Induction Motor Multiple Fault Analysis using Stray Flux Signals: A Review

Luka Čulić, Nediljko Kaštelan, Marko Zubčić, Ivan Pavić

Induction motors are integral to many industrial applications due to their reliability, simplicity, and efficiency. However, they are susceptible to various faults, including bearing issues and broken rotor bars (BRB), which can lead to unplanned downtime, performance degradation, and significant financial losses. Traditional methods, such as Motor Current Signature Analysis (MCSA), have been widely used for fault detection in induction motors, primarily due to their non-invasive nature and effectiveness in identifying faults through stator current analysis. However, MCSA has limitations in detecting complex, multiple fault conditions. Stray Flux Signature Analysis (SFSA) has emerged as a promising alternative, offering the ability to detect faults by measuring magnetic flux variations external to motor housing. This method provides valuable insights into the motor's internal electromagnetic and mechanical conditions, making it particularly useful for detecting rotor-related faults such as broken rotor bars and eccentricity. Despite its potential advantages, SFSA has not been as extensively researched as MCSA, particularly in the context of multiple fault detection, such as combined BRB and bearing faults. An analysis of publications in the Web of Science reveals that MCSA is a more established method with a larger body of research, while SFSA remains underexplored, with limited studies on its application to multiple fault scenarios. This indicates a significant gap in the research and suggests that further investigation into SFSA could provide a more comprehensive and reliable solution for fault detection in induction motors, especially in multi-fault scenarios.

KEYWORDS
~ Induction motor
~ Broken rotor bar
~ Bearing fault
~ Stray flux
~ Motor Current Signature Analysis

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1. INTRODUCTION

Induction motors are fundamental to numerous industrial systems, from manufacturing and transport to energy systems. Their widespread popularity is due to their plain design, robustness, reliability and efficiency (Noureddine et al., 2020). Despite their advantages, induction motors, like all electrical machines, are liable to many types of faults and monitoring them is crucial to avoid sudden stop, which can cause unplanned downtime and lead to significant financial losses. Induction motors rely on a combination of electrical and mechanical components for their operation (Mehrjou et al., 2011). The most common faults in induction motors include broken rotor bars, bearing faults, stator winding faults and other mechanical or electrical anomalies. Bearings play a crucial role as they allow the rotor to rotate smoothly in the stator, minimizing friction and mechanical wear. Over time, when bearing faults occur, they not only generate mechanical vibrations, but also affect the electromagnetic behavior of the motor. Another significant fault in asynchronous motors are broken rotor bars. The rotor is a crucial component that interacts with the magnetic field generated by the stator to produce torque. The rotor bars, the conductive elements within the rotor, are essential for generating the current flow required for operation. If one or more rotor bars break, imbalances occur in the motor's electromagnetic field, resulting in reduced efficiency, vibration and overheating.

Condition monitoring of rotating electrical machines has become increasingly important. There are many proposed methods for monitoring electrical machines, some of which are used commercially for condition monitoring. The condition monitoring techniques are designed not only to ensure a prominent level of reliability during operation, but also to track the efficiency, safety and performance of the electrical machines (Jiang C. et al., 2017). Among these methods, Motor Current Signature Analysis (MCSA) has gained popularity due to its non-invasive approach and effectiveness in identifying a wide range of faults. However, MCSA alone is not always sufficient to capture the complexity of multiple fault conditions. The limitation has awakened interest in alternative diagnostic methods, with Stray Flux Signature Method (SFSM) as promising approach. Stray flux magnetic signals contain information about the internal electromagnetic and mechanical conditions of the motor, making the valuable resource for fault detection. Stray Flux Signature Method offers several advantages over conventional methods: it is non-invasive, cost-effective, and able to detect faults at an early stage. It can also provide additional information that increases the accuracy and reliability of fault detection when combined with other methods. Multiple faults in induction motor often interact with each other and create complex signal patterns that can only be analyzed with advanced signal techniques.

The aim of this paper is to present comparison by number of publications of stray flux and MSCA method regarding combined BRB and bearing fault. Furthermore, because our future research will be focused on stray flux method the overview of combined BRB and bearing fault with stray flux detection will be given.

2. INDUCTION MOTOR FAULTS

2.1. Bearing Fault

One of the most common problems with induction motors is bearing faults. According to (Gangsar and Tiwari, 2020) bearing faults take 42 % of total analyzed faults (IEEE study). The bearings play a crucial role in the smooth operation of an induction motor. They function as an interface between the rotor and the stator. Generally, rolling bearings are made up of an inner and an outer race which are separated by cylindrical rollers or balls that are held within the cage. Construction of the bearing is shown in Figure 1.

