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Magnetic Flux Analysis for the Condition Monitoring of Electric Machines: A Review

Abstract— **Magnetic flux analysis is a condition monitoring technique that is drawing the interest of many researchers and motor manufacturers. The great enhancements and reduction in the costs and dimensions of the required sensors, the development of advanced signal processing techniques that are suitable for flux data analysis, along with other inherent advantages provided by this technology are relevant aspects that have allowed the proliferation of flux-based techniques. This paper reviews the most recent scientific contributions related to the development and application of flux-based methods for the monitoring of rotating electric machines. Particularly, aspects related to the main sensors used to acquire magnetic flux signals as well as the leading signal processing and classification techniques are commented. The discussion is focused on the diagnosis of different types of faults in the most common rotating electric machines used in industry, namely: squirrel cage induction machines (SCIM), wound rotor induction machines (WRIM), permanent magnet machines (PMM) and wound field synchronous machines (WFSM). A critical insight of the techniques developed in the area is provided and several open challenges are also discussed.**

Index Terms—**Fault diagnosis, condition monitoring, magnetic flux analysis, electric machines, industry.**

I. INTRODUCTION

IN recent years, the rotating electric machines condition monitoring area has received great interest from both academia and industry. This is partly due to the relevance of these machines in the industrial sector, which is primordial for the economy of many developed countries [1]. In order to ensure a high efficiency, safety, and performance of the different electric machines involved in a wide variety of industrial processes, it is essential to have schemes, methodologies and monitoring systems capable of diagnosing and detecting anomalies or defects on them. Additionally, these instruments enables to achieve adequate maintenance actions, which prevents unscheduled downtimes and reduces maintenance costs [2]. To this end, a large percentage of methodologies, which are based on the analysis of different physical magnitudes have been proposed, namely: stator/rotor currents, mechanical vibrations, partial discharges, temperature, among others [2], [3]. Despite the relevant advances obtained with the vast diversity of proposed approaches, each specific technique is subjected to its own constraints. As a result, it has been concluded that there is no single technique capable of diagnosing all the failures that usually occur in a rotating electric machine. Moreover, even for the faults for which the techniques have shown good results, there are still some problems that need to be addressed. This situation has triggered a number of research studies focused on the analysis of diverse signals from rotating electric machines and the application of signal processing techniques to find an optimal solution to the main drawbacks of conventional methodologies.

In order to find complementary and/or alternative options to well-established condition monitoring techniques, the investigation of other physical magnitudes has turned out to be a solution. In this context, the analysis of the magnetic flux has drawn the attention of many researchers in this area as well as some motor manufacturers who have decided to install magnetic sensors embedded in their machines with the aim of providing integrated self-diagnostic capabilities [4], [5]. This clear trend is partially due to the diverse advantages and benefits offered by the flux data analysis over other conventional techniques. In order to explain these advantages, it should be noticed that magnetic flux-based methodologies can be split into two main groups: 1) those based on *stray flux analysis (*which is the study of the magnetic flux that radiates outside the machine frame), and 2) techniques based on *airgap flux analysis* (which is the evaluation of the internal flux present in the air gap).

Taking this into account, the advantages of the magnetic flux analysis for condition monitoring purposes are listed next:

1) It has proven to be efficient and reliable in cases where conventional techniques produce false indications (i.e., rotor axial air ducts, rotor magnetic anisotropy, low frequency load oscillations, etc.)[6], [7].
2) In the case of stray flux, its noninvasive nature and simplicity in the implementation [8].
3) Very low cost sensors are required [9].
4) Flexibility and simplicity of installation of the available sensors [10].

Despite its great advantages, like every technique, magnetic flux analysis presents its own constraints. Some of the current research works are intended to provide reliable solutions to some of these disadvantages that, according to the available literature, are the following:

1) In the case of stray flux analysis, the difficulty for modeling the magnetic field that strongly depends on the electromagnetic behavior of the stator yoke and the motor frame, which have an important shielding effect [11].
2) Difficult introduction of fault severity indicators [12].
3) In the case of stray flux, influence of the sensor position over the results [13], [14].
4) In the case of air-gap flux analysis, requirement of sensor installation inside the machine.

