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Mathematical Models of Linear Magnetic Chains of Electromagnetic Converters of Flow with a Ring Channel

AMIROV SULTON FAYZULLAEVICH, ATAULLAEV AMINJON ODILOVICH

Doctor of Technical Sciences, Professor,Head of the Department of Power Supply of Railways of the Tashkent Institute of Railway Engineers*;*
Senior Lecturer of the Department of "Electric Power Engineering" Navoi State Mining Institute.

ABSTRACT*:* Mathematical models of magnetic circuits of electromagnetic flow transducers with an annular channel have been developed, taking into account the distribution of the parameters of the magnetic circuit and leakage fluxes closed through non-working air gaps. The possibility of compensating for the difference in magnetic resistance of coaxially arranged concentric ferromagnetic cores due to the difference in their circumference by selecting the thickness of the cores is shown. It is established that the magnetic flux in concentric ferromagnetic cores is nonlinearly distributed along the angular coordinate, and the magnetic induction in the annular channel is unevenly distributed along the angular and radial coordinates. It is revealed that with an increase in the value of the magnetic field attenuation coefficient in the magnetic circuit, the degree of non-uniformity of the magnetic induction in the annular channel with respect to the angular coordinate increases, and with respect to the radial coordinate it remains constant.

KEYWORDS: Electromagnetic converter, ring channel, magnetic circuits, concentric ferromagnetic core, magnetic flux, magnetic induction, mathematical model, distributed parameter, magnetic flux of scattering.

I. INTRODUCTION

When measuring fluid flow in process control systems, along with other transducers, electromagnetic flow transducers (EFT) are widely used [1]. Along with commercially available EFT [2,3], special EFT are used to control and control some technological processes (to control and control the quantity and quality of dairy products, heat supply, liquid metal flux and various acids, etc.) [4,5].

The metrological characteristics of the EFT mainly depend on the state of the magnetic field in the working channel of the converter. Therefore, much attention is paid to the study of the magnetic fields of these converters. In this case, it is required to determine the law of change in the magnetic induction in the annular channel between coaxially arranged ferromagnetic cores depending on the coordinates α, ρ and z.

II. STATEMENTOFAPROBLEM

As is known [6], electromagnetic processes are most fully described by the equations of the electromagnetic field, i.e. Maxwell equations. But they are applicable to the study of magnetic fields of electrical measuring converters are not very suitable, i.e. The solutions obtained are inconvenient for engineering calculations of converter characteristics. Therefore, the magnetic fields of the measuring transducers are most often investigated in the form of chains [7].

Magnetic circuits of electromagnetic flow transducers with an annular channel are referred to circuits with distributed parameters [6]. These parameters include linear values of magnetic resistances of coaxially arranged ring ferromagnetic cores ($Z_{\mu p}$) and magnetic capacity (magnetic conductivity by the classical analogy of electric and magnetic circuits) of the annular air channel ($C_{\mu p}$) between them, per unit angular coordinate α.

Electromagnetic processes in magnetic circuits with distributed parameters are characterized by two integral values: magnetic flux $Q_{\mu}(\alpha, t)$ and magnetic voltage by the difference of magnetic potentials $U_{\mu}(\alpha, t)$, which vary both in the α coordinate (chain length) and in time.

Unlike electrical circuits with distributed parameters, long magnetic circuits with distributed parameters are more complex, namely: in magnetic circuits, even for small linear dimensions (in units of centimeters), a significant part of the magnetic flux branches off from the main circuit in the form of magnetic fluxes. This is because in the case

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of electrical circuits it is possible to create very long directional paths for the electric current, which is the result of a very large difference (of the order of 10^{20}) of the conductivity of the conductors and the conductivity of the surrounding insulating medium, and in the case of magnetic circuits there is no such big difference between the absolute magnetic permeability of ferromagnetic materials and the environment: their ratio is, as a rule, of the order of 10^3–10^4 [7].

In the EFT with the annular channel in the path of the working magnetic flux there is a large gap. For this reason, the magnetic converter circuit operates in the linear portion of the main magnetization curve. Therefore, the magnetic circuit can be considered linear.

The article is devoted to the development of mathematical models of linear magnetic circuits of several EFT with an annular channel, developed with the participation of the authors [8, 9].

The constructive scheme of the magnetic circuit of the first EFT with an annular channel and the scheme for replacing its elementary portions $d\alpha$ is shown in Fig. 1 a and b [8].

