Electromagnets friction surfaces contamination diagnostics method based on weber-ampere characteristics analysis

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Abstract. In the production of electrical products, an important element is conducting exit and intermediate control operations to reduce risks. A promising approach to the diagnosis of electromagnetic devices is the analysis of their weber-ampere characteristics. Control of the magnetic properties of products allows identifying defects without the need for long-term operations of disassembly / assembly mechanisms. The introduction of sensors of magnetic magnitudes into the design of electromagnets is impractical in terms of cost and reliability. With the help of the "working" elements of electromagnets already available in the design, it is possible to measure the weber-ampere characteristics. The article solves the problem of analysis and identification of the relationship between the critical defect of armored-type electromagnets with the weber-ampere characteristic of the product and the development of a method for the technical diagnosis of a malfunction.

1. Introduction
Output and intermediate monitoring of electromagnetic devices are mandatory steps in the manufacture of products. To solve this problem, a number of methods [1-4] and devices [5-10] were developed earlier. In the course of the work, new possibilities were identified for diagnosing faults in electromagnetic devices. A promising approach to the diagnosis of electromagnetic devices is the analysis of their weber-ampere characteristics [11]. Control of the magnetic properties of products allows identifying defects without the need for long-term operations of disassembly / assembly mechanisms. However, the most informative characteristics of electromagnets, which include weber-ampere characteristics, are practically impossible to obtain with the help of known magnetic-value sensors [12, 13], since their "introduction" into the finished device without violating its integrity is in most cases impossible. Thus, the actual task is the development of methods for technical diagnostics of the most common faults of electromagnetic devices. The most common faults of electromagnetic mechanisms include contamination of contacting working surfaces, increasing the coefficient of friction and interfering with the work of the product for the given parameters of electrical signals.

2. Materials and Methods
When developing elements of the theory of the magnetic field, methods of the theory of experimental design, measurement theory, mathematical modeling using licensed packages of GMSH, Octave
application software were used.
Consider the magnetic system (Fig. 1), the main elements of which are: the magnetizing winding of the product with the number of turns \( w \) connected to the current source \( i(t) \), two ferromagnetic elements (for example, the core and the armature of the electromagnet) with an air gap between these elements.

![Figure 1. Electromagnet. 2D axisymmetric model: 1 - armature, 2 - core, 3 - magnetizing coils, 4 - case made of non-magnetic material, 5 - air gap](image)

To analyze the influence of contamination of the contacting working surfaces of the core and the armature of the electromagnet increasing the friction coefficient between them, let us consider an equation describing the distribution of forces acting on the armature of an electromagnet and describing its motion:

\[
F_{em-z} + m \frac{d^2z}{dt^2} - P + F_{em-x} \cdot k_u \cdot \text{sign} \frac{dz}{dt} = 0,
\]

where \( F_{em-z} \) - functional dependence of the electromagnetic force acting on the armature along the \( z \)-axis, \( i \) - instantaneous current in the magnetizing windings of the product, \( z \) - the relative position of the armature along the axis \( z \); \( m \) - armature weight; \( P \) - gravity at anchor, \( P=mg \), \( g \) - acceleration of gravity; \( F_{em-x} \) - functional dependence of the electromagnetic force acting on the armature across the axis \( z \), along the axis \( x \); \( k_u \) - coefficient of friction between the contacting surfaces of the armature and the core; \( \text{sign} \frac{dz}{dt} \) - parameter that defines the direction of motion of the armature.

The mechanical force in a magnetic field is expressed as a derivative of the energy of the magnetic field along the coordinate [14] is:

\[
F = \left| \frac{\partial W_M}{\partial x} \right| = \left| \frac{L^2}{2 \mu_0} \right|,
\]

where \( W_M \) - magnetic field energy; \( L \) - coil electromagnet inductance; \( i \) - magnetizing current in the coil of an electromagnet.

