obtaining the most complete information about the studied control object (CO). Therefore, the issue of designing new types of multiparameter electromagnetic converters (EMCs), which operate at the same frequency of alternating current and have a spatially periodic structure of the magnetic field, is quite relevant.

2. Literature review and problem statement

Theoretical and practical results of research on one- and two-parameter electromagnetic control methods are reported in [1, 2]. It is shown that these methods partially satisfy the needs of qualitative determination of the characteristics of metal articles and structures. However, issues related to the simultaneous determination of three or more parameters of the object under study remain unresolved, which means that it is necessary to use a larger number of independent equations. In this case, it is necessary to measure a larger number of electrical parameters of the converter. Such parameters can be determined in a converter operating on the basis of the method of several fixed frequencies [3, 4]. However, the use of this method in practice is complicated. The likely reason is the difficulty associated with the impossibility of synchronizing the exciting field in time and isolating the output electrical parameters from the resulting converter signal. This same drawback applies to converters operating on the basis of the use of pulsed fields with the subsequent isolation of the necessary time harmonics, by which the product parameters are found [5].

Analytical solution to a nonlinear electrodynamics problem in a domain with discontinuous coefficients and local inhomogeneities is hardly possible. In this regard, modeling of electromagnetic processes in the implementation of electromagnetic NDT is carried out on the basis of numerical methods, which makes the corresponding studies impractical [6].

By using modern numerical methods, in particular the finite element method (FEM), it is possible to model the distribution of the electromagnetic field in objects of complex geometric shape, including in nonlinear and anisotropic media. Usually, the simplest elements are used, such as triangles or quadrilaterals – for two-dimensional problems, and elements such as tetrahedra or hexahedra – for three-dimensional problems. On the grid obtained in this way, a set of basis functions is determined. The solution to the problem is a linear combination of these functions. FEM is considered the most universal method for solving field problems. The accuracy of the solution depends on the discretization parameters of the solution domain. FEM is also successfully used to solve electromagnetic control problems. The disadvantages of FEM, which limit its application, include the complexity of constructing the computational domain and the high dimensionality of the resulting system of equations. This is the approach used in [7], but it leads to very significant costs of highly qualified specialists and a significant duration of the computational process.

This problem is not solved by a simple mechanical increase in the number of nodes without any restrictions. The fact is that with the increase in the number of nodes, not only the calculation time but also the rounding error increases sharply. Thus, there is some optimal partition, the determination of which requires a large amount of computational experiments. At the same time, when calculating the voltage introduced into the converter, a fairly high accuracy of calculations is required. This is due to the need to determine the difference of close numbers.

The increase in information parameters controlled by one converter can be carried out in several ways. For example, using current of different frequencies to power the converter with subsequent filtering and separation of the amplitude and phase at each frequency. Such an implementation of multi-parameter sensors is quite complex and does not always reflect the true picture of the processes occurring in the control object due to different depths of field penetration (skin effect). This same drawback applies to converters that operate on the basis of the use of pulsed fields with the subsequent extraction of the necessary time harmonics [8].

All this gives grounds to argue that it is advisable to conduct a study aimed at obtaining more complete information about CO, which could not be acquired using conventional methods.

3. The aim and objectives of the study

The purpose of our research is to expand the functionality of methods and devices for multiparameter control using EMC with a spatially periodic representation of the exciting magnetic field. The use of a combination of separate exciting systems with currents in the conductors that vary in direction will make it possible to distinguish the amplitudes of individual spatial harmonics and their phase in the measuring windings of the converter. This will make it possible to design devices for controlling informative parameters of a metal article on their basis.

To achieve the goal, the following tasks were set:

– to construct a physical and mathematical model of the interaction of a non-uniform electromagnetic field of a linear conductor with a current located along the side surface of a cylindrical metal article with eddy currents excited in a cylindrical CO;

– to derive mathematical expressions for the amplitude and phase of the *n*th harmonic of the transducer signals, which are given in the measuring windings located along the surface of the cylindrical article, with the angular coordinate φ on a circle of radius d;

– to find universal transformation functions for the amplitude and phase of the *n*th harmonic for EMC with a spatially periodic structure of the electromagnetic field;

– to devise a method and design a device for non-contact control of electrical, magnetic, and geometric parameters of cylindrical articles using the amplitudes of the 1st and 3rd spatial harmonics and the phase of the 1st harmonic.

4. The study materials and methods

The object of our research is the process of interaction of the inhomogeneous electromagnetic field of the primary converter with a metal cylindrical article to obtain multiparameter information.

