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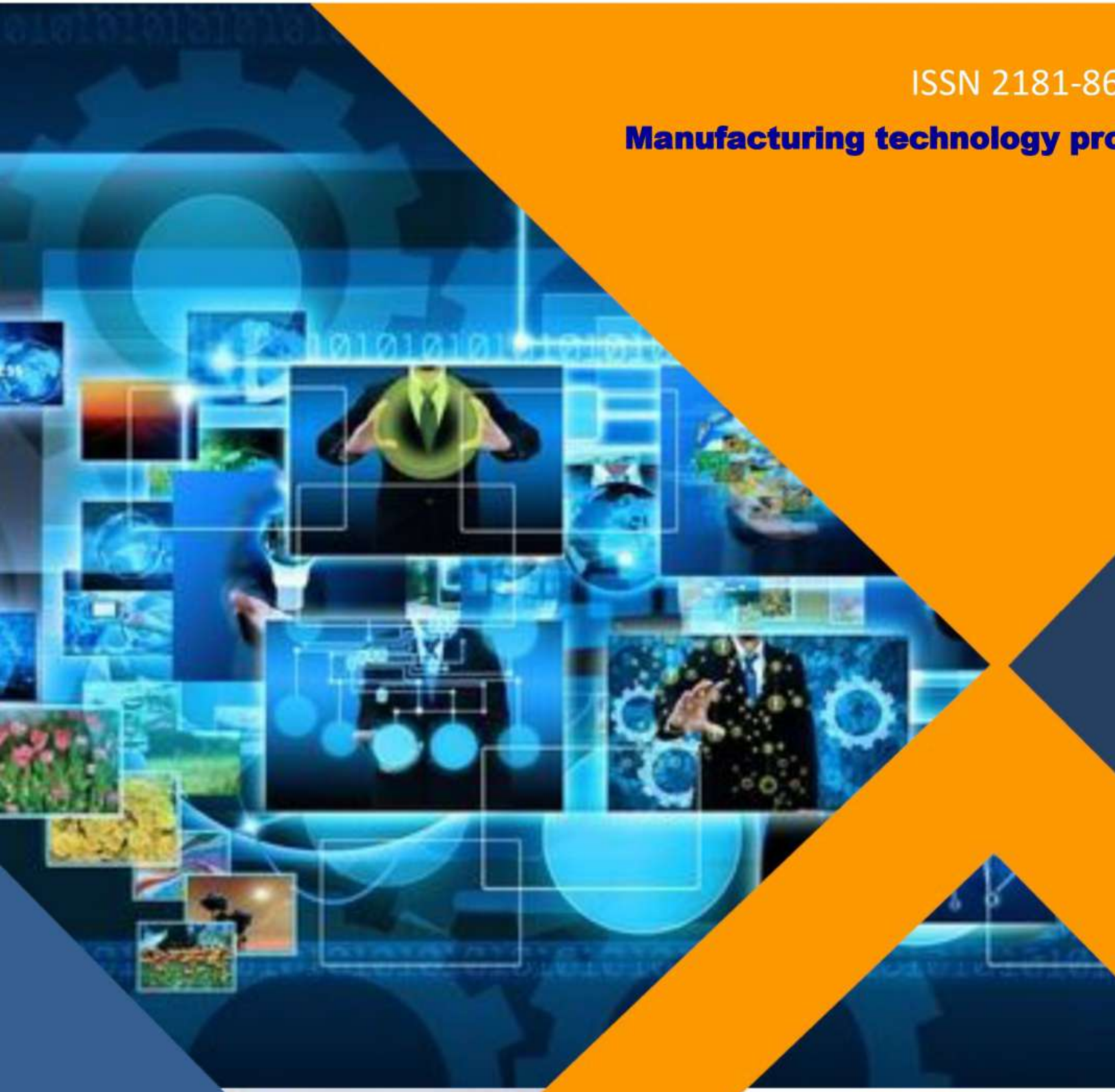

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DEVELOPMENT OF A PROGRAM FOR DETERMINING ECCENTRICITY BY ANALYZING THE MAGNETIC FIELD IN THE AIR GAP OF AN ASYNCHRONOUS MOTOR

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Abstract: This article examines the work on identifying motor defects by calculating the magnetic field in the air gap of asynchronous motor used in railway rolling stock at industrial enterprises. The software for calculations and visualization is programmed in Python, and its analysis is presented.

