УДК(UDC) 621.314

TRANSFORMER CONVERTERS OF ANGULAR DISPLACEMENT WITH VARIABLE ACTIVE AREA OF A MOVABLE CORE

Amirov S.F.[1], Mamadaliyev U.Sh.[1]
[1] – Tashkent state transport university (Tashkent, Uzbekistan)

Abstract: The article develops mathematical models of a transformer converter of angular displacements with a variable active area of a crescent-shaped open ring made of electrically insulating non-magnetic and magnetic materials, on which the excitation coils are wound. In this case, the magnetic circuit is considered as a circuit with distributed parameters, in which the width of the excitation coil is a function of the angular displacement of the controlled object. The obtained mathematical models of the magnetic circuit of the transformer converter of angular displacements in the form of analytical expressions of the magnetic flux in long ferromagnetic rods and the magnetic voltage between them allow us to take into account the distribution of the parameters of the magnetic resistance of long ferromagnetic rods and the magnetic capacity of the air gap between them, as well as the magnetic capacity of the air gap between these rods and a movable ferromagnetic crescent-shaped open ring. Studies have found that with an increase in the value of the attenuation coefficient of the magnetic field in the magnetic circuit, the working magnetic fluxes decrease, and the degree of nonlinearity of the dependence of these fluxes on the angular displacement of the moving part of the converter increases. It is shown that these properties are especially strongly manifested in a transformer converter of angular displacements with a ferromagnetic crescent-shaped open ring.

Key words: transformer converter, angular displacement, crescent-shaped open ring, magnetic circuit, distributed parameter, linear magnetic resistance, linear magnetic capacitance, magnetic flux, magnetic voltage, degree of nonlinearity of flow distribution, magnetic flux propagation coefficient, characteristic sections of the magnetic circuit.

Introduction. In automatic monitoring and control systems for various technological and production processes, to obtain reliable information about the angular movements of controlled objects, converters of the electromagnetic operating principle, in particular, transformer converters, are widely used [1,2]. Compared to other types of converters, they have high reliability and stable metrological characteristics under extreme operating conditions [3,4]. At the same time, they have relatively low sensitivity and nonlinear static characteristics [5].

Transformer angular displacement converters have been developed at the Electric Power Supply Department of the Tashkent State Transport University [6], the design diagram of one of them is shown in Fig. 1.

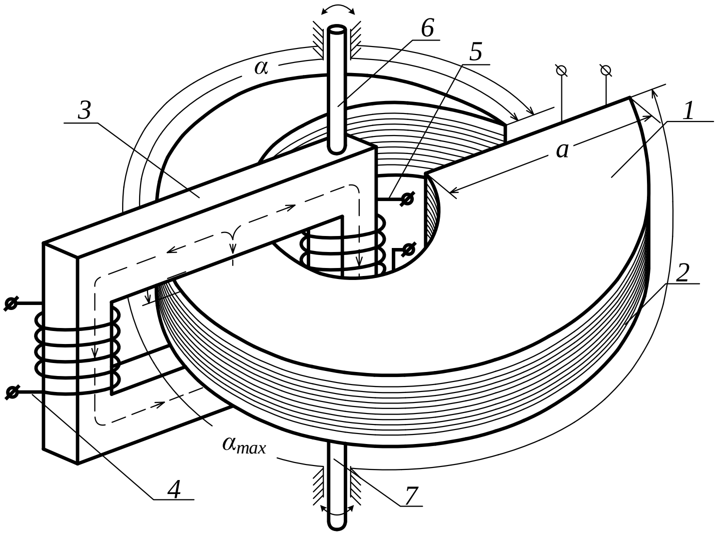


Fig.1. Constructive diagram of transformer angular displacement transducers: 1 – fixed excitation coil; 2 - sickle-shaped open ring; 3 – movable O-shaped magnetic circuit; 4.5 – sections of the measuring winding connected in series and accordingly; 6,7 - axle shafts mechanically rigidly connected to the controlled object.

Transformer angular displacement transducers contain a stationary excitation coil 1 wound on a crescent-shaped open ring 2. Ring 2 is placed in the gap of the O-shaped magnetic circuit 3, at the bases of which identical sections of the measuring winding 4 and 5 are concentratedly wound, connected to each other in series and in accordance. The end parts of one of the bases of the magnetic circuit 3 are mechanically rigidly connected to two axle shafts 6 and 7.

Transformer angular displacement transducers work as follows. When the excitation winding is powered from a source of sinusoidal current, the sinusoidal magnetic flux formed by this current is closed along the magnetic circuit, closing through its base, where sections of the measuring winding are wound in series and in accordance with each other, inducing in them, according to the law of electromagnetic induction, electromotive forces E_{out}. Electromotive forces are proportional to the current (I_{ev}) of the power source and the angular frequency (ω) of its change, the number of turns ($w_{v.}$) of the excitation winding and its active area ($S_{\mu\delta}$ (α)), as well as the number of turns ($w_{out.}$) measuring winding, those:

$$\dot{E}_{\text{out.}} = j\omega w_{\text{out.}}\dot{B} = j\omega w_{\text{out.}}\dot{Q}_{\mu}S_{\mu\delta}(\alpha) = j\omega w_{\text{out.}}\dot{I}_{ev}w_{\text{v.}}\mu_0\frac{ba}{\delta\pi}\alpha, \quad (1)$$

here $\dot{B}$, $\dot{Q}_{\mu}$ – respectively, magnetic induction and magnetic flux in the active area of the field winding coil; $\mu_0 = 4\pi \cdot 10^{-7}[H \cdot m^{-1}]$ – magnetic constant; $S_{\mu\delta}(\alpha) = \frac{ba}{\pi}\alpha$ – active area of the sector of a fixed crescent-shaped open ring 1, covered by long rods of a movable O-shaped magnetic conductor; b – width of long rods; a is the maximum width of a crescent-shaped open ring, equal to twice the pitch of the Archimedean spiral; α, α_m – angular displacement of the moving magnetic conductor and its maximum value.