The inhomogeneity of the magnetic field of a conductor with a current located along the surface of a metal article makes it possible to solve a multidimensional problem, i.e., obtaining an infinite number of equations that relate the characteristics of the product to the field parameters. When solving the equations, it was assumed that the cylindrical sample and the conductor with a current are long enough to ignore the end effects, and they are placed parallel to each other. The simplification concerned the condition that the magnetic permeability of the sample material depended weakly on the magnitude of the magnetic field strength (the initial segment of the magnetization curve), and the specific electrical conductivity of the material was constant in the cross section of the cylindrical sample.

Analytical, numerical, and experimental methods were used. To describe the interaction of an inhomogeneous electromagnetic field with a metal CO, the theory of solving boundary value problems of electrodynamics of continuous media, the theory of electric and magnetic circuits, and methods of differential and integral calculus were used. The basics of measurement theory were also applied to evaluate the metrological characteristics of the designed multi-parameter converter, based on the separation of the amplitude and phase of spatial harmonics of an inhomogeneous probing field, represented in the form of a Fourier series. The verification of the devised method was carried out in the process of experimental research on a laboratory setup using specially manufactured samples of various assortments.

5. Results of research on the electromagnetic converter

5. 1. Physical and mathematical model of the interaction of a non-uniform electromagnetic field of a linear conductor with a cylindrical article

In [9, 10], expressions were derived that describe the characteristics of the magnetic field of an EMC with a single conductor with a current having infinitely small transverse dimensions. In practice, conductors with a finite width and radial height are mainly used in real converters. The latter is conveniently implemented in one of two design options: the use of a strip conductor with a current or a pole containing many thin conductors with currents flowing along the forming pole in the same direction. In this case, the currents of individual conductors generate the total current of the exciting pole of EMC.

Fig. 1 shows a physical and mathematical model of the interaction of a non-uniform electromagnetic field with a conducting cylindrical article. The model takes into account the spatial-periodic distribution of the magnetic field induced by the excitation windings with different directions of currents.

Based on the system of equations of the diffusion of the magnetic field in a conductive medium and taking into account the boundary conditions, an analytical solution was found for different regions – inside the article, between the article and the excitation conductor, and outside it. In this case, modified Bessel functions of the first kind were used to solve the equations, which allowed us to obtain generalized expressions. The resulting formulae make it possible to determine the spatial distribution of the magnetic field of the converter depending on the material parameters, geometric dimensions, and characteristics of the excitation current.

At the same time, for region $a \le r \le d$:

$$Ç_{r0}\left(r,\phi,t\right)=\frac{I}{2\eth d}e^{i\omega t}\sum_{n}\left(\frac{r}{d}\right)^{n-1}\frac{\sin\left(n\gamma\right)}{n\gamma}\sin\left(n\phi\right); \qquad (1)$$

$$Ç_{\phi 0}\left(r,\phi,t\right)=\frac{I}{2\eth d}e^{i\omega t}\sum_{n}\left(\frac{r}{d}\right)^{n-1}\frac{\sin\left(n\gamma\right)}{n\gamma}\cos\left(n\phi\right). \qquad (2)$$

To exclude from the spatial distribution of the field of even and odd harmonics, a system of conductors with the same and different directions of currents in them can be used [11].

Moreover, to maintain a certain symmetry of the magnetic field, these conductors must be shifted relative to each other in azimuth by angles $\varphi = 2\pi / m$, where m is the number of conductors.

The electromagnetic field strength of a converter consisting of m conductors with currents can be obtained by replacing the angular coordinate φ by $\varphi + (2\pi / m) k$, where $k = 1, 2, 3$.

The expression that describes the field distribution pattern in this case can be found using the sum formula, which takes the following form

$$\sum_{k=1}^{m-1}\sin\left[n\left(\phi+\frac{2\pi}{m}k\right)\right]=m\sin\left(n\phi\right), \qquad (3)$$

where $n = pm$, $p = 0, 1, 2....$

When $n \ne pm$ the left-hand side of expression (3) collapses to zero. The sum formula for cosines takes a similar form.

Fig. 1 shows excitation systems consisting of two (*a*) and four (*b*) poles with currents of equal magnitude and alternating direction in them. The signs "+" and "–" indicate the direction of currents I along and against the direction of the z-axis.

The field of m pairs of conductors with alternating current directions in them (Fig. 1, *a*, *b*) is found using the formula for the sum (3). In this case, after some transformations, we obtain an expression for the radial component of the field strength

$$H_r\left(r,\phi,t\right)=2m\,e^{i\omega t}\sum_{p=0}^{\infty}\frac{\sin\left(n\gamma\right)}{n\gamma}f_n\left(r,i,\omega\right)\sin\left(n\phi\right), \qquad (4)$$

where $n = (2p + 1)\,m$ – number of conductor pairs. $p = 0, 1, 2....$

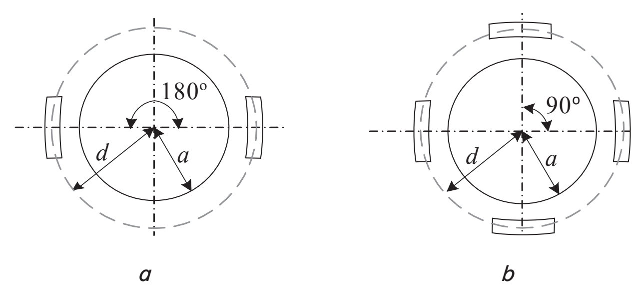

Fig. 1. Cross section of exciting systems with currents that change alternately in direction and are equal in magnitude: *a* — system with two poles; *b* — system with four poles

