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Investigation of Nonlinear Magnetic Circuits with Distributed Parameters and a Shielded Movable Part

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ABSTRACT: In the article, the analysis of nonlinear magnetic circuits with distributed parameters and a movable, shielded part was carried out using two different methods. The first method is based on determining the characteristic parameters through differential equations, while the second method involves dividing the magnetic circuit into small loop segments and performing calculations for each. The results obtained from both methods were compared. Based on the comparison, it was demonstrated that analysing and calculating nonlinear magnetic circuits with distributed parameters by dividing them into small loops provides higher accuracy.

KEYWORDS: Magnetic circuit, induction, magnetic flux, shield, magnetic core, electromotive force (EMF), magneto motive force (MMF), magnetic potential.

I. INTRODUCTION

Figure 1 illustrates that concentrically and symmetrically wound excitation coils generate a magnetic flux equally distributed between two magnetic conductors. The measuring coil allows for the measurement of the electromotive force (EMF) at coordinates x1x_1x1 and x2x_2x2 on the left and right sides, respectively, equidistant from the center.

There are several methods to analyze the quantities that characterize the processes occurring in nonlinear distributed-parameter magnetic circuits with a shielded movable part [1,4,5,6,7,8].

In this article, we use two approaches:

1. In the first approach, we relate the quantities characterizing the processes in the shielded movable part of the nonlinear distributed-parameter magnetic circuit using differential equations.
2. In the second approach, we divide the magnetic circuit into small loop segments and analyze each loop based on fundamental laws, establishing interrelations and computing the solutions accordingly.

Finally, we compared the graphical results of the quantities characterizing the processes in the shielded movable part of the nonlinear distributed-parameter magnetic circuit.

II. METHODOLOGIY

The quantities characterizing the processes in distributed-parameter nonlinear magnetic circuits with a movable and shielded part are governed by second-order differential equations, and the problem of finding the solution to these equations is considered.

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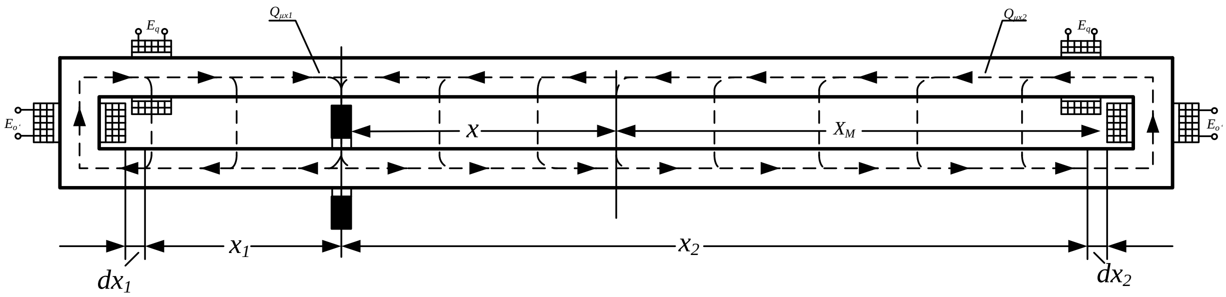

Figure 1. Distributed-parameter magnetic circuit with a movable coil part

We derive equations for the left and right sides of the magnetic circuit for an element of length dx based on Ohm's and Kirchhoff's first and second laws for magnetic circuits[2,5,6,7,8].

$$\frac{dQ_{\mu x_1}}{dx_1} = C_{\mu p} U_{\mu x_1} \quad (1) \qquad \frac{dQ_{\mu x_2}}{dx_2} = C_{\mu p} U_{\mu x_2} \quad (4)$$

$$\frac{dU_{\mu x_1}}{dx_1} = 2Z_{\mu p} Q_{\mu x_1} \quad (2) \qquad \frac{dU_{\mu x_2}}{dx_2} = 2Z_{\mu p} Q_{\mu x_2} \quad (5)$$

$$Z_{\mu x_1} = \frac{U_{\mu x_1}}{Q_{\mu x_1}} \quad (3) \qquad Z_{\mu x_2} = \frac{U_{\mu x_2}}{Q_{\mu x_2}} \quad (6)$$

Here: $C_{\mu p}$ – the magnetic permeance between the magnetic conductors for the element dx of the magnetic circuit; $Z_{\mu p}$ – the magnetic reluctance of the magnetic conductor for the element dx of the magnetic circuit; $Q_{\mu x_1}$ and $Q_{\mu x_2}$ – the magnetic flux varying with respect to coordinates x_1 and x_2; $U_{\mu x_1}$ and $U_{\mu x_2}$ – the magnetic potential varying with respect to coordinates x_1 and x_2; $Z_{\mu x_1}$ and $Z_{\mu x_2}$ – the magnetic reluctance varying with respect to coordinates x_1 and x_2.

