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Diagnostics of Damage to the Rotor of an Induction Machine Using the Method of Instantaneous Power Analysis

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ABSTRACT: The relevance of the problem under study is that in the modern world, where induction machines are widely used in industry, early detection of rotor damage using the method of instantaneous power analysis is critical to maintaining uninterrupted equipment operation and reducing operating costs. The purpose of this study is to investigate and determine the effectiveness of the method of instantaneous power analysis for diagnosing rotor damage in induction machines to improve their reliability and reduce the risk of production failures. The methods used include the analytical method, classification method, functional method, statistical method, synthesis method. In today's industry, asynchronous machines play a central role, creating a high demand for their reliable and safe operation. Malfunctions and failures in the operation of these machines can lead to serious downtime and considerable losses that affect the financial position of the company. One method of accurate fault diagnosis is to analyses the theoretical components added to the motor current. The analysis revealed that the locus of the space vector, instantaneous power, and sideband frequencies around the fundamental frequency indicate possible broken rotor cores of an induction machine. These components become key indicators for fault detection in induction machines. Furthermore, the experiments on a three-phase squirrel-cage induction confirmed the theoretical analysis, reinforcing the practical significance of the developed methodology for early diagnosis and improving equipment reliability, as well as reducing maintenance and repair costs. The practical significance lies in the development of a methodology that can be used in the industry for early diagnosis of rotor damage in induction machines, ensuring increased equipment reliability and reduced maintenance and repair costs.

Keywords: Squirrel Cage Induction Machine, Rotor Bars Fault Detection, Stator Current Space Vector, Spectral Analysis, Instantaneous Power.

I. INTRODUCTION

Investigation of this subject is crucial for many reasons. Firstly, the growing use of induction machines in industry, transport, and other sectors makes it important to improve the methods of diagnostics and maintenance of this equipment. Secondly, incorrectly detected or ignored rotor damage can lead to excessive downtime and serious losses. Thus, early detection of problems becomes a key aspect of effective equipment maintenance and management. Thirdly, modern technologies and methods allow for the development of innovative approaches to diagnostics, including instantaneous power analysis, which can considerably improve the accuracy and speed of fault detection. Therefore, the study of this problem is a major step towards improving equipment reliability and reducing operating costs in various industrial sectors.

The problem of this study is substantially related to the complexity and diversity of possible damage to the rotor of induction machines. Damage can occur because of a range of factors such as wear, vibration, exceeding operating parameters, and many others. This diversity makes it difficult to develop universal diagnostic methods. Many rotor damages can be difficult to identify due to their small size or early stage of development, when they are not yet easily observable. Furthermore, there are other factors, such as measurement noise and signal non-stationarity, which can complicate analysis and diagnosis. Thus, the study of the problem of diagnosing rotor damage in induction machines is a challenge and requires the development of novel approaches and methods to achieve reliable and efficient results.

Induction motors are widely used in various industries due to their durability, availability and minimal maintenance requirements. However, defects in induction motors can lead to unexpected periods of downtime and significant repair costs. Therefore, timely fault detection is critical for effective maintenance and to prevent performance degradation. A common problem is the presence of broken rotor bars (BRBs) which, if not noticed, can lead to rotor damage. This has prompted significant research into new methods of detecting BRB defects. Early detection of BRB problems is difficult due to a variety of reasons. BRB problems can occur due to several factors such as heat stress, fatigue, manufacturing defects, and others. In addition, these problems are difficult to detect early with standard motor current signature analysis. Accurate diagnosis is complicated by environmental noise and load variations. Therefore, sophisticated signal processing techniques must be used to accurately identify BRS.

In this context, instantaneous power analysis appears to be a very promising method. This process involves the study of power signals containing fault indications that are not affected by load variations. Researchers have confirmed the effectiveness of using instantaneous power spectral analysis to detect faults in PDBs. However, there are still obstacles to overcome when it comes to creating robust algorithms and utilizing them in industrial settings. The aim of this research is to investigate and verify the effectiveness of instantaneous power analysis for detecting rotor problems in induction motors. The objective is to provide an accurate and simple method that can be easily implemented to improve reliability, minimize failure probability, and reduce maintenance costs. Specific contributions include:

- Empirical verification of theoretical principles concerning the effect of BRB faults on instantaneous power.
- Displaying characteristic failure indicators using real-time power spectral analysis.
- Presenting evidence supporting the use of instantaneous power analysis as an effective diagnostic tool for detecting faults in an induction motor rotor.

The results of this study will contribute to advances in motor fault diagnosis and enable the use of instantaneous power analysis to accurately diagnose rotor faults in industrial applications.

II. RELATED WORKS

A. Chaban et al. [1] underscores the significance of utilizing mathematical modelling to examine the instantaneous power in induction machines. However, the research did not delve into the aspect of creating models that could enable precise forecasts of alterations in power consumption in induction machines when subjected to rotor damage. According to P. J. O. Suárez et al. [2], the use of artificial intelligence and data analysis is proposed to detect unusual phenomena in the operation of asynchronous machines. The study demonstrates how machine learning can improve diagnostic accuracy. However, the study did not decide how these methods could be implemented.

V. Harish et al. [3] is actively engaged in advancing cutting-edge sensors and enhancing data acquisition systems with the goal of attaining precise measurements of current and voltage. These measurements serve as the foundation for subsequent investigations into instantaneous power. Analysing the elements contributing to losses and crafting efficient control strategies for permanent magnet synchronous reluctance machines are pivotal facets of research within the field of electrical and energy engineering. Nevertheless, the challenges related to scrutinizing loss components and devising effective control strategies for synchronous reactive machines remain unaddressed. W. Purbowaskito et al. [4] suggest that integrating physical measurements with mathematical models within rotor diagnostics can enhance the precision and dependability of fault detection procedures. However, the research did not address the challenge of finding a specific blend of various hybrid techniques to enhance the monitoring of induction machine conditions and their integration into the measurement system.