In order to simplify the analysis of magnetic circuits, we take the following assumptions: 1) ring ferromagnetic rings and ferromagnetic rods connecting them to each other, are made in a monolithic form of the same material; 2) the magnetic fluxes at both ends of the ring ferromagnetic cores along the pipe axis are so small that they can not be taken into account; 3) the magnetic resistance of the ferromagnetic cores does not depend on the value of the magnetic field induction in them, that is, the magnetic circuit operates in the linear part of the main magnetization curve (if we take into account the presence of a large air gap in the path of the working magnetic flux, this assumption is quite acceptable); 4) because of the small frequency of the change in the magnetic field with time, the eddy currents in the ferromagnetic cores are too small to neglect.

These assumptions do not have a significant effect on the accuracy of the analysis of magnetic circuits, but they simplify the calculations much [6].

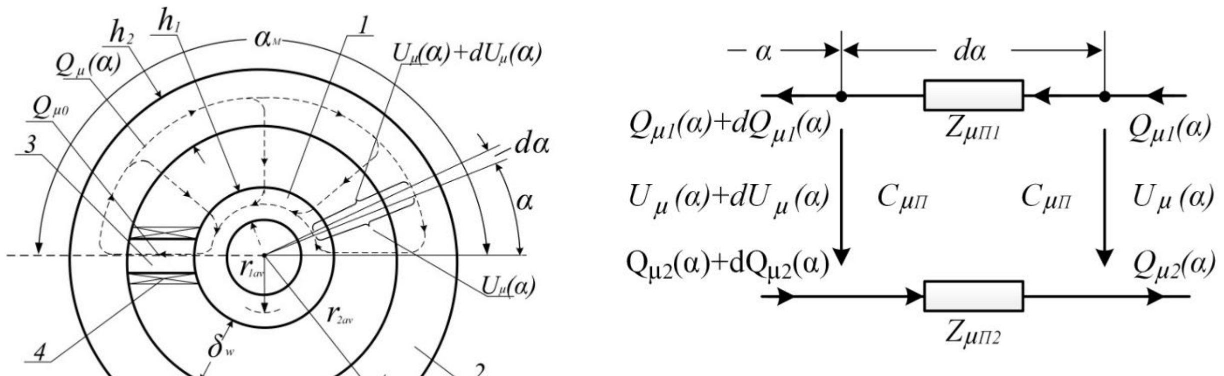

Fig.1. Constructive scheme (a) of an EFT magnetic circuit with an annular channel and its equivalent circuit dα (b)

Taking into account the fact that the magnetic circuit is symmetric about the horizontal axis, it is sufficient to study it for one, for example, the upper half of the circuit.

Based on the Kirchhoff laws, we compose the following differential equations for the magnetic flux in coaxial ferromagnetic ring cores and the magnetic voltage between them created by the magnetomotive force (MMF) F_e of the concentrated winding for the elementary part of the magnetic circuit $d\alpha$ (Fig. 1) [6]:

$$\frac{dQ_\mu(\alpha)}{d\alpha} = U_\mu(\alpha)C_{\mu p}, \quad (1)$$

$$\frac{dU_\mu(\alpha)}{d\alpha} = \left(Z_{\mu p1} + Z_{\mu p2}\right)Q_\mu(\alpha), \quad (2)$$

where $Q_\mu(\alpha)$ and $U_\mu(\alpha)$ are respectively the values of the magnetic flux in the concentric ferromagnetic cores and the magnetic voltage between them, created by the MMF F_e of the magnetization winding; $Z_{\mu p1} = \frac{\pi r_{1av}}{\mu\mu_0 b h_1 \alpha_m}$ and $Z_{\mu p2} = \frac{\pi r_{2av}}{\mu\mu_0 b h_1 \alpha_m}$ are the linear values of the complex magnetic resistances of concentric ferromagnetic cores 1 and 2 per unit of

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the angle of the magnetic circuit of the magnetic circuit of the magnetic core of 1 and 2 $C_{\mu п} = \mu_0 \frac{0{,}5b\pi(r_{1av}+r_{2av})}{\delta \alpha_m}$ is the linear value of the magnetic capacitance (magnetic conductivity in the classical analogy of electric and magnetic circuits) of the annular gap δ between coaxial concentric ferromagnetic cores 1 and 2; $h_1 h_2$, b and δ are respectively the thicknesses of concentric ferromagnetic cores and a ferromagnetic bridge connecting them to each other, their length along the axis of the annular channel, as well as the gap between the cores; r_{1av} and r_{2av} are the average radii of the ring cores; μ, $\mu_0 = 4\pi \cdot 10^{-7}\, {}^{H}/_{m}$ is the relative magnetic permeability of the material of the ferromagnetic cores and the absolute magnetic permeability of air, respectively; $\alpha_m = 180^0$ - the maximum value of α.