By transforming the derived differential equations, we determine the variables that change along the coordinates x_1 and x_2. First, we take the second derivative of the equations characterizing the left side of the magnetic circuit.

$$\frac{d^2Q_{\mu x_1}}{dx_1^2} = C_{\mu p} \cdot \frac{dU_{\mu x_1}}{dx_1} \; yoki \; Q''_{\mu x_1} = C_{\mu p} \cdot U'_{\mu x_1} \quad (7)$$

$$\frac{d^2U_{\mu x_1}}{dx_1^2} = 2Z_{\mu p} \cdot \frac{dQ_{\mu x_1}}{dx_1} \; yoki \; U''_{\mu x_1} = 2C_{\mu p} \cdot Q'_{\mu x_1} \quad (8)$$

We substitute expressions (2) and (1) into expressions (7) and (8).

$$\frac{d^2Q_{\mu x_1}}{dx_1^2} = 2C_{\mu p} Z_{\mu p} Q_{\mu x_1} \; yoki \; Q''_{\mu x_1} = 2C_{\mu p} Z_{\mu p} Q_{\mu x_1} \quad (9)$$

$$\frac{d^2U_{\mu x_1}}{dx_1^2} = 2C_{\mu p} Z_{\mu p} U_{\mu x_1} \; yoki \; U''_{\mu x_1} = 2C_{\mu p} Z_{\mu p} U_{\mu x_1} \quad (10)$$

We divide expression (10) by expression (9), and as a result, equality (11) is obtained on the left and right sides of the expression.

$$\frac{U''_{\mu x_1}}{Q''_{\mu x_1}} = \frac{U_{\mu x_1}}{Q_{\mu x_1}} \quad (11)$$

On the left side of equation (11), the second-order derivative of the magnetic reluctance appears, while on the right side, the magnetic reluctance itself emerges according to expression (3).

$$Z''_{\mu x_1} = Z_{\mu x_1} \quad (12)$$

We find the solution of the differential equation (12).

$$Z_{\mu x_1} = A_1 e^{x_1} + A_2 e^{-x_1} \quad (13)$$

Here, A_1 and A_2 are the constants of integration, and their values are determined from the initial conditions given in (14)

$$x_1 = 10^{-12} da \; Z_{\mu x_1} = Z_{\mu min} \; va \; x_1 = X_m \; da \; Z_{\mu x_1} = Z_{\mu m} \quad (14)$$

$$\begin{cases} Z_{\mu x_1 = 0} = A_1 + A_2 = Z_{\mu min} \\ Z_{\mu x_1 = X_m} = A_1 e^{X_m} + A_2 e^{-X_m} = Z_{\mu max} \end{cases} \quad (15)$$

In the system of equations (15), H_m and B_m are the maximum values of the magnetic field intensity and magnetic flux density of the ferromagnetic element used in the magnetic circuit, taken from reference data, and S is the cross-sectional area of the conductor. From the system of equations (15), we determine the values of A_1 and A_2.

$$A_1 = -A_2 = \frac{Z_{\mu max}}{2sh(X_m)} \quad (16)$$

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By substituting equality (16) into expression (13), we recalculate the value of $Z_{\mu x_1}$.

$$Z_{\mu x_1} = \frac{Z_{\mu max}}{sh(X_m)} \cdot sh(x_1) \qquad (17)$$

We find $U_{\mu x_1}$ from expression (3) and substitute it into equality (1).

$$\frac{dQ_{\mu x_1}}{dx_1} = C_{\mu p} \cdot Z_{\mu x_1} \cdot Q_{\mu x_1} \qquad (18)$$

By substituting expression (17) into equality (18), we compute the first-order differential equation.

$$\frac{dQ_{\mu x_1}}{dx_1} = C_{\mu p} \frac{Z_{\mu max}}{sh(X_m)} sh(x_1) Q_{\mu x_1} \qquad (19)$$

$$Q_{\mu x_1} = e^{C_{\mu p}\frac{Z_{\mu max}}{sh(X_m)} ch(x_1) + A_3} \qquad (20)$$

Here, A_3 is the constant of integration, and its value is determined from the initial condition given in (21).

$$x_1 = 10^{-12} \; da \; Q_{\mu x_1} = Q_{\mu min} = B_{min} \cdot S \qquad (21)$$

$$A_3 = \ln(Q_{\mu min}) - \frac{Z_{\mu max}}{sh(X_m)} C_{\mu p} ch(x_1) \qquad (22)$$

By substituting equality (22) into expression (20), we recalculate the value of $Q_{\mu x_1}$.

$$Q_{\mu x_1} = e^{\frac{Z_{\mu max}}{sh(X_m)} C_{\mu p}(ch(x_1)-1) + \ln(Q_{\mu min})} \qquad (23)$$

We find $Q_{\mu x_1}$ from expression (3) and substitute it into equality (2).

$$\frac{dU_{\mu x_1}}{dx_1} = 2Z_{\mu p} \frac{U_{\mu x_1}}{Z_{\mu x_1}} \qquad (24)$$

$$Z_{\mu p} = \frac{dZ_{\mu x_1}}{dx_1} \qquad (25)$$

By substituting expression (25) into equality (24), we compute the first-order differential equation.