As noted by S. K. Gundewar and P. V. Kane [5], a significant challenge lies in implementing advanced signal processing algorithms to identify faults in induction machines during their initial stages of development. However, the author does not provide specific resolutions for this matter. A. Ur Rehman et al. [6] actively exploring the potential application of acoustic emission and instantaneous power analysis as a novel approach for detecting rotor damage, particularly in actual operational settings. This research holds significance for the advancement of induction machine diagnostics. However, the challenge of putting these methods into practice in a real-world environment remains unresolved.

Rangel-Magdaleno et al. [7] investigated the use of discrete wavelet transform analysis to detect partially damaged rotor bars in induction motors under different loading conditions, which showed promising results in detecting incipient damage. However, further improvement in classification accuracy is needed, especially under different loading conditions, which can be addressed in future work by exploring alternative classifiers such as multilayer perceptron (MLP), support vector machines (SVM) and artificial neural networks (ANN). In the work of Resendis-Ochoa et al. [8], a methodology was proposed that uses automatic learning and non-segmented infrared imaging to diagnose faults in induction motors and their kinematic circuits. It demonstrates effectiveness in analyzing thermal conditions from thermograms and classifying faults including rotor core failure, bearing damage, and misalignment. However, there are potential problems with accurate fault identification in real industrial applications due to factors such as environmental interference or complex fault combinations.

A universal asymmetric mathematical model for simulating marine induction motor faults, particularly rotor core breakage faults, to aid in centralized control and diagnosis of marine electrical equipment was presented by Dzhagarov et al. [9]. However, there may be limitations in extrapolating experimental results to real shipboard conditions, given the complexity of shipboard environments and potential variations in fault manifestations. In their study, Yatsugi et al. [10] proposed a method to diagnose and classify major induction motor faults, including bearing faults, rotor core failure, and insulation short circuit, using spectral characteristics of motor stator current and motor speed. However, diagnosis of simultaneous occurrence of multiple classes of faults, which are common in industrial applications, requires future research.

Researchers Sabir et al. [11] presented a new experimental technique for the diagnosis of incipient faults in induction motor rotors based on the analysis of the linear stator current, highlighting six critical aspects for detection and classification. Despite the promising results of early diagnosis without direct access to the machine, there may be limitations regarding the generalizability of the method for different fault types and operating conditions. Scholars Martinez-Herrera et al. [12] considered a simple technique for detecting multiple faults in induction motors during the start-up transient based on the calculation of homogeneity and excess over a single phase of the electric current signal. Despite the promising results in detecting and classifying different faults with high confidence, there may be limitations regarding the robustness of the method under different operating conditions and its ability to generalize additional fault types beyond those considered in this study.

Although previous studies have shown the potential of using instantaneous power analysis to detect faults in the rotor of induction motors, there is a need to more fully experimentally validate and investigate the distinctive features of fault indicators detected using instantaneous power spectral analysis. Previous studies have mainly focused on theoretical analysis or modeling-based methodology. This study aims to comprehensively illustrate the specific fault harmonics that can be observed in instantaneous power signals caused by rotor faults. This work aims to make a significant contribution to the establishment of instantaneous power analysis as a reliable diagnostic tool for induction motors in real industrial applications. For this purpose, it is necessary to validate the theoretical foundations and to identify fault indications through practical tests. The experimental results will contribute to expanding the knowledge base of fault signs, in particular those related to instantaneous power fluctuations.

III. MATERIAL AND METHOD

The analytical method helped to significantly improve the forecasting of the need for repair and maintenance of the induction machine. This method allowed real-time analysis of the machine's operation and the prompt detection of any anomalies that could indicate rotor damage. This helped to take prompt action to eliminate problems and prevent serious failures, which considerably reduced repair costs and increased equipment productivity. Furthermore, the analytical method contributed to the efficient use of resources and service planning based on real needs.

The statistical method provided important information in the context of the study. This method made it possible to investigate substantial amounts of data and identify patterns that may go unnoticed during a cursory examination. For instance, a statistical study could reveal correlations between different variables or factors affecting the phenomenon under study, which should be considered in further decisions. Thanks to the statistical method, it was possible to build reliable forecasts and models to predict future events or trends. All these findings and the results of the statistical study helped to improve the quality of decisions and the efficient use of resources.

By applying the functional method, considerable improvements were made in the context of the study. This method is based on the investigation of the functional aspects of a system or process and helps to study their functional relationships in detail. Based on the data obtained, it was possible to determine how the elements of the system interact with each other, which helped optimize their operation and improve productivity. One of the main advantages of the functional method is the ability to identify weaknesses or problems in the system that can be further optimized. The assessment of functional relationships helped identify and eliminate excessive complexity, unnecessary steps or duplicate processes, leading to more efficient solutions and resource savings. Thus, the functional method has proved to be a powerful tool for optimizing operations and improving research or production results.

The structural-functional method helped in understanding and optimizing complex systems and processes. Using this method, a detailed decomposition of the system into its structural components and the functional relationships between them were assessed. This helped to clarify the role of each component in the system and its contribution to the overall result. Furthermore, the structural-functional method helped to identify possible weaknesses, inefficiencies, and redundancies in the system. The review of structural interconnections made it possible to improve the joint operation of the components and optimize their interaction. This has led to improved system performance and resource utilization, reduced unnecessary costs and increased reliability.

The deduction method helped in the systematic and logical consideration of complex problems and tasks. This method is based on establishing general principles, rules, and hypotheses, and then using them to reach concrete conclusions. Deduction also helped to structure information and come up with logical solutions to problems, even in cases where the source data was ambiguous or limited.

By applying the synthesis method, meaningful results have been achieved in creating new systems, products, or solutions. The synthesis method involves combining different components, ideas, or elements to create something new or optimize an existing one. The synthesis method allows combining distinct concepts, technologies, or elements in an innovative way, resulting in something valuable and effective.

