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Diagnostic Indicators of Broken Rotor Bars in Induction Motors

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Abstract: Induction motors are widely used as the primary drive for industrial installations due to their high reliability, ease of control, and low operating costs. In operation, broken rotor bars in a squirrel-cage winding are among the most challenging faults due to their prolonged development period and diagnostic difficulty. An analysis of the literature leads to the conclusion that, despite the abundance of existing methods for diagnosing broken rotor bars, there remains a need to develop methods that improve the reliability of detection. This improvement can be achieved by shifting from analyzing only the current spectrum to the complex processing of interrelated instantaneous values of currents and voltages, which will enable the extraction of more robust diagnostic features. Preliminary studies on the possibility of diagnosing broken rotor bars using vibrometry methods confirmed the complexity of test impacts, the subjectivity of diagnostic symptom manifestation, and the low amplitude of fault-related components. These findings necessitate the development of approaches based on measuring electrical quantities. The aim of this work is to develop methods for diagnosing broken rotor bars by monitoring the angle between the generalized vectors of stator phase currents and voltages, or by monitoring the sum of stator phase current angles, using instantaneous current and voltage values. The practical value of this approach lies in the possibility of fault diagnosis using standard industrial measurement tools. This aim is achieved through theoretical research and testing of the developed diagnostic methods based on a mathematical model of an induction motor. The model accounts for the distributed rotor winding and is built on a system of complete differential equations presented in a three-phase coordinate system for stator currents. This approach allows for obtaining instantaneous values of phase currents and voltages for the subsequent determination of diagnostic criteria: the angle between the generalized vectors of phase currents and voltages, and the sum of stator phase current angles.

Keywords: Induction Motor, Squirrel-Cage Rotor Bars, Fault, Diagnostic Symptom (Indicator).

Research Paper

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INTRODUCTION

Induction motors are widely used as the primary drive for industrial installations due to their high reliability, ease of control, and low operating costs [1]. However, sudden failures of induction motors operating without backup lead to the shutdown of the entire technological complex. Among such failures, broken rotor bars in the squirrel-cage winding hold a special place. This fault is notably difficult to diagnose at an early stage due to the accumulation of fatigue damage in the bars, associated with manufacturing quality and operational conditions such as frequent starts/stops of heavily loaded mechanisms. According to research, this type of damage accounts for about 20% of all induction motor failures [2, 3]. The prolonged development period of the damage is accompanied by a reduction in mechanical characteristics, an increase in the overall motor temperature, and leads to stator winding insulation failure, which, along with increased high-frequency vibration, also results in significant destruction.

Therefore, the development of highly sensitive and reliable methods for the early detection of broken rotor bars in the squirrel-cage winding of an induction motor is critically important for preventing unscheduled downtime, thereby establishing the core motivation for this research.

The presence of broken rotor bars in the squirrel-cage winding is typically confirmed only after motor disassembly, through visual inspection or non-destructive testing methods. The application of vibration-based diagnostic techniques faces limitations due to the remoteness of this fault from traditional monitoring points, such as bearing housings. Moreover, this approach necessitates the use of advanced vibration instrumentation operated by qualified specialists.

This thesis is supported by studies [4, 5], which suggest an increase in diagnostic information content through the simultaneous analysis of vibration and current signatures. The detection of broken rotor bars in an induction motor using vibration analysis is presented at the level of a practical case study in [6]. In terms of addressing general diagnostic challenges, this direction has become an object of research in works [7, 8]. However, vibration-based methods for diagnosing broken rotor bars in induction motors exhibit low sensitivity to the initial stage of the fault. This is due to the attenuation of the high-frequency vibration component as it propagates from the rotor to the monitoring points on the stator and bearing housings, which in turn necessitates the installation of highly sensitive sensors and complex signal processing.