$$U_{\mu x_1} = e^{2\ln(Z_{\mu x_1}) + A_4} \qquad (26)$$

Here, A_4 is the constant of integration, and its value is determined from the initial condition given in (27).

$$x_1 = X_m \; da \; U_{\mu x_1 = X_m} \approx I_q w - Q_{\mu x_1 = X_m} \cdot Z_{\mu x_1 = X_m} \qquad (27)$$

$$A_4 = \ln\left(\frac{I_q w - Q_{\mu max} \cdot Z_{\mu max}}{Q^2_{\mu max}}\right) \qquad (28)$$

By substituting equality (28) into expression (26), we recalculate the value of $U_{\mu x_1}$.

$$U_{\mu x_1} = e^{ln\left(\frac{U^2_{\mu max}}{(I_q w - U_{\mu max}) \cdot sh^2(X_m)} \cdot sh^2(x_1)\right)} \qquad (29)$$

Since the left part of the distributed parameter nonlinear magnetic circuit is symmetric with the right part, the obtained value is also applicable to the right part.

$$Z_{\mu x_2} = \frac{Z_{\mu max}}{sh(X_m)} \cdot sh(x_2) \qquad (30)$$

$$Q_{\mu x_2} = e^{\frac{Z_{\mu max}}{sh(X_m)} C_{\mu p}(ch(x_2)-1) + \ln(Q_{\mu min})} \qquad (31)$$

$$U_{\mu x_2} = e^{ln\left(\frac{U^2_{\mu max}}{(I_q w - U_{\mu max}) \cdot sh^2(X_m)} \cdot sh^2(x_2)\right)} \qquad (32)$$

We determine the values of the electromotive forces (EMFs) induced in the measuring winding.

$$\dot{E}_{x_1} = -j\omega w e^{\frac{Z_{\mu max}}{sh(X_m)} C_{\mu p}(ch(x_1)-1) + \ln(Q_{\mu min})} \qquad (33)$$

$$\dot{E}_{x_2} = -j\omega w e^{\frac{Z_{\mu max}}{sh(X_m)} C_{\mu p}(ch(x_2)-1) + \ln(Q_{\mu min})} \qquad (34)$$

We perform the calculation of the distributed parameter nonlinear magnetic circuit with a movable screened part by dividing it into small segments. In analyzing the magnetic circuit, we determine the value of the magnetomotive force generated by the excitation winding[3].

$$F_q = I_q \cdot w_q \qquad (35)$$

We determine the value of the magnetic potential in the movable part of the excitation winding.

$$U_{\mu x0} = F_q \qquad (36)$$

Using the magnetic potential formula, we determine the value of the magnetic field intensity at point x_0.

$$H_{\mu x0} = \frac{U_{\mu x0}}{x_M} \qquad (37)$$

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Corresponding to the value of $H_{\mu x_o}$, we determine the magnetic induction value $B_{\mu o}$ from the experimental data table, and then determine the corresponding value of the magnetic flux.

$$Q_{\mu x0} = B_{\mu 0} \cdot S_{\mu 0} \tag{38}$$

We draw the equivalent circuit of the right part of the distributed parameter magnetic circuit shown in Figure 1 and present the parameters that characterize the magnetic circuit.

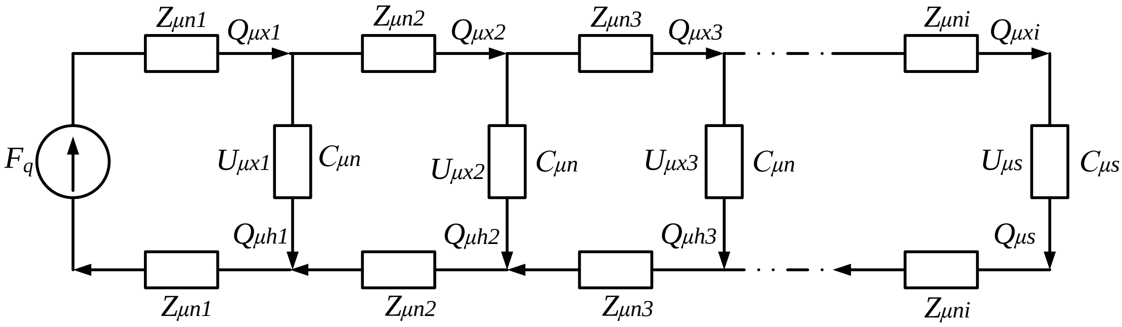

Figure 2. Equivalent circuit of the Distributed Parameter Nonlinear Magnetic Circuit (DPNMC).

