A METHOD FOR INCREASING THE LINEARITY OF MAGNETIC FLUX DISTRIBUTION IN ELECTROMAGNETIC CIRCUITS OF SIMPLE STRUCTURE

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Abstract: The article presents a method for ensuring a linear distribution of working magnetic flux along a distributed-parameter, nonlinear magnetically coupled circuit of simple structure by selecting an appropriate law for varying the working air gap between ferromagnetic cores. It is shown that introducing the condition of zero second derivative of the magnetic flux along the chain length into the system of differential equations enables obtaining an exact analytical solution. It is established that the air gap variation law and the magnetic voltage distribution follow a semi-parabolic function, with minimum at one end of the chain and maximum at the other. It is also demonstrated that the magnetic flux remains strictly linear even for different values of the nonlinearity coefficient, while the magnetic voltage variation increases with its growth.

Key words: distributed parameter magnetic circuits, nonlinear magnetic circuits, magnetically coupled circuits.

Introduction. Electromagnetic transducers (EMTs) used for measuring electrical and non-electrical quantities are widely applied in electrical engineering, power systems, and in monitoring and control systems of technological processes [1–3]. These transducers are characterized by high output power and sensitivity, and they maintain their technical performance within the limits specified by national standards even under severe operating conditions [4–7].

In most practical cases (for example, in electromagnetic transducers converting displacement, velocity, acceleration, and fluid flow into electrical signals), it is required that the magnetic flux in distributed-parameter, nonlinear magnetically coupled circuits varies linearly along the chain. In some cases, such as magnetoelectric, electro- and ferrodynamic measuring mechanisms, as well as current transducers, it is necessary to ensure that the magnetic field intensity (magnetic induction) in the working air gaps between ferromagnetic cores remains constant along the chain. In other applications, including transducers simultaneously converting displacement, velocity, and acceleration, both conditions must be satisfied: linear variation of magnetic flux along the chain and constant magnetic induction in the working air gaps. Therefore, a number of scientific studies have been devoted to methods for improving the linearity of magnetic flux distribution along the chain and maintaining constant magnetic induction in the working air gaps of electromagnetic transducers [8–10]. However, analysis of these studies shows that the existing methods are mainly developed for linear distributed-parameter magnetic circuits. When electromagnetic transducers operate in the nonlinear region of the magnetization curve, these methods often fail to provide sufficiently accurate results.

Therefore, in this article, one of the methods for reducing the degree of nonlinear distribution of working magnetic fluxes along the chain in distributed-parameter, nonlinear magnetically coupled circuits (NMCC) is considered.

To determine the law of variation of the function $\delta_x = f(x)$, which ensures the linearity of magnetic flux distribution along the chain in NMCC, we write the differential equations describing the variation of magnetic flux $Q_{\mu x}$ and magnetic potential (magnetic voltage) $U_{\mu x}$ along the chain length in the following form (Fig. 1) [9,12]:

$$Q'_{\mu x} = U_{\mu x} C_{\mu п x} = U_{\mu x}\mu_0 \frac{b}{\delta_x} = k_1\, U_{\mu x}/\delta_x\,, \tag{1}$$

$$U'_{\mu x} = 2Z_{\mu п}(Q_{\mu x})Q_{\mu x} = 2\rho_\mu(Q_{\mu x})\frac{Q_{\mu x}}{bh} = 2\left(p + q\frac{Q_{\mu x}^2}{b^2h^2}\right)\frac{Q_{\mu x}}{bh} =$$

$$= k_2 Q_{\mu x} + k_3 Q_{\mu x}^3, \tag{2}$$

where $Z_{\mu п}(Q_{\mu x}) = \rho_\mu(Q_{\mu x})\frac{1}{bh}$ - the per-unit-length (specific) magnetic reluctance of a long ferromagnetic core in a nonlinear magnetic circuit, $[H^{-1} \cdot m^{-1}]$; $\rho_\mu(Q_{\mu x})$ – the specific magnetic reluctivity of the ferromagnetic core material, $[H^{-1} \cdot m]$ $k_1 = \mu_0 b, [H]$; $k_2 = 2p/bh, [H^{-1}{\cdot}m^{-1}]$; $k_3 = 2q/(b^3h^3), [H^{-1}{\cdot}T^{-2}{\cdot}m^{-5}]$; $p, [A \cdot m^{-1}]$ and $q, [A \cdot T^{-2} \cdot m^{-1}]$ The corresponding geometric dimensions of the NMCC are shown in Fig.

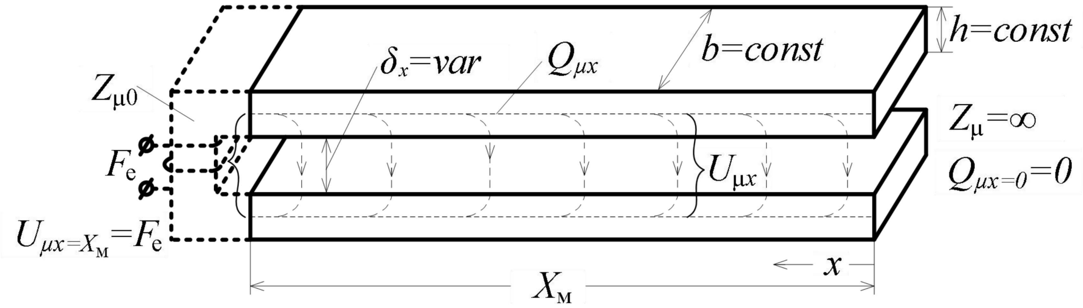

Fig. 1. Structural diagram of a nonlinear NMCC of simple structure with a variable air gap δ_x

For the considered NMCC (assuming that the magnetic reluctance of the base on which the excitation winding is placed is zero, i.e., $Z_{\mu\text{base}} = 0$, and the magnetic reluctance of the open left end of the chain is infinitely large, i.e., $Z_{\mu\text{end}} = \infty$), the following boundary conditions are satisfied (the origin of the coordinate xxx is taken at the end of the chain):

$$Q_{\mu x=0} = 0;\ \delta_{x=0} = \delta_0;\ U_{\mu x=X_M} = F_K, \tag{3}$$

where F_e – the magnetomotive force of the excitation winding, $[A]$.