Differentiating (1) by the α coordinate and substituting (2) into it, we obtain the following second-order linear differential equation [6]:

$$\frac{d^2 Q_\mu(\alpha)}{d\alpha^2} = (Z_{\mu p\,1} + Z_{\mu p\,2}) C_{\mu p}\, Q_\mu(\alpha). \tag{3}$$

The general solution of the differential equation (3) has the following form [7]:

$$Q_\mu(\alpha) = A_1 e^{\gamma\alpha} + A_2 e^{-\gamma\alpha}, \tag{4}$$

where $\gamma = \sqrt{2(Z_{\mu p\,1} + Z_{\mu p\,2})C_{\mu p}}$ is the complex value of the coefficient of propagation of the magnetic flux along the magnetic circuit, *1/degree*; A_1 and A_2 are the integration constants.

Substituting the general solution (4) into the differential equation (1), we obtain the following expression for the magnetic voltage:

$$U_\mu(\alpha) = \frac{\gamma}{C_{\mu p}} A_1 e^{\gamma\alpha} - \frac{\gamma}{C_{\mu p}} A_2 e^{-\gamma\alpha}. \tag{5}$$

The integration constants A_1 and A_2 are determined on the basis of the following boundary (boundary) conditions:

$$\left.\begin{array}{c} Q_\mu(\alpha)|_{\alpha=0} = 0, \\ U_\mu(\alpha)|_{\alpha=\alpha_m} = F_e - Q_\mu(\alpha)|_{\alpha=\alpha_m} Z_{\mu 0}, \end{array}\right\}, \tag{6}$$

where $Z_{\mu 0}$ is the magnetic resistance of the ferromagnetic jumper k, $1/H$.

Substituting in (6) the values of magnetic fluxes and magnetic voltages corresponding to the boundary conditions, we obtain the following system of algebraic equations:

$$\left.\begin{array}{c} A_1 + A_2 = 0, \\ \left(Z_{\mu 0} + \frac{\gamma}{C_{\mu p}}\right) e^{\gamma\alpha_m} A_1 + \left(Z_{\mu 0} - \frac{\gamma}{C_{\mu p}}\right) e^{-\gamma\alpha_m} A_2 = F_e. \end{array}\right\}. \tag{7}$$

Solving the system of algebraic equations (7) for the unknowns A_1 and A_2, we find the following values:

$$A_1 = -A_2 = \frac{F_e}{2\Delta_1}, \tag{8}$$

where$\Delta_1 = Z_{\mu 0} sh(\gamma\alpha_m) + \frac{\gamma}{C_{\mu p}} ch(\gamma\alpha_m)$.

Substituting the found values of A_1 and A_2 in expressions (4) and (5), we finally have:

$$Q_\mu(\alpha) = \frac{F_e}{\Delta_1} sh(\gamma\alpha), \tag{9}$$

$$U_\mu(\alpha) = \frac{\gamma F_{в}}{C_{\mu p}\,\Delta_1} ch(\gamma\alpha). \tag{10}$$

The law of change of the magnetic induction of the magnetic field in the annular channel between coaxially arranged ferromagnetic cores is determined by the coordinate α using the following expression:

$$B(\alpha) = \mu_0 \frac{U_\mu(\alpha)}{\delta_w} = \mu_0 \frac{\gamma F_e}{C_{\mu p}\,\Delta_1 \delta_w} ch(\gamma\alpha). \tag{11}$$

Due to the distributed nature of the magnetic resistances of coaxially arranged ferromagnetic cores and the magnetic capacitance of the gap between them along the coordinate α, the magnetic induction in the annular channel is distributed unevenly along the angular coordinate. The degree of non-uniformity of the magnetic induction is found using the following expression:

$$\delta B(\alpha), \% = \left[\frac{B(\alpha_m) - B(0)}{B(\alpha_m)}\right] \cdot 100\% = \left[1 - \frac{1}{ch(\beta)}\right] \cdot 100\%, \tag{12}$$

where $\beta = \gamma\alpha_m$ is the attenuation coefficient of the magnetic field in the magnetic circuit.