The equivalent circuit represents the elementary parts of the DPNMC, where:
F_q – magnetomotive force generated by the excitation winding [A],
$Z_{\mu n1} \cdots Z_{\mu ni}$ – step values of magnetic reluctance of the elementary parts of the magnetic conductor [1/(H·m)],
$Q_{\mu x1} \cdots Q_{\mu xi}$ – step values of magnetic flux in the elementary parts of the magnetic conductor [Wb],
$U_{\mu x1} \cdots U_{\mu xi}$ – step values of magnetic potential in the elementary parts of the magnetic conductor [A].
Here: $Q_{(\mu xo)}$ – magnetic flux generated at point x_0,
$S_{\mu 0}$ – cross-sectional area of the magnetic conductor at point x_0.
We determine the distributed magnetic flux in the elementary part of the DPNMC.

$$Q_{h(x_0 \div x_1)} = U_{\mu x0} \cdot C_{h(x_0 \div x_1)} = U_{\mu x0} \cdot \frac{b \cdot \Delta x}{\mu_0 \cdot \delta_{(x_0 \div x_1)}} \tag{39}$$

Here:
$C_h(x_0 \div x_1)$ – magnetic permeance defined for the interval between two magnetic conductors from x_0 to x_1,
b – width of the magnetic conductor,
Δx – elementary part of the magnetic conductor,
μ_0 – magnetic constant (permeability of free space),
$\delta\_(x_0 \div x_1)$ – distance between the two magnetic conductors over the interval x_0 to x_1.
We determine the value of $Q_{\mu x1}$ based on Kirchhoff's first law for magnetic circuits.

$$Q_{\mu x_1} = Q_{\mu x_0} - Q_{h(x_0 \div x_1)} \tag{40}$$

We determine the value of $U_{\mu x_1}$.

$$U_{\mu x_1} = U_{\mu x_0} - \Delta U_{\mu(x_0 \div x_1)} = U_{\mu x_0} - Q_{\mu x_1} \cdot Z_{\mu(x_0 \div x_1)} \tag{41}$$

Or

$$U_{\mu x_1} = U_{\mu x_0} - Q_{h(x_0 \div x_1)} \cdot \frac{\Delta x}{\mu_{x_0} \cdot \mu_0 \cdot S_{\mu x_0}} = U_{\mu x_0} - Q_{\mu x_1} \cdot \frac{H_{\mu x_0} \cdot \Delta x}{B_{\mu x_0} \cdot b \cdot h} \tag{42}$$

Here: $Z_{\mu(x_0 \div x_1)}$ – magnetic reluctance of the magnetic conductor in the interval $x_0 \div x_1$, $B_{\mu x_0} = \mu_{x_0} \cdot \mu_0 \cdot H_{\mu x_0}$ – magnetic induction in the magnetic conductor, based on the relationship between magnetic permeability of the ferromagnetic material, magnetic field intensity, and magnetic induction. From this relationship, the magnetic resistivity is determined and substituted into the formula: $\rho_{\mu x_0} = \frac{1}{\mu_{x_0} \cdot \mu_0} = \frac{H_{\mu x_0}}{B_{\mu x_0}}$ The cross-sectional area of the magnetic conductor is given as $S_{\mu x_0} = b \cdot h$, where h is the thickness of the magnetic conductor.
In the same way, the values of the magnetic circuit parameters are determined for the elementary part of the second magnetic conductor.

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$$Q_{h(x_1 \div x_2)} = U_{\mu x_1} \cdot C_{h(x_1 \div x_2)} = U_{\mu x_1} \cdot \frac{b \cdot \Delta x}{\mu_0 \cdot \delta_{(x_1 \div x_2)}} \tag{43}$$

Here: $C_{h(x_0 \div x_1)}$– magnetic permeance defined for the interval $x_0 \div x_1$ between two magnetic conductors, $b = const$ – the width of the magnetic conductor, which does not change along the length of the magnetic circuit,$\Delta x = \frac{X_M}{n}$ – the elementary segment of the magnetic conductor, μ_0 – the magnetic constant (permeability of free space),$\delta_{(x_1 \div x_2)} = const$ – the distance between the two magnetic conductors in the interval $x_0 \div x_1$, which remains constant along the length of the magnetic circuit. Using Kirchhoff's first law for magnetic circuits, we determine the value of $Q_{\mu x_2}$.

$$Q_{\mu x_2} = Q_{\mu x_1} - Q_{h(x_1 \div x_2)} \tag{44}$$

We determine the value of $U_{\mu x_2}$.

$$U_{\mu x_2} = U_{\mu x_1} - \Delta U_{\mu(x_1 \div x_2)} = U_{\mu x_1} - Q_{\mu x_2} \cdot Z_{\mu(x_1 \div x_2)} \tag{45}$$

Or

$$\boldsymbol{U_{\mu x_2} = U_{\mu x_1} - Q_{h(x_1 \div x_2)} \cdot \frac{\Delta x}{\mu_{x_1} \cdot \mu_0 \cdot S_{\mu x_1}} = U_{\mu x_0} - Q_{\mu x_2} \cdot \frac{H_{\mu x_1} \cdot \Delta x}{B_{\mu x_1} \cdot b \cdot h}} \tag{46}$$