The range of converted angular movements in the proposed converter is approximately 350^0.

When deriving expression (1), the distribution of the parameters of the magnetic circuit of the converter under study is not taken into account. This circumstance to some extent reduces the accuracy of determining the analytical equation of the static characteristics of the transformer angular displacement transducers under consideration.

In this article, we study the magnetic circuit of the transformer angular displacement transducers under consideration, taking into account the distribution of the parameters of the magnetic resistance of the long rods of the O-shaped magnetic conductor and the magnetic capacitance between them for the following two cases: 1) the coil is wound on a crescent-shaped open ring made of electrically insulating and non-magnetic material; 2) the coil is wound on a crescent-shaped open ring made of ferromagnetic material.

In all cases of analysis of magnetic circuits, the nonlinearity of the characteristics of the magnetic resistance of the steel part of the magnetic circuit, the bulging flows at the side ends of the circuit and in the area of the excitation coil are neglected. These assumptions, as shown in [3], do not introduce significant inaccuracies, but significantly simplify the analysis of the magnetic circuit under study.

The design diagram of the linear magnetic circuit under study is shown in Fig. 2. In the calculations, the magnetic circuit is represented in the form of an O-shaped magnetic circuit; between the parallel long rods, an excitation coil is placed freely with some gaps δ_p the active area of which changes due to a linear change in its width along the length of the long rods depending on the value of the rotation angle of the O-shaped magnetic circuit, those $2x = \frac{a}{\pi}\alpha$ (when the rotation angle α of the O-shaped magnetic core changes from 0 to α_m, the x coordinate changes within the limits: $0 \leq x \leq X_м$).

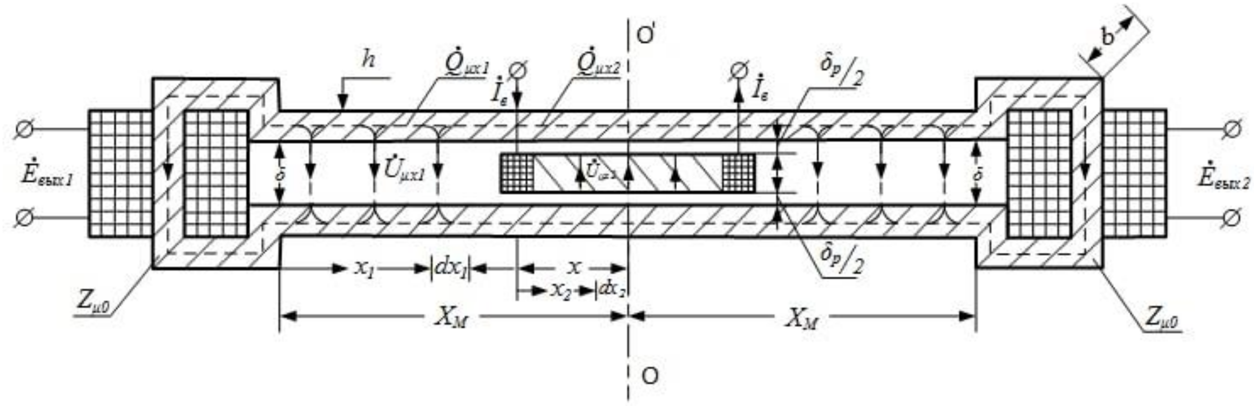


Fig.2. Constructive diagram of the linear magnetic circuit under study

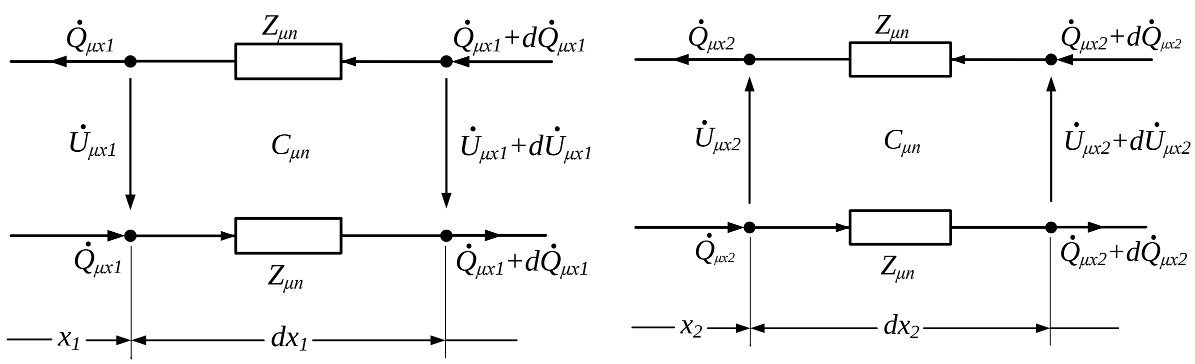
Considering that the magnetic circuit under consideration is symmetrical with respect to the vertical axes $O-O'$, it is sufficient to consider only one, for example, its left part from this part.