In work [9], it is noted that the harmonic composition of the external magnetic field of an induction motor with a squirrel-cage rotor partially coincides with the magnetic field arising in the air gap between the outer surface of the rotor and the inner surface of the stator. The similarity of the magnetic fields inside and outside the induction motor has enabled the development of methods for detecting broken rotor bars based on the analysis of the external magnetic field [10-12]. The disadvantages of this diagnostic approach include the need to install specialized sensors in close proximity to the motor. Furthermore, the signal is highly sensitive to external electromagnetic interference and the geometric position of the sensor on the motor housing, which limits its application in industrial operating conditions.

The spectral analysis of stator currents is most frequently used for detecting broken rotor bars [13-24]. The diagnostic methodology for assessing the condition of a squirrel-cage rotor in an induction motor, based on stator current spectral analysis, relies on the principle that any changes in the mechanical or electrical parts of the motor cause variations in the magnetic flux within the air gap between the rotor and stator, consequently modulating the stator currents.

Despite the commonality of this general approach, the considerable volume of research in this direction indicates practical implementation challenges when analyzing the spectrum of harmonic component variations upon fault occurrence. However, widespread application has revealed several drawbacks of spectral analysis, namely: low sensitivity when the motor is loaded below 30%, the absence of universal threshold values for unambiguous rotor fault identification, and the possibility of false fault diagnosis due to load torque oscillations, supply voltage instability, and eccentricity. These phenomena can manifest in the current spectrum in a way that is mistakenly interpreted as symptoms of broken rotor bars.

The conducted analysis of the literature allows us to conclude that, despite the abundance of existing methods for diagnosing broken rotor bars, there remains a need to develop methods that enhance the reliability of detection. This enhancement should be achieved by moving beyond the analysis of only the current spectrum towards the complex processing of interrelated instantaneous values of currents and voltages. Such an approach will enable the extraction of more robust diagnostic features.

Thus, the aim of this work is to develop methods for diagnosing broken rotor bars by monitoring the angle between the generalized vectors of stator phase currents and voltages, or by monitoring the sum of stator phase current angles, using instantaneous current and voltage values. The practical value of this approach lies in its ability to diagnose the fault using standard industrial measurement tools.

The experimental part of the study was conducted during a vibration condition survey of an induction motor driving a mine cage hoist mechanism at a metro construction enterprise. Vibration measurements were performed during the equipment's normal operation using a 795M vibration analyzer and a DN-10 piezoelectric sensor. The sensor was mounted using a magnet.

Measurements were taken in the vertical (V), horizontal (H), and axial (A) directions. The measurement point was the motor bearing on the coupling side. Overall vibration parameters were measured. The controlled frequency range was 2…800 Hz. Measurements were carried out during both ascent and descent at a shaft rotational speed of 735 rpm.

The results of the overall vibration level measurements are presented in Table 1.

Table 1: Vibration Measurement Values at the Motor Monitoring Point by Direction

Root Mean Square (RMS) Vibration Displacement, μm			Root Mean Square (RMS) Vibration Velocity, mm/s			Root Mean Square (RMS) Vibration Acceleration, m/s²		
В	Г	О	В	Г	О	В	Г	О
4/4	2/7	4	1,2/1,3	0,5/1,1	1,2	0,6/1,2	0,2/0,8	1,6

Note: *The values in the numerator represent cage ascent conditions; those in the denominator represent cage descent conditions.*

Analysis of the measured root mean square (RMS) vibration values shows:

- Vibration displacement — up to 7.0 μm;
- Vibration velocity — below the permissible limit, at 2.8 mm/s;
- Vibration acceleration — no more than 1.6 m/s².
- These values indicate good condition of the bearing supports. However, a nearly twofold increase in values during cage ascent is noted, which is a sign of unstable technical condition.

During motor operation in the descent mode, distinct strong impacts with a frequency of 2…3 beats per second are clearly audible from the drive-end bearing side. The sound is superficial. During ascent operation, the intensity of the impacts significantly decreases.

Spectrum analysis revealed a component at a frequency of 246 Hz (Fig. 1). This component is associated with the number of rotor bars (20). Descending the cage with the motor disengaged confirmed the diagnosis—the impacts disappeared.