Here: $Z_{\mu(x_1 \div x_2)}$ – magnetic reluctance of the magnetic conductor in the interval $x_1 \div x_2$, $B_{\mu x_1} = \mu_{x_1} \cdot \mu_0 \cdot H_{\mu x_1}$ – magnetic induction in the magnetic conductor, based on the relationship between magnetic permeability of the ferromagnetic material, magnetic field intensity, and magnetic induction. From this relationship, the magnetic resistivity is determined and substituted into the formula: $\rho_{\mu x_1} = \frac{1}{\mu_{x_1} \cdot \mu_0} = \frac{H_{\mu x_1}}{B_{\mu x_1}}$ The cross-sectional area of the magnetic conductor is given as $S_{\mu x_1} = b \cdot h$, where h is the thickness of the magnetic conductor.

In the same manner, we determine the values of the magnetic circuit quantities for the elementary segment of the third magnetic conductor.

$$Q_{h(x_2 \div x_3)} = U_{\mu x_2} \cdot C_{h(x_2 \div x_3)} = U_{\mu x_2} \cdot \frac{b \cdot \Delta x}{\mu_0 \cdot \delta_{(x_2 \div x_3)}} \tag{47}$$

Here: $C_{h(x_2 \div x_3)}$– magnetic permeance defined for the interval $x_2 \div x_3$ between two magnetic conductors, $b = const$ – the width of the magnetic conductor, which does not change along the length of the magnetic circuit,$\Delta x = \frac{X_M}{n}$ – the elementary segment of the magnetic conductor, μ_0 – the magnetic constant (permeability of free space),$\delta_{(x_2 \div x_3)} = const$ – the distance between the two magnetic conductors in the interval $x_2 \div x_3$, which remains constant along the length of the magnetic circuit. Using Kirchhoff's first law for magnetic circuits, we determine the value of $Q_{\mu x_3}$.

$$Q_{\mu x_3} = Q_{\mu x_2} - Q_{h(x_2 \div x_3)} \tag{48}$$

We determine the value of $U_{\mu x_3}$.

$$\boldsymbol{U_{\mu x_3} = U_{\mu x_2} - \Delta U_{\mu(x_2 \div x_3)} = U_{\mu x_2} - Q_{\mu x_3} \cdot Z_{\mu(x_2 \div x_3)}} \tag{49}$$

Or

$$U_{\mu x_3} = U_{\mu x_2} - Q_{h(x_2 \div x_3)} \cdot \frac{\Delta x}{\mu_{x_2} \cdot \mu_0 \cdot S_{\mu x_2}} = U_{\mu x_2} - Q_{\mu x_3} \cdot \frac{H_{\mu x_2} \cdot \Delta x}{B_{\mu x_2} \cdot b \cdot h} \tag{50}$$

Here: $Z_{\mu(x_2 \div x_3)}$ – magnetic reluctance of the magnetic conductor in the interval $x_2 \div x_3$, $B_{\mu x_2} = \mu_{x_2} \cdot \mu_0 \cdot H_{\mu x_2}$ – magnetic induction in the magnetic conductor, based on the relationship between magnetic permeability of the ferromagnetic material, magnetic field intensity, and magnetic induction. From this relationship, the magnetic resistivity is determined and substituted into the formula: $\rho_{\mu x_2} = \frac{1}{\mu_{x_2} \cdot \mu_0} = \frac{H_{\mu x_2}}{B_{\mu x_2}}$ The cross-sectional area of the magnetic conductor is given as $S_{\mu x_2} = b \cdot h$, where h is the thickness of the magnetic conductor.

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In the same manner, we determine the values of the magnetic circuit quantities for the elementary segment of the n-th magnetic conductor.

$$\boldsymbol{Q}_{\boldsymbol{h}(x_{n-1}\div x_n)} = \boldsymbol{U}_{\boldsymbol{\mu x_{n-1}}} \cdot \boldsymbol{C}_{\boldsymbol{h}(x_{n-1}\div x_n)} = \boldsymbol{U}_{\boldsymbol{\mu x_{n-1}}} \cdot \frac{\boldsymbol{b}\cdot\Delta\boldsymbol{x}}{\boldsymbol{\mu_0}\cdot\boldsymbol{\delta}_{(x_{n-1}\div x_n)}} \tag{51}$$

Here: $C_{h(x_{n-1}\div x_n)}$– magnetic permeance defined for the interval $x_{n-1} \div x_n$ between two magnetic conductors, $b = const$ – the width of the magnetic conductor, which does not change along the length of the magnetic circuit,$\Delta x = \frac{X_M}{n}$ – the elementary segment of the magnetic conductor, μ_0 – the magnetic constant (permeability of free space),$\delta_{(x_{n-1}\div x_n)} = const$ – the distance between the two magnetic conductors in the interval $x_{n-1} \div x_n$, which remains constant along the length of the magnetic circuit. Using Kirchhoff's first law for magnetic circuits, we determine the value of $Q_{\mu x_n}$

$$Q_{\mu x_n} = Q_{\mu x_{n-1}} - Q_{h(x_{n-1}\div x_n)} \tag{52}$$

We determine the value of $U_{\mu x_n}$.