Keywords: Magnetic field, magnetic induction, bearing diagnostics, electric motor, air gap conductivity.

Introduction. During the operation of asynchronous motors, the magnitudes of the magnetic field in the air gap were theoretically calculated using its parameters. Data was collected and analyzed through technical means.

The calculation of diagnostic signals for the eccentric state is based on the calculation of the magnetic field in the engine. In an unsaturated machine, the magnetic strength of the steel parts is significantly less than the air gap, so for unsaturated machines we assume that the magnetic conductivity of the steel is $\mu_p = \infty$.

Literature review. One of the most common methods for describing the magnetic field in the air gap is the comparative conductivity method, which was developed in the works of A.I. Woldek, B. Geller, V. Gamata, and N.G. Nikiyana, and others [5], [4] [1]. According to this method, the field in the air gap, the magnetomotive force (MMF) of the winding, and the conductivity of the air gap are expressed as the sum of harmonics. The main drawback of this method is the difficulty of accounting for the saturation of the magnetic circuit. The magnetic field in the air intake has a complex harmonic composition, determined by the diagram of the stator and rotor windings, the configuration and characteristics of the magnetic cycles, the state and operating mode of the asynchronous machine. To simplify the expressions, we introduce the designation of the harmonic quantity.

Methodology & empirical analysis. The programming language (Python) allows the user to analyze the magnetic field and its deviations from the norm. Based on the induction, frequency, and amplitude entered by the user, a 3D magnetic field graph and deviations from the norm are displayed in the form of a histogram diagram. The code creates a user-friendly interface for diagnostics and visual analysis.

In general, the field induction harmonics in the air gap, taking into account air gap and air gap conductivity, magnetic strength, and bending, can be described by the following expressions [5], [4], [10], [11]:

$$\widetilde{A_\nu} = f(t,\varphi) = A_{\nu m} cos\left(\omega_\nu t - \nu\varphi - \varphi_0 + \frac{2\nu x b_{sk}}{l_\delta D_a}\right) \qquad (2.1)$$

$$\widetilde{A_{\nu'}} = f(t,\varphi) = A_{\nu' m} cos\left(\omega_{\nu'} t - \nu' \varphi_{эл} - \varphi_0 + \frac{2\nu' p x b_{sk}}{l_\delta D_a}\right) \quad (2.2)$$

Here

$A_{\nu m}$- ν^{th} harmonic amplitude;

ω_ν, $\omega_{\nu'}$ – the circular rotation frequency of the field harmonic;

ν – the number of even polar harmonics (absolute order);

ν'= ν/p relative order of harmonics;

p – number of pole pairs of the engine;

$\varphi, \varphi_{эл}$ - the angular coordinate of the stator's circumference (physical and electrical angles, respectively);

φ_0- the initial phase of middle harmonics along the length of the machine;

x – the coordinate of the machine core length;

b_{sk} - linear bend along the length of the machine core;

l_δ – the length of the machine core;

D_a – inner diameter of the stator

Thus, denoting a certain $\tilde{X}$ value with the "tilde" symbol X indicates that the value X is a function of time and space (an angle along the circumference of the stator) and represents one harmonic of a certain value X. In a particular case, $\tilde{X}$ can only be a function of time or space. At the same time, the constant component $\tilde{X}$ can be designated (according to Fourier series theory), which is acceptable as a harmonic at a frequency ω = 0 and when the number of polar pairs ν = 0. The distribution of a specific physical quantity can be expressed as the sum of the harmonics X (magnetic strength, induction, air gap conductivity) in the air gap and can be written as:

$$X = f(t,\varphi) = X_0 + \sum_{k=1}^{\infty} X_{km} cos(\omega_k t - \nu\varphi - \varphi_0) = \sum_{k=0}^{\infty} \widetilde{X_k} \quad (2.3)$$