Possible test verification options include:

1. Checking for the presence or absence of impacts during motor coast-down with the power supply disconnected and the coupling detached.
2. Checking during cage descent with no voltage applied to the motor and the drum brake released.

The necessity for such additional diagnostic clarification highlights the limited informational content of the vibration-based method for diagnosing faults such as broken rotor bars in an induction motor.

Preliminary studies conducted on the possibility of diagnosing broken rotor bars using vibrometry methods confirmed the conclusions presented in works [7, 8]. The complexity of test procedures, the subjectivity of diagnostic symptom manifestation, and the low amplitude of fault-related components all necessitate the development of approaches based on the measurement of electrical quantities.

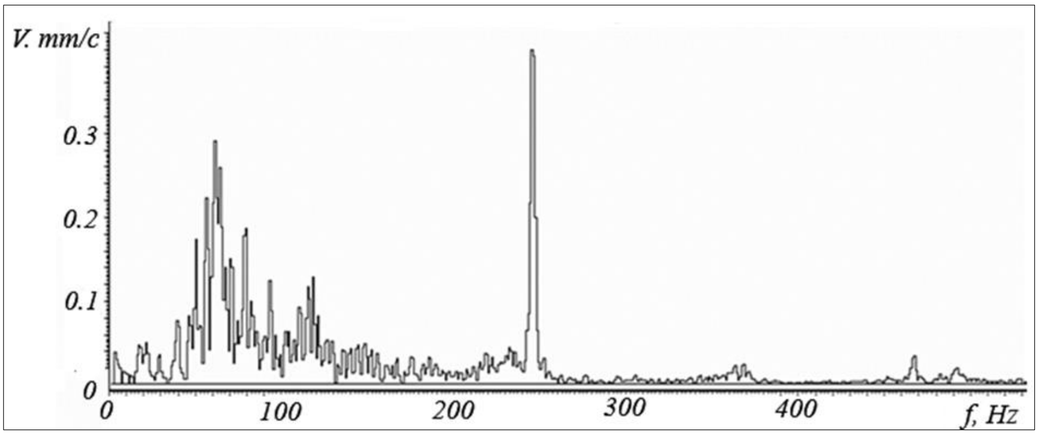

Fig. 1: Vibration velocity spectrogram

MATERIALS AND METHODS

For conducting theoretical research and testing the developed diagnostic methods for broken rotor bars, this study employs a mathematical model of an induction motor [25]. The applied model accounts for the distributed rotor winding and is based on a system of complete differential equations presented in a three-phase coordinate system for stator currents. This approach enables the acquisition of instantaneous values of phase currents and voltages for the subsequent determination of diagnostic criteria: the angle between the generalized vectors of phase currents and voltages, and the sum of stator phase current angles.

The number of rotor equations corresponds to the physical number of rotor bars (72 for the investigated 1700 kW motor), which allows for accurate modeling of electromagnetic transients in the induction motor arising from localized damage. Furthermore, the employed mathematical model permits specifying any number of broken rotor bars in an arbitrary sequence by modifying the resistance of the circuit loop corresponding to the damaged.

The first proposed method for diagnosing broken rotor bars is based on monitoring the emergence of magnetic flux asymmetry in the air gap between the rotor and stator of an induction motor, using measured instantaneous values of stator phase currents. When one or several rotor bars break, an asymmetry arises, manifesting as a distortion of the rotating magnetic field in the air gap. This distortion is clearly evident as a disturbance in the phase shift of the stator phase currents. Therefore, this method proposes using the sum of stator phase current angles as the diagnostic indicator. Mathematically, this criterion can be described by the formula:

$$\varphi_{\Sigma} = \varphi_A + \varphi_B + \varphi_C \quad (1)$$

For a healthy rotor winding, the value of the sum of phase current angles in steady-state operation remains constant and close to zero. In the event of rotor damage, it leads to periodic oscillations of this sum, indicating the occurrence of a fault.