As can be seen from (4), the amplitude of the magnetic field strength of m pairs of conductors with current, the directions of which change alternately, is $2m$ times greater than the amplitude of the field of one conductor. At the same time, the H_r component of the magnetic field in this case contains harmonics that are multiples of the number of pairs of conductors.

For example, with one pair of conductors (Fig. 1, *a*), the described magnetic field (4) contains only odd harmonics: the first, third, fifth, etc. With the number of pairs $m = 2$ (Fig. 1, *b*) – only even harmonics: the second, sixth, tenth, etc.

When controlling the parameters of tested articles, one of the main issues is to determine the methods and means for isolating the necessary harmonics from the resulting EMC signals and weakening the influence of harmonics with higher numbers on the control results.

The main ways to reduce the influence of spatial harmonic amplitudes that interfere are as follows:

– placement of sections of measuring windings on radii smaller than the radii of the magnetizing poles;

– rational choice of the number of pairs of poles with oppositely directed currents ($m \geq 1$, Fig. 1, *a, b*);

– placement of sections of measuring windings on certain rays $\varphi = \text{const}$ and corresponding inclusion of such sections;

– choice of the angular width of the sections of the measuring winding.

For example, for a converter with two poles with currents in opposite directions (Fig. 1, *a*), at $\gamma = 36°$ and $d/a = 0.5$, the influence of the 5th spatial harmonic on the selected 1st and 3rd is zero, and the influence of the 7th on the 1st and 3rd is 0.36% and 2.7%, respectively. The influence of the 7th harmonic on the 3rd can be reduced to 1% if we take $d/a = 0.4$.

5. 2. Mathematical expressions for the amplitude and phase of the *n*th harmonic of the converter signals

Based on the generalized solution of the magnetic field equations, it was obtained for the radial component of the field H_r, which contains harmonics that are multiples of the number of conductors or pairs of conductors in the excitation winding (EW). For a system with two poles with opposite current directions (Fig. 1, *a*), it was determined that only odd harmonics (1st, 3rd, 5th, etc.) are present in the field, since the 2nd harmonic is absent in this system [12].

Fig. 2 shows a ferromagnetic cylinder of radius a, which is in an electromagnetic field generated by conductors with mutually opposite currents, which are located along the surface of the sample at distance d from the z axis.

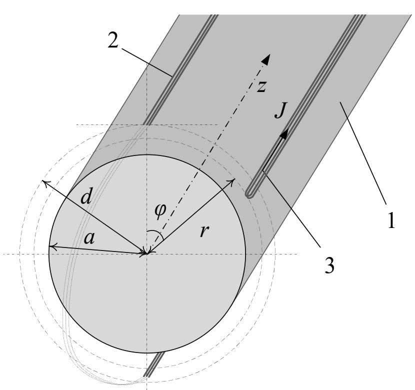

Fig. 2. Mutual arrangement of the measuring and exciting windings and the test sample: 1 — test sample; 2 — exciting winding; 3 — measuring winding

Moreover, the longitudinal axes of the conductor with current and the sample under study are parallel to the z axis.

Due to the fact that the EW, which encircles the sample along, has parts (Fig. 2) in which the same countercurrents I flow, then the resulting field pattern will lack even harmonics.

When designing primary EMCs with spatially periodic fields, it is advisable to use transformer EMCs in which the measuring windings (MW) are placed at radii $r \approx a$, smaller than the radius d of the EW placement. For example, if the MW is placed between the article and EW ($a < a_m < d$), then to determine the r-th component of EMC of the converter with the article, based on expressions (1)–(4), the formulae for calculating the module and phase are obtained:

$$E_r^{(n)} = -i\omega W_m \Phi_r = -i\omega\mu_0 e^{i\omega t}\frac{IW_e}{2\pi d}W_m S \times$$
$$\times \sum_n \left[\left(\frac{a_m}{a_e}\right)^{n-1} + h_r^{(n)}\left(\frac{a_m}{a_e}\right)^{n-1}\left(\frac{a}{a_m}\right)^{2n}\right]\frac{\sin(n\gamma)}{n\gamma}\cos(n\phi); \quad (5)$$

$$\operatorname{tg}\Phi^{(n)} = \operatorname{Im} h_r^{(n)} \big/ \operatorname{Re} h_r^{(n)}, \quad (6)$$