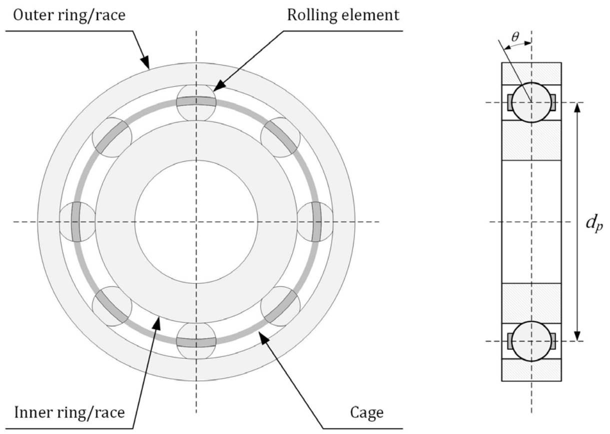

Figure 1. Bearing construction elements and cross section view; (Source: Authors).

Their main function is to reduce friction, support the shaft and maintain correct alignment during operation. Bearing damage generates shock pulses at characteristic frequencies, which vary based on the affected component. These frequencies are determined using the bearing's geometry and rotational speed. (Mboo and Hameyer, 2016). For the ideal case where outer ring/race is fixed and inner ring/race is rotating the characteristics frequencies are (Ruiz-Sarrio et al., 2024) (Briglia et al., 2024)

$$f_{BPO} = \frac{n_b}{2}\left[1 - \frac{d_b \cos(\theta)}{d_p}\right] f_r \tag{1}$$

$$f_{BPI} = \frac{n_b}{2}\left[1 + \frac{d_b \cos(\theta)}{d_p}\right] f_r \tag{2}$$

$$f_C = \frac{1}{2}\left[1 - \frac{d_b \cos(\theta)}{d_p}\right] f_r \tag{3}$$

$$f_{BS} = \frac{d_p}{2d_b}\left[1 - \frac{d_b^2 cos^2(\theta)}{d_p^2}\right] f_r \tag{4}$$

where subscripts *BPO*, *BPI*, *C* and *BS* stand for, respectively, Ball Passing Frequency Outer (ring), Ball Passing Frequency Inner (ring), Cage and Ball Spin frequency; n_b – number of rolling elements, d_p – pitch diameter, d_b- ball diameter, θ – contact angle and f_r – rotating frequency of the motor shaft.

There are several types of bearings, depending on the load and speed requirements of the motor such as ball bearing, roller bearing, angular contact ball bearing, cylindrical roller, sealed and shielded bearing. Despite their longevity, bearings are susceptible to significant mechanical and environmental stresses. Bearing damage causes oscillations in current signals by altering radial movement between the rotor and stator. This leads to rotational eccentricity, load torque fluctuations and modulation of motor current signals in amplitude, phase, and frequency.

2.2. Broken Rotor Bar

Broken rotor bar (BRB) implies disconnection of rotor bar that appears along the bar itself or on the joint with the rotor end ring. An illustrative example of BRB is shown in Figure 2. This type of fault in an induction motor is a type that takes 8 % of total analyzed faults (IEEE study) (Liang et al., 2020). Although broken rotor bars are less common than other faults such as bearing faults or stator faults, they can still cause enormous damage to electrical machines. There are several reasons that can lead to problems with rotor bars. Mechanical stresses affect the bars when an induction motor starts and stops frequently or handles heavy loads. Corrosion, vibration and the expansion of the bars in the shaft direction due to heat are also some of the main reasons for bar breakage, which can be particularly damaging in large motors. Broken rotor bars can also be caused by air bubbles that form inside the bars during casting and eventually lead to hot spots and small cage cracks in cast aluminum cages. Rotor bars are short-circuited on both sides by end rings. Defective casting or defective end ring connections can lead to end rings defect. Once the first defect occurs, localized overheating can occur in the cage *(*Mehrjou et al., 2011*).* In general, the rotor is exposed to a variety of stresses from thermal, mechanical, dynamic and magnetic sources, which together lead to rotor failures (Atta et al., 2022). Avoiding broken rotor bars requires proper motor design, maintenance and controlled operating conditions. There are several ways to detect broken rotor bars. One of the most popular methods is Motor Current Signature Analysis. Other methods for BRB detection are voltage method (zero sequence voltage), vibration, acoustics, flux (airgap and external) (Atta el al., 2022).