IV. DATA ANALYSIS

A. CHARACTERIZATION OF INDUCTION MOTORS

Due to their availability, stability, easy controllability, reliability, and minimal maintenance requirements, induction motors have become an integral part of modern electric utilities and the processing industry [13]. Damage, such as broken rotor bars (BRBs), can lead to further breakdowns, which adversely impacts on induction machine performance and increases operating costs. Therefore, the prompt detection of rotor defects, such as BRBs, is critical. Any abnormality or defect in the machine can be detected at an early stage thanks to appropriate condition monitoring, accompanied by an efficient signal processing method. Recently, monitoring the condition of induction motors has become vital to reduce maintenance costs and prevent unplanned outages [14]. Therefore, a considerable amount of research has been conducted to develop new monitoring methods and create more efficient induction motors. Failure of induction machines during operation can be caused by a range of factors, such as natural ageing, assembly problems, operating conditions, cooling conditions, environmental influences, or a combination of various mechanical faults.

Rotor defects can occur even at the production stage due to deficiencies in the rotor casing casting process, especially when using the injection molding method [15]. A loose connection can also cause malfunctions when the rotor housing is connected by brazing or welding the end rings. These defects lead to an increase in resistance, which leads to overheating and reduced housing strength at hot temperatures. This can lead to cracks in the rotor bars, usually located on the casing end rings, especially if the bars are not properly supported by the rotor core [16]. Electrical, mechanical, or thermal faults can occur during operation of an induction machine, especially when it is operated in intermittent mode [17]. In this case, the initial currents can exceed the rated current by a factor of six to seven, and the motor runtime will be very short. The large amount of heat energy causes the rotor bars to crack.

When a three-phase induction motor is excited by a balanced three-phase power source, the windings set up a uniform magnetic field that revolves around the rotor periphery at synchronous speed. The magnetomotive force of induction machine is calculated by the following expression (3):

$$F_s(\alpha, t) = F_{f1m}\, sin(\omega_1 t - p\alpha). \tag{1}$$

where: F_{f1m} is a peak value of fundamental magnetomotive force. The flux cutting action induces an electromotive force and thereby a current in the rotor conductors. The angular frequency of the rotor current ω2 can be expressed as follows (1):

$$\omega_2 = s\omega_1, \tag{2}$$

where: *s* is the slip of the induction machine and can be calculated as follows (2):

$$s = \frac{\omega_1 - \omega}{\omega_1} = \frac{\Omega_1 - \Omega}{\Omega_1} = \frac{n_1 - n}{n_1}, \tag{3}$$

where: *Ω1* and ω1 represent the angular velocities of the magnetic field in radians per second and electrical radians per second, respectively, *n1* indicates the synchronous speed of rotation of the magnetic field in revolutions per second, n indicates the rotor speed in revolution per second and p indicates the number of pole pairs.

The magnitude of the rotating magnetic field stays unchanged and is calculated using the following expression (4):

$$F_{1m} = \frac{3\sqrt{2}}{\pi} \frac{N k_{y1} k_{d1}}{p} I_1, \tag{4}$$

where: *N* indicates the number of turns that are connected in series in each phase, *ky1* and *kd1* are and the distribution winding factor, respectively, related to the fundamental harmonic. *I1* represents the root-mean-square value of the stator winding current.

The currents flowing through each rotor bar are calculated using the following expression (5):

$$i_{b(n)} = I_{mb}\, sin(s\omega_1 t - n\phi), \tag{5}$$

where: *ib(n)* represents the instantaneous current value of the nth bar of the rotor; *ϕ=2πp/Zr* is the angle between two adjacent rotor bars; *Zr* determines the number of rotor bars; n is an integer from 1 to *Zr*, and Ibm is the maximum value of the rotor current. Each rotor bar generates a magnetomotive force (MMF) as follow (6):

$$f_{b,n}(\alpha, t) = I_{bm}\, sin[s\omega_1 t - n\phi]\, cos[p\alpha - n\phi], \tag{6}$$

where: *fb,n* represents magnetomotive of the nth rotor bar, and *α* is the air gap of the asynchronous machine in radians.

The total MMF of rotor bars can be expressed as follows (7):

$$f_r(\alpha, t) = \frac{Z_r}{4} I_{bm}\, sin(s\omega_1 t - p\alpha). \tag{7}$$

According to (7), the magnetic flux generated by the rotor bar currents rotating at a speed *sω1* related to rotor reference frame. The rotor MMF revolves according the stator reference frame can be expressed as follows (8):

$$\Omega_2^{(1)} = s\Omega_1 + \Omega = s\Omega_1 + (\Omega_1 - s\Omega_1) = \Omega_1. \tag{8}$$

As shown in (8), when the stator winding of three-phase induction machine is connected to a three-phase power source, it produces a magnetic field that is constant in magnitude and revolves around the periphery of the rotor at constant speed which determined by the frequency of the applied source [18]. The interaction of magnetic flux and the rotor bar currents generates an electromagnetic torque. The space vector of voltage and currents of stator winding also the space vector of rotor currents according stator reference frame can be expressed as follows (9-11):

$$\bar{\iota}_s = \frac{2}{3}[i_{sA}(t) + a i_{sB}(t) + a^2 i_{sC}(t)] = \bar{I}_1 e^{j\omega_1 t}, \tag{9}$$

$$\bar{v}_s = \frac{2}{3}[v_{sA}(t) + a v_{sB}(t) + a^2 v_{sC}(t)] = \bar{V}_1 e^{j\omega_1 t}, \tag{10}$$

$$\bar{\iota}_r = \frac{2}{3}[i_{ra}(t) + a i_{rb}(t) + a^2 i_{rc}(t)] = \bar{I}_2 e^{j\omega_1 t}. \tag{11}$$

The unit space vector of the currents of the stator and rotor windings is denoted as 1, a, a2, indicating the direction of the magnetic axes of the stator phases winding [a=exp(2π/3)]. The locus of space vector of stator current can be represented as a circle with a constant radius equal the magnitude of the stator phase current *Im*. The instantaneous power of three phases of an induction machine under normal operating conditions can be expressed as follows (12):

$$p(t) = v_{sA}(t) i_{sA}(t) + v_{sB}(t) i_{sB}(t) + v_{sC}(t) i_{sC}(t). \tag{12}$$

The instantaneous power can be expressed using the space vector of voltage and current of stator winding as follows (13):

$$p = \frac{3}{2} Re(\bar{v}_s * \bar{\iota}_s^{\,*}) = 3V_1 * I_1 \cos\varphi. \tag{13}$$

The values *V1* and *I1* represent the root-mean-square values of the voltage and current on the stator winding of the induction machine. According to (12), the instantaneous power of an induction machine operating under normal conditions is a constant value.