Recently, some state-of-the-art papers on stray flux analysis ([9], [15]) have been published in conference proceedings (two and four years ago, respectively), in which the discussion is limited to stray-flux based techniques. As research on the magnetic flux application for the condition monitoring of electric machines has recently received special interest, many interesting research works have been published in the last couple of years, and some investigations have been even extended to other machines, such as permanent magnet machines (PMMs). This paper aims to update the state of the art, adding outstanding contributions based on both stray and airgap flux analysis. The structure of this review is based on the block diagram shown in Fig 1. It is organized according to the technology and techniques available for the analysis of magnetic flux signals, following a diagnosis scheme with 3 basic stages: signal acquisition (stage 1), signal processing (stage 2), and final fault diagnosis/detection (stage 3). In each stage, different contents are addressed, and they are developed in more detail along the different sections of this review. Fig.1 references the reader to each specific subject of this paper.

Special emphasis is made on important practical aspects, such as the available flux sensors technologies as well as the signal processing and classification techniques that have been proposed for flux-based diagnosis purposes. The paper is mainly focused on the application of the methodology to the advanced fault condition monitoring of the most common industrial rotating electric machines. In this context, squirrel cage induction machines (SCIM), wound rotor induction machines (WRIM), permanent magnet machines (PMM), and wound field synchronous machines (WFSM) are explored. The work can be of especial interest for researchers as well as for field engineers involved in the electric motors condition monitoring area who can find here a rapid insight and approximation to the state of the technology in this field. The challenges and pending issues on the magnetic flux technology are also commented.

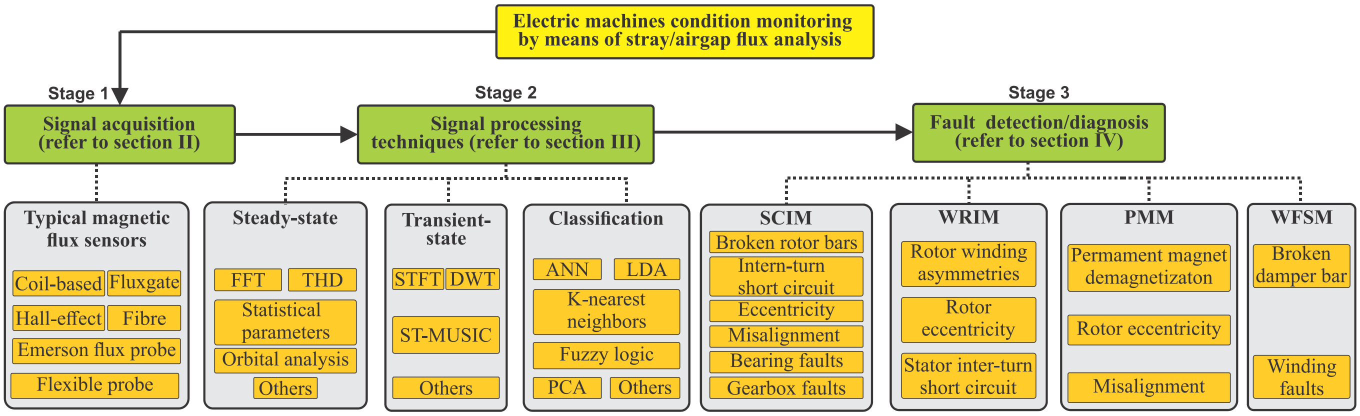

Fig. 1. Flowchart of signal acquisition and processing for fault detection / diagnosis by means of magnetic flux signals.

II. TYPICAL SENSORS FOR MEASURING MAGNETIC FLUX

The airgap flux is the radial magnetic flux located at the machine airgap. It can be acquired by introducing a magnetic flux sensor on the stator bore or around the stator slot tooth of a core packet [16]–[18]. Since the required sensors must be placed inside the machine, either during the manufacturing process or, by opening and inserting the appropriate sensor, this technique is usually considered as intrusive.

On the other hand, methods based on the analysis of the stray flux are founded on the fact that the presence of certain faults in the different electrical machines modify the magnetic flux in their vicinity [8], [19], [20]. In a healthy symmetrical machine, the stator and rotor currents are balanced in end-windings and the stray flux is negligible. As reported in [21], it is possible to study the magnetic stray flux by means of its axial and radial decompositions. Both fields can be measured separately by installing convenