VIBRATIONAL DIAGNOSTICS OF THE INDUCTION MOTOR ATD-5000 ROTOR DAMAGES ON THE BASIS OF DIAGNOSTIC COEFFICIENTS ANALYSIS

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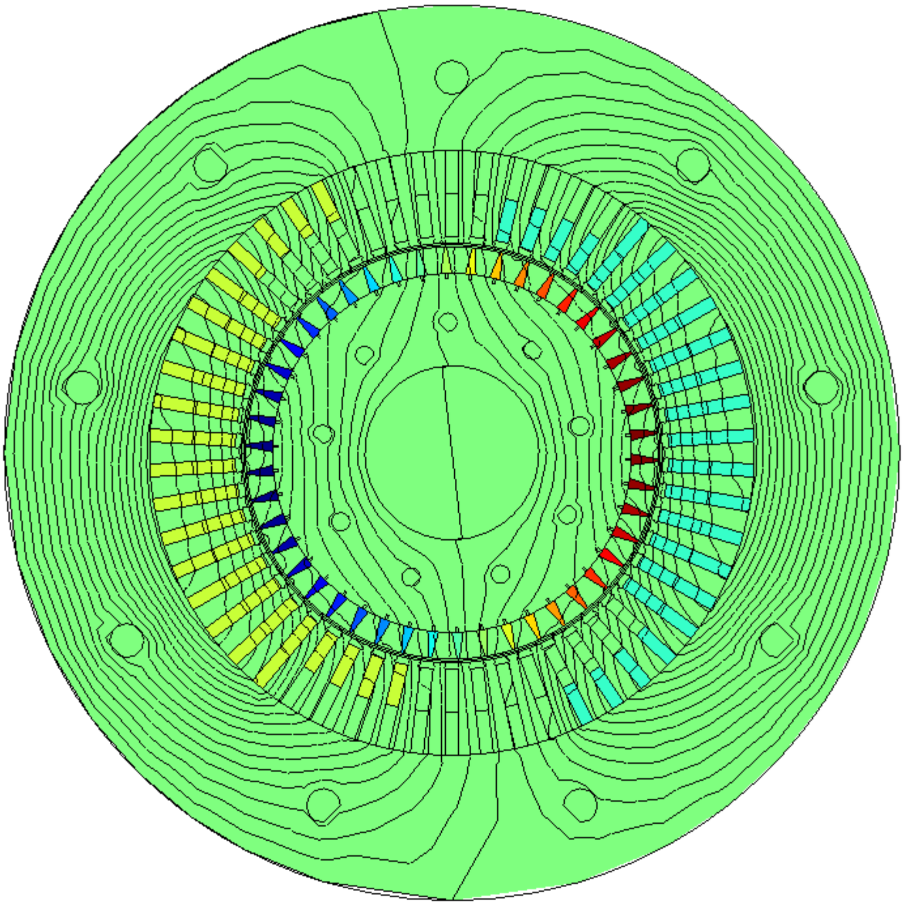
Introduction. Induction motors (IM) with a short-circuited rotor with a power of 300 ... 5000 kW are widely used in power stations of different types to drive their own needs: ventilation systems, pump-compressor units, ball mills and other devices. A significant number of powerful operated IMs have already worked out their warranty terms, which leads to a decrease in the reliability of their work and an increase in the number of cases of sudden emergency stop. In this regard, in today's conditions, in order to prevent the negative consequences of a sudden emergency stop of IM, special importance the establishment of effective systems for monitoring the technical condition and diagnosis of IM damages becomes special importance. In particular, the diagnosis of short-circuited rotor damage is a topical component of the design, which is most difficult to diagnose. Also, in the IM may damage the various elements of the rotor design: break of rods short-circuited rotor windings, break of short-circuiting rings segments, and also static and dynamic eccentricities, which can also be attributed to damages of the rotor. Therefore, the diagnostic system should not only detect the damage of the rotor, but also to determine the specified types of damage, which requires the construction and justification of the appropriate system of diagnostic features.

Today, various methods and corresponding systems of control of technical condition and diagnostics of IM damages are known: diagnostics based on the results of spectral analysis of consumed current, diagnostics of the power consumption spectrum, vibration diagnostics [1]. The most promising is vibration diagnostics, which has the greatest sensitivity and which is expedient to use for the diagnosis of powerful electric machines. In vibration diagnostics systems, vibration acceleration sensors are used, the basis of which is the piezoelectric effect. It is expedient to substantiate the system of diagnostic signs by methods of mathematical modeling, for which it is necessary to develop mathematical models of IM with the corresponding defects. At the same time, unlike the approximate analytical models, field models allow strict consideration of various factors: features of the geometry of the toothed-grooved zone of IM, saturation effects, displacement of the current, etc. Therefore, the justification of the system of diagnostic signs should be carried out on the basis of field models of IMs.