For the first case, let's compose the following equations based on Kirchhoff's laws for the corresponding elementary sections of the magnetic circuit with lengths dx_1 and dx_2, respectively (Fig. 3) [3]:

$$Q'_{\mu x_1} = U_{\mu x_1} C_{\mu п}, \quad (2) \qquad U'_{\mu x_1} = 2Z_{\mu п} Q_{\mu x_1}, \quad (3)$$

$$Q'_{\mu x_2} = -U_{\mu x_2} C_{\mu п}, \quad (4) \qquad U'_{\mu x_2} = -2Z_{\mu п} Q_{\mu x_2}, \quad (5)$$

where $Q_{\mu x_1}$, $Q'_{\mu x_2}$, $[Wb]$; $U_{\mu x_1}$, $U'_{\mu x_2}$, $[A]$ are respectively, magnetic fluxes in parallel long rods and magnetic voltages between them for the corresponding sections; $Z_{\mu п} = \frac{1}{\mu \mu_0 bh}$, $[H^{-1} \cdot m^{-1}]$,$C_{\mu п} = \mu_0 \frac{b}{\delta}$, $[H \cdot m^{-1}]$ – linear values, respectively, of the magnetic resistance of long rods and magnetic capacitance of the air gap between them, per unit length of the rods; μ=const–relative magnetic permeability of the magnetic core material; x, X_M – width of the active area of the excitation coil along the length of the long rods of the O-shaped magnetic circuit and its maximum value, $[m]$. Geometric dimensions are shown in Fig. 2.



a) b)

Fig.3. Equivalent circuits of elementary sections of the linear magnetic circuit under study with coordinates x_1 (a) and x_2 (b)

Having differentiated equations (2) and (4) and substituting into them (3) and (4) respectively, we obtain the following homogeneous second-order differential equations with constant coefficients:

$$Q''_{\mu x_1} = 2Z_{\mu п}C_{\mu п}Q_{\mu x_1}. \quad (6) \qquad Q''_{\mu x_2} = 2Z_{\mu п}C_{\mu п}Q_{\mu x_2}. \quad (7)$$

The general solution of differential equations (6) and (7), as is known [8], has the following form:

$$Q_{\mu x_1} = A_1 e^{\gamma x_1} + A_2 e^{-\gamma x_1}, \quad (8)$$

$$Q_{\mu x_2} = A_3 e^{\gamma x_2} + A_4 e^{-\gamma x_2}, \quad (9)$$

where $A_1 \div A_4$ – constants of integration, $[Wb]$; $\gamma = \sqrt{2Z_{\mu п}C_{\mu п}}$, $[m^{-1}]$ – speed of propagation of the magnetic field in the magnetic circuit.

From equations (2) and (4) taking into account (8) and (9) for magnetic stresses we obtain the following equations:

$$U_{\mu x_1} = \frac{\gamma}{C_{\mu п}} A_1 e^{\gamma x_1} - \frac{\gamma}{C_{\mu п}} A_2 e^{-\gamma x_1}, \quad (10)$$

$$U_{\mu x_2} = -\frac{\gamma}{C_{\mu п}} A_3 e^{\gamma x_2} + \frac{\gamma}{C_{\mu п}} A_4 e^{-\gamma x_2}. \quad (11)$$

The values of $A_1 \div A_4$ are found based on the following boundary conditions [9]:

$$U_{\mu x_1=0} = -Q_{\mu x_1=0} Z_{\mu 0}, \ (12) \qquad Q_{\mu x_1=X_м - x} = -Q_{\mu x_2=0}, \quad (13)$$

$$U_{\mu x_1=X_м - x} = F_в - U_{\mu x_2=0}, \ (14) \qquad Q_{\mu x_2=x} = 0, \quad (15)$$

where $F_в$, $[A]$ is the magnetomotive force of the field winding; $Z_{\mu 0} = \frac{\delta}{\mu\mu_0 bh}$ - magnetic resistance to the base of the O-shaped magnetic circuit, $[H^{-1}]$.

Substituting the boundary values $Q_{\mu x_1}, Q_{\mu x_2}$ and $U_{\mu x_1}, U_{\mu x_2}$ into the corresponding equations (12)-(15) we obtain the following system of algebraic equations:

$$\begin{cases} \left(\frac{\gamma}{C_{\mu п}} - Z_{\mu 0}\right) A_1 - \left(\frac{\gamma}{C_{\mu п}} + Z_{\mu 0}\right) A_2 = 0, \\ A_1 e^{\gamma(X_м - x)} + A_2 e^{-\gamma(X_м - x)} - A_3 - A_4 = 0, \\ \frac{\gamma}{C_{\mu п}} A_1 e^{\gamma(X_м - x)} - \frac{\gamma}{C_{\mu п}} A_2 e^{-\gamma(X_м - x)} - \frac{\gamma}{C_{\mu п}} A_3 + \frac{\gamma}{C_{\mu п}} A_4 = \dot{F}_в, \\ A_3 e^{\gamma x} + A_4 e^{-\gamma x} = 0. \end{cases} \quad (16)$$

Solving the resulting system of algebraic equations (16) for the unknowns $A_1 \div A_4$, we find their following values:

$$A_1 = \frac{F_к(Z_{\mu 0}C_{\mu п} + \gamma)sh(\gamma x)}{\Delta_1}, \quad (17)$$

$$A_2 = \frac{F_к(\gamma - Z_{\mu 0}C_{\mu п})sh(\gamma x)}{\Delta_1}, \quad (18)$$

$$A_3 = -\frac{F_к[ch(\gamma x) - sh(\gamma x)]\left(Z_{\mu 0}C_{\mu п}sh[\gamma(X_м - x)] + \gamma ch[\gamma(X_м - x)]\right)}{\Delta_1}, \quad (19)$$

$$A_4 = \frac{F_к[ch(\gamma x) + sh(\gamma x)]\left(Z_{\mu 0}C_{\mu п}sh[\gamma(X_м - x)] + \gamma ch[\gamma(X_м - x)]\right)}{\Delta_1}, \quad (20)$$

where $\Delta_1 = -\frac{2\gamma}{C_{\mu п}}\left[Z_{\mu 0}C_{\mu п}sh(\gamma X_м) + \gamma ch(\gamma X_м)\right], [H^{-1} \cdot m^{-1}]$.