The law of change of the magnetic induction of the magnetic field in the annular channel between coaxially arranged ferromagnetic cores on the radial coordinate ρ is defined as:

$$B(\rho) = \frac{2Q_\mu(\alpha)}{\pi b\rho} = \frac{F_e}{\pi b\rho\Delta_1} sh(0{,}5\beta), \tag{13}$$

here $r_1 \le \rho \le r_2$.

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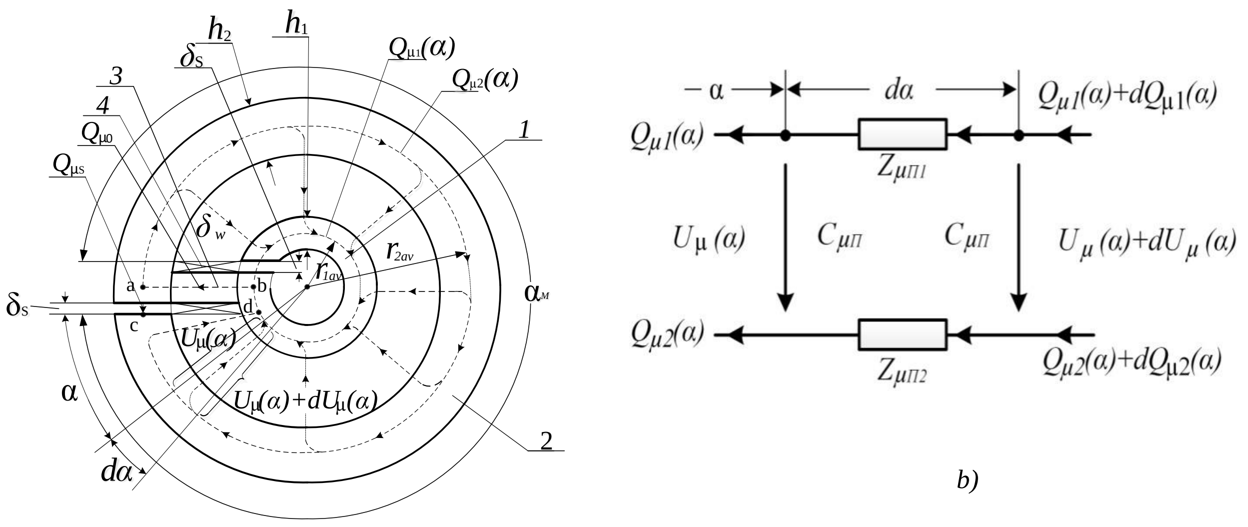
Expressions (9) - (11) and (13) are mathematical models of the linear magnetic EFT circuit shown in Figure 1, and they can be used to determine the design parameters of magnetic circuits and to study the static and dynamic characteristics of an EFT with an annular channel.

An analysis of the mathematical models obtained shows that the magnetic flux in concentric ferromagnetic cores is nonlinearly distributed over the angular coordinate, and the magnetic induction in the annular channel (in the working active EFT channel) is unevenly distributed along the angular and radial coordinates, and if with an increase in the attenuation coefficient of the magnetic field magnetic conductor β, the degree of non-uniformity of magnetic induction in the angular coordinate increases, it remains constant in the radial coordinate.

The constructive scheme of the magnetic circuit of another, developed with the participation of the authors of the article, and the scheme of replacing its elementary sections are shown in Fig. 2 [9].



a)

Fig.2. Constructive scheme (a) and the equivalent circuit of the elementary sections (b) of a linear magnetic EFT circuit with an annular channel

A distinctive feature of this magnetic circuit is that it creates the same conditions for closing the magnetic flux lines along the entire annular working gap between coaxially arranged open ferromagnetic cores interconnected by various ends using a ferromagnetic jumper with a magnetizing winding, i.e. the magnetic resistance of any path along which the magnetic flux line is the same. In this case, the difference between the values of magnetic resistances of concentric ferromagnetic cores, which appears due to the difference in their lengths, can be eliminated by choosing their thickness using the ratio $(h_2/h_1) = r_{2av}/r_{1av})$. Then we can assume that $Z_{\mu p1} = Z_{\mu p2} = Z_{\mu p}$.

