The Determination of Accuracy Characteristics of The Electromechanical Transducer of Movements for Automatic Thickness Control

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Abstract: In the work analytical expressions of the target characteristic and temperature errors of the electromagnetic transference converter with section a winding of excitation and a measuring winding are received. With this purpose the equations of the heating temperature and magnetic forces of windings are used. It is established that the error of the output signal decreases with increase of the quality coefficient of the affected winding.

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1. INTRODUCTION

The current period of the development of electrical devices of automation is characterized by an increase in the requirements for the accuracy and reliability of the operation of electrical apparatuses while reducing their weight and dimensions. One of the directions for solving these problems is the development of electromagnetic and electromechanical devices of automation, among them inductive and transformer type primary electromagnetic inverters of displacements have great importance. They have found wide application in automatic control schemes for the parameters of various technological processes, including the continuous conversion of non-electrical quantities to electrical ones.

It is known that automatic control of technological parameters of moving materials is quite a challenge. For example, automation of the process of controlling the thickness of insulation during the winding process has always been a complex but urgent task. Problems arise when the diameter is automatically controlled when the wire is wound into the drum, when the thickness of the thermal insulation is automatically measured during the winding process on moving frames with different diameters and lengths, etc. The usage of these electromagnetic inductive and transformer displacement transducers and other types of transducers does not allow to solve the task successfully. A comparative analysis of the designs and characteristics of existing converters shows that if we improve the design of linear induction hangers with levitation element (LE), create effective methods for transferring displacements to LE and take into account the influence factors on the accuracy of the output parameters of the converter, then the obtained non-traditional designs with LE can be successfully used for automatic control of linear dimensions during the process.

The exact characteristics of electromechanical displacement transducers (EDT) with a LE depend on many factors, including temperature errors. The currents increase because of the displacement of LE in excitation winding (EW) and LE (Seydaliyev, 2002). At the result, in EW and LE the overheating temperatures increases(Abdullayev, 2000):

\[ \tau_1 = \frac{I_1^2 R_1}{k_1 S_{CL1}}; \quad \tau_2 = \frac{I_2^2 r_{SC}}{k_2 S_{CL2}}, \]  

where \( I_1 \) and \( I_2 \) are the currents of EW and LE; \( R_1 \) and \( r_{SC} \) - active resistance of EW and LE; \( k_1 \) - coefficient of heat transfer; \( S_{CL1} \) and \( S_{CL2} \) - cooling surfaces. Resistance \( R_1 \) also includes reduced resistance from the PE circuit to the EW circuit.

Assume EW EDT (Fig. 1) consists of two successively-on sections included, the number of turns of which are equal to \( W^s_1 \) and \( W^s_2 \). The sections of the winding are located respectively on the lower \( W^s_1 \) and \( W^s_2 \) upper parts of the middle rod. The followings are the same for the measuring winding (MW). Therefore(Seydaliyev, 2016):

\[ W_1 = W_1^s + W_1^s = W_1(1 + \frac{W_1^s}{W_1^s}) = (1 + k_2)W_1^s; \]

\[ W_2 = W_2^s + W_2^s = W_2(1 + \frac{W_2^s}{W_2^s}) = (1 + n_2)W_2^s, \]

where \( W^s_1 > W_1^s \); \( W^s_2 > W_2^s \); \( k_2 = \frac{W^s_2}{W^s_1}; \) \( n_2 = \frac{W^s_2}{W^s_2} \).

The voltage at the output of the converter is determined by:

\[ U_z = \omega MI_z, \]
where M is the mutual inductance between EW and MW, which depends on the displacement x of the LE; \( I \) is the EW current. The mutual inductance and current of the EW are respectively:

\[
M = M_{12}^* - M_{12} = \lambda W_{12}^* + \lambda_x W_{12}^*; \quad I = \frac{U_i}{\sqrt{R_i^* + x^2}},
\]

where

\[
M_{12}^* = W_{12}^*\lambda(l - x); \quad M_{12} = W_{12}^*\lambda(l + x); \quad W_{12}^* = W_{12}^* + W_{12}^*; \quad W_{12}^* = W_{12}^* - W_{12}^*.
\]

The distances between \( l_1 \) and \( l_2 \) are shown in Fig. 1.

