Virtual model of an induction motor with rotor eccentricity

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Abstract. A squirrel-cage induction motor is the most common motor used to drive working machines in various technological processes, including in the agricultural sector. A sufficiently large resource is laid in them by the manufacturer, but in practice the engine serves much less, due to various factors, including imperfection of diagnostic systems. Failure analysis showed that one of the common causes of failure is increased bearing wear. An increase in the rotor eccentricity is the main diagnostic parameter of this malfunction, for the detection of which a diagnostic method was developed that allows using the indirect indicator, the rotor speed, to evaluate the technical condition of the engine bearings. To identify the dependence of diagnostic parameters on the technical condition, a virtual model of an asynchronous motor with rotor eccentricity was built. The model is implemented using a package of applied mathematical programs and allows you to simulate the operation of an induction motor in various modes, such as starting, idling, steady state with the ability to change the nature of the load. As a result, we obtained the dependences of the angular velocity of rotation of the rotor, stator current, and torque on the shaft versus time for various technical conditions of the engine.

1. Introduction

The widespread use of squirrel-cage induction motors in both industry and agriculture is due to their low cost and reliability of use. The effective use of these engines in agriculture is hindered by an aggressive environment and their unsustainable operation, as evidenced by the results of studies cited in the authors [1-6]. As practice shows, one of the most common mechanical failures is the eccentricity of the rotor caused by bearing wear [7-13].

A promising area of research is the diagnosis of engines in transient modes of operation, since this process proceeds briefly, but has high information content. Despite the fact that a lot of work has been devoted to the study of transient processes in induction motors, the start-up mode is a poorly studied process [14-17].

To identify diagnostic parameters and the nature of their dependence on the eccentricity value, it is necessary to obtain a system of equations of the electromechanical equilibrium of an induction motor taking into account malfunctions [18, 19].

Changes in the mechanical parameters of an induction motor, including the air gap, can be estimated using appropriate algorithms that allow analysis of the signals available for measurement without interfering with the process. Such signals are the voltage and current of the stator, as well as the frequency of rotation of the rotor of the motor [20, 21]. In mathematical modeling of electromechanical processes in an induction motor in transient modes of operation, the calculation model of a two-phase generalized electric machine is most often used, this is due to the complexity of mathematical
expressions describing this process [22, 23]. For an induction motor, the calculation model consists of a cylindrical stator and a rotor with two layers of concentric windings. The system of equations of electromechanical equilibrium taking into account the eccentricity is written in the form [24]:

\[
U_{1f,nom} \cdot \frac{e}{2 \delta_0 \, k_{c1} \, k_{c2}} = R_s \cdot i_s + \frac{U_{1f,nom}}{l_{1f,nom}} + \frac{2U_{1f,nom}}{l_{1f,nom}(\omega_1 + \omega_e)} \cdot \left( L_s \cdot \frac{di_s}{dt} + 2M \cdot \frac{di_r}{dt} \right),
\]

\[
0 = R_r \cdot i_r + \frac{U_{1f,nom}}{l_{1f,nom}} + \frac{2U_{1f,nom}}{l_{1f,nom}(\omega_1 + \omega_e)} \cdot \left( L_r \cdot \frac{di_r}{dt} + 2M \cdot \frac{di_s}{dt} \right),
\]

\[
J \cdot \frac{d\omega}{dt} = 2M \cdot i_s \cdot i_r \cdot \sin[(\omega_1 + \omega_e) - \omega] \cdot t - M_c
\]

where is \( U_{1f,nom} \) - the nominal phase voltage; \( I_{1f,nom} \) - rated phase current; \( R_s, R_r \) - active stator and rotor resistances, respectively; \( i_s, i_r \) - current in the stator and rotor windings, respectively; \( M \) - is the nominal electromagnetic moment; \( M_c \) - active moment; \( J \cdot \omega \) - angular momentum; \( L_s, L_r \) - intrinsic inductance of the stator and rotor windings respectively.

The obtained mathematical expressions allow us to simulate the operation of an induction motor at various values of the rotor eccentricity. As a result of the calculations, it is possible to obtain functional dependences of the angular velocity of rotation of the rotor, stator current, and torque on the shaft as a function of time \( \omega(t), i(t), M(t) \).

2. Materials and methods

To check the theoretical premises for diagnosing the rotor eccentricity of an induction motor by changing the oscillations of the rotor speed and the decay time of these oscillations, a virtual model of the asynchronous motor was created. It was performed in a fixed orthogonal coordinate system (expressions 1-3), using the Matlab + Simulink software package [24, 25], which takes into account the eccentricity for the spatial harmonic of induction with serial number \( i = 1 \) rotating in the direction of the fundamental harmonic figure 1.

The model consists of the main blocks:

1. The «\( \Omega \)» unit sets the frequency of rotation of the fundamental harmonic of the voltage applied to the three-phase stator windings of the induction motor. Functional blocks «\( Fcn - Fcn2 \)» define a symmetric system of three-phase voltage supplied to the stator windings (voltage \( V_{ag}, V_{bg}, V_{cg} \) [25].