B. AN INDUCTION MACHINE WITH DAMAGED ROTORS

This chapter focuses on how BRBs effect on instantaneous power of three-phase induction machine. In the previous section, it was assumed that a symmetrical three-phase voltage with a frequency f1 is supplied to the induction machine, and symmetrical three-phase currents with the same frequency flow through the stator windings. These stator currents produce a magnetomotive force wave with constant magnitude which revolves in the air gap at synchronous speed. A resultant air gap flux-density wave generates an electromotive force EMF in the rotor bars with a frequency sf1 [19].

To simplify the mathematical expression of the magnetomotive force (FMM) in case of rotor bars cracked, first assume that the currents in each bar maintain constant, as in the symmetrical scenario. Furthermore, assume that the current in the damaged bars is negligible (zero). Considering these assumptions for the resulting FMM generated by the rotor winding, can be obtain by the resulting FMM in the normal condition, subtracting the FMM introduced by the BRBs. Thus, the FMM of rotor bars can be expressed as follows (14):

$$F(\alpha,t) = \frac{1}{2}\left(\frac{Z_r}{p} - 1\right) I_{mb} \sin(s\omega_1 t - \alpha) - \frac{1}{2} I_{mb} \sin\left(\alpha + s\omega_1 t - \frac{2\pi p}{Z_r}\right). \tag{14}$$

As can be deduced from the above expression, the magnetomotive force (FMM) generated by the rotor winding consists two components. The first component on the right-hand side of (15) means a positive FMM wave rotating with an angular velocity sω1 (relative to the rotor reference frame), and it can be formulated as follows:

$$F_2^{(+)}(\alpha,t) = \frac{1}{2}\left(\frac{Z_r}{p} - 1\right) I_{m,b} \sin(s\omega_1 t - \alpha). \tag{15}$$

The second component means the negative MMF wave, which also rotates with an angular velocity sω1, but in the opposite direction to the rotor rotation. Its value can be expressed as follows (16):

$$F_2^{(-)}(\alpha,t) = \frac{1}{2} I_{m,b} \, sin\left(\alpha + s\omega_1 t - \frac{2\pi p}{Z_r}\right). \tag{16}$$

The negative FMM wave will generate a magnetic flux that rotates with an angular velocity (1-2s)ω1 based the stator reference frame. Thus, the stator winding current, except the fundamental component with angular frequency *ω1*, contain an additional component with angular frequency (1-2s)ω1. Therefore, the instantaneous values of the stator phase currents in an induction machine with BRBs can be expressed as follows (17):

$$\begin{aligned} i_{sA}(t) &= I_m \cos(\omega_1 t + \varphi) + I'_m \cos[(1-2s)\omega_1 t + \varphi_1{}'] \\ i_{sB}(t) &= I_m \cos(\omega_1 t + \varphi - 2\pi/3) + I'_m \cos[(1-2s)\omega_1 t + \varphi_1' + 2\pi/3]. \\ i_{sC}(t) &= I_m \cos(\omega_1 t + \varphi - 4\pi/3) + I'_m \cos[(1-2s)\omega_1 t + \varphi_1' + 4\pi/3] \end{aligned} \tag{17}$$

$I_m^{'}$ denotes the magnitude value of the harmonic (1-2s)f1, while φ′ represents its phase angle. The space vector of stator winding currents in a fixed reference frame can be expressed as follows (18):

$$\bar{\imath}_s = \bar{I}_1 e^{j\omega_1 t} + \bar{I}_1' e^{j[(1-2s)\omega_1 t]}. \tag{18}$$

Equation (18) demonstrates that when the rotor bars are broken, the space vector of stator currents contains an additional component rotating with an angular velocity (1-2s)ω1. The value of this additional component depends on motor loaded and the number of BRBs. The value of the space vector of the phase currents fluctuates with the frequency (1-2s)f1. The instantaneous power of an induction machine operating with BRBs can be expressed as follows (19):

$$p = {}^3/_2 \, Re\big(\bar{u}_s * \bar{\imath}_s^* = {}^3/_2 \, Re[\bar{V}_1 e^{j\omega_1 t}(\bar{I}_1 e^{j\omega_1 t} + \bar{I'}_1 e^{j[(1-2s)\omega_1 t]})^*\big] = 3V_1 * I_1 cos\varphi_1 + 3V_1 * I'_1 cos\varphi'_1 + 3V_1 * I'_1 \cos\,(2s\omega_1 t - \varphi'_1). \tag{19}$$

According to (19), the instantaneous power of an asynchronous machine operating under broken rotor bars consists of two components: one which is constant and does not vary by time, while the other components fluctuations with a frequency of *2sf1*. Comparing (14) with (19), it becomes clear that when the rotor bars are broken, the instantaneous power of the asynchronous machine fluctuates with a frequency *2sf1*. On the other hand, the constant component of instantaneous power is increase. Thus, in case of induction machine is working with rotor bars damage results in higher power losses [20-22]. The interaction between the main magnetic field of the stator winding and the negative sequence of the rotor current creates a pulsating torque that oscillates with a frequency *2sf1*. This pulsating torque, causing rotor speed fluctuations. Consequently, these speed fluctuations induce sideband components around the fundamental frequency in the stator winding of the induction machine. The frequency of these sideband components is matched (20):

$$f_{brb,s} = (1 \pm 2ks)f_1. \tag{20}$$

Sideband frequencies denoted as *fbrb,s* are related to the presence of broken rotor bars, while *k* represents an integer (1, 2, 3, …). When analyzing the spectral composition of the instantaneous power, additional harmonics ±*2ksf1* are appears. Based on research, the BRBs in an induction machine can be detected using the following approaches [23]:

- monitoring of stator phase currents;
- the locus of space vector of the stator current;
- estimation of the instantaneous power of an induction machine;
- monitoring the axial fluxes;
- monitoring the shaft speed;
- analysis of stator frame vibration;
- spectral analysis of the stator current.