The energy of the magnetic field in a gap of length \( l_a \) is:

\[
W_M = \frac{B H S l_a}{2},
\]

where \( B \) - magnetic induction in the gap, \( H \) - magnetic field strength in the gap; \( S \) - cross-sectional area of the magnetic circuit, \( l_a \) - air gap length.

So the force tending to reduce the air gap, determined by the derivative in the direction perpendicular
to the plane of the air gap (along the z axis), according to (2) taking into account (3):

\[ F = \frac{\partial W_B}{\partial l_B} = \frac{BH}{2} = \frac{B^2}{2\mu_0} S, \]  

where \( \mu_0 = 4\pi 10^{-7} \text{ Gm/m} \) – magnetic constant.

Let's represent formula (4), expressing the induction \( B \) in the air gap through the parameters of the electromagnet. We take the cross section of the magnetic circuit constant. Using the law of total current for a magnetic core with an air gap in the approximation of the absence of scattering fields and homogeneity of the induction \( B \) of the magnetic field in the cross section \( S \) of the magnetic circuit, we write:

\[ Hl + H_{g_{s=1}} = \omega, \]

where \( H = B/\mu_0 \) and \( H_{g_s} = B/\mu_0 \) – the magnetic field strength in the magnetic circuit and in the air gap; \( \omega \) – number of turns of the coil of electromagnet; \( l \) – length of the centerline of the magnetic circuit; \( \mu \) - magnetic permeability of magnetic material.

Consequently, we will have:

\[ B = \frac{\mu_0\omega}{(1/\mu + l_B)}. \]  

Substituting the induction expression \( B \) (5) into formula (4), we obtain the expression for the force acting along the z axis and tending to decrease the air gap \( l_0 \), in the form:

\[ F_{em-z} = \frac{\mu_0\omega}{2(l + \mu l_B)^2} \frac{\pi d^2}{4} \frac{de}{d\sqrt{e^2 - e^2}}, \]

If the anchor is placed concentrically with respect to the hole of the yoke, then because of the symmetry of this arrangement, the total radial force acting on the anchor across the z axis along the x axis (Fig. 1) is zero [15]. However, in most cases the condition of concentric arrangement is not fulfilled and the anchor is located eccentrically relative to the yoke. In this case, the radial force of unilateral attraction acts on the anchor. This force, in accordance with [15], has the form:

\[ F_{em-x} = 4.06 \cdot 10^{-8} \cdot B^2 \frac{\pi d^2}{4} \frac{de}{4h_e \sqrt{e^2 - e^2}}, \]

where \( d \) – anchor diameter, \( e \) – the amount of armature displacement from the center, \( e \) – half the air gap between the friction surfaces of the anchor and the yoke, \( h_e \) – height of anchoring in the yoke.

Substituting (5) into (7), taking into account the fact that in this case it is necessary to consider the value of \( e \) as the air gap, we obtain:

\[ F_{em-x} = 4.06 \cdot 10^{-8} \cdot \left( \frac{\mu_0\omega}{(1/\mu + e)} \right)^2 \frac{\pi d^2}{4} \frac{de}{4h_e \sqrt{e^2 - e^2}}. \]

Taking into account (6) and (8), expression (1) takes the form:

\[ \frac{\mu_0(\mu W)^2 S}{2(l + \mu l_B)^2} + m \frac{d^2 z}{dt^2} - mg + 4.06 \cdot 10^{-8} \left( \frac{\mu_0\omega}{(1/\mu + e)} \right)^2 \frac{\pi d^2}{4} \frac{de}{4h_e \sqrt{e^2 - e^2}} \cdot k_{fr} \cdot \text{sign } \frac{dz}{dt} = 0. \]