A necessary and sufficient condition for linear distribution of magnetic flux in the NMCC is that its second derivative with respect to x is equal to zero, i.e., [8, 13]:

$$Q''_{\mu x} = 0. \tag{4}$$

By integrating differential equation (4) twice, the following expression is obtained:

$$Q_{\mu x} = A_1 x + A_2, \tag{5}$$

where A_1 and A_2 – the constants of integration.

Taking into account the initial condition of (3), it follows that $A_2 = 0$, and expression (5) takes the following form:

$$Q_{\mu x} = A_1 x. \tag{6}$$

From (6), it follows that $Q'_{\mu x} = A_1 = \text{const}$, i.e., (7).

By determining $U_{\mu x}$ from (1), substituting (7) into it, and differentiating the result, the following two equations are obtained:

$$U_{\mu x} = (A_1/k_1)\delta_x, \qquad (8) \qquad\qquad U'_{\mu x} = (A_1/k_1)\delta'_x, \qquad (9)$$

By substituting (6) into (2) and equating the right-hand side of the resulting equation with that of equation (9), the derivative δ'_x is obtained:

$$\delta'_x = k_1\left(k_2 x + k_3 A_1^2 x^3\right). \qquad (10)$$

By integrating differential equation (10), the following general solution for δ_x is obtained:

$$\delta_x = \frac{k_1 k_2}{2}x^2 + \frac{k_1 k_3}{4}A_1^2 x^4 + A_3. \qquad (11)$$

By substituting the second boundary condition from (3) into (11), the integration constant A_3 is determined. Substituting it back into (11), the following expression is obtained:

$$\delta_x = \delta_0 + \frac{k_1 k_2}{2}x^2 + \frac{k_1 k_3}{4}A_1^2 x^4. \qquad (12)$$

By substituting (12) into (8), the following expression is obtained:

$$U_{\mu x} = \frac{A_1}{k_1}\left(\delta_0 + \frac{k_1 k_2}{2}x^2 + \frac{k_1 k_3}{4}A_1^2 x^4\right). \qquad (13)$$

By substituting the third boundary condition from (3) into (13), the following third-order algebraic equation with respect to A_1 is obtained:

$$\frac{k_1 k_3}{4}X_{_М}^4 A_1^3 + \left(\delta_0 + \frac{k_1 k_2}{2}X_{_М}^2\right)A_1 - k_1 F_{_К} = 0. \qquad (14)$$

Equation (14) can be solved using known analytical methods, such as the Cardano method [11, 14]. Analysis shows that, for the parameter values of the NMCC under consideration, the discriminant of equation (14) is greater than zero, and the equation has a single real solution given by:

$$A_1 = \sqrt[3]{\frac{2F_e}{k_3 X_{_М}^4} + \sqrt{\frac{4F_e^2}{k_3^2 X_{_М}^8} + \left(\frac{a}{3}\right)^3}} + \sqrt[3]{\frac{2F_e}{k_3 X_{_М}^4} - \sqrt{\frac{4F_e^2}{k_3^2 X_{_М}^8} + \left(\frac{a}{3}\right)^3}}, \qquad (15)$$

where $a = \frac{4\delta_0 + 2k_1 k_2 X_{_М}^2}{k_1 k_3 X_{_М}^4}$.

Thus, according to the proposed method for improving the linearity of magnetic flux distribution along the chain in NMCCs of simple structure – by selecting an appropriate law for variation of the working air gap δ_x between ferromagnetic cores along the chain length-it is required that, for the working magnetic flux to vary linearly according to (6), the air gap δ_x between long ferromagnetic cores must vary according to law (12), assuming constant core thickness $h = \text{const}$ and width $b = \text{const}$.

Analysis of expressions (6) and (12) shows that the magnetic flux in the considered NMCC of simple structure is strictly linearly distributed along the chain, and its values are practically independent of the coefficient characterizing the nonlinearity of the circuit. At the same time, the values of δ_x differ significantly from those in the nonlinear case without compensation. Analysis of the function $U_{\mu x} = f(x)$ indicates that achieving linearity of the magnetic flux in ferromagnetic cores by varying the working air gap between them preserves a nonlinear distribution of magnetic potential (magnetic voltage) along the chain.

Conclusion. In distributed-parameter, nonlinear magnetically coupled circuits of simple structure, linear distribution of working magnetic fluxes along the chain can be achieved by selecting an appropriate law for variation of the working air gap between ferromagnetic cores. Under this approach: Introducing the condition that the second derivative of magnetic flux along the chain length is equal to zero into the system of differential equations enables obtaining an exact analytical solution of the nonlinear differential equations. For circuits of simple structure, the law of air gap variation and the corresponding magnetic voltage distribution follow a semi-parabolic function, with the minimum value at one end of the chain and the maximum at the other. In such circuits, the magnetic flux in long ferromagnetic cores remains strictly linear even for different values of the coefficient characterizing the nonlinearity of the chain.

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