C. EXPERIMENTAL DATA FOR A FUNCTIONING INDUCTION MACHINE

In this study, instantaneous power analysis was performed to detect BRBs in an induction machine. To confirm the theoretical analysis of induction machine faults described earlier, a series of experiments were conducted. The experimental data collected during these experiments with the induction machine are summarised in Table 1.

Table 1. Experimental data from the induction machine

Description	Value
Pn (KW)	3
Vn (V)	230
In (A)	6.9
fn (Hz)	50
nn (rpm)	1410
p (pole pairs)	2

Source: compiled by the authors.

In this study, the induction machine was loaded by DC generators. The experimental setup presented in Figure 1 involved connecting an induction machine to a symmetrical three-phase network with a frequency of 50 Hz. Velleman PCS 500 instruments, including an oscilloscope, transient recorder, spectrum analyzer, and TDS digital oscilloscope, were used to perform spectral analysis of the stator current winding, as well as to analyses the instantaneous power waveform and locus current vector. At the beginning of the study, experiments were conducted with an induction machine that operated under normal conditions. This machine was powered by a three-phase symmetrical network using a 3-phase variable autotransformer.

FIGURE 1. Arrangement of the experimental setup.

Source: compiled by the authors.

Figure 2 shows the instantaneous currents of an induction machine during normal operation. The phase current displays a symmetrical characteristic.

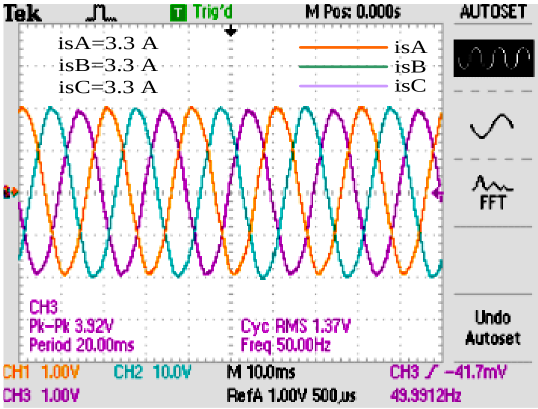

FIGURE 2. Current waveforms of the induction machine during normal operation

Source: compiled by the authors.

Figure 3 shows an instantaneous power graph of an induction machine under normal operating conditions.

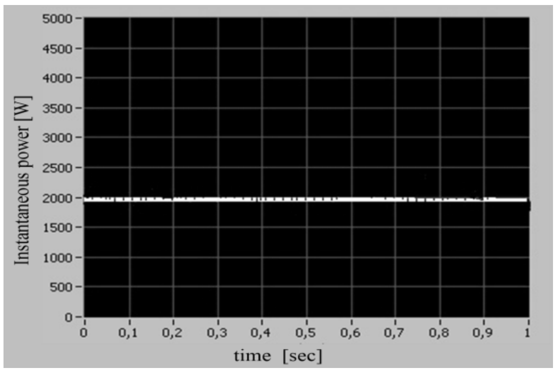

FIGURE 3. The power instantaneously generated by an induction motor during normal operation

Source: compiled by the authors.

As Figure 3 shows, the instantaneous power of the induction machine stays constant as expected. Figure 4 also shows a spectral analysis of the stator current.

FIGURE 4. The current frequency spectrum of an induction motor

Source: compiled by the authors.

As Figure 4 shows, it only displays the main components, such as the power supply frequency. An experiment was also conducted on the same induction machine in which two rotor bars were broken. Figure 5 shows a graph of the stator current of an induction machine with such rotor damage.

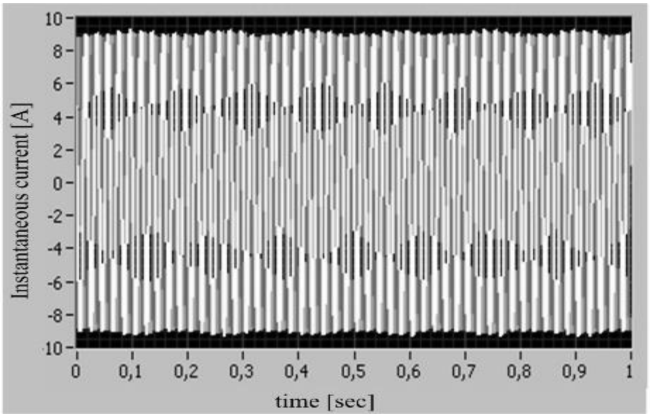

FIGURE 5. Current waveforms of an induction motor operating at rated power with rotor bars damage

Source: compiled by the authors.

As Figure 5 shows, the maximum value of the motor current does not stay constant, but instead there is a pulsation with a frequency 2sf1. On the other hand, Figure 6 shows the instantaneous power of an induction machine. Notably, the instantaneous power of an induction machine in the presence of rotor damage does not stay constant but has a pulsating nature. The pulsation frequency of the instantaneous power of an asynchronous machine is 2sf1.

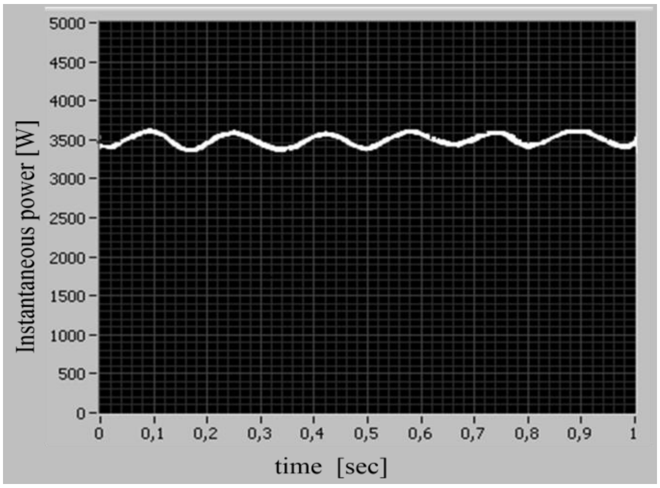

FIGURE 6. The instantaneous power of an induction motor that is operating at full capacity with rotor bars damage

Source: compiled by the authors.