The goal of the work. The goal of the article is to substantiate the methodology of vibration diagnostics of short-circuited rotors defects of IMs on the basis of the system of diagnostic coefficients.

Material and results of the research. For the research, a powerful three-phase IM ATD type of 5000 kW power was chosen (pic. 1), which operates in nominal mode and whose parameters are as follows: nominal voltage - 6 kV, stator current 545 A, efficiency 94.8%, power coefficient 0.89, nominal rotational speed 2985 rpm, number of pole pairs - 1; air gap - 6 mm; diameter of the stator - 675 mm.



Picture 1 – Distribution of currents and magnetic field lines in ATD-5000

An important component of this mathematical model is the model of vibration damping electromagnetic forces [2], which are determined using Maxwell's tensor of magnetic tension $\vec{T}$, which characterizes the density of electromagnetic force, which is applied to the stator's cutting surface. In a normal-tangential coordinate system, the vector of the tensor of magnetic tension is divided into a normal one $\overrightarrow{T_n}$ and tangential $\overrightarrow{T_\tau}$ constituents: $\vec{T} = n\overrightarrow{T_n} + \tau\overrightarrow{T_\tau}$. The normal component of the tensor of magnetic tension (directed along the vector normal to the stator plots surface) characterizes the action of radial vibroperturbing electromagnetic forces on the stator core, and a tangential component (directed along the tangent to the surface of the rotor) - oscillation of electromagnetic moment. For the task of vibration diagnosis is relevant analysis of radial vibrations, which are fixed by vibration acceleration sensors. Therefore, in the future, the normal component of the tensor of magnetic tension is investigated. At the same time, given the periodic nature of the change in the vibroperturbing forces, it is expedient to perform a spectral analysis of the tensor of magnetic tension and proceed to the study of the individual components of the spectrum. This allows to install diagnostic features that meet different types of damage.

The system of diagnostic coefficients for determining IM rotor damages. The following system of diagnostic coefficients is introduced, which give a quantitative estimate of changes in the spectra of vibration sensors signals in the event of damage. The numerical values of these coefficients are investigated depending on the nature and degree of damage of the rotor, and the possibility of their use in vibration control and diagnostic systems is substantiated.

Diagnostic coefficients are the following coefficients.

1. ***Coefficient of the change in RMS of the vibration acceleration spectrum*** $k_{СКЗ\_a}$, which characterizes the ratio RMS of the vibration acceleration spectrum damaged IM to RMS of the vibration acceleration spectrum intact IM and is calculated by the formula:

$$k_{СКЗ\_a} = \frac{\sqrt{\sum_{i=1}^{N} \left|T_{ni\_П}\right|^2}}{\sqrt{\sum_{i=1}^{N} \left|T_{ni\_НП}\right|^2}}, \qquad (1)$$

where N - the number of harmonics taken into account in the spectrum; i - harmonic number; $T_{ni\_П}$, $T_{ni\_НП}$ - i-th harmonics amplitude of the normal component of the tensor of magnetic tension in the spectra of vibration sensors signals of damaged and intact IM, respectively.

2. ***Coefficient of the variation in RMSV of vibration velocity spectrum*** $k_{СКЗ\_v}$, which characterizes the ratio RMS of the vibration velocity spectrum damaged IM to RMS of the vibration velocity intact IM and is calculated by the formula:

$$k_{СКЗ\_v} = \frac{\sqrt{\sum_{i=2}^{N} \left(\frac{\left|T_{ni\_П}\right|}{i}\right)^2}}{\sqrt{\sum_{i=2}^{N} \left(\frac{\left|T_{ni\_НП}\right|}{i}\right)^2}}. \qquad (2)$$

Designation of variables in the formula (2) are the same, as in the formula (1). Coefficients $k_{СКЗ\_a}$ and $k_{СКЗ\_v}$ are calculated without taking into account the constant component of the spectrum T_{n0}, because this component is not directly measured by piezoelectric vibration acceleration sensors. Coefficients $k_{СКЗ\_a}$ and $k_{СКЗ\_v}$ represent integral indicators that characterize the overall existing level of vibration in the studied IM.

3. ***Coefficient of reversible harmonics*** $k_{ОБ}$, which characterizes the ratio of RMSV reversible harmonics, whose frequencies are multiple frequencies of IM rotor rotation, to the harmonic amplitude with the frequency of 100 Hz of intact IM and is calculated by the formula:

$$k_{ОБ} = \frac{\sqrt{\sum_{i=1}^{N} \left| T_{niОБ\_П} \right|^2}}{T_{n100\_НП}}, \quad (3)$$

where $T_{niОБ\_П}$ – the *i*-th reversible harmonic amplitude of the tensor of magnetic tension in the spectrum of the vibration sensor signal of the damaged IM, and $T_{n100\_НП}$ – harmonic amplitude with the frequency of 100 Hz in the spectrum of the vibration sensor signal of the intact IM.