At one time, mathematical models of the magnetic circuit of this EFT were developed, but due to the fact that it did not take into account the magnetic capacitance of the non-working air gap, the error in the calculations of the circuit was 10-15%.

To simplify the calculations, we assume that the magnetic capacitances of the non-working air gaps δ_{s1} and δ_{s2} are equal to each other, ie: $C_{\mu s1} = \mu_0\,(bh_1)/\delta_{s1} = C_{\mu s2} = \mu_0\,(bh_2)/\delta_{s2}$. From this equation it follows that $\delta_{s2} = \delta_{s1}(h_2/h_1)$. Under this condition, we can assume that $Q_{\mu s1} = Q_{\mu s2} = Q_{\mu s}$.

Differential equations compiled on the basis of Kirchhoff's laws for magnetic flux and magnetic voltage generated by the MMF F_e excitation winding for the elementary part of the magnetic circuit $d\alpha$ will take the following form:

$$\frac{dQ_{\mu 1}(\alpha)}{d\alpha} = U_\mu(\alpha)C_{\mu p}; \quad \frac{dQ_{\mu 2}(\alpha)}{d\alpha} = -U_\mu(\alpha)C_{\mu p}; \quad \frac{dU_\mu(\alpha)}{d\alpha} = Z_{\mu p}\left[Q_{\mu 1}(\alpha) - Q_{\mu 2}(\alpha)\right], \tag{14}$$

where $Z_{\mu p1} = \frac{2\pi r_{1av} - h_3 - \delta_{s1}}{\mu\mu_0 b h_1 \alpha_m}$, $Z_{\mu p2} = \frac{2\pi r_{2av} - h_3 - \delta_{s2}}{\mu\mu_0 b h_2 \alpha_m}$; $C_{\mu p} = \mu_0 \frac{b\pi(r_{1av} + r_{2av}) - (\delta_{s1} + \delta_{s2} + h_3)}{\delta \alpha_m}$; where h_3 is the thickness of the ferromagnetic bridge, connecting the concentric ferromagnetic cores. The remaining designations are shown in Fig.2, a.

After simple calculations we get the following differential equation:

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$$\frac{d^2U_\mu(\alpha)}{d\alpha^2} = 2Z_{\mu p}C_{\mu p}U_\mu(\alpha). \quad (15)$$

The general solution of this differential equation is as follows:

$$U_\mu(\alpha) = A_1e^{\gamma\alpha} + A_2e^{-\gamma\alpha}, \quad (16)$$

For the studied magnetic circuit, the following condition is satisfied:

$$Q_{\mu 1}(\alpha) + Q_{\mu 2}(\alpha) = Q_{\mu 2}(\alpha_m) + Q_{\mu s} = Q_{\mu 1}(0) + Q_{\mu s}, \quad (17)$$

here$Q_{\mu s}$ is the magnetic flux closing through non-working air gapsδ_{s1} andδ_{s2}.

From (17) we find$Q_{\mu 2}(\alpha)$ and substituting it into the third equation (14) we determine from the resulting equation the expression$Q_{\mu 1}(\alpha)$ as follows:

$$Q_{\mu 1}(\alpha) = \frac{\gamma}{2Z_{\mu p}}(A_1e^{\gamma\alpha} - A_2e^{-\gamma\alpha}) + \frac{1}{2}[Q_{\mu 2}(\alpha_m) - Q_{\mu s}]. \quad (18)$$

Similarly, we find the expression$Q_{\mu 2}(\alpha)$:

$$Q_{\mu 2}(\alpha) = -\frac{\gamma}{2Z_{\mu p}}(A_1e^{\gamma\alpha} - A_2e^{-\gamma\alpha}) + \frac{1}{2}[Q_{\mu 2}(\alpha_m) - Q_{\mu s}]. \quad (19)$$

The integration constants A_1 and A_2 are subject to the following boundary (boundary) conditions:

$$\left.\begin{aligned} Q_{\mu 1}(\alpha)|_{\alpha=0} = Q_{\mu 1}(0) = Q_{\mu 2}(\alpha_m), \\ Q_{\mu 2}(\alpha)|_{\alpha=\alpha_m} = Q_{\mu 2}(\alpha_m). \end{aligned}\right\} \quad (20)$$