The angular velocity of rotation in the harmonic in the air gap described by the expressions (2.1) and (2.2) is equal to the phase velocity of the wave:

$$\Omega_\nu = \frac{\omega_\nu}{\nu}$$

The forward-rotating harmonic has parameters $\omega_\nu > 0$ and $\nu > 0$. The reverse-rotating harmonic is generally defined by the condition $\omega_\nu\ \nu < 0$. For clarity, the reverse-rotating harmonic has parameters \omega_\nu>0 and \nu<0. According to (2.1) and (2.2), the harmonic quantity can also be expressed in standard form:

$$\dot{A_\nu} = A_{\nu m} e^{j\varphi_0} \quad (2.4)$$

According to the specific magnetic conductivity method of the air gap, it is possible to ignore the unsaturated magnetic period of the machine and the magnetic voltage of the magnetic conductors relative to the magnetic voltage of the air gap ($\mu_{ст} = \infty$), the field in the air gap is determined by the product of the magnetic voltage therein and the specific magnetic conductivity of the gap [5]:

$$\sum \widetilde{B_\delta} = \sum \widetilde{F_\delta} \sum \widetilde{\lambda_\delta} = \left(\sum \widetilde{F_{\delta s}} + \sum \widetilde{F_{\delta r}}\right) \sum \widetilde{\lambda_\delta} = \sum \widetilde{F_{\delta s}} \sum \widetilde{\lambda_\delta} + \sum \widetilde{F_{\delta r}} \sum \widetilde{\lambda_\delta} \quad (2.5)$$

Here

$\sum \widetilde{F_\delta}$ – the sum of the magnetic stresses of the air gap formed in the stator and rotor windings.

$\sum \widetilde{\lambda_\delta}$ – air gap magnetic conductivity (air gap conductivity)

$\sum \widetilde{F_{\delta s}}, \sum \widetilde{F_{\delta r}}$- the magnetic stresses generated by the stator and rotor windings in the air gap, respectively.

Magnetic stresses $\widetilde{F_\delta}$, $\widetilde{F_{\delta s}}$, $\widetilde{F_{\delta r}}$ and air gap conductivity $\widetilde{\lambda_\delta}$ show the sum of harmonics according to the values scattered over the Fourier series. The magnetic field in the air gap is determined by the full MMF of the winding.

$$F_{\delta\nu} = \frac{F_{\sum\nu}}{k_{\mu\nu}}$$

Here, $k_{\mu\nu}$ is the saturation coefficient for the magnetic circuit of the ν^{th} harmonic of the field. The value of $k_{\mu\nu}$ is taken from the electromagnetic calculation of the asynchronous motor.

When calculating the magnetic field in the air gap, we take into account the following assumptions.

- with static and dynamic eccentricity, the displacement of the axis of the outer surface of the rotor occurs parallel to the axis of the inner surface of the stator;

- the magnitude of the rotor sliding does not change;

- the influence of induction harmonics in the air gap on saturation is taken into account by the saturation coefficient $k_{\mu\nu}$;

- the inductive resistance of distribution is constant in all slots of the stator windings and rotor windings.

A magnetic field in the same air gap. Magnetic conductivity of the air gap.

In the absence of eccentricity in the same air gap, the conductivity of the air gap is determined by the formula [5]:

$$\lambda_\delta = \frac{\mu_0}{\delta_0 k_\delta} \qquad (2.6)$$

Here

$\mu_0 = 4\pi \cdot 10^{-7}$ Gn/m – magnetic constant

δ_0 – air gap size

k_δ- air gap coefficient

The field calculation according to formula 2.6 can be obtained using the main harmonics of the field. According to [5], to account for the magnetoconductivity of the serration, we can express the conductivity of the air gap in the following form.