Substituting the found values of $A_1 \div A_4$ into equations (9)-(11), we obtain the following:

$$Q_{\mu x_1} = \frac{F_в sh(\gamma x)}{\Delta_1}\left[Z_{\mu 0}C_{\mu п}sh(\gamma x_1) + \gamma ch(\gamma x_1)\right], \quad (21)$$

$$U_{\mu x_1} = \frac{\gamma F_в sh(\gamma x)}{C_{\mu п}\Delta_1}\left[Z_{\mu 0}C_{\mu п}ch(\gamma x_1) + \gamma sh(\gamma x_1)\right], \quad (22)$$

$$Q_{\mu x_2} = \frac{F_в}{\Delta_1}\left\{Z_{\mu 0}C_{\mu п}sh[\gamma(X_м - x)] + \gamma ch[\gamma(X_м - x)]\right\}sh[(\gamma(x - x_2)]), \quad (23)$$

$$U_{\mu x_2} = \frac{F_в}{C_{\mu п}\Delta_1}\left\{Z_{\mu 0}C_{\mu п}sh[\gamma(X_м - x)] + \gamma ch[\gamma(X_м - x)]\right\}ch[(\gamma(x - x_2)]). \quad (24)$$

Expressions for magnetic fluxes and magnetic voltages for the right side of the magnetic circuit can be obtained using the above method. They differ from the corresponding expressions (21)-(24) only in the coordinates x_3 and x_4 instead of x_1 and x_2, those:

$$Q_{\mu x_3} = \frac{F_в sh(\gamma x)}{\Delta_1}\left[Z_{\mu 0}C_{\mu п}sh(\gamma x_3) + \gamma ch(\gamma x_3)\right], \quad (25)$$

$$U_{\mu x_3} = \frac{\gamma F_в sh(\gamma x)}{C_{\mu п}\Delta_1}\left[Z_{\mu 0}C_{\mu п}ch(\gamma x_3) + \gamma sh(\gamma x_3)\right], \quad (26)$$

$$Q_{\mu x_4} = \frac{F_в}{\Delta_1}\left\{Z_{\mu 0}C_{\mu п}sh[\gamma(X_м - x)] + \gamma ch[\gamma(X_м - x)]\right\}sh[(\gamma(x - x_4)]), \quad (27)$$

$$U_{\mu x_4} = \frac{F_в}{C_{\mu п}\Delta_1}\left\{Z_{\mu 0}C_{\mu п}sh[\gamma(X_м - x)] + \gamma ch[\gamma(X_м - x)]\right\}ch[(\gamma(x - x_4)]). \quad (28)$$

The values of the working magnetic fluxes involved in creating the output electromotive force are found as:

$$Q_{\mu x.р1} = Q_{\mu x_1 = 0} = Q_{\mu x_3 = 0} = \frac{F_в \gamma sh(\gamma x)}{\Delta_1}. \quad (29)$$

The output electromotive force of the transformer angular displacement transducers under consideration, removed from the output terminals in series and according to the connected sections of the excitation winding, is defined as:

$$\dot{E}_{\text{вых.1}} = j\omega 0{,}5 w_{\text{вых}}\left(\dot{Q}_{\mu x_1=0} + \dot{Q}_{\mu x_3=0}\right) = j\omega w_{\text{вых}} \dot{I}_{\text{эв}} w_{\text{в}} \frac{\gamma sh(\gamma x)}{\Delta_1}. \quad (30)$$

If we take into account that $x = \frac{a}{2\pi}\alpha$, expression (30) has the following form:

$$\dot{E}_{\text{вых.1}} = j\omega w_{\text{вых}} \dot{I}_{\text{эв}} w_{\text{в}} \frac{\gamma sh\left(\frac{\gamma a}{2\pi}\alpha\right)}{\Delta_1}. \quad (31)$$

Expressions (21)-(29) are mathematical models of the magnetic circuit, and expression (30) and (31) are mathematical models of the transformer angular displacement transducers under consideration, taking into account the distribution of the parameters of the magnetic resistance of the long rods of the O-shaped magnetic core and the magnetic capacitance between them for the case manufacturing a crescent-shaped open ring on which the excitation winding is wound, from an electrically insulating and non-magnetic material.

Now we examine the magnetic circuit of the transformer angular displacement transducers under consideration for the case of manufacturing a crescent-shaped open ring in order to increase the sensitivity of the transducer made of ferromagnetic material.