To determine the value of the sum of stator phase current angles, the use of the Fourier transform is proposed. This transform allows for determining the phase and amplitude of a periodic measured signal. The value of the phase current angle can be determined using Fourier coefficients according to the formula:

$$\varphi_n = arctan\left(\frac{a_n}{b_n}\right) \quad (2)$$

где:*n* – harmonic number of the measured signal;
a_n, b_n- fourier transform coefficients.

The Fourier coefficients over the measurement interval *T* are determined using the following formulas

$$a_n = \frac{2}{T}\int_{t-T}^{t} f(t)\cos(n\omega t dt) \quad (3)$$

$$b_n = \frac{2}{T}\int_{t-T}^{t} f(t)\sin(n\omega t dt) \quad (4)$$

determined from the frequency *f* of the measured signal using the formula:

$$T = \frac{1}{f} \quad (5)$$

An important and necessary condition for using the proposed method is the careful selection of the analysis period duration. If the frequency of the measured phase current signal deviates from 50 Hz, it can lead to spectral leakage, which in turn introduces an error in determining the phase current angle value.

Thus, the use of the proposed method enhances sensitivity to the asymmetry caused by broken rotor bars by monitoring the sum of stator phase current angles. The key stages of this method are: determining the phase current angles using the Fourier transform, calculating the sum of stator phase current angles, filtering, and assessing the oscillation level. A core requirement for accurate operation is the synchronization of the analysis interval with the power system frequency period.

The second proposed method for diagnosing broken rotor bars is based on monitoring the angle between the generalized vectors of stator phase currents and voltages. Unlike the first method, which analyzes the sum of phase current angles, the second method evaluates the magnitude of the angle between the generalized current and voltage vectors of the stator. As is known, broken rotor bars lead to an increase in losses and a change in slip, which in turn is reflected in a change in the angle between the generalized vectors of stator phase currents and voltages. With a healthy rotor winding under steady-state motor operation, the magnitude of this angle remains relatively constant. In the event of a fault, such as a broken bar, oscillations in this angle arise.

The angle between the generalized vectors of stator phase currents and voltages can be determined using the following formula:

$$\varphi = arccos\left(\frac{P}{S}\right) \quad (6)$$

where: *P* – instantaneous active power of the induction motor;
S – instantaneous apparent power of the induction motor.

The values of instantaneous active and apparent power for an induction motor can be determined using the following formulas:

$$P = i_A \cdot u_A + i_B \cdot u_B + i_C \cdot u_C \quad (7)$$

$$S = \sqrt{\left(i_A{}^2 + i_B{}^2 + i_C{}^2\right) \cdot \left(u_A{}^2 + u_B{}^2 + u_C{}^2\right)} \quad (8)$$

where: u_A, u_B, u_C - instantaneous stator phase voltages,
i_A, i_B, i_C - instantaneous stator phase currents.

The algorithm of the proposed method consists of the following steps: using formulas (6) – (8), the magnitude of the angle between the generalized vectors of stator phase currents and voltages is determined. Next, the nature of its change is evaluated. If the angle magnitude remains constant over time during steady-state operation, it is concluded that there is no damage to the rotor winding. If, however, the angle magnitude changes with constant periodicity, it is concluded that there is damage to the rotor bars of the squirrel-cage winding.

The advantages of the presented method include the use of standard electrical measurements and potential robustness to symmetrical load variations.

RESULTS AND DISCUSSION

Figure 2 shows the results of computer simulation for the algorithm based on monitoring the sum of stator phase current angles (Fig. 2a) and the results for the algorithm based on monitoring the angle between the generalized vectors of stator currents and voltages (Fig. 2b), both under the condition of a healthy rotor winding.