$$\lambda_\delta = \frac{\mu_0}{\delta_0 k_\delta} \frac{\lambda_{z1}^* \cdot \lambda_{z2}^*}{\lambda_{z1}^* + \lambda_{z2}^* - \lambda_{z1}^* \cdot \lambda_{z2}^*} \qquad (2.7)$$

$\lambda_{z1}^*, \lambda_{z2}^*$ - The relative conductivity of the air gap and the conditional serration structure of the rotor and stator, respectively.

$$\lambda_{z1}^* = 1 + \sum\nolimits_{k_{z1}} \Lambda_{z1 k_{z1}}^* \cos(k_{z1} z_1 \varphi) \qquad (2.9)$$

$$\lambda_{z2}^{*} = 1 + \sum_{k_{z2}} \Lambda_{z2k_{z2}}^{*} \cos(k_{z2} z_2 \varphi) \qquad (2.10)$$

$\Lambda_{z1}^{*}, \Lambda_{z2}^{*}$ lar – relative amplitude of the air gap conductivity of the gear harmonic. z_1, z_2 the number of stator and rotor slots, respectively.

Substituting (2.9) and (2.10) into (2.8), we can obtain the conductivity of the serration air gap of the stator and rotor for the faultless state of the asynchronous machine.

$$\sum \lambda_\delta = \Lambda_0 \left(1 + \sum_{k_{z1}=1}^{\infty} \Lambda_{z1k_{z1}}^{*} \cos(k_{z1} z_1 \varphi) + \sum_{k_{z2}=1}^{\infty} \Lambda_{z2k_{z2}}^{*} \cos(k_{z2} Z_2) \left(\frac{(1-s)}{p} \right) \omega t - \varphi \right)$$

$$+ \sum_{k_{z1}=1}^{\infty} \sum_{k_{z2}=1}^{\infty} \Lambda_{z1k_{z1}}^{*} \Lambda_{z2k_{z2}}^{*} \left[cos \left(\frac{(1-s)}{p} k_{z2} Z_2 \omega t - (k_{z1} Z_1 + k_{z2} Z_2) \varphi \right) + cos \left(\frac{(1-s)}{p} k_{z2} Z_2 \omega t - (k_{z1} Z_1 - k_{z2} Z_2) \varphi \right) \right] \qquad (2.11)$$

here

s - sliding of an asynchronous motor;

$\omega = 2\pi f$ consumption voltage rotation frequency

Analysis of (2.11) shows that, based on the different number of polar pairs $\nu = k_{z_1} z_1 + k_{z_2} z_2$, an interference harmonic of the air gap of the same frequency is involved in $\frac{(1-s)}{p} h_{z_2} z_2 \omega$ [5].

[5] provides graphs for calculating the conductivity harmonics of the air gap leading to magnetic permeability occlusion. The amplitudes of these harmonics depend on the geometric relationships of the tooth zone - the ratio of the gear compartment to the value of the groove slider is $b_ш / t_з$ and $b_ш / \delta_0$. The literature presents data for calculating the dental harmonic of a field up to k_z=4 of the fourth order.

Analytical expressions for calculating the amplitudes of tooth harmonics of air gap conductivity are given in the works of B. Geller and V. Gamata:

$$\lambda_{zk_z}^{*} = \beta(b_ш/\delta_0) \frac{4}{\nu\pi} \left(0.5 + \frac{(b_ш/t_z)^2}{0.78 - 2(b_ш/t_z)^2} \right) sin(1.6\pi\nu b_ш/t_z), \qquad (2.12)$$

$\beta(b_ш/\delta_0)$ - $b_ш/\delta_0$ relativitity is the calculation of the air gap conductivity harmonic according to 2.12 should ignore 2.7 and 2.8 k_δ, and at 2.9 and 2.10 the first conjugate should be changed to $1/k_\delta$. Because we take into account the equivalent change in the air gap at 2.12.