where Φ_r is the instantaneous value of the magnetic flux (r-th component) that excites the EMC E_r in MW; S is the cross-sectional area of the frame MW; W_e and W_m are the number of turns EW and MW; the complex parameter $h_r(n)$ characterizes the reaction of the article to the magnetic field (n-th harmonic):

$$h_r^{(n)} = \frac{A_{h1}B_{h1} + A_{h2}B_{h2}}{B_{h1}^2 + B_{h2}^2} + i\frac{A_{h2}B_{h1} - A_{h1}B_{h2}}{B_{h1}^2 + B_{h2}^2};$$

$$A_{h1} = (\mu_r - 1)ber_{n-1}x + (\mu_r + 1)ber_{n+1}x;$$

$$A_{h2} = (\mu_r - 1)bei_{n-1}x + (\mu_r + 1)bei_{n+1}x;$$

$$B_{h1} = (\mu_r + 1)ber_{n-1}x + (\mu_r - 1)ber_{n+1}x;$$

$$B_{h2} = (\mu_r + 1)bei_{n-1}x + (\mu_r - 1)bei_{n+1}x.$$

In this case, transducer EMC without an article

$$E_{r0}^{(n)} = -i\omega W_m \Phi_{r0} = -i\omega\mu_0 e^{i\omega t}\frac{IW_e}{2\pi d}W_m S \times$$
$$\times \sum_n \left(\frac{a_m}{a_e}\right)^{n-1}\frac{\sin(n\gamma)}{n\gamma}\cos(n\phi). \quad (7)$$

For example, Fig. 3 shows an image of the expanded picture of the distribution of odd spatial harmonics of EMC (from the 1st to the 9th) along the angular coordinate φ on the lateral surface of the cylinder along the circumference of radius d.

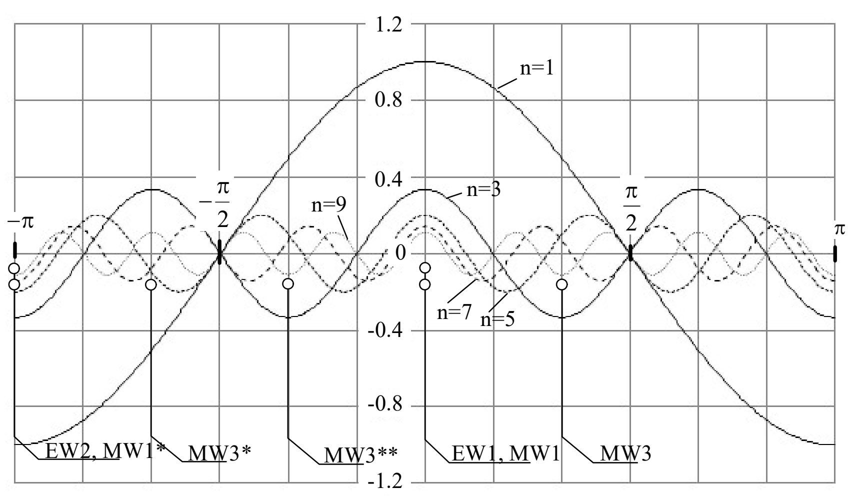

Fig. 3. Distribution of spatial harmonics of a non-uniform field of a transducer with two excitation windings without a test sample

The measured values of EMC at the output of each MWs, located at fixed points with angular coordinate φ, when φ changes in the range from $-180° \leq \varphi \leq 180°$, have values corresponding to the algebraic sum of all harmonics, taking into account their phase.

5. 3. Universal transformation functions and algorithm for determining informative parameters of cylindrical articles

For practical implementation of the proposed method, it is advisable to normalize the values of EMC of the converter in the case of the presence of the controlled item E_n to EMC in the absence of the controlled item E_{n0}. That is, $A_1 = E_1 / E_{10}$, etc.

Normalization of the amplitude of the output signal of EMC makes it possible to ensure weak sensitivity to the instability of the field parameters due to the non-coincidence of the axis of the cylindrical sample and the longitudinal axis of the cylinder on the surface of which the windings are located, as well as due to the presence in the field of the converter of extraneous elements that are not directly related to the EW-MW-CO system, other reasons that affect the location of the windings and the sample under study in space.

Based on the calculated data, the dependences of the universal transformation functions for the amplitude and phase of spatial harmonics (Fig. 4–6) were obtained, which makes it possible to calculate the electromagnetic parameters of the controlled item.

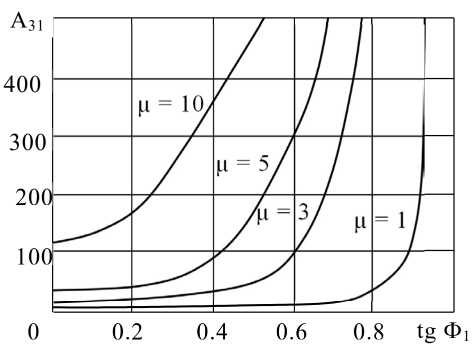

Fig. 4. Universal dependences of parameter A_{31} on the phase of the 1st harmonic signal for different μ_r values

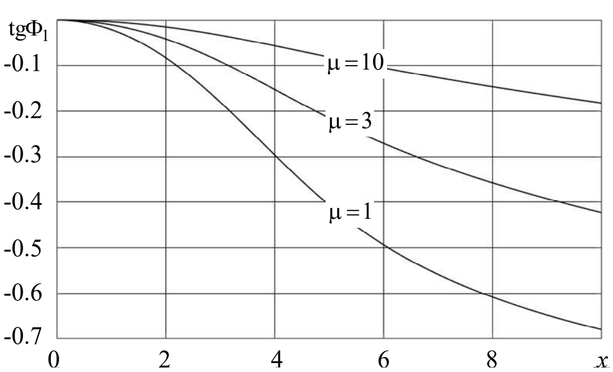

Fig. 5. Universal functional dependences for determining the generalized parameter x

The algorithm for determining these parameters is as follows. Based on the obtained values of the amplitudes of the 1st and 3rd harmonics and the phase of the 1st harmonic, the normalized parameters A_1 and A_3 are found. Then the A_{31} parameter is determined from the following expression

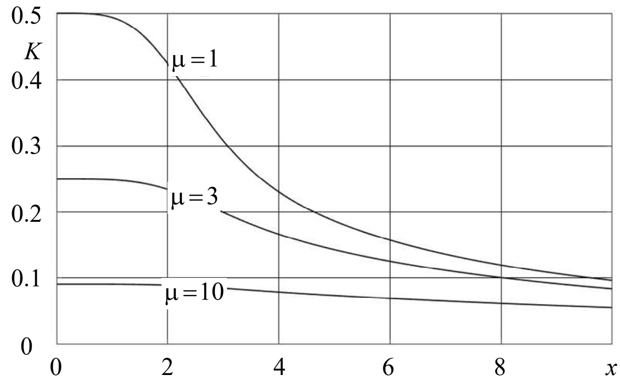

Fig. 6. Dependences of parameter K on the generalized parameter x for different μ_r values of the sample

$$A_{31} = \frac{A_3}{A_1^3}. \quad (8)$$

Next, from the dependences in Fig. 4, for the calculated A_{31} value at the intersection of the lines corresponding to the A_{31} value and the measured $tg\Phi_1$ value, μ_r is determined, after which, using the dependence in Fig. 5, for the found μ_r value and the measured $tg\Phi_1$ value, the generalized parameter x is determined.

For the found μ_r and x values, from the dependence in Fig. 6, the value of the normalized magnetic flux $K = A_1 (d / a)$ is found, while the radius a of the controlled item is determined from the following expression

$$a = \frac{A_1 d}{K}, \quad (9)$$

where d is the distance from the measuring winding of the converter to the axis of the article.

After that, the value of σ is determined from the expression

$$\sigma = \frac{x^2}{\mu_0 \mu_r a^2 \omega}, \quad (10)$$

where $\mu_0 = 4\pi\, 10^{-7}$ H/m is the magnetic constant; $\omega = 2\pi f$ is the frequency of the probing field.

Thus, having the measurement results for E_1, E_3, E_{10}, E_{30} and Φ_1 and the devised indirect control method, it is possible to determine the μ_r, σ and a parameters of the cylindrical article under study.

5. 4. Method and device for implementing an electromagnetic converter with two exciting poles and different current directions

When using an exciting system with two poles in which currents flow in opposite directions (Fig. 1, *a*), to implement three-parameter control, it is necessary to isolate the 1st and 3rd spatial harmonics, as well as the phase of the 1st harmonic. The scheme of switching on the measuring windings for isolating the amplitude and phase of the 1st harmonic and the amplitude of the 3rd harmonic is shown in Fig. 7.

In the diagram in Fig. 7, voltmeters V1 and V3 measure the amplitudes of the 1st and 3rd harmonics, respectively; phase meters Φ1 and Φ3 measure the phases of the specified harmonics; Fig. 3 shows the geometric location of EW and MW in the angular coordinate φ.