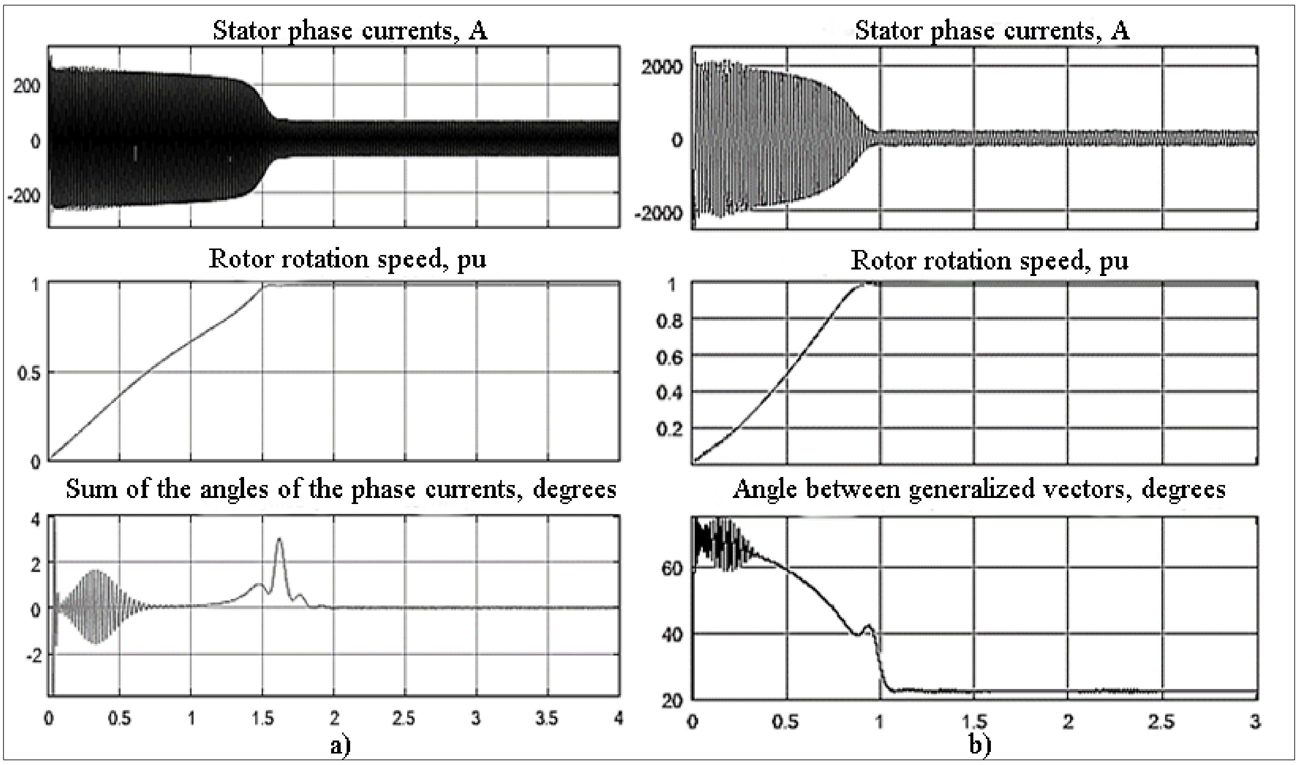

Fig. 2: Results of computer simulation of the diagnostic algorithms presented in this work for a healthy rotor winding

From the results of computer simulation presented in Fig. 2a, it is evident that after the motor reaches steady-state operation, the value of the sum of stator phase current angles becomes practically constant and oscillates around zero, which corresponds to a symmetrical three-phase system. The oscillation amplitude does not exceed 0.5°, which is due to the discretization of the numerical simulation with a given integration step.

As can be seen from Fig. 2b, in the steady-state regime, the stator currents are symmetrical, and the magnitude of the angle between the generalized vectors of stator currents and voltages stabilizes at a constant level (approximately 22 electrical degrees for this load) and shows no oscillations, remaining constant over time.

Thus, the obtained values of the diagnostic criteria for both methods can be used as baseline references for subsequent comparison with the operation of the motor having a damaged squirrel-cage rotor winding.

Figure 3 presents graphs showing the variation of diagnostic parameters for a case with one broken rotor bar. These differ significantly from the stable values observed with a healthy rotor winding (shown in Fig. 2) and exhibit clearly pronounced periodic oscillations after reaching the steady-state regime.