The magnetomotive force of the stator and rotor winding (MMF). The stator MMF according to [5] is written as follows:

$$\sum \widetilde{F_{\delta s}} = \frac{m_1\sqrt{2}}{\pi} w_1 I_1 \sum_{\nu=(1+6c)p} \frac{k_{об\nu}}{\nu k_{\mu\nu}} cos(\omega t - \nu\varphi) \quad (2.13)$$

here ν^{th} - the number of polar pairs (absolute order) of the MMF harmonic of the stator (c=0,$\pm1, \pm2, \pm3, \ldots = \infty \ldots +\infty$)

[5] Each harmonic of the stator field with the number of polar pairs , the MMF of the rotor and the windings of the rotor can be written in the form of the following expression, which creates a system of currents and a spectral harmonic.

$$\sum \widetilde{F_{\delta s}} = \frac{Z_2}{\sqrt{2}\pi} I_{rv} \sum_{\nu=(1+Z_2c')} \frac{1}{\nu k_{\mu\nu_1}} cos(\omega_{r\nu}t - \nu_r\varphi - \nu_r\varphi_{\nu r}) \qquad (2.14)$$

Harmonic amplitude $F_{\delta r\nu m} = \frac{Z_2}{\sqrt{2}\pi\nu_r k_{\mu\nu_r}} I_{r\nu}$,

here c'=0,$\pm1, \pm2, \pm3, \ldots . = \infty \ldots +\infty$ (The c' notation is inserted to differentiate the harmonic expression on the stator and rotor)

$I_{r\nu}$ – The actual current in the rotor rod caused by the ν^{th} harmonic of the air gap field.

$\omega_{r\nu}$ – The ν^{th} harmonic of the rotor's MMF according to the rotor rotation frequency relative to the stator.

$\varphi_{\nu r}$ - $c' = 0$ rotor winding phase on MMF

In (2.14) we obtain the MMF harmonic of the rotor when $c' = 0$, the order of which is equal to the order of the field harmonic generated by the number of polar pairs $\nu_r = \nu$. This MMF harmonic is the rotor's reaction to the field harmonic in the air gap $B_{\delta\nu}$. For c'=0,$\pm1, \pm2, \pm3, \ldots$., we obtain the MMF rotor winding's gear harmonic from current $I_{r\nu}$ due to the discrete position of the winding.

When ν_r= 0, we accept a multipolar magnetic flux. If the body of an asynchronous motor is made of aluminum, this stability is small and can be neglected. Then the addition in 2.14 can be disregarded in the case where ν_r = 0. In the case of a sufficiently large magnetic conductivity of a multipolar flow, its value is calculated separately.

Air gap magnetic field. The magnetic field in the air gap is represented by the expression 2.5. Each field harmonic $B_{\delta\nu}$, with the number of pole pairs ν, generates a current and MMF on the rotor, forming the initial harmonic ν_r= ν + Z_2c', which is the number of pole pairs ν and the MMF of the rotor's serration harmonic.

Excluding the gear harmonics in the rotor, the field harmonic order ν=p ± k exhibits the following composition.

1. The main harmonic of the field generated by the constant components of the air gap conductivity and the magnetomotive force (MMF) of the stator

$$B_{\delta\nu} = F_s\lambda_\delta \, cos(\omega t - (p \pm k)\varphi);$$

1. The harmonics of the rotor reaction according to 2.14;

2. $\nu^n \neq \nu$ (the rotor's reaction to another field harmonic) is the product of the number of polar pairs and the rotor's MIC field harmonic permeability of the air gap λ_δ and the resulting order ν.

The rotor reaction to the $B_{\delta\nu}$ field harmonic [4] and the damping coefficient Dν according to [1] can be considered. The value of D_ν is close to 1 for the main harmonic for the serrated order field harmonics and the idle mode. In perfectly symmetrical unsaturated asynchronous machines, there are main and serrated harmonics of the field in the air gap, therefore a close approximation of the field in the air gap can be obtained without taking into account the damping field of the rotor slot. Dempfering is taken into account by multiplying the main harmonic by D_v.