For this case, the differential equations and their solutions for sections with the corresponding coordinates x_1 and x_2 have the following form:

$$Q''_{\mu x_1} = 2Z_{\mu\text{п}} C_{\mu\text{п}} Q_{\mu x_1}. \quad (6) \qquad Q''_{\mu x_2} = 2Z_{\mu\text{рп}} C_{\mu\text{рп}} Q_{\mu x_2}. \quad (32)$$

$$Q_{\mu x_1} = A_1 e^{\gamma x_1} + A_2 e^{-\gamma x_1}, \quad (33)$$

$$Q_{\mu x_2} = A_3 e^{\gamma_{\text{р}} x_2} + A_4 e^{-\gamma_{\text{р}} x_2}, \quad (34)$$

$$U_{\mu x_1} = \frac{\gamma}{C_{\mu\text{п}}} A_1 e^{\gamma x_1} - \frac{\gamma}{C_{\mu\text{п}}} A_2 e^{-\gamma x_1}, \quad (35)$$

$$U_{\mu x_2} = -\frac{\gamma_{\text{р}}}{C_{\mu\text{рп}}} A_3 e^{\gamma_{\text{р}} x_2} + \frac{\gamma_{\text{р}}}{C_{\mu\text{рп}}} A_4 e^{-\gamma_{\text{р}} x_2}. \quad (36)$$

here $Z_{\mu\text{рп}} = \frac{1}{\mu\mu_0 b h_{\text{р}}}$, $[H^{-1} \cdot m^{-1}]$, $C_{\mu\text{рп}} = \mu_0 \frac{b}{\delta_{\text{р}}}$, $[H \cdot m^{-1}]$ – linear values, respectively, of the magnetic resistance of long rods and the magnetic capacity of the air gap $\delta_{\text{р}}$ between them, per unit length of the rods; $h_p=0{,}5(h+h_c)$ and h_c – respectively, the thickness of the magnetic circuit in the section of the magnetic circuit with coordinate x_2 and the crescent-shaped open ring made of ferromagnetic material; $\delta_{\text{р}}$ – total air gap between the rods of the O-shaped magnetic core and the crescent-shaped ferromagnetic open ring (Fig. 2); $\gamma_{\text{р}} = \sqrt{2Z_{\mu\text{рп}} C_{\mu\text{рп}}}$, $[m^{-1}]$.

The boundary conditions for determining the integration constants $A_1 \div A_4$ do not change. Substituting the boundary values $Q_{\mu x_1}, Q_{\mu x_2}$ and $U_{\mu x_1}, U_{\mu x_2}$ into the corresponding equations (12)-(15) we obtain the following system of algebraic equations:

$$\begin{cases} \left(\frac{\gamma}{C_{\mu п}} - Z_{\mu 0}\right)A_1 - \left(\frac{\gamma}{C_{\mu п}} + Z_{\mu 0}\right)A_2 = 0, \\ A_1 e^{\gamma(X_м - x)} + A_2 e^{-\gamma(X_м - x)} - A_3 - A_4 = 0, \\ \frac{\gamma}{C_{\mu п}} A_1 e^{\gamma(X_м - x)} - \frac{\gamma}{C_{\mu п}} A_2 e^{-\gamma(X_м - x)} - \frac{\gamma_р}{C_{\mu рп}} A_3 + \frac{\gamma_р}{C_{\mu рп}} A_4 = \dot{F}_в, \\ A_3 e^{\gamma_р x} + A_4 e^{-\gamma_р x} = 0. \end{cases} \quad (37).$$

Solving the resulting system of algebraic equations (37) for the unknowns $A_1 \div A_4$, we find their following values:

$$A_1 = \frac{F_к(\gamma + Z_{\mu 0} C_{\mu п}) sh(\gamma_p x)}{\Delta_2}, \quad (38)$$

$$A_2 = \frac{F_к(\gamma - Z_{\mu 0} C_{\mu п}) sh(\gamma_p x)}{\Delta_2}, \quad (39)$$

$$A_3 = -\frac{F_к[ch(\gamma_p x) - sh(\gamma_p x)]\{Z_{\mu 0} C_{\mu п} sh[\gamma(X_м - x)] + \gamma ch[\gamma(X_м - x)]\}}{\Delta_2}, \quad (40)$$

$$A_4 = \frac{F_к[ch(\gamma_p x) + sh(\gamma_p x)]\{Z_{\mu 0} C_{\mu п} sh[\gamma(X_м - x)] + \gamma ch[\gamma(X_м - x)]\}}{\Delta_2}, \quad (41)$$

where $\Delta_2 = -\frac{2}{C_{\mu п} C_{\mu рп}}\{\gamma\gamma_p C_{\mu п} ch(\gamma_p x) ch[\gamma(X_м - x)] +$

$$+\gamma^2 C_{\mu рп} sh(\gamma_p x) sh[\gamma(X_м - x)] + \gamma_p Z_{\mu 0} C_{\mu п}^2 ch(\gamma_p x) sh[\gamma(X_м - x)] +$$

$$+\gamma Z_{\mu 0} C_{\mu п} C_{\mu рп} sh(\gamma_p x) ch[\gamma(X_м - x)]\}.$$

Substituting the found values of $A_1 \div A_4$ into equations (33)-(36), we obtain the following:

$$Q_{\mu x_1} = \frac{F_к sh(\gamma_p x)}{\Delta_2}[Z_{\mu 0} C_{\mu п} sh(\gamma x_1) + \gamma ch(\gamma x_1)], \quad (42)$$

$$U_{\mu x_1} = \frac{\gamma F_к sh(\gamma_p x)}{C_{\mu п}\Delta_2}[Z_{\mu 0} C_{\mu п} ch(\gamma x_1) + \gamma sh(\gamma x_1)], \quad (43)$$

$$Q_{\mu x_2} = \frac{F_к}{\Delta_2}\{Z_{\mu 0} C_{\mu п} sh[\gamma(X_м - x)] + \gamma ch[\gamma(X_м - x)]\} sh[\gamma_p(x - x_2)], \quad (44)$$

$$U_{\mu x_2} = \frac{\gamma_p F_к}{C_{\mu п}\Delta_2}\{Z_{\mu 0} C_{\mu п} sh[\gamma(X_м - x)] + \gamma ch[\gamma(X_м - x)]\} ch[\gamma_p(x - x_2)]. \quad (45)$$

It should be noted that when $\gamma_p = \gamma$ and $C_{\mu рп} = C_{\mu п}$, those if the value of the relative magnetic permeability of the crescent-shaped open ring on which the excitation winding is wound is equal to the value of the relative magnetic permeability of air, equations (42)-(45) go to the corresponding equations (21)-(24), which shows the correctness of the obtained expressions.