From the computer simulation results presented in Fig. 3, it can be seen that for the method based on monitoring the sum of phase current angles (Fig. 3a), the oscillation amplitude is approximately 1° with a period of 0.5 seconds. For the method based on monitoring the angle between the current and voltage vectors (Fig. 3b), the oscillation amplitude is significantly higher, reaching approximately 15°, with an oscillation period of 0.8 seconds.

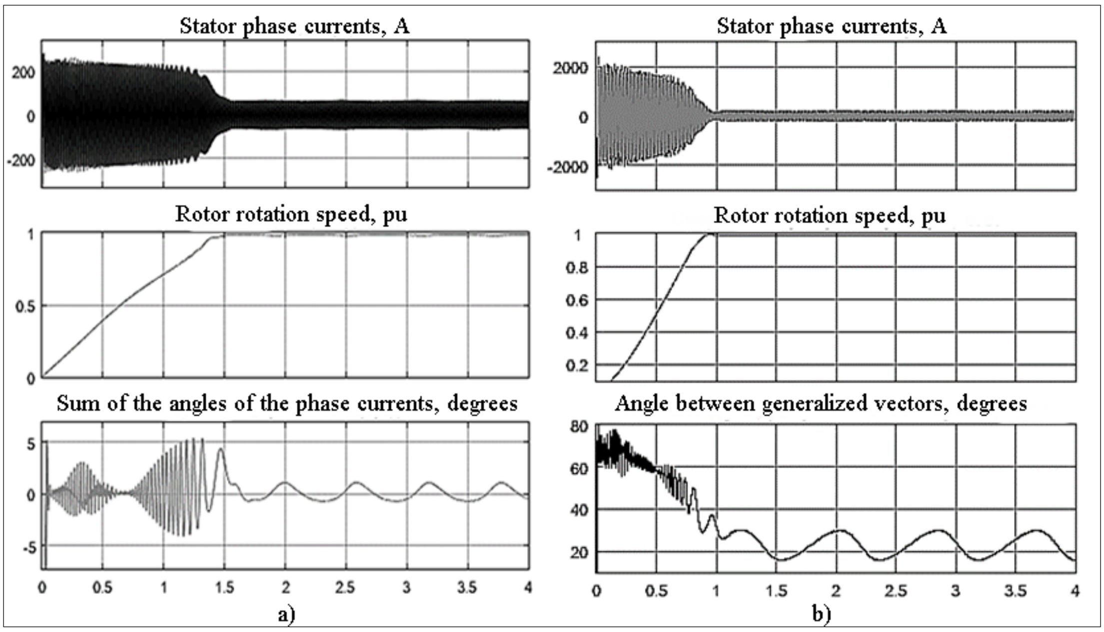

Fig. 3: Results of computer simulation of the diagnostic algorithms presented in this work for a case with one broken rotor bar

The observed oscillations in the monitored criteria are caused by fluctuations in the resultant magnetic flux in the air gap. These fluctuations arise due to the disruption of rotor current symmetry resulting from a broken rotor bar in the squirrel-cage winding.

The recorded differences in the amplitude and period values of the two methods demonstrate their varying sensitivity to the diagnosed fault. This difference in sensitivity is due to their different responses to various components of the arising disturbances.

The obtained data confirm the fundamental feasibility of diagnosing broken rotor bars using the proposed criteria.

Figure 4 presents the results of computer simulation for the operation of the presented diagnostic methods in the case of several broken rotor bars.