Figure 7 shows a graphical representation of space current vector of the stator of an induction machine. As this figure shows, the space stator current vector forms represent a circle.

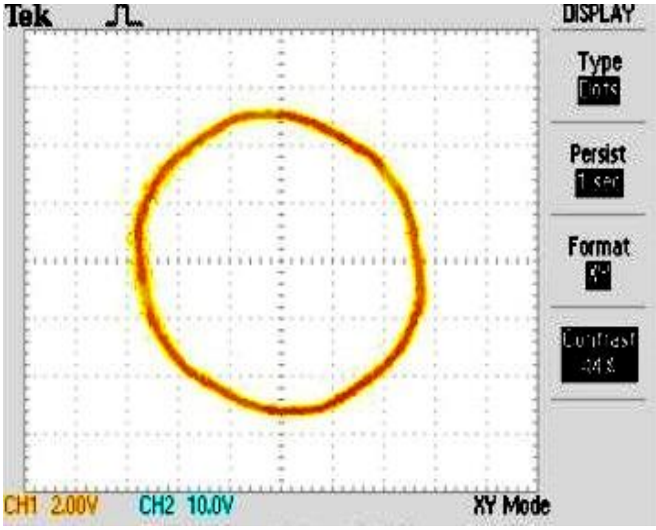

FIGURE 7. A graphical representation of the trajectory of the spatial current vector of an induction motor operating at half its rated power and with defects in the rotor

Source: compiled by the authors.

On the other hand, Figure 7 shows the results of the spectral analysis of the instantaneous power of an induction machine loaded at rated power and operating in the event of a rotor busbar failure. As Figure 8 shows, the presence of damage in the rotor of the induction machine appeared the harmonics with a frequency 2sf1, which is an important and unique result.

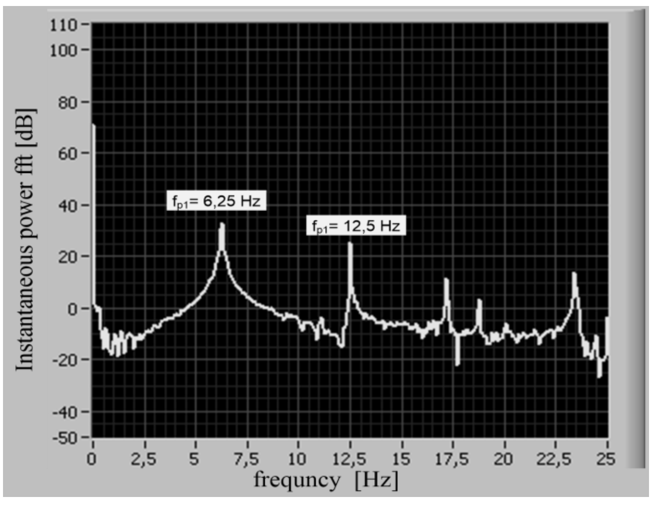

FIGURE 8. Analysis of the frequency spectrum of the instantaneous power of an induction motor operating at rated power with rotor bars damage

Source: compiled by the authors.

In the presence of defects in the rotor bars, such as cracks or ring damage, a negative current sequence occurs in the rotor, which causes stator line currents with added side bands [24]. These currents have a double sliding frequency around the fundamental frequency. This results in a change in the instantaneous power of the induction machine over time, and the fluctuations in power depend on the number of defects and the motor load. The spectral analysis of the instantaneous power of an induction machine shows the predominance of the double slip frequency, which is displayed as 2ksf1.

V. RESEARCH FINDINGS

Investigation of the instantaneous power in induction motors reveals a distinct component that oscillates at twice the slip frequency (2sfs), especially in the presence of cracks in the rotor bars. This phenomenon is due to multiple factors: when the motor is operating under normal conditions, an electric current is induced in the rotor rods, which generates a forward rotating magnetomotive force (MFM) at the slip frequency (sfs). However, breakage of the rotor rods leads to the breaking of this symmetry, causing air gap flux imbalances and aberrant rotor currents that generate a counter-rotating MMF at the slip frequency. The interaction of the stator forward rotation magnetomotive force and the reverse rotation magnetomotive force of the defective rotor leads to electromagnetic torque oscillations at twice the synchronous frequency (2sfs), which causes rotor speed oscillations. As a result, the stator currents experience amplitude modulation at twice the synchronous frequency (2sfs) due to the rotor moving along the stator flux.

The appearance of an additional harmonic at 2sfs serves as a definitive indication of the existence of a reverse rotating field. This provides a theoretical basis for detecting defects in the rotor by studying instantaneous power signatures. The power analyzer was used to check the instantaneous power of a 3-phase induction motor under normal operating conditions, without rotor damage. The analyzer was connected to the stator terminals. The motor was operated at specified voltage and frequency of 400 V and 50 Hz respectively. The waveform of the measured instantaneous power in the time domain had a constant character without any noticeable amplitude modulations or variations. This is consistent with the theoretical prediction that the instantaneous power of a symmetrical induction motor should remain constant in the absence of any defects. Fast Fourier Transform (FFT) was used to calculate the spectral analysis of the instantaneous power signal. The obtained power spectrum showed the presence of a single and prominent harmonic at 50 Hz, which coincides with the fundamental frequency of the power supply. The absence of any other noticeable frequency components in the power spectrum confirms the expected theoretical instantaneous power property for a well-functioning induction motor. This implies the absence of any defects or anomalies in the rotor state that could generate additional harmonics, indicating its symmetry.

In particular, there is no evidence of the 2sfs component, which often appears in the presence of open circuits. The absence of peaks occurring at twice the slip frequency is strong evidence that the observed instantaneous power signal is consistent with normal operation, indicating the absence of rotor asymmetry or any associated signs of failure. The practical results confirm the theoretical prediction that a motor with intact rotor bars will not have fault harmonics in its instantaneous power spectrum. The reference point for the comparative analysis with faulty examples was determined based on this initial normal state estimation to look for clear fault signals. Thus, the instantaneous power study clearly demonstrates the striking divergence of the spectral characteristics of the normal and problematic engines. This demonstrates the ability of the method to accurately detect abnormalities in the rotor structure by detecting specific harmonic components that serve as fault indicators.