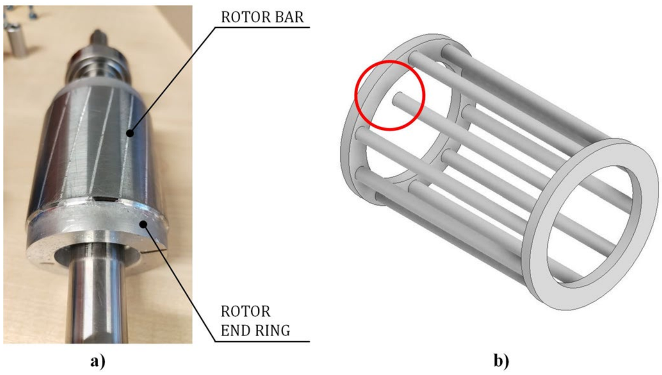

Figure 2. (a) Induction motor squirrel cage rotor; (b) Illustrative example of broken rotor bar; (Source: Authors).

3. DIAGNOSTIC ANALYSIS

3.1. Motor Current Signature Analysis

Motor Current Signature Analysis (MCSA) is a powerful, non-invasive technique for diagnosing bearing faults and broken rotor bars in induction motors. MCSA is the sensing of the stator current and utilizes the results of its spectral analysis to pinpoint an existing or incipient failure in the induction motor. The stator current is sensed during the normal operation of induction motor or its start-up (Mehrjou et al., 2011). When a bearing failure or broken rotor bar occurs, it causes fluctuations in the motor's load, resulting in variations in the current patterns and interruptions in the electromagnetic field. If a rotor bar breaks, no current can flow through it, which prevents the generation of a magnetic flux around the bar. This imbalance disturbs the magnetic field of the rotor and creates a backward rotating field that moves with slip frequency relative to the rotor. It therefore induces harmonic currents in the stator windings, which are superimposed on the stator currents. These changes in stator current produce specific frequency components that can be identified using advanced signal processing techniques such as Fast Fourier Transformation (FFT). Specific frequency components for bearing faults in stator current are (Boudinar et al., 2016)

$$f_{BF} = |f_s \pm k f_v| \quad k = 1, 2, 3, \ldots \tag{5}$$

where f_s is supply frequency, f_v is characteristics frequency depending of type of bearing fault (f_{BPO}, f_{BPI}, f_C or f_{BS}).

Specific frequency components for broken rotor bar fault in stator current are (Liang et al., 2020):

$$f_{BRB} = (1 \pm 2ks) f_s \quad k = 1, 2, 3, \ldots \tag{6}$$

where f_s is supply frequency, s is slip of the induction motor.

MCSA enables the early detection of faults without the need for direct access to the motor. This makes it an attractive option for industries where minimizing downtime is a priority. One of the key benefits of MCSA is its ability to detect faults under normal operating conditions. In industry, MCSA is often used as part of condition-based maintenance strategies to increase reliability, minimize unplanned downtime and extend equipment life.

While MCSA is a powerful tool for fault detection, it is not without its challenges. Factors such as electrical noise, load variations and complex motor designs can affect the accuracy of fault diagnosis. False positive indications in motor diagnostic can occur due to rotor asymmetry and load torque oscillations while false negatives arise when faults are masked by load variations, low slip, speed estimation errors or non-adjacent broken bars (Rafaq et al., 2022). To increase reliability, MCSA is often combined with other diagnostic techniques such as vibration analysis, flux leakage analysis and thermography. Ensuring the long-term reliability of asynchronous motors requires a proactive approach to fault detection and maintenance.

3.2. Stray Flux Signature Aanalysis

Stray flux analysis is another powerful technique for detecting faults in induction motors. Stray flux refers to the stray magnetic field that escapes from the motor housing during operation. Illustrative example of stray flux is shown in Figure 3. This method uses coil sensors installed on the frame of induction motor, measuring radial and axial stray flux (Noureddine et al., 2020). By measuring and analyzing stray flux fluctuations, it is possible to detect faults at an early stage before they develop into major failures (Sabir et al., 2022). Despite the potential benefits of flux-based motor fault detection, it has not been as well received in practise and academia as MCSA. This is mainly because the sensors need to be installed on the frame or inside the motor, which requires physical access to the motor (Park et al., 2020). Stray flux sensors placed around the motor detect anomalies caused by mechanical and electrical irregularities and provide valuable insights into the condition of the motor. The flux measurement output of this sensor depends on various parameters, such as the permeability of the core, number of turns, and the area of the coil (Gurusamy et al., 2022). Analyzing the stray flux is particularly effective in identifying faults associated with the rotor, including broken rotor bars and eccentricity problems. Stray flux is generated externally around the machine housing in both radial and axial directions. In the radial direction, this stray flux attenuates the main flux in a plane perpendicular to the machine axis. The stray flux influences the extremities of the stator coils as well as the end rings of the squirrel cage rotor in a plane that includes the machine axis (Figure 4) (Gérard-André Capolino et al.,2019). When a bar breakage occurs, a backward rotating magnetic field is generated due to an open circuit bar. This creates in the rotor cage an asymmetry that is clearly reflected in the motor's harmonic content (Panagiotou et al., 2019). This manifests as specific frequency components in the FFT spectrum, which can be used for early detection.