Expressions for magnetic fluxes and magnetic stresses for the right side of the magnetic circuit can be obtained from the corresponding expressions (42)-(45) by replacing the coordinates x_1 and x_2 with x_3 and x_4.

The values of the working magnetic fluxes involved in creating the output electromotive force are found as:

$$Q_{\mu x.\text{р}2} = Q_{\mu x_1=0} = Q_{\mu x_3=0} = \frac{F_{\text{в}} \gamma sh(\gamma_p x)}{\Delta_2}. \quad (46)$$

The output electromotive force of the transformer angular displacement transducers under consideration, removed from the output terminals in series and according to the connected sections of the excitation winding, is defined as:

$$\dot{E}_{\text{вых}.2} = j\omega 0{,}5 w_{\text{вых}} \left(\dot{Q}_{\mu x_1=0} + \dot{Q}_{\mu x_3=0}\right) = j\omega w_{\text{вых}} \dot{I}_{\text{эв}} w_{\text{в}} \frac{\gamma sh\left(\frac{\gamma_p a}{2\pi}\alpha\right)}{\Delta_2}. \quad (47)$$

Expressions (42)-(46) are mathematical models of a magnetic circuit, and expression (47) is a mathematical model of the transformer angular displacement transducers under consideration, taking into account the distribution of the parameters of the magnetic resistance of the long rods of the O-shaped magnetic core and the magnetic capacitance between them for the case of manufacturing a sickle-shaped open ring , on which the excitation winding is wound, made of ferromagnetic material.

To construct curves of the dependence of working magnetic fluxes on the coordinates of the moving part α based on analytical expressions (29) and (46), we proceed to their relative units:

$$Q^*_{\mu\text{р}1} = \frac{Q_{\mu x.\text{р}1}}{Q_{\mu x.\text{р}1.max}} = \frac{Q_{\mu x.\text{р}1}}{F_{\text{в}} C_{\mu\text{п}} X_{\text{м}}} = \frac{sh(\beta x^*)}{\Delta_1^*}, \quad (48)$$

$$Q^*_{\mu\text{р}2} = \frac{Q_{\mu x.\text{р}2}}{Q_{\mu x.\text{р}2.max}} = \frac{Q_{\mu x.\text{р}2}}{F_{\text{в}} C_{\mu\text{рп}} X_{\text{м}}} = \frac{sh(\beta_{\text{р}} x^*)}{\Delta_2^*}, \quad (49)$$

where $\Delta_1^* = Z_{\mu 0} C_{\mu\text{п}} X_{\text{м}} sh\beta + \beta ch\beta, [-]; \Delta_2^* = \beta_{\text{р}} ch(\beta_{\text{р}} x^*) ch[\beta(1-x^*)] +$

$$+\beta \frac{C_{\mu\text{рп}}}{C_{\mu\text{п}}} sh(\beta_{\text{р}} x^*) sh[\beta(1-x^*)] + \frac{\beta_{\text{р}}}{\beta} Z_{\mu 0} C_{\mu\text{п}} X_{\text{м}} ch(\beta_{\text{р}} x^*) sh[\beta(1-x^*)] +$$

$+Z_{\mu 0} C_{\mu\text{рп}} X_{\text{м}} sh(\beta_{\text{р}} x^*) ch[\beta(1-x^*)], [-];$ $Q_{\mu x.\text{р}1.max} = F_{\text{в}} C_{\mu\text{п}} X_{\text{м}}; Q_{\mu x.\text{р}2.max} = F_{\text{в}} C_{\mu\text{рп}} X_{\text{м}}$ – the maximum possible values of working magnetic fluxes for the cases under consideration; $\beta = \gamma X_{\text{м}}, [-]$; $\beta_{\text{р}} = \gamma_p X_{\text{м}}, [-]$; $x^* = x/X_{\text{м}}$. Since $x = \frac{a}{2\pi}\alpha$, then $x^* = \frac{a\alpha_{\text{м}}}{2\pi X_{\text{м}}}\alpha^*$.

The dependence curves $Q^*_{\mu p1} = f(\alpha^*)$ and $Q^*_{\mu p2} = f(\alpha^*)$ in accordance with (48) and (49) were plotted for the following design and magnetic parameters of the magnetic circuits under study: $X_м = 0{,}1\ m$; $\alpha_м = 355^0$; $a \approx X_м = 0{,}1\ m$; $b = 0{,}02\ m$; $h = 0{,}01\ m$; $\delta = 0{,}01\ m$; $\delta_{p.1} = 10^{-3}\ m$;$\delta_{p.2} = 2 \cdot 10^{-3}\ m$; $\delta_{p.3} = 3 \cdot 10^{-3}\ m$; $\mu = 10^3$.

Let us evaluate the degree of linearity of the dependence of the working magnetic flux on the movement of the moving part of transformer angular displacement transducers. To do this, we use the most practical method for determining the degree of nonlinearity of the characteristics of measuring transducers, proposed by prof. Zaripov M.F. [3].