$$\boldsymbol{U}_{\boldsymbol{\mu x_n}} = \boldsymbol{U}_{\boldsymbol{\mu x_{n-1}}} - \Delta\boldsymbol{U}_{\boldsymbol{\mu}(x_{n-1}\div x_n)} = \boldsymbol{U}_{\boldsymbol{\mu x_{n-1}}} - \boldsymbol{Q}_{\boldsymbol{\mu x_n}} \cdot \boldsymbol{Z}_{\boldsymbol{\mu}(x_{n-1}\div x_n)} \tag{53}$$

Or

$$U_{\mu x_n} = U_{\mu x_{n-1}} - Q_{h(x_{n-1}\div x_n)} \cdot \frac{\Delta x}{\mu_{x_{n-1}}\cdot\mu_0\cdot S_{\mu x_{n-1}}} = U_{\mu x_{n-1}} - Q_{\mu x_n} \cdot \frac{H_{\mu x_{n-1}}\cdot\Delta x}{B_{\mu x_{n-1}}\cdot b\cdot h} \tag{54}$$

Here: $Z_{\mu(x_{n-1}\div x_n)}$ – magnetic reluctance of the magnetic conductor in the interval$x_{n-1} \div x_n$, $B_{\mu x_{n-1}} = \mu_{x_{n-1}} \cdot \mu_0 \cdot H_{\mu x_{n-1}}$ – magnetic induction in the magnetic conductor, based on the relationship between magnetic permeability of the ferromagnetic material, magnetic field intensity, and magnetic induction. From this relationship, the magnetic resistivity is determined and substituted into the formula: $\rho_{\mu x_{n-1}} = \frac{1}{\mu_{x_{n-1}}\cdot\mu_0} = \frac{H_{\mu x_{n-1}}}{B_{\mu x_{n-1}}}$ The cross-sectional area of the magnetic conductor is given as $S_{\mu x_{n-1}} = b \cdot h$, where h is the thickness of the magnetic conductor.
We determine the values of the EMF generated in each identified elementary segment.

$$E_{o'_{x_n}} = -j\omega \cdot \omega_{o'} \cdot Q_{\mu x_n} \tag{55}$$

We determine the magnetic circuit parameters for each elementary segment and enter them into Table 1.
Initial values and magnetic circuit dimensions: $\omega_q = 1000$, $I_q = 1\,[A]$, $F_q = I_q \cdot w_q = 1 \cdot 1000 = 1000\,[A]$. The magneto motive force (MMF) generated in the left and right parts of the magnetic circuit is assumed to be symmetric. Therefore, we first calculate the parameters for the left side, which will also apply to the right side due to symmetry.
Given values: $\omega_{o'} = 100$, $= 0{,}01\,[m], h = 0{,}01\,[m], \delta = 0{,}01\,[m], X_M = 0{,}1\,[m]$, $H_{\mu x_0} = \frac{U_{\mu x_0}}{X_M} = \frac{100}{0.1} = 1000\,[A]$. $B_{\mu x_0} = 1{,}29\,[Tl]$ (Taken from the experimental data table).

Table 1
Values of parameters generated in the elementary segments of the distributed-parameter magnetic circuit.

x	$U_{\mu x_n}$	$Q_{h(x_{n-1}\div x_n)}$	$Q_{\mu x_n}$	$E_{o'_{x_n}}$	x	$U_{\mu x_n}$	$Q_{h(x_{n-1}\div x_n)}$	$Q_{\mu x_n}$	$E_{o'_{x_n}}$
0,5	100	6,28E-07	0,000129	4,0506	0,25	49,49495	3,1083E-07	4,83707E-05	1,51884
0,495	98,9899	6,2166E-07	0,000128372	4,030881	0,245	48,48485	3,0448E-07	4,80599E-05	1,50908
0,49	97,9798	6,1531E-07	0,00012775	4,011361	0,24	47,47475	2,9814E-07	4,77554E-05	1,499519
0,485	96,9697	6,0897E-07	0,000127135	3,99204	0,235	46,46465	2,918E-07	4,74573E-05	1,490158
0,48	95,9596	6,0263E-07	0,000126526	3,972918	0,23	45,45455	2,8545E-07	4,71655E-05	1,480995
0,475	94,94949	5,9628E-07	0,000125923	3,953996	0,225	44,44444	2,7911E-07	0,00004688	1,472032
0,47	93,93939	5,8994E-07	0,000125327	3,935273	0,22	43,43434	2,7277E-07	4,66009E-05	1,463268
0,465	92,92929	5,836E-07	0,000124737	3,916748	0,215	42,42424	2,6642E-07	4,63281E-05	1,454703
0,46	91,91919	5,7725E-07	0,000124154	3,898424	0,21	41,41414	2,6008E-07	4,60617E-05	1,446337