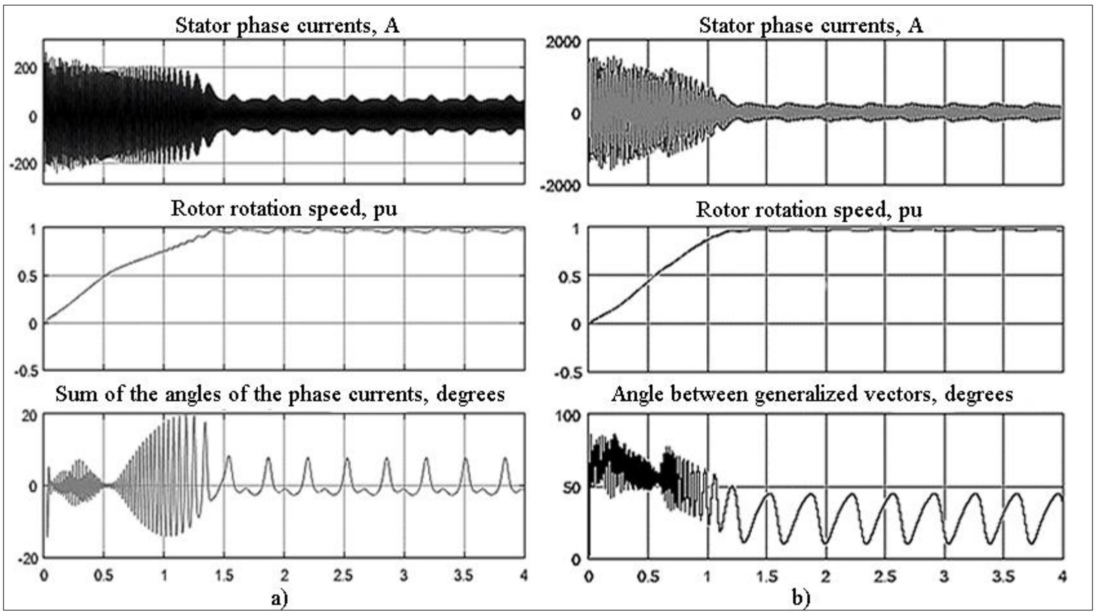

Fig. 4: Results of computer simulation of the diagnostic algorithms presented in this work for a case with several broken rotor bars.

Analysis of Fig. 4 shows that the response of both methods intensifies with an increasing number of broken bars. For the method monitoring the sum of phase current angles (Fig. 4a), with four broken bars, the oscillation amplitude increases to 8°, which is eight times the level observed with one broken bar (~1°). The oscillation period simultaneously decreases to 0.3 seconds. For the method monitoring the angle between vectors (Fig. 4b), with five broken bars, the oscillation amplitude increases from ~15° to ~33° (more than twofold), and the oscillation period decreases from 0.8 s to 0.35 seconds. The changes in amplitude and period are caused by the increased magnetic asymmetry in the air gap between the rotor and stator. More severe rotor damage and the resulting greater asymmetry lead to higher amplitude and faster oscillations of the monitored parameters.

Conclusion

Thus, the obtained results demonstrate that the proposed criteria not only detect the presence of a fault but also exhibit sensitivity to its severity by altering the amplitude-frequency characteristics of the monitored parameter.

Scientific Novelty and Theoretical Significance

Based on a critical analysis of existing diagnostic methods, a novel approach has been substantiated and implemented. This approach involves a shift from current spectral analysis to the complex processing of interrelated instantaneous values of stator currents and voltages. Within this framework, two new diagnostic criteria have been developed and mathematically described: the sum of stator current phase angles and the angle between the generalized vectors of currents and voltages. These criteria provide a direct link to the physics of the fault occurrence (magnetic asymmetry in the air gap) and offer greater information content compared to traditional methods.

Experimental Validation of Method Effectiveness

Using a mathematical model of an induction motor, it has been proven that under healthy conditions, both criteria exhibit stable behavior, establishing a clear baseline. When simulating broken rotor bars, a clear emergence of pronounced periodic oscillations in the diagnostic parameters was recorded, confirming their fundamental ability to detect the fault. A direct correlation was established between the amplitude-frequency characteristics of the oscillations and the number of broken bars, indicating that the methods are sensitive not only to the fact of damage but also to assessing its severity.

Practical Significance and Implementation Potential

The proposed methods possess a key practical advantage: their implementation requires only standard tools for measuring instantaneous current and voltage values, which are already used in power monitoring and metering systems. This eliminates the need for installing specialized sensors (vibration, magnetic) and allows for the integration of the algorithms into existing diagnostic or predictive maintenance systems without significant capital expenditure.

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