If the characteristic is studied in one (first) quadrant, then the value of the degree of nonlinearity is determined by this following expression:

$$\varepsilon = \frac{f(x_k) - \frac{f(X_м)}{X_м} x_k}{f(X_м)} \cdot 100\ \%, \qquad (50)$$

here x_k is found as the roots of the equation $\frac{d[f(x)]}{dx} = \frac{f(X_м)}{X_м}$. For function (29) we obtain the following value x_k:

$$x_k = \gamma^{-1} Arch(sh\beta)\beta^{-1}. \qquad (51)$$

Substituting (51) into (50), we obtain the following value of the degree of nonlinearity of the dependence $Q_{\mu x.p1} = f(x)$ for the case when the crescent-shaped open ring on which the excitation winding is wound is made of electrically insulating non-magnetic material:

$$\varepsilon_1 = \left\{sh\left[Arch[(sh\beta)\beta^{-1}]\right](sh\beta)^{-1} - \beta^{-1}[Arch(sh\beta)\beta^{-1}]\right\} \cdot 100\ \%. \qquad (52)$$

To determine the degree of nonlinearity of the dependence $Q_{\mu x.p2} = f(x)$ for the case when the crescent-shaped open ring on which the excitation winding is wound is made of electrically insulating ferromagnetic material. Taking into account $\beta_p \gg \beta$ we will assume that $\Delta_2 = const$. Then for this case expression (52) will take the following form:

$$\varepsilon_2 = \left\{sh\left[Arch\left(sh\beta_p\right){\beta_p}^{-1}\right]\left(sh\beta_p\right)^{-1} - {\beta_p}^{-1}\left[Arch\left(sh\beta_p\right){\beta_p}^{-1}\right]\right\} \cdot 100\ \%. \qquad (52)$$

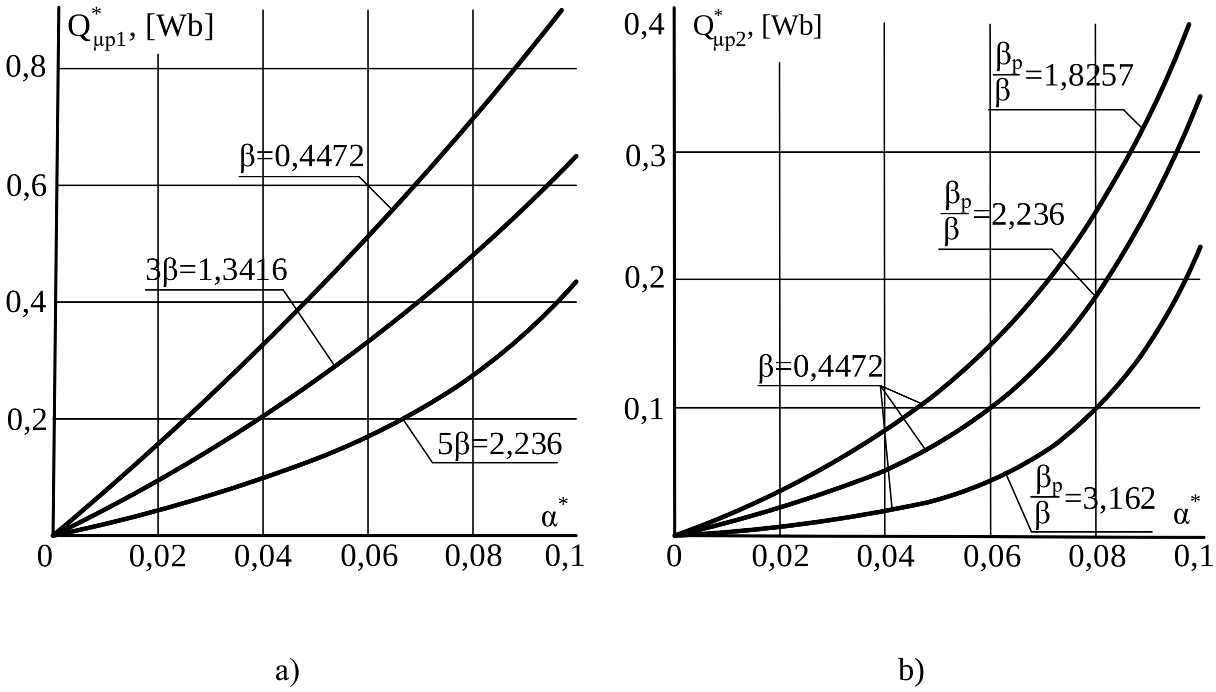


Fig.4. Dependence curves $Q^*_{\mu p1} = f(\alpha^*)$ and $Q^*_{\mu p2} = f(\alpha^*)$ for different values of β and β_p for the cases of making a crescent-shaped open ring from electrically insulating non-magnetic (a) and magnetic (b) materials

At $\beta = 0{,}45$, the degree of nonlinearity is $\varepsilon_1 = 2{,}72\%$, and at $\beta_p = 1{,}41$ it is $\varepsilon_2 = 12{,}1\%$.

Analysis of the curves $Q^*_{\mu p1} = f(\alpha^*)$ and $Q^*_{\mu p2} = f(\alpha^*)$ (Fig. 4) shows that with an increase in the attenuation coefficient of the magnetic field in the magnetic circuit, the working magnetic fluxes at the base of the O-shaped magnetic circuit decrease , and the degree of nonlinearity in the dependence of these flows on the movement of the moving part of the converter increases. In transformer angular displacement transducers with a crescent-shaped open ring made of ferromagnetic material, with an increase in the β_p/β ratio, the operating magnetic flux and the degree of nonlinearity in the dependence of this flux on the movement of the moving part of the transducer sharply increases.