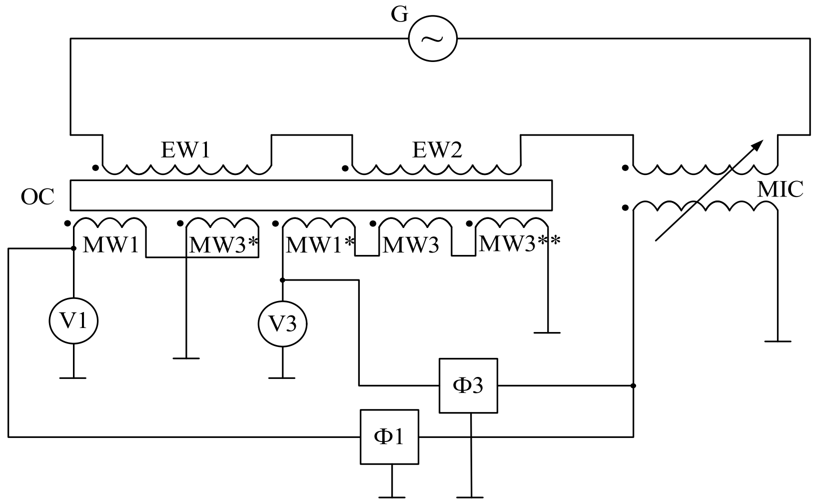

Fig. 7. Scheme of switching on the converter windings for isolating the amplitude and phase of the 1st and 3rd spatial harmonics

al solutions of a converter with two EWs with oppositely directed currents *I* and located one relative to the other in azimuth at an angle $\varphi = 180°$ (Fig. 3).

According to the schematic electrical diagram (Fig. 7), the total EMC is measured using the MW1 winding, which consists of the 1st, 3rd, 5th, and other odd harmonics. Using MW2, the EMC is determined, which includes the 3rd, 5th, and other harmonics.

For the same current value in the excitation windings and the same parameters of the CO converter as in the previous case, the values of the resulting EMC in MW of this system are calculated. In this case: $E_{10} = 533$ mV; $E_{30} = 178$ mV; $E_{50} = 53.3$ mV; $A_1 = 0.187$; $A_3 = 0.170$; $A_5 = 0.134$; $\mathrm{tg}\Phi_1 = -0.360$; $\mathrm{tg}\Phi_3 = -0.073$; $\mathrm{tg}\Phi_5 = -0.032$; $E_1 = 99.5$ mV; $E_3 = 30.2$ mV; $E_5 = 7.1$ mV.

The resulting EMC of the measuring winding MW1, taking into account the 1st, 3rd, and 5th harmonics, is 36.4 mV, and the total EMC MW2, consisting of the 3rd and 5th harmonics, is 2.7 mV. The calculation error associated with the rejection of, for example, the 5th harmonic when determining the resulting EMC MW1 is 1.5%. This error is reduced when using EW with a value of $\gamma = 15°$. In this case, it is only 1%.

One of the main metrological characteristics of primary converters is sensitivity. Since all informative parameters of the studied sample are included in the formula for determining the generalized parameter *x*, the sensitivity is determined by changing the parameter *x*

$$S_{A_1} = \frac{dA_1}{dx} = f(x),$$

$$S_{tg\phi_1} = \frac{d\mathrm{tg}\phi_1}{dx} = f(x),$$

$$S_{A_3} = \frac{dA_3}{dx} = f(x),$$

$$S_{tg\phi_3} = \frac{d\mathrm{tg}\phi_3}{dx} = f(x).$$

Fig. 8 shows dependences of the sensitivity on the amplitude and phase of the 1st and 3rd harmonics on the generalized parameter *x*.

Analyzing the behavior of dependences of sensitivity on amplitude and phase for the 1st and 3rd harmonics, it is possible to distinguish a rational mode of operation of the converter when studying CO with different electromagnetic and geometric parameters. Moreover, the choice of a rational mode is carried out by selecting the frequency of the probing field.

Solving this issue makes it possible to select measuring instruments with characteristics that best meet the requirements for implementing a multi-parameter electromagnetic control method using the designed primary EMCs with a spatially periodic structure of the probing field.