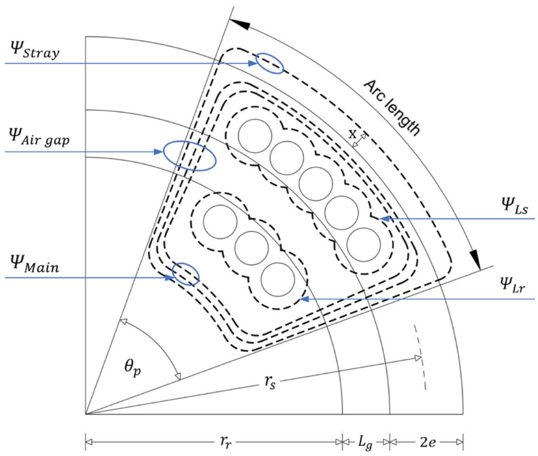

Figure 3. Illustration of stray flux; (Source: Koroglu *et al.*, 2009).

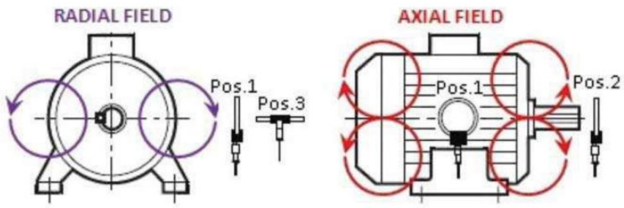

Figure 4. Coil sensor in different measurement positions; (Source: Ceban et al., 2012).

Stray flux-based bearing fault diagnosis method was implemented in several papers, most of which use several search coils and flux probes. Several authors have demonstrated that the presence of certain defects in the motor amplifier enhances some components in the stray flux spectrum. Most of these works suggested the use of external coil sensors for the acquisition of the required signals and the subsequent Fourier analysis of these signals to detect the components that are amplified by rotor damage and other faults (Iglesias-Martinez et al*.*, 2019). Although bearing faults are usually clearly visible using vibration analysis, in case of stator current it is difficult to observe them due to their low amplitude and noise disturbance. Nevertheless, vibrations influence the magnetic field of the motor, which leads to fluctuations in stray flux signals. One of the main advantages of stray flux analysis is its ability to monitor and diagnose faults in real time. Conventional methods of fault detection, such as vibration analysis and thermal imaging, require access to the motor and can be time consuming. By integrating advanced signal processing techniques, the effectiveness of stray flux analysis is further improved. Techniques such as FFT enable the precise identification of fault-related frequency components in the stray flux signals. By analyzing these frequencies, the difference between normal and faulty operating conditions can be determined. The widespread use of the FFT is mainly due to its simplicity, easy implementation in electronic devices and the wide variety of faults that can be analysed and diagnosed using this diagnostic scheme (Zamudio-Ramirez et al., 2022). Despite its advantages, stray flux analysis is associated with some challenges. Ambient noise and electromagnetic interference can affect the accuracy of measurements, requiring the use of advanced filtering and signal processing methods. In addition, variations in motor design and operating conditions can affect stray flux patterns, requiring baseline measurements for accurate fault detection. Implementing stray flux analysis as part of a comprehensive predictive maintenance strategy offers significant benefits for industries that rely on induction motors.