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0,455	90,90909	5,7091E-07	0,000123576	3,880298	0,205	40,40404	2,5374E-07	4,58016E-05	1,438171
0,45	89,89899	5,6457E-07	0,000123005	3,862371	0,2	39,39394	2,4739E-07	4,55479E-05	1,430203
0,445	88,88889	5,5822E-07	0,000122441	3,844644	0,195	38,38384	2,4105E-07	4,53005E-05	1,422435
0,44	87,87879	5,5188E-07	0,000121883	3,827116	0,19	37,37374	2,3471E-07	4,50594E-05	1,414866
0,435	86,86869	5,4554E-07	0,000121331	3,809787	0,185	36,36364	2,2836E-07	4,48247E-05	1,407496
0,43	85,85859	5,3919E-07	0,000120785	3,792657	0,18	35,35354	2,2202E-07	4,45964E-05	1,400326
0,425	84,84848	5,3285E-07	0,000120246	3,775726	0,175	34,34343	2,1568E-07	4,43743E-05	1,393354
0,42	83,83838	5,2651E-07	0,000119713	3,758995	0,17	33,33333	2,0933E-07	4,41587E-05	1,386582
0,415	82,82828	5,2016E-07	0,000119187	3,742463	0,165	32,32323	2,0299E-07	4,39493E-05	1,380009
0,41	81,81818	5,1382E-07	0,000118667	3,72613	0,16	31,31313	1,9665E-07	4,37463E-05	1,373635
0,405	80,80808	5,0747E-07	0,000118153	3,709996	0,155	30,30303	1,903E-07	4,35497E-05	1,36746
0,4	79,79798	5,0113E-07	0,000117645	3,694061	0,15	29,29293	1,8396E-07	4,33594E-05	1,361485
0,395	78,78788	4,9479E-07	0,000117144	3,678325	0,145	28,28283	1,7762E-07	4,31754E-05	1,355709
0,39	77,77778	4,8844E-07	0,000116649	3,662789	0,14	27,27273	1,7127E-07	4,29978E-05	1,350131
0,385	76,76768	4,821E-07	0,000116161	3,647452	0,135	26,26263	1,6493E-07	4,28265E-05	1,344754
0,38	75,75758	4,7576E-07	0,000115679	3,632314	0,13	25,25253	1,5859E-07	4,26616E-05	1,339575
0,375	74,74747	4,6941E-07	0,000115203	3,617375	0,125	24,24242	1,5224E-07	4,2503E-05	1,334595
0,37	73,73737	4,6307E-07	0,000114734	3,602636	0,12	23,23232	1,459E-07	4,23508E-05	1,329815
0,365	72,72727	4,5673E-07	0,000114271	3,588095	0,115	22,22222	1,3956E-07	4,22049E-05	1,325234
0,36	71,71717	4,5038E-07	0,000113814	3,573754	0,11	21,21212	1,3321E-07	4,20653E-05	1,320851
0,355	70,70707	4,4404E-07	0,000113363	3,559612	0,105	20,20202	1,2687E-07	4,19321E-05	1,316669
0,35	69,69697	4,377E-07	0,000112919	3,545669	0,1	19,19192	1,2053E-07	4,18053E-05	1,312685
0,345	68,68687	4,3135E-07	0,000112482	3,531925	0,095	18,18182	1,1418E-07	4,16847E-05	1,3089
0,34	67,67677	4,2501E-07	0,00011205	3,518381	0,09	17,17172	1,0784E-07	4,15705E-05	1,305315
0,335	66,66667	4,1867E-07	0,000111625	3,505035	0,085	16,16162	1,0149E-07	4,14627E-05	1,301929
0,33	65,65657	4,1232E-07	0,000111207	3,491889	0,08	15,15152	9,5152E-08	4,13612E-05	1,298742
0,325	64,64646	4,0598E-07	0,000110794	3,478942	0,075	14,14141	8,8808E-08	4,12661E-05	1,295754
0,32	63,63636	3,9964E-07	0,000110388	3,466195	0,07	13,13131	8,2465E-08	4,11773E-05	1,292966
0,315	62,62626	3,9329E-07	0,000109989	3,453646	0,065	12,12121	7,6121E-08	4,10948E-05	1,290376
0,31	61,61616	3,8695E-07	0,000109595	3,441297	0,06	11,11111	6,9778E-08	4,10187E-05	1,287986
0,305	60,60606	3,8061E-07	0,000109208	3,429146	0,055	10,10101	6,3434E-08	4,09489E-05	1,285795
0,3	59,59596	3,7426E-07	0,000108828	3,417195	0,05	9,090909	5,7091E-08	4,08855E-05	1,283803
0,295	58,58586	3,6792E-07	0,000108454	3,405444	0,045	8,080808	5,0747E-08	4,08284E-05	1,282011
0,29	57,57576	3,6158E-07	0,000108086	3,393891	0,04	7,070707	4,4404E-08	4,07776E-05	1,280417
0,285	56,56566	3,5523E-07	0,000107724	3,382537	0,035	6,060606	3,8061E-08	4,07332E-05	1,279023
0,28	55,55556	3,4889E-07	0,000107369	3,371383	0,03	5,050505	3,1717E-08	4,06952E-05	1,277828
0,275	54,54545	3,4255E-07	0,00010702	3,360428	0,025	4,040404	2,5374E-08	4,06634E-05	1,276832
0,27	53,53535	3,362E-07	0,000106677	3,349672	0,02	3,030303	1,903E-08	4,06381E-05	1,276035
0,265	52,52525	3,2986E-07	0,000106341	3,339115	0,015	2,020202	1,2687E-08	4,0619E-05	1,275438