Numerator in the formula (3) is a RMS of reversible harmonics that appear in the spectrum of the damaged IM. The level of vibration of IM varies not only due to the main reversible harmonic (its frequency is equal to the frequency of rotor rotation), but also due to the set of harmonics, whose frequencies are multiple frequencies of the main reversible harmonic. In the vibration spectrum of intact IM, there are no reversible harmonics. Therefore, in order to obtain the coefficient in the relative form, by the base value, the amplitude of the base harmonic of electromagnetic oscillations (100 Hz) is adopted.

4. ***The coefficient of lateral reversible harmonics*** $k_{ОБ\_Б}$, which characterizes the ratio of RMS summation of lateral (right and left) reversible harmonics, located close to the main reversible harmonic, to the harmonic amplitude with the frequency of 100 Hz in intact IM and is calculated by the formula:

$$k_{ОБ\_Б} = \frac{\sqrt{\sum_{i=1}^{N} \left| T_{niОБ\_Б\_П} \right|^2}}{T_{n100\_НП}}, \quad (4)$$

where $T_{niОБ\_Б\_П}$ – amplitude *i*- th side reversible harmonic in the spectrum of the vibration sensor signal of the damaged IM, and $T_{n100\_НП}$ – amplitude of the harmonic frequency of 100 Hz in the spectrum of the vibration sensor signal of the intact IM.

Coefficients $k_{ОБ}$ and $k_{ОБ\_Б}$ are components of the total coefficient $k_{СКЗ\_а}$. Validity of selection and separate analysis of coefficients $k_{ОБ}$ and $k_{ОБ\_Б}$ is that when the damage occurs in the spectra there are reversible and lateral reversible harmonics whose amplitudes are directly related to the degree of damage.

5. ***Frequency harmonic factor of 100 Hz*** k_{100}, which characterizes the ratio of the harmonic amplitude with the frequency of 100 Hz in damaged IM to the amplitude of the harmonic frequency of 100 Hz intact IM and is calculated by the formula:

$$k_{100} = \frac{T_{n100\_П}}{T_{n100\_НП}}, \quad (5)$$

where $T_{n100\_П}$ i $T_{n100\_НП}$ – the harmonics amplitudes of the magnetic tension tensor of the frequency of 100 Hz in the spectra of the vibration sensors signals of the damaged and intact IM, respectively.

6. ***Coefficient of toothed harmonic change*** k_Z , which characterizes the ratio of the first harmonic amplitude of the damaged IM to the amplitude of the first toothed harmonic of the intact IM and is calculated by the formula:

$$k_Z = \frac{T_{nZ\_П}}{T_{nZ\_НП}}, \quad (6)$$

where $T_{nZ\_П}$ – the first toothed harmonic amplitude of the magnetic tension tensor in the spectrum of the vibration sensor signal in damaged IM, and $T_{nZ\_НП}$ – the amplitude of the first toothed harmonic in the spectrum of vibration of the intact IM. The frequencies of the toothed harmonics in the signal of sensor is related to the number of teeth and the speed of rotor rotation and are calculated by the formulas $f_{zk} = k\, f_{ОБ} \cdot Z_2$, where $f_{ОБ}$ – frequency of rotor rotation, and Z_2 – a number of rotor teeth, k=1,2,… If k=1 it is the first toothed harmonic. For ATD-5000 $f_{Z1} = 2{,}3$ kHz.

7. ***Coefficient of constant component change*** k_0, which characterizes the ratio of the constant components of the electromagnetic forces of attraction between the stator and the rotor in the damaged and intact IM and is calculated by the formula:

$$k_0 = \frac{T_{n0\_П}}{T_{n0\_НП}}, \quad (7)$$

where $T_{n0\_П}$ – constant component of the magnetic tension tensor of the damaged IM, and $T_{n0\_НП}$ – constant component of the magnetic tension tensor of the intact IM.

It should be emphasized that the permanently active component of the magnetic attraction between the stator and the rotor really exists in the IM, and its value varies with the appearance of rotor damage. This creates the preconditions for the analysis of the indicated force in the diagnosis of damages in IM. Although piezoelectric vibration accelerators do not directly measure the constant component of the effort, but by calibrating the received signal in such a way that its minimum value is taken to be zero, it is possible after the spectral analysis of the received signal to determine experimentally its constant component.

Conclusions. The methodology and bases of scientific and methodical support for systems of vibration control and diagnostics of rotors damages of powerful IM are developed. The set of diagnostic coefficients is an important part of the system of vibration diagnostics.

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