Fig. 1. Schematic diagram of EDT with LE

When \( x = 0 \), the result is \( U_i = 0 \), therefore according to (5) we find(Seydaliyev, 2002):

\[
W_{12}^* W_{12}^* - W_{12}^* W_{12}^* = 0. \tag{6}
\]

Hence we obtain the condition:

\[
\frac{W_{12}^*}{W_{12}^*} = \frac{l_1}{l_2}, \tag{7}
\]

the execution of which is necessary to eliminate the residual signal. This is achieved by selecting the number of turns in the EW and MW sections. Obviously \( l_1 > l_2 \), and \( W_{12}^* W_{12}^* > W_{12}^* W_{12}^* \). Then the mutual inductance will be determined from the expression:

\[
M = W_{12}^*\lambda x. \tag{8}
\]

The voltage at the output of the converter is determined in accordance with (3), (4) and (8):

\[
U_i = \frac{\alpha W_1^* U_i^*}{\sqrt{R_i^* + x^2}}. \tag{9}
\]

Hence it can be seen that the output voltage depends on the resistances \( R_i \) and \( x_i \), which depend on the overheating temperatures \( \tau_i \) and \( \tau_x \). We express the resistance of the sections of the EW and LE through the overheating temperatures \( \tau_i \) and \( \tau_x \) for this purpose, we determine the total resistance of the EW sections:

\[
Z_i = R_i^* + jx_i^*; \quad Z_x = R_x^* + jx_x^*. \tag{10}
\]

Active resistances \( R_i^* \) and \( R_x^* \) through reduced resistance \( r_{SC} \) are determined from the expressions:

\[
r_i^* = r_{SC} + r_{SC}^*; \quad r_x^* = r_{SC} + r_{SC}^* k_{21}^*. \tag{11}
\]

where, \( r_1^* \), \( r_2^* \) and \( r_{SC} \) - the resistance of the sections and the screen; \( k_{SC1} \) and \( k_{SC2} \) - transformation ratios; \( b_i = 0.98 + 0.99 \) coefficient of electromagnetic coupling between circuits:

\[
r_i^* = r_i^* (\Delta_i + \alpha_i \tau_i); \quad r_x^* = r_x^* (\Delta_x + \alpha_x \tau_x); \quad k_{SC1} = \frac{W_{12}^*}{W_{SC}^*} = r_{SC}^*; \quad \tag{12}
\]

The EW sections are made of copper wire, and LE from aluminum. Therefore, the coefficients \( \alpha_u, \alpha_d, \Delta_u, \Delta_d \) are defined as(Abdullayev and Seydaliyev, 2004):

\[
\alpha_u = 0.0042 \frac{1}{C}; \quad \alpha_d = 0.0043 \frac{1}{C}; \quad \Delta_u = 1 + \alpha_u (\theta_u - 20); \quad \Delta_d = 1 + \alpha_d (\theta_d - 20). \tag{13}
\]

 Resistances \( r_{10}^*, r_{10}^* r_{SC} \) are determined through specific ohmic resistance at the temperature of 20 °C:

\[
r_{10}^* = \rho_{M20} W_{12}^*/l_{md1}^* q_1; \quad r_{10}^* = \rho_{M20} W_{12}^*/l_{md2}^* q_1; \quad r_{SC} = \rho_{l20} l_{md2}^*/q_2, \tag{14}
\]

where \( l_{md1}^* \) and \( l_{md2}^* \) are the average length of section turns; \( q_1 \) and \( q_2 \) are the cross-sectional areas of the wires; \( \rho_{M20} = 1.72 \times 10^{-8} \text{Omm}^2 \); \( \rho_{l20} = 2.8 \times 10^{-8} \text{Omm}^2 \).