Conclusion. Thus, in the article, the magnetic circuit of a transformer angular displacement transducer with a variable active area of the excitation winding is considered as a magnetic circuit with distributed parameters, in which the width of the excitation coil is a function of the angular displacement of the controlled object. Mathematical models of this converter have been developed taking into account the distribution of the parameters of the magnetic resistance of long ferromagnetic rods and the magnetic capacitance between them, as well as the magnetic capacitance between these rods and the movable sickle-shaped open ring. Research has established that with an increase in the attenuation coefficient of the magnetic field in the magnetic circuit, the operating magnetic fluxes decrease, and the degree of nonlinearity in the dependence of these fluxes on the angular movement of the moving part of the converter increases. It is shown that these properties are especially pronounced in transformer angular displacement transducers with a variable active area of the excitation winding and with a ferromagnetic crescent-shaped open ring.

Literature

1. Агейкин Д.И., Костина Е.Н., Кузнецова Н.Н. Датчики контроля и регулирования: справочные материалы / 2-е изд., перераб. и доп. — Москва: Машиностроение, 1965. — 928 с.

2. Юсупбеков Н.Р., Игамбердиев Х.З., Маликов А.В. Основы автоматизации технологических процессов: Учебное пособие для высшего и среднего специального образования. В 2-х ч. – Ташкент: ТГТУ, 2007. ч.1, 2. – 152 с., 173 с.

3. Зарипов М.Ф. Преобразователи с распределенными параметрами для ав-томатики и информационно-измерительной техники. Москва, Энергия, 1969, 177с.

4. Федотов А.В. Теория и расчет индуктивных датчиков перемещений для систем автоматического контроля: монография /. – Омск: Изд-во ОмГТУ, 2011. – 176 с.

5. Конюхов Н.Е., Медников Ф.М., Нечаевский М.Л. Электромагнитные датчики механических величин. – Москва: Машиностроение, 1987. – 256 с.

6. Заявка на патент РУз (UZ) № IAP 20220111. Трансформаторный преобразователь угловых перемещений / Амиров С.Ф., Каримов И.А., Юлдашев Н.Р., Мамадалиев У.Ш., Шоимкулов А.А.// Дата подачи заявки: 11.03.2022 г.

7. Атабеков Г.И. Теоретические основы электротехники. Линейные электрические цепи: Учебное пособие. 7-е изд., стер. – Санкт-Петербург: Издательство «Лань», 2009. – 592 с.

8. Бронштейн И.Н., Семендяев К.А. Справочник по математике для инженеров и учащихся втузов. Изд.,13–е, исправленное. – Москва: Наука. Гл. ред. Физ.–мат. лит., 1986. – 544 с.

9. Зарипов М.Ф., Ураксеев М.А. Электромеханические счетно-решающие преобразователи. Учебноепособие, Уфа, УАИ, 1974. – 202 с.

References

1. Ageikin D.I., Kostina E.N., Kuznetsova N.N. Sensors of control and regulation: reference materials / 2nd ed., reprint. and add. — Moscow: Mashinostroenie, 1965. — 928 p.

2. Yusupbekov N.R., Igamberdiev H.Z., Malikov A.V. Fundamentals of automation of technological processes: A textbook for higher and secondary special education. In 2 hours – Tashkent: TSTU, 2007. part 1, 2. – 152 p., 173 p.

3. Zaripov M.F. Converters with distributed parameters for automation and information and measurement technology. Moscow, Energiya, 1969, 177c.

4. Fedotov A.V. Theory and calculation of inductive displacement sensors for automatic control systems: monograph /. - Omsk: Publishing House of OmSTU, 2011. - 176 p

. 5. Konyukhov N.E., Mednikov F.M., Nechaevsky M.L. Electromagnetic sensors of mechanical quantities. – Moscow: Mashinostroenie, 1987. – 256 p.

6. Patent application of the Republic of Uzbekistan (UZ) no. IAP 20220111. Transformer converter of angular displacements / Amirov S.F., Karimov I.A., Yuldashev N.R., Mamadaliev U.S., Shoimkulov A.A.// Date of application: 11.03.2022

7. Atabekov G.I. Theoretical foundations of electrical engineering. Linear electrical circuits: A textbook. 7th ed., erased. – St. Petersburg: Publishing House "Lan", 2009. – 592 p

. 8. Bronstein I.N., Semendyaev K.A. Handbook of Mathematics for engineers and students of higher education institutions. Ed., 13th, revised. – Moscow: Nauka. Gl. ed. Phys.–mat. lit., 1986. – 544 p.

9. Zaripov M.F., Urakseev M.A. Electromechanical calculating and solving converters. Textbook, Ufa, UAI, 1974. – 202 p.

Сведения об авторах

Амиров Султан Файзулаевич – д.т.н., профессор, заведующий кафедрой «Электроснабжения», Ташкентский государственный транспортный университет, г. Ташкент e-mail: amirovsf@bk.ru

Мамадалиев Улугбек Шухратович – докторант кафедры «Электроснабжения», Ташкентский государственный транспортный университет, г. Ташкент e-mail: ulugshuxma@mail.ru

Information about the authors

Amirov Sultan Fayzulaevich– doctor of technical Sciences, Professor, head of the Department of "power Supply", Tashkent State Transport University, Tashkent. e-mail:amirovsf@bk.ru

MamadalievUlugbekShukhratovich – Doctoral student of the Department of "Power Supply", Tashkent State Transport University, Tashkent e-mail: ulugshuxma@mail.ru