An example of calculating the EMC and phase in MW for structur-

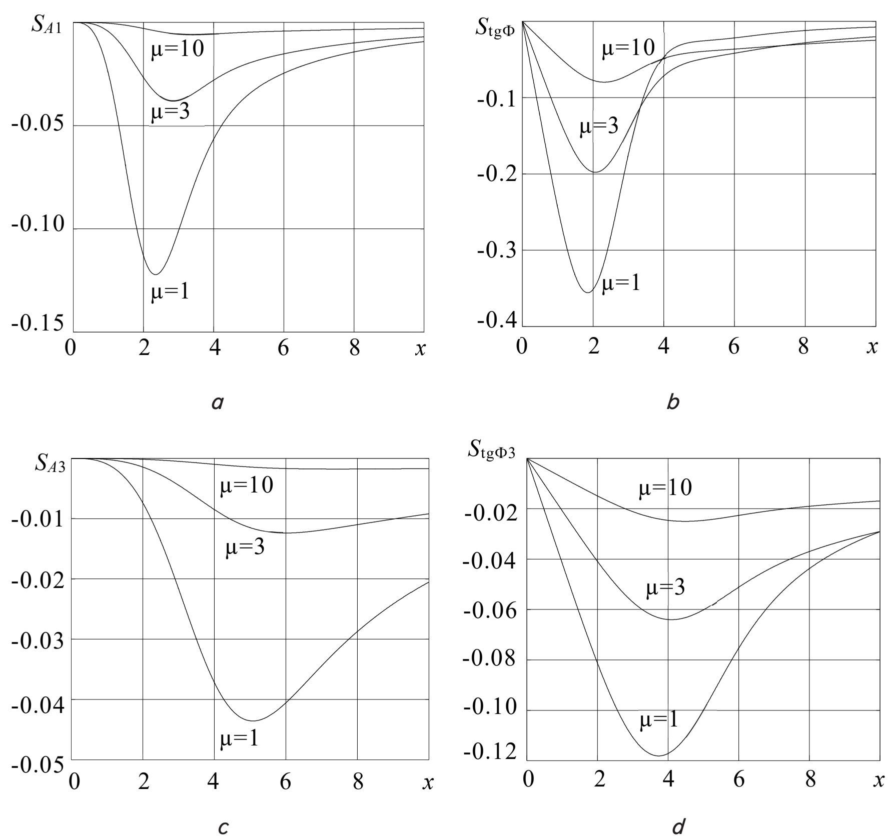

Fig. 8. Dependences of sensitivity on the amplitude and phase of the transformation on the generalized parameter *x* for different μ_r values: *a* — on the amplitude for the 1st harmonic; *b* — on the phase for the 1st harmonic; *c* — on the amplitude for the 3rd harmonic; *d* — on the phase for the 3rd harmonic

6. Non-contact determination of magnetic, electrical, and geometric parameters of cylindrical metal articles: results and summary

A physical and mathematical model of the interaction of an inhomogeneous electromagnetic field generated by a linear conductor with current with eddy currents in a cylindrical article has been built.

The system of equations (1), (2) of the diffusion of the magnetic field has been solved taking into account the boundary conditions for three regions – inside the article, between the article and the excitation system, and outside it. For this purpose, modified Bessel functions of the first kind have been applied, which allowed us to obtain analytical expressions for the components of the magnetic field in cylindrical coordinates. The absence of even harmonics is explained by formula (3), where $n=(2p+1)m$. At $m=1$ (two poles, opposite currents) – only odd harmonics, which is visible in Fig. 3 (the amplitude of even ones is zero). The zero influence of the 5th harmonic is explained by the geometric arrangement of the measuring winding on the rays, where $\cos(5\varphi)=0$. Fig. 1 shows the configurations of exciting systems that form harmonics of different orders.

(4) was derived, which describes the spatial distribution of the field depending on the geometric parameters of the system (radii a, d, angular coordinate φ), the magnetic properties of the material and the characteristics of the exciting current.

The model allowed us to show the influence of the number of poles, the direction of currents in the conductors and the angular width of the exciting elements on the harmonic composition of the field, as well as to identify the conditions under which odd harmonics prevail in the resulting field. Thus, as a result of the theoretical analysis of the model, analytical expressions were obtained for determining the amplitudes and phases of spatial harmonics of the field for different power systems and their dependence on the parameters of the material and geometry of the converter and the control object.

For a transformer EMC with spatially periodic fields (Fig. 2), in which MWs are located at radii $r \approx$ a, smaller than the radius d of EW placement ($a < a_m < d$), based on expressions (5) and (6), we calculate the modulus and phase of the r-th component of the EMC of the converter with the article.

Universal transformation functions were constructed for the amplitude and phase of the n-th harmonic of EMC, which make it possible to us to link the EMC signals with the parameters of the control object. This provides the possibility of implementing multi-parameter control. Fig. 4 demonstrates the unambiguous dependence of parameter A_{31} on the phase of the first harmonic signal for different values of magnetic permeability μ_r when changing external factors.

For practical implementation of the proposed method, it is advisable to normalize the values of EMC of the converter in the case of the presence of the controlled item E_n to the EMC in the absence of the controlled item E_{n0}. That is, $A_1 = E_1/E_{10}$, etc. Normalization of the amplitude of the output signal will provide weak sensitivity to instability of the field parameters due to the non-coincidence of the axis of the cylindrical sample and the longitudinal axis of the cylinder on the surface of which the windings are located.

It was found that the rejection of higher harmonics ($n \geq 5$) almost does not affect the accuracy of measurements, which confirms the adequacy of the constructed mathematical model and the effectiveness of the selected excitation system (Fig. 1, *a*).

It is shown that each selected spatial harmonic of EMC reacts differently to the probing field of the excitation systems (Fig. 4–6). Such discrepancy is manifested in a change in the characteristic features of the harmonics, i.e., their amplitudes and phases. This makes it possible to select and use different types of transducers with spatially periodic structures of the magnetic field for multi-parameter control.