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0,26	51,51515	3,2352E-07	0,000106011	3,328758	0,01	1,010101	6,3434E-09	4,06063E-05	1,275039
0,255	50,50505	3,1717E-07	0,000105688	3,318599					

Based on the analytical functions (23), (31), (33), and (34) obtained from the first method, and the values in Table 1 obtained from the second method, we construct the characteristics of the nonlinear magnetic circuit with distributed parameters.

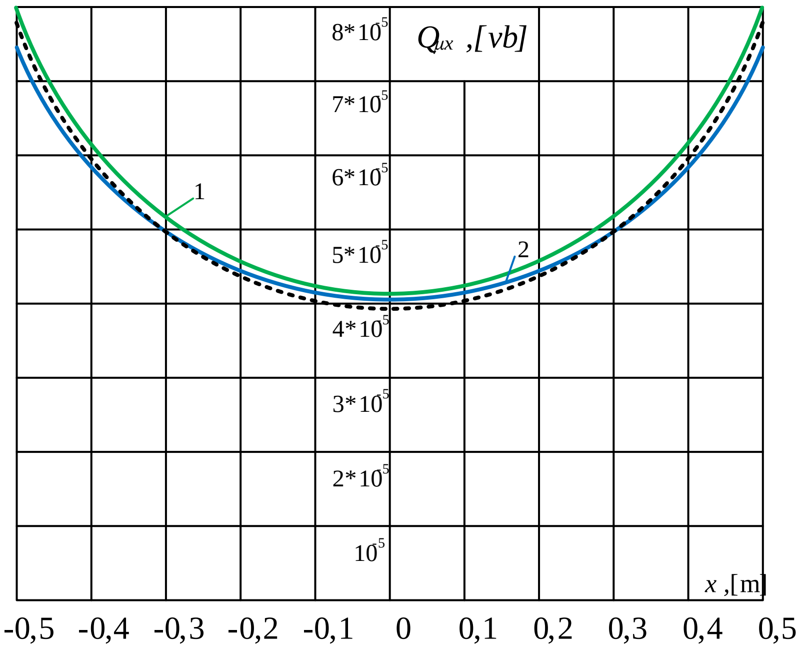

Figure 2. Distribution of magnetic flux in a nonlinear magnetic circuit with distributed parameters.

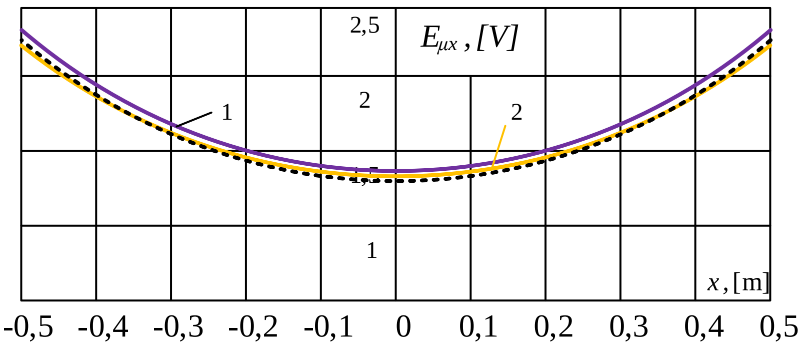

Figure 3. Distribution of the electromotive force (EMF) induced in the measuring coil of a nonlinear magnetic circuit with distributed parameters.

III. CONCLUSION

The characteristic parameters of a nonlinear magnetic circuit with distributed parameters and a movable, shielded part were calculated using two different methods. In the first method, the solution was obtained based on differential equations, while in the second method, the circuit was divided into segments and calculations were performed using interpolated cotours for each segment. The results obtained from both methods were presented in graphical form.

The analysis of the results showed that the pointwise errors in the first method (based on differential equations) ranged from 1.6% to 7.8% relative to the actual values, whereas in the second method (segmentation and cotour-based calculation), the errors ranged from 0.86% to 4.72%.

Based on this comparison, it was determined that the method of dividing the system into segments and calculating using cotours provides higher accuracy in analyzing nonlinear magnetic circuits with distributed parameters and a movable shielded part, and is therefore more preferable.

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