4. WEB OF SCIENCE RESULTS

The Web of Science (WOS) is a valuable resource for researchers, engineers and industry professionals who want to learn about advances in induction motor fault diagnosis. This database contains an extensive collection of journals, conference proceedings and technical articles that contribute to the development and refinement of diagnostic methods. By reviewing the literature available in the Web of Science, researchers can gain insight into current trends, innovative diagnostic techniques and the experimental validation of fault detection methods. Despite the significant potential of Stray Flux Signature Analysis and Motor Current Signature Analysis in fault detection and diagnosis, there is a lack of comprehensive research and articles on these topics in the Web of Science database. When searching with Advanced Search Query Builder for research articles on the topic of multiple faults, in this case combinations of BRB and bearing fault, following term was used for stray flux case:

$$ALL = \left(\begin{array}{c}(\text{Induction motor})\\ AND\ (\text{broken rotor bar OR broken bar})\\ AND\ (\text{bearing fault OR bearing})\\ \text{AND (stray flux OR magnetic stray flux OR external flux OR external magnetic field)}\end{array}\right) \tag{7}$$

And following term for MCSA case:

$$ALL = \left(\begin{array}{c}(\text{Induction motor})\\ AND\ (\text{broken rotor bar OR broken bar})\\ AND\ (\text{bearing fault OR bearing})\\ \text{AND (stator current OR Motor Current Signature Analysis)}\end{array}\right) \tag{8}$$

The number of publications over the years for queries expressed with Eq. 7 and 8 are shown in Figure 5.

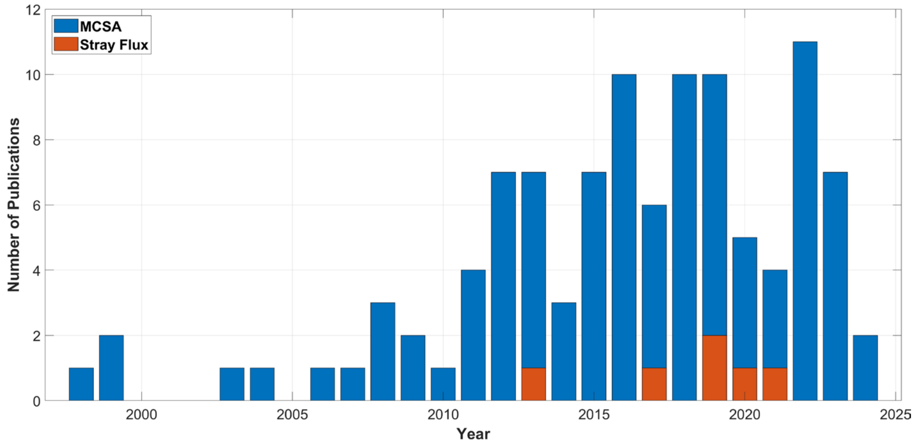

Figure 5. Number of publications over the years for MCSA and Stray Flux regarding BRB and bearing fault combined; (Source: WOS).

From Figure 5 it can be observed that MSCA when compared with Stray Flux method is longer present as a research method. Furthermore, the total number of publications is much greater for MCSA method.

Search results for stray flux case are presented by fault detection technique, type of fault and signal analysis method in Table 1.

Ref.	Fault detection technique	Type of fault	Signal analysis method	Note
(Noureddine et al., 2020b)	MCSA Vibration Stray flux	Bearing fault: Inner Raceway	FFT	
(Rusek and Goño, 2019)	Stray flux	BRB Eccentricity	FFT	Comparison with Finite Element Method (FEM)
(G.A.Capolino et al, 2019.)				State of the art article
(C.Jiang et al, 2017.)				A Review article
(R.Pusca et al,2013.)	Stray flux	BRB Eccentricity	FFT	All analysis was conducted with FEM
(Alvarado-Hernandez et al., 2021)	Infrared thermography	Misalignment Unbalance 1 BRB 2 BRB Bearing Fault Gearbox Fault	Background Segmentation; Automatic Region of Interest Detection; Histogram Characteristics	Each fault was investigated one by one (no multiple fault analysis)

Table 1. Stray flux combined BRB and bearing fault article analysis; (Source: WOS).

From Table 1 it is observable that search query defined by Eq. 7 produces no relevant result, i.e., the topic of combined BRB and bearing fault using stray flux method is not present in any of the publications from Table 1.

Stray flux analysis, for instance, is a relatively emerging technique in the field of motor diagnostics and may not be as researched as established methods such as MCSA, vibration analysis or temperature monitoring. Its application for the diagnosis of multiple faults, particularly in combination with stray flux, may still be in the initial stages of development and application.

5. CONCLUSION

In this paper, MCSA and stray flux methods have been graphically compared by number of publications over the years. The comparison has been made for combined BRB and bearing fault. The results show that MCSA is a prevailing method due to longer presence in the research community and consequently it has far more publications. Stray flux method on the topic of combined fault has only six articles present in WOS base. The results presented in a tabulated format show that none of the articles found by WOS relate or refer to combined BRB and bearing fault. This leads to the conclusion that this area is not investigated at all and consequently has potential for future research.

CONFLICT OF INTEREST

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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