Multi-parameter methods of non-contact control of informative parameters of cylindrical articles using normalized amplitudes of the 1st, 3rd, and phase of the 1st spatial harmonics of the EMC signal have been improved, which expanded the functional capabilities.

The practical significance of our results for the electrical engineering industry is the possibility of simultaneously controlling the electrical (σ), magnetic (μ_r), and geometric (a) parameters of cylindrical articles of various assortments and nomenclature [13].

The limitation of the application of the devised method includes the control of metal articles with diameters less than 10–15 mm due to the complexity of the location of the magnetizing and measuring windings of the converter in space as close as possible to the sample under study. Also, when controlling metal articles with $\mu_r > 200$ for which the obtained results will not be adequate due to the significant influence of the demagnetization coefficient. In practical application, it is necessary to take into account the influence of extraneous elements and possible deviations in the geometry of the sample. The exact orientation of the sample relative to the z axis is required (deviation by an angle of 5°, the error increases by 5%). The influence of anisotropy and the influence of edge effects on the reliability of resulting expressions (1), (2) are not taken into account. The method depends on the accuracy of the placement of the windings and the stability of field parameters.

The disadvantages of our method include the inability to control the informative parameters of metal articles, the shape of which differs from the cylindrical (channel, square, sheet, etc.). To eliminate them in the future, it is necessary to build another physical and mathematical model and solve a complex electrodynamics problem. The implementation of the devised method is accompanied by the use of rather complex mathematical calculations; without the use of a computer, the practical use of this method is complicated.

Further advancement of the physical and mathematical model and the solution of the electrodynamics problem to it will make it possible to determine the informative parameters for metal articles of various configurations, and not only cylindrical shapes. Design solutions of measuring windings, their localization, will make it possible to determine article parameters not integrated in the volume but local. This will expand the possibility of their use not only in determining the structure of the material but also in flaw detection. The use of a neural network will solve the problem of automating the process of manual determination of parameter μ_r, x and K (Fig. 4–6). In order to increase accuracy or further expand the functionality of the method, it is possible to use higher-order harmonics.

7. Conclusions

1. Based on the field diffusion equations and Bessel functions, a physical and mathematical model of the primary converter with a non-uniform distribution of the electromagnetic field of a conductor with a current has been constructed. The conductor is located along the side surface of a cylindrical metal article, which made it possible to derive analytical expressions for H_r and H_φ. A distinctive feature is the absence of even

harmonics with opposite currents in the exciting conductors, which simplifies the separation of the 1st and 3rd harmonics. It is explained by the translational symmetry of the field along the z axis. Advantage: one frequency of the exciting field instead of several. The model error is < 1% at $d / a > 0.4$.

2. Mathematical expressions for determining the amplitude and phase of the nth harmonic of EMC signals, as well as a picture of the distribution of spatial harmonics, have been obtained. Due to the technique of placement and inclusion of the measuring windings, the influence of the 5th harmonic is 0%, the 7th – 1%, which provides the possibility of unambiguous calculation of article parameters. It is explained by the zero sum of cos($n\varphi$) by sections. Advantage: mechanical filtering of harmonics, unlike digital filtering.

3. The universal functions $A_1(x, \mu_r)$, $A_3(x, \mu_r)$, $tg\varphi(x, \mu_r)$ have been derived. The monotonicity of functions $A_{31}(tg\varphi_1)$ provides an unambiguous determination of μ_r in the range $(1 < \mu_r < 200)$. It is explained: due to the normalization of EMC E_n to E_{n0}, the stability of the method is ensured when changing external conditions. Advantage: universality for any values of a and d, unlike calibration curves.

4. A method for controlling three parameters of a cylindrical article (μ_r, σ, a) has been devised, which is based on the normalized amplitudes of the 1st and 3rd harmonics and the phase of the 1st harmonic, expanding the functional capabilities of the method. The method provides high sensitivity to the phase of the 1st harmonic – up to 0.15 rad/unit x at $x = 2.5$, which is confirmed by graphical dependences. It has been established that the influence of higher spatial harmonics on the measurement results is insignificant, which allows the use of simplified calculation models and is acceptable for practical application. Advantage: the error does not exceed 1.5% without the 5th harmonic, in contrast to single-frequency methods with an error of >5%

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study, as well as the results reported in this paper.

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Data availability

All data are available, either in numerical or graphical form, in the main text of the manuscript.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

Authors' contributions

Shaiban Tamer: Validation, Investigation, Formal analysis; **Borys Gorkunov:** Conceptualization, Methodology, Supervision; **Anna Tyshchenko:** Corresponding Author, Methodology, Writing – original draft; **Serhii Lvov:** Investigation, Data curation, Visualization; **Vitaliy Vevenko:** Validation, Formal analysis.

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