Then for the active resistances of the sections and the total active resistance of the EW, we can write:

\[
R_i = R_i^* + m_1^* \tau_1 + m_2^* \tau_2; \quad R_x = R_x^* + m_1^* \tau_1 + m_2^* \tau_2; \quad R_i = R_i^* + R_x^* = R_0 + m_1^* \tau_1 + m_2^* \tau_2, \tag{15}
\]

where are denoted:

\[
R_0 = R_0^* + R_0^*; \quad m_1 = m_1^* + m_2^*; \quad m_2 = m_1^* + m_2^*; \quad \alpha_1 = \alpha_1^*; \quad \alpha_d = \alpha_d^*; \quad m_1 = \alpha_d^* r_{SC}^* k_{21}^*; \quad m_2 = \alpha_1 k_{21}^*; \quad \tau_0 = \tau_0^* \Delta_d^* + r_{SC}^* \Delta_d^* k_{21}^*; \quad \tau_0^* = \tau_0^* \Delta_d^* + r_{SC}^* \Delta_d^* k_{21}^* \tag{16}
\]

The inductive resistances of the sections and the total inductive resistance of the EW through the displacement x can be defined as:

\[
x_1^* = \alpha W_{12}^* \lambda (h_{12}^* + l_1) = m_1^* (H_1 - x); \quad x_2^* = \alpha W_{12}^* \lambda (h_{12}^* + l_2) = m_2^* (H_2 + x); \quad x_1 = x_1^* + x_2^* = m_1 (H_0 - k_0 x), \tag{17}
\]

where

\[
H_1 = h_{12}^* + l_1^*; \quad H_2 = h_{12}^*; \quad H_0 = H_1 + k_{21}^* H_2; \quad k_0 = 1 - k_{21}^*; \quad k_{21}^* = \frac{W_{12}^*}{W_{12}^*} \tag{18}
\]

\[
W_{12}^* = W_{12}^* + W_{12}^* (1 + k_{21}) \tag{19}
\]
\[ m_s = \frac{\omega W^2 \lambda}{(1 + k_{21})^2}; \]
\[ W'_1 = \frac{W_1}{1 + k_{21}}; \]
\[ W''_1 = \frac{W_1}{1 + k_{21}}; \]
\[ l'_c = l - (h_1 + h_2); \]
\[ l'_2 = l - x; \]
\[ l_2 = x. \]  
(20)

Total resistance of the sections and EW:
\[ \dot{\dot{Z}}'_1 = R'_0 + m'_1 \tau_1 + m'_2 \tau_2 + jm'_3 (H_1 - x); \]
\[ \dot{\dot{Z}}'_1 = R'_0 + m'_1 \tau_1 + m'_2 \tau_2 + jm'_3 (H_1 + x); \]
\[ \dot{\dot{Z}}_1 = \dot{\dot{Z}}'_1 + \dot{\dot{Z}}''_1 = R_0 + m_1 \tau_1 + m_2 \tau_2 + jm_3 (H_0 - k_0 x) \]  
(21)

We consider the error of the output voltage \( U_o \), caused by a change in temperature \( \tau = \tau_i \) by an amount \( \Delta \tau \).

In this case:
\[ R_i = R_0 + m \tau, \]  
(22)

where
\[ m = m_1 + m_2 = r_o \alpha_M + r_{SC} \Delta \alpha M k^2; \]
\[ r_0 = r'_0 + r''_0; \]
\[ k_{12} = k^2_{SC} + k^2_{SC2} - W^2_1 + W^2_1; \]
\[ R_i = r_o \Delta \alpha M + r_{SC} \Delta \alpha M k^2. \]  
(23)

Absolute error:
\[ \Delta \delta_i = \gamma_a \Delta \tau, \]  
(24)

where
\[ \gamma_a = \frac{\partial U_o}{\partial R_0} \frac{\partial R_0}{\partial \tau}. \]  
(25)