To confirm the theoretical failure rates, controlled studies were conducted where rotor rod failure was deliberately induced in the test engine. This was accomplished by perforating some of the rotor rods to simulate cracks or fragments. Out of 28 rods, 2 were broken, resulting in a significant change in amplitude at a particular frequency in the instantaneous power waveform. Spectral analysis revealed a significant harmonic component at 29.8 Hz in addition to the fundamental frequency of 50 Hz. The 29.8 Hz frequency corresponds to a doubled slip frequency (sfs) of 14.9 Hz for the test motor. After the introduction of 4 damaged rods, the amplitude modulations in the form of time signal became more prominent. The amplitude of the 29.8 Hz peak in the spectrum was noticeably higher compared to the scenario with 2 damaged bars. This illustrates a clear correlation between the size of the harmonics and the severity of the faults. Further experiments were conducted with increasing numbers of intentionally induced faults and reached a maximum of 10 broken bars. As the number of broken rods increased, the amplitude of the 29.8 Hz harmonic also increased in direct proportion. The amplitude of the 50 Hz component also increased with more severe damage.

The constant appearance and increase of the 2sfs harmonic depending on the number of broken rods experimentally confirms that it is a reliable indicator of rotor asymmetry resulting from breakage defects. The results confirm the theoretical prediction that the magnitude of the 2sfs component is directly related to the degree of rotor structure irregularity. Moreover, experiments conducted by repeatedly breaking and reconnecting the rods confirm that the amplitude of the 2sfs harmonics increases and decreases simultaneously with the appearance and removal of fracture defects. The effectiveness of the instantaneous power signature analysis method for detecting and quantifying rotor defects in induction motors has been thoroughly verified. The study showed that the 2sfs harmonic component was easily detected even when damage was present in only 2 of the 28 rotor bars. Although the damage was not severe, the 29.8 Hz peak was clearly visible in the instantaneous power spectrum. The effectiveness of this early detection method is confirmed by its ability to detect even the initial stages of asymmetry, which often manifests itself as a small number of broken rods in practical rotor damage conditions.

The results show that even minor rotor disturbances, which may not lead to immediate failure, can still generate characteristic patterns in the instantaneous power signal. In addition, tests under different loads were conducted to evaluate the stability of the system. The 2sfs harmonic was consistently observed in the instantaneous power spectrum at idle, 50% rated load, and 100% rated load. Its detection was clear and error free even when no load was present and the slip level and frequency component of 2sfs were minimal. The consistent presence of the problem sign under different operating loads indicates that the diagnostic results are not influenced by external load factors. The ability of the instantaneous power analysis method to detect rotor faults is confirmed by its stable performance under different settings, indicating its robustness. The reliable empirical observation of the 2sfs harmonic even under minor faults and varying loads confirms the effectiveness and robustness of the instantaneous power signature analysis method for detecting faults in induction motor rotors. In specific test scenarios involving minor rotor damage (2 broken bars), the stator current spectra did not exhibit any noticeable sidebands around the fundamental frequency, which usually indicate an inadequate rotor condition. Nevertheless, in identical experiments, the 2sfs harmonic was clearly discernible in the instantaneous power spectrum. This indicates that the method considered is capable of detecting problems at an early stage, even in cases where a conventional stator current study gives no indication. This emphasizes the increased sensitivity of using instantaneous power spectral fingerprints for accurate and early detection of rotor faults.

Moreover, a fault harmonic at a frequency 2 times the synchronous frequency (2sfs), which was predicted by theory, was consistently detected in experimental measurements performed under different rotor asymmetry test conditions. Both analytical and experimental results are consistent with respect to the characteristic frequency component that serves as a distinctive sign of fault. The agreement between mathematical prediction and observed confirmation shows that instantaneous power analysis can effectively detect aberrant rotor states by the presence of the 2sfs harmonic. The reliable empirical observation of the expected fault harmonics predicted by the theoretical calculations provides reliable confirmation of the effectiveness of using instantaneous power spectral analysis as a diagnostic tool for detecting induction motor rotor faults. Thus, the combination of analytical principles and rigorous empirical data unambiguously confirms the effectiveness and efficiency of the application of the considered method for the diagnosis of induction motor rotor faults.

VI. DISCUSSION

Diagnosing damage to the rotor of an induction machine is an important task in the maintenance and service of electromechanical equipment. Rotor damage can lead to serious accidents and costs that can be avoided or reduced by early detection of such defects. One potential method for detecting rotor defects is to use instantaneous power analysis and spectral analysis of machine currents. Based on the findings of this study, instantaneous power analysis can be an effective method for diagnosing damage to the rotor of an induction machine [25]. Under normal operating conditions, the instantaneous power is a constant value, and its change is mainly related to the load of the machine. However, in the case of rotor defects such as cracks or ring damage, there is a change in instantaneous power over time. This change is conditioned by the presence of added side current bands that have a double slip frequency relative to the fundamental frequency. The main indicator of detecting rotor defects in this method is the instantaneous power spectral analysis, which reflects the dominance of the double slip frequency 2ksf1. The occurrence of this frequency is an essential indicator of rotor damage and can be used to detect the problem early and launch preventive measures. Experiments confirm the effectiveness of this method. The results obtained during the experiments coincide with theoretical analyses, which indicates its accuracy and reliability. Thus, instantaneous power analysis using spectral analysis can be a useful tool for diagnosing rotor damage in induction machines. This method enables the detection of defects at an early stage of their development and prevents serious accidents and costs.

According to the recent research by S. T. Dadabaev [26], modelling the starting and transient processes of induction motors at reduced supply voltage is a major area of research in electrical engineering and automation. When the mains voltage drops, induction motors can experience various issues, such as an increase in starting current, a decrease in efficiency and the risk of overheating of the windings. Modelling these processes allows predicting and analyzing their impact on engine operation and developing measures for their management and control. One of the key aspects of modelling is to consider the dynamic characteristics of induction motors, such as the inertial properties of the rotor and the effect of voltage changes on motor torque. This enables the analysis of motor behavior under voltage conditions and predict what measures can be taken to minimize the negative effects.