Substituting in (20) the values of magnetic fluxes and magnetic voltages corresponding to the boundary conditions, and solving the resulting system of algebraic equations for unknowns, we have:

$$A_1 = -\frac{Z_{\mu p}[Q_{\mu 2}(\alpha_m) + Q_{\mu s}]}{2\gamma sh(\gamma\alpha_m)}(e^{-\gamma\alpha_m} + 1), \quad (21)$$

$$A_2 = -\frac{Z_{\mu p}[Q_{\mu 2}(\alpha_m) + Q_{\mu s}]}{2\gamma sh(\gamma\alpha_m)}(e^{\gamma\alpha_m} + 1). \quad (22)$$

Substituting the found values of A_1waA_2 into equations (16), (18) and (19), we obtain the following expressions for magnetic voltages between coaxial concentric ferromagnetic cores and for magnetic fluxes in them:

$$U_\mu(\alpha) = -\frac{Z_{\mu p}Q_{\mu 0}}{\gamma sh(\gamma\alpha_m)}\{ch(\gamma\alpha) + ch[\gamma(\alpha_m - \alpha)]\}, \quad (23)$$

$$Q_{\mu 1}(\alpha) = -\frac{Q_{\mu 0}}{2sh(\gamma\alpha_m)}\{sh(\gamma\alpha) - sh[\gamma(\alpha_m - \alpha)]\} + \frac{1}{2}[Q_{\mu 2}(\alpha_m) - Q_{\mu s}], \quad (24)$$

$$Q_{\mu 2}(\alpha) = \frac{Q_{\mu 0}}{2sh(\gamma\alpha_m)}\{sh(\gamma\alpha) - sh[\gamma(\alpha_m - \alpha)]\} + \frac{1}{2}[Q_{\mu 2}(\alpha_m) - Q_{\mu s}]. \quad (25)$$

To determine the expressions $U_\mu(\alpha), Q_{\mu 1}(\alpha)$ and $Q_{\mu 2}(\alpha)$, expressed in terms of MMFF_e of the excitation winding, it will be necessary to determine the values of $Q_{\mu 0}$ (total magnetic flux), $Q_{\mu s}$ and$Q_{\mu 2}(\alpha_m)$, expressed in terms of MMFF_e.

To do this, based on the Kirchhoff laws for the node «a», and also for the closed circuits «$aa'b'ba$» and «$baa'a''b''b$» of the magnetic circuit under study:

$$Q_{\mu 0} = Q_{\mu 2}(\alpha_m) + Q_{\mu s}, \quad (26)$$

$$Z_{\mu 0}Q_{\mu 0} + U_\mu(\alpha_m) + W_{\mu s}Q_{\mu s} = F_e, \quad (27)$$

$$Z_{\mu 0}Q_{\mu 0} + Z_{\mu p}\int_0^{\alpha_m} Q_{\mu 2}(\alpha)d\alpha + U_\mu(0) = F_e, \quad (28)$$

where$W_{\mu s} = \frac{1}{C_{\mu s}}$ is the magnetic rigidity of the magnetic circuit (according to the energy-information model of circuits of different physical nature [10]), and by the classical analogy of electric and magnetic circuits, this parameter is called the magnetic resistance of the circuit [7].

Solving together equations (26) - (28) for$Q_{\mu 0}$, $Q_{\mu s}$и$Q_{\mu 2}(\alpha_m)$, we get the following expressions:

$$Q_{\mu 0} = -F_e\frac{2\beta sh\beta(W_{\mu s} + Z_{\mu p}\alpha_m)}{\Delta_1}, \quad (29)$$

$$Q_{\mu 2}(\alpha_m) = -F_e\frac{2\beta sh\beta(W_{\mu s} + 0{,}5Z_{\mu p}\alpha_m)}{\Delta_1}, \quad (30)$$

$$Q_{\mu s} = -F_e\frac{\beta sh\beta Z_{\mu p}\alpha_m}{\Delta_1}, \quad (31)$$

here$\Delta_1 = (Z_{\mu p}\alpha_m + W_{\mu s})(2Z_{\mu p}\alpha_m(1 + ch\beta) - 2Z_{\mu 0}\beta sh\beta) - \beta Z_{\mu p}W_{\mu s}sh\beta$.