Because of the:
\[ \frac{\partial R_0}{\partial \tau} = m; \frac{\partial U_o}{\partial \tau} = -2 \omega MU_1 R_0 R^2 + x^2_i, \]  
(26)

then we can write:
\[ \gamma_a = 2 \omega MU_1 m \frac{(R_0 + m \tau)}{(R_0 + m \tau)^3 + x^2_i}; \]
\[ \Delta \delta_i = -2 \omega MU_1 m \frac{(R_0 + m \tau) \Delta \tau}{(R_0 + m \tau)^3 + x^2_i}. \]  
(27)

Relative value of error:
\[ \delta_i = \frac{\Delta \delta_i}{U_o} = -\frac{2 m \Delta \tau}{\sqrt{1 + Q_i^2}}, \]  
(28)

where \( Q_i \) - the Q-factor:
\[ Q_i = \frac{x_i}{R_0 + m \tau} = \frac{x_1}{R_1}. \]  
(29)

according to this, it is clear that with an increase in the quality factor \( Q \), the error \( \delta_i \) can be reduced.

From the equations of levitation(Abdullayev, 1996):
\[ \frac{1}{2} \dot{\dot{W}}^2_1 I_1^2 = \frac{1}{2} \dot{\dot{W}}^2_2 U_1^2 = \frac{1}{2} \dot{\dot{W}}^2_1 R^2_1 + x^2_1 = k_0 P_g, \]  
(30)

we obtain:
\[ x_1 = \frac{\dot{\dot{W}}^2_1 U_1^2}{2k_0 P_g} - R^2_1, \]  
(31)

where \( P_g \) - is the gravity of the LE; \( k_0 \) - a coefficient that takes into account the of the \( P_{eg} \) and \( P_{ag} \). \( P_{eg} \) - gravitational force of the force carrying element, \( P_{ag} \) - the additional force (force of abutment):
\[ k_0 = 1 + \frac{P_{eg} + P_{ag}}{P_g} = 1.2 + 1.3 \]  
(32)

Substituting (17) in (31), we find the current value of the displacements of the LE:
\[ x = \frac{H_0}{k_0} \frac{1}{k_0 m_x} \sqrt{\frac{\dot{\dot{W}}^2_1 U_1^2}{2k_0 P_g} - R^2_1} \]  
(33)

or taking into account (22):
\[ x = \frac{H_0}{k_0} \frac{1}{k_0 m_x} \sqrt{\frac{\dot{\dot{W}}^2_1 U_1^2}{2k_0 P_g} - (R_0 + m \tau^2)}. \]  
(34)

The absolute error of displacement is defined similarly:
\[ \Delta \delta_x = \gamma_x \Delta \tau, \]  
(35)

Define:
\[ \frac{\partial \dot{\dot{W}}_1}{\partial R_1} = \frac{2m(R_0 + m \tau)}{k_0 m_x \sqrt{\frac{\dot{\dot{W}}^2_1 U_1^2}{2k_0 P_g} - (R_0 + m \tau)^2}}; \]
\[ \Delta \delta_x = - \frac{2m(R_0 + m \tau) \Delta \tau}{k_0 m_x \sqrt{\frac{\dot{\dot{W}}^2_1 U_1^2}{2k_0 P_g} - (R_0 + m \tau)}}. \]  
(38)

The relative error value of the changes in \( x \) will be determined from the expression:
\[ \delta_x = \frac{\Delta \delta_x}{x} = - \frac{2m(R_0 + m \tau) \Delta \tau}{k_0 m_x \sqrt{\frac{\dot{\dot{W}}^2_1 U_1^2}{2k_0 P_g} - (R_0 + m \tau)^2} \times \frac{1}{H_x m_x \sqrt{\frac{\dot{\dot{W}}^2_1 U_1^2}{2k_0 P_g} - (R_0 + m \tau)}}}. \]  
(39)

For the levitation state of the moving part of the EDT or when the LE is not pressed against the surface of the object under control, the total error is:
\[ \delta_x = \delta_u + \delta_x. \]  
(40)

3. CONCLUSIONS

Analysis of the numerical values of the errors \( \delta \) and \( \delta_x \) show that the temperature error \( \delta_x \) for a temperature variation of \( \Delta \tau = (8+1)C \) is not more than 0.1%, if the quality factor is \( Q \geq 10 \).

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