Let us consider the stationary state of the electromagnetic system of an electromagnet in which: \( e=\text{const}, \varepsilon=\text{const}, d=\text{const}, w=\text{const}, h_e=\text{const}, \mu=\text{const}, S=\text{const}, l_0 =\text{const} \). Then, valid for further calculations, will be the notation:

\[ b_1 = \frac{\mu_0(\mu W)^2 S}{2(l + \mu l_B)^2} \text{ and } b_2 = 4.06 \cdot 10^{-8} \left( \frac{\mu_0\omega}{(1/\mu + e)} \right)^2 \frac{\pi d^2}{4} \frac{de}{4h_e \sqrt{e^2 - e^2}}. \]

Then, expression (9) takes the form:
\[ b_1 i^2 + m \frac{d^2 z}{dt^2} - mg + b_2 \cdot i^2 \cdot k_{trp} \cdot \text{sign} \frac{dz}{dt} = 0. \]  

(10)

For the motion of the armature of the electromagnet, the following condition must hold:

\[ m \frac{d^2 z}{dt^2} \geq 0. \]

In addition, in this case, \( \text{sign} \frac{dz}{dt} = -1 \). Consequently, we will have:

\[ 0 \leq m \frac{d^2 z}{dt^2} = -b_1 i^2 + mg + b_2 \cdot i^2 \cdot k_u \quad \text{or} \quad b_1 i^2 - mg - b_2 \cdot i^2 \cdot k_u \leq 0. \]

If we will solve this inequality with respect to the friction coefficient \( k_u \):

\[ k_{trp} \geq \frac{b_1 - mg}{b_2 - b_2 i^2}. \]  

(11)

If we will solve this inequality with respect to the current in the magnetizing windings \( i \):

\[ i \geq \sqrt{\frac{mg}{b_1 - b_2 k_u}}. \]  

(12)

3. Results and Discussion

Weber-ampere characteristic of the product is a dependence of the form \( \Phi(i) \), where \( \Phi \) – magnetic flux in the magnetic series of the core and the armature of the electromagnet. In this case, the magnetic flux is determined both by the properties of the materials of the ferromagnetic elements and by the dimensions of the air gap (Fig. 1). On the basis of the obtained dependence (12), we conclude that with an increase in the coefficient of friction \( k_u \), for example, with clogging or oxidation of the contacting surfaces of the electromagnetic system, the amount of current necessary to ensure the movement of the armature should increase. And this dependence is nonlinear. On the basis of this conclusion, and based on the expression (11), we obtain: an increase in the current \( i \), it is necessary to achieve a certain value of the magnetic flux \( \Phi(i) \), with all other conditions being equal, is a sign of the presence of additional opposing forces, in particular frictional forces. On the basis of this conclusion, an algorithm is proposed for conducting technical diagnostics of the presence of clogging in electromagnetic devices on the basis of an analysis of their web-ampere characteristics, which consists of the following:

1. The measurement of the web-ampere characteristic is performed in the form of \( \psi_j(i_s) \) of suitable electromagnetic device and stored in memory for later comparison \( (j=1,2..m, \text{where } m \text{ – number of points on the web-ampere characteristic}) \).
2. The measurement of the web-ampere characteristic \( \psi_j(i_d) \) of a diagnosed electromagnetic device is performed.
3. If the condition is \( i_s(\psi_j) \ll i_d(\psi_j) \) – a conclusion about the clogging of an electromagnet is made.

4. Conclusion

Analysis of the dependencies between the change in the configuration of the magnetic system of a typical electromagnetic mechanism and its magnetic characteristics showed that the determination of the presence and type of a product malfunction can be carried out by monitoring its web-ampere characteristic. Derived analytical dependencies can be used to diagnose not only electromagnets, but also other electrical products.

Acknowledgments

This article is based on results of the project No. SP-359.2018.1, implemented under the program “Scholarship provided by the President of the Russian Federation for young scientists and graduate students engaged in advanced research and development in priority areas of modernization of the
Russian economy” using equipment of shared facility “Diagnosis and energy-efficient electrical equipment” (NPI).

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