The resulting field at 2.5 involves harmonics of different orders and frequencies relative to the stator [1]:

1. Main harmonic $\nu = p$
2. Field harmonics in the stator are ordered by the serrated order. $\nu = p \pm k_{z1}Z_1$
3. Field harmonics in the rotor's serrated order $\nu = p \pm k_{z2}Z_2$
4. The serrated order of the harmonics of the rotor and stator field

$$\nu = p \pm k_{z1}Z_1 \pm k_{z2}Z_2$$

$\nu = p \pm k_{z2}Z_2$ and $\nu = p \pm k_{z1}Z_1 \pm k_{z2}Z_2$ unlike the main harmonic of the frequency field relative to the stator, the stator winding is assigned an EMF frequency, unlike the frequency of the power source.

Results. A three-dimensional image of a magnetic field created based on the input magnetic induction, frequency, and amplitude. This graph shows the spatial distribution of the magnetic field. This program allows the user to analyze and visualize the magnetic field based on various parameters. The program describes the magnetic field in three-dimensional space based on the input values of magnetic induction, frequency, and amplitude. This allows the user to see the spatial distribution of the magnetic field and evaluate its properties. (Photo -1).

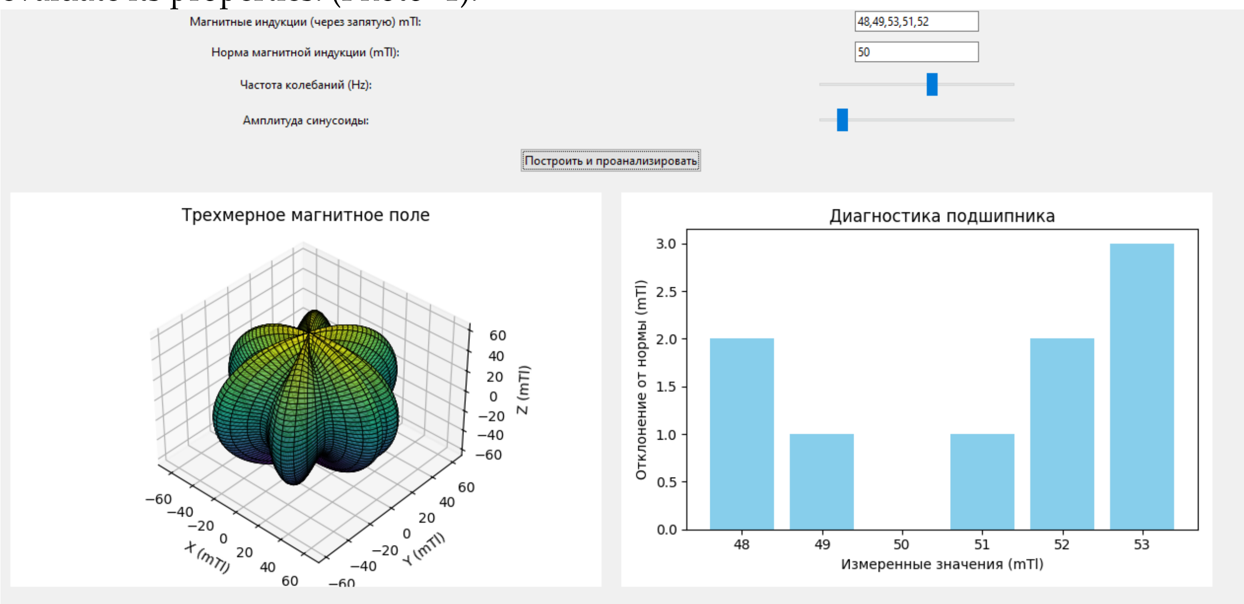

Photo 1. – Magnetic field visualization in Python

The deviation diagram from the norm also clearly shows the deviation for each value of the induction, which is important for determining the initial defects of the bearing. Diagrams and 3D graphics help the user see how the magnetic field is changing and can be used to identify potential problems.

Conclusions. This program is especially convenient for engineers engaged in bearing diagnostics and is designed for real-time analysis and presentation of results. This Python program allows the user to visualize a magnetic field and analyze its deviations from the norm. This is especially convenient for bearing diagnostics and eccentricity determination, helping to analyze changes in the magnetic field.

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