Referring to the definition by N. Pirmatov and A. Panoev [27], frequency regulation of induction motors of textile enterprises' weaving machines is a crucial aspect of optimizing their productivity and efficiency. Textile weaving machines rely on induction motors for various weaving operations, and controlling their frequency can have several advantages. Frequency control enables precise speed control of various loom components such as warp and weft bundles, shuttle and shedding mechanism. This precise control is essential to achieve the desired fabric quality, especially when producing intricate patterns or fine textiles. By adjusting the motor frequency, textile operators can maintain a constant warp tension and ensure consistent weft insertion, resulting in a high-quality end product. Frequency control can lead to considerable energy savings. Traditionally, asynchronous motors have operated at fixed speeds, which often resulted in unnecessary energy consumption when the loom was not in full power. By adjusting the motor frequency according to real production needs, textile companies can reduce energy costs and contribute to more sustainable and environmentally friendly operations. Furthermore, frequency control can extend the service life of the motor and other mechanical components of the loom. Traditional on-off or constant speed operation of the motor can lead to wear and tear, whereas variable frequency drive allows for smooth start-up and gradual speed changes. This reduces the mechanical stress on the equipment and minimizes maintenance requirements, which ultimately reduces operating costs for textile mills [28, 29].

Z. Li et al. [30] found that the implementation and analysis of the modernization of a large-size induction motor to a permanent magnet motor (PM) in a circular economy is a major step in improving the efficiency and competitiveness of industrial enterprises. This modernization can have several key benefits and challenges. The benefits include increased engine efficiency and reduced power consumption. PM motors typically have a higher power factor and lower losses than traditional induction motors. This can lead to considerable energy savings, which is important for businesses operating in a closed-loop environment where resources may be limited. However, the introduction of diesel particulate matter (DPM) engines can also present some challenges, including high initial investment in the purchase of new equipment and the need to redesign the system to integrate the new engines. Therefore, it is important for industrial enterprises in a closed-loop economy to conduct a thorough cost-benefit analysis to estimate the feasibility of modernization.

W. Qinglong et al. [31] determined that the technology of direct poly-oriented control (DPC) of an induction motor is an important achievement in the field of industrial automation and energy saving. The main idea behind the DPC is the ability to control an induction motor accurately and efficiently by aligning the stator field with the rotor field. This ensures high accuracy of motor speed and torque control, which substantially expands the scope of its application. The air pollution control technology is successfully used in various industries, including manufacturing, transport, and energy. Its high efficiency, precise control, and resistance to load changes make it indispensable in modern automation systems and electric drives. However, implementing and maintaining a DPC requires specialized knowledge and resources, which may require additional investment and expertise. J.S. Fayzullayev and K. K. Jurayeva [32] proved with his research that the study of the transfer function of a traction induction motor controlled by a quadrangular converter is an important aspect in the field of electric drives and automated systems. This transfer function allows evaluating and analyzing the motor’s response to various input signals, which is crucial for optimizing drive performance and ensuring precise control.

Quadrature inverters are modern devices that enable efficient control of induction motors, which is especially important in industrial and transport applications [33]. Understanding and analyzing the transfer function in this context allows engineers and researchers to improve drive system performance and efficiency, as well as reduce energy consumption and wear and tear on equipment, which is essential for today’s technological and environmental requirements. According to M. A. Ugwiri et al. [34], vibration and current characteristics measurements play a vital role in detecting faults in induction motors. Vibration is a sensitive indicator of the machine’s condition, enabling the detection of problems in the mechanical part of the engine. Vibration analysis can detect imbalances, bearing wear, magnetic field irregularities, and other mechanical faults that can lead to motor failure. On the other hand, current characteristic analysis can detect electrical faults such as open windings, short circuits, and other problems with the electrical circuit. The thermionic coating method with preliminary bombardment of the substrate surface using low-energy ions, as discussed by Hrechko et al. [35], presents a significant advancement in surface coating technology. This method enhances adhesion and the quality of coatings, making it valuable for various industrial applications. Meanwhile, Pavliuk's study [36] on electron modeling in conjunction with vacuum modeling opens new avenues in the field of high-precision electronic device development. Understanding electron dynamics in vacuum conditions is crucial for improving the design and efficiency of electronic components. Both of these studies contribute to the broader field of electromechanical systems and have implications for the efficiency and reliability of such systems.

Monitoring current characteristics can help prevent severe damage and reduce downtime. The use of modern methods and technologies, such as vibration spectrum analysis and current monitoring using sensors and artificial intelligence systems, makes fault detection more precise and efficient. This enables prompt maintenance and repair of induction motors, which increases the reliability and durability of the equipment.

VII. CONCLUSION

The diagnostic methodology proposed in this study is based on the analysis of the instantaneous power and currents circulating in the induction motor during its operation. The basic assumption behind this method is that an induction motor has a constant instantaneous power under normal operating conditions. However, the presence of defects, such as torn or broken rotor bars, can lead to instantaneous power fluctuations and other non-periodic changes. This approach to fault diagnostics can detect anomalies at an early stage of their development and serve as an effective tool to support the maintenance of induction motors in various industrial sectors.

Studies and experiments have suggested that this diagnostic method is quite effective in detecting faults in induction motors. It enables the detection of rotor bar breaks and damage at an early stage when other methods may not be as sensitive. Furthermore, instantaneous power analysis can be performed without major time and resource investment, making it convenient and affordable for many manufacturers and service providers. Research has revealed that vibration and noise in induction motors can be added indicators of faults, especially when they are related to the rotor. These signs can be used for more precise diagnosis and early detection of problems. Overall, the instantaneous power analysis methodology has proven to be effective and useful for diagnosing induction motors, allowing them to maintain their reliability and performance at a prominent level.

Further improvement of the diagnostics of induction motors requires more research on the development of algorithms and data processing methods based on instantaneous power analysis to ensure higher accuracy and feasibility in practice. It is necessary to investigate the possibility of integrating this method into industrial monitoring and diagnostic systems, as well as developing standards and recommendations for its implementation in industrial areas.

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