Substituting (29) - (31) into equations (11) - (13), respectively, we obtain the following final expressions for magnetic voltage and magnetic fluxes:

$$U_\mu(\alpha) = F_e\frac{2(W_{\mu s} + Z_{\mu p}\alpha_m)}{\Delta_1}\{ch(\beta\alpha^*) + ch[\beta(1 - \alpha^*)]\}. \quad (32)$$

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$$Q_{\mu 1}(\alpha)=F_e\frac{\beta}{\Delta_1}\{(W_{\mu s}+Z_{\mu p}\alpha_m)\{sh(\beta\alpha^*)-sh[\beta(1-\alpha^*)]\}-W_{\mu s}sh\beta\}. \quad (33)$$

$$Q_{\mu 2}(\alpha)=-F_e\frac{\beta}{\Delta_1}\{(W_{\mu s}+Z_{\mu p}\alpha_m)\{sh(\beta\alpha^*)-sh[\beta(1-\alpha^*)]\}+W_{\mu s}sh\beta\}, \quad (34)$$

here$\alpha^*=\frac{\alpha}{\alpha_m}$.

The dependence of the magnetic induction of the magnetic field in the annular channel on the α coordinate is determined using the following expression:

$$B(\alpha)=\mu_0\frac{U_\mu(\alpha)}{\delta}=F_в\mu_0\frac{2(W_{\mu s}+Z_{\mu p}\alpha_m)}{\delta\Delta_1}\{ch(\beta\alpha^*)+ch[\beta(1-\alpha^*)]\}. \quad (35)$$

The degree of non-uniform distribution of the magnetic field in the annular channel along the coordinate α is calculated by the formula:

$$\delta B(\alpha),\%=\left[\frac{B(0)-B(0{,}5\beta)}{B(0)}\right]\cdot 100\%=\left[1-\frac{2ch(0{,}5\beta)}{1+ch\beta}\right]\cdot 100\%. \quad (36)$$

The law of change of the magnetic field in the annular channel along the radial coordinate ρ is determined using the following expression:

$$B(\rho)=\left|\frac{Q_{\mu 2}(\alpha_m)}{b[2\pi\rho-(\delta_{s1}+\delta_{s2}+h_3)]}\right|=\left|F_e\frac{2\beta sh\beta(W_{\mu s}+0{,}5Z_{\mu p}\alpha_m)}{b[2\pi\rho-(\delta_{s1}+\delta_{s2}+h_3)]\Delta_2}\right|. \quad (37)$$

When $W_{\mu s}\to\infty$ or $C_{\mu s}=0$, expressions (29) - (31) and (32) - (35) will be equal to:

$$Q_{\mu 0}=Q_{\mu 2}(\alpha_m)=-F_e\frac{2\beta sh\beta}{\Delta_2}, Q_{\mu s}=0, \quad (38)$$

$$U_\mu(\alpha)=F_e\frac{2Z_{\mu p}\alpha_m}{\Delta_2}\{ch(\beta\alpha^*)+ch[\beta(1-\alpha^*)]\}. \quad (39)$$

$$Q_{\mu 1}(\alpha)=F_e\frac{\beta}{\Delta_2}\{sh(\beta\alpha^*)-sh[\beta(1-\alpha^*)]-sh\beta\}. \quad (40)$$

$$Q_{\mu 2}(\alpha)=-F_e\frac{\beta}{\Delta_2}\{\{sh(\beta\alpha^*)-sh[\beta(1-\alpha^*)]+sh\beta\}\}, \quad (41)$$

$$B(\alpha)=F_e\mu_0\frac{2Z_{\mu п}\alpha_m}{\delta\Delta_2}\{ch(\beta\alpha^*)+ch[\beta(1-\alpha^*)]\}, \quad (42)$$

here$\Delta_2=2Z_\mu(1+ch\beta)-2Z_{\mu 0}\beta sh\beta-Z_\mu\beta sh\beta; Z_\mu=Z_{\mu p}\alpha_m$.

Expressions (32) - (35) are mathematical models of the linear magnetic EFT circuit shown in Fig. 2, taking into account the distribution of the parameters of the magnetic circuit and leakage fluxes, closed through non-working gaps. They can be used in determining the design parameters of magnetic circuits and studying the static and dynamic characteristics of an EFT with an annular channel.

III. CONCLUSION

Thus, the article developed mathematical models of linear magnetic EFT circuits with an annular channel and with distributed parameters. They can be used in determining the design parameters of magnetic circuits and studying the static and dynamic characteristics of an EFT with an annular channel.

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