2. The «\( \Omega \)» block sets the frequency of rotation of the spatial harmonic of the electromotive force with serial number \( i = 1 \), rotating in the direction of the fundamental harmonic due to the eccentricity of the rotor of the induction motor. Functional blocks «\( Fcn3 - Fcn5 \)» define a symmetric system of three-phase electromotive force arising in the stator windings of an induction motor in the presence of an eccentricity of its rotor [27].

3. The block of the subsystem «Subsystem» defines a virtual model of an asynchronous motor in a fixed orthogonal coordinate system [28]. The computational blocks of the Subsystem model perform the following functions:

- transformation of a three-phase motionless coordinate system (a, b, c) into a motionless two-phase coordinate system (q, d). The transition to a two-phase coordinate system allows us to eliminate the dependence of the mutual inductances of the windings of the induction motor on the angle of rotation of the rotor, i.e. eliminate the variability of the corresponding coefficients in a virtual calculation model;
- allows you to calculate: the component of the flux linkage of the stator and rotor along the axes (q, d), as well as the current component;
- calculate the electromagnetic torque of the engine and the ratio of the angular velocity of rotation of the rotor to the angular velocity of rotation of the fundamental harmonic of the stator field;
sets the load diagram on the rotor shaft of the induction motor.

4. The «Total Harmonic Distortion» unit measures the total harmonics coefficient (THD) of the stator phase current. THD is defined as the rms value of all harmonics of the current divided by the rms value of the fundamental current frequency of 50 Hz.

5. The «Fourier» block performs a Fourier analysis of the signal equal to the current value for one period of the fundamental frequency [27]. For the considered virtual model, the block is programmed in such a way as to calculate the amplitude of the fundamental frequency of the input signal in the same units (amperes) as the input signal corresponding to the stator phase current.

6. The «Power Spectral Density» spectrum analyzer is used to view the signal spectral density equal to the current value (Simulink Extras / Additional Sinks / Power Spectral Density).

The described mathematical model of an asynchronous motor with rotor eccentricity performed using the Matlab + Simulink software package allows you to simulate its operation in various modes, such as starting, idling, steady state with the ability to change the nature of the load.

3. Results of the study, their discussion
The simulation was carried out for a 2.2 kW engine with a nominal rotor speed of 1460 rpm; the results are shown in figure 2.

As a result, we obtained the dependences of the rotational speed of the induction motor rotor as a function of time for various values of the eccentricity of its rotor figure 2 and the dependences of the change in the electromagnetic moment on time for the values of eccentricity of 0 and 60%.

![Virtual model of an asynchronous motor with rotor eccentricity.](image)
Figure 2. The dependence of the rotor speed on time at the rotor eccentricity of 0, 20, 40, 60 % in idle mode.

The figure shows that with an increase in the eccentricity of the rotor, the amplitude of the oscillations of the rotor speed increases, relative to the same amplitude of a technically sound engine. For example, with an eccentricity of 20%, the difference in the amplitudes of the rotor speed is 11 rpm, and with an eccentricity of 60%, 34 rpm.

The dependences of the change in the electromagnetic moment on time were also obtained for the eccentricity of the rotor figure 3. With an increase in the eccentricity of the rotor in the steady-state mode of operation, the moment increases and takes the form of a sinusoid with a variable amplitude.

Figure 3. Dependences of the change of the electromagnetic moment on time at the value of the eccentricity of 0 and 60 % in the idle mode.
Based on the data obtained as a result of the simulation, we obtained a linear dependence of the change in the amplitude of the oscillations of the rotor speed on the value of its eccentricity $\varepsilon = 1,772 \cdot \Delta A - 0,759$ with the reliability of the approximation $R^2 = 0,97$.

Verification of the virtual model was carried out in laboratory conditions, as well as in operating conditions in various technological processes in order to establish functional dependencies. As a result of experimental studies, it was found that the eccentricity of the rotor is directly proportional to the difference in the amplitudes of the change in the rotational speed during tests both under load and at idle with an approximation reliability of $R^2 \geq 0,83$, while diagnosing the engine under load allows more reliable results.

4. Conclusion
The developed virtual model of an asynchronous motor makes it possible to model and determine the technical condition of the bearings of the asynchronous motor with the difference in the amplitudes of the change in the rotor speed.

The developed mathematical model of an induction motor with rotor eccentricity based on the equations of electromechanical equilibrium of an induction motor is confirmed.

Using the approximation function, it is possible during operation, as well as after repair, to determine the eccentricity of the rotor, based on the difference in the amplitudes of the change in speed.

Increase in rotor eccentricity Change in stator current leads to an increase in stator current and electromagnetic moment, which in aggregate negatively affects the operation of an induction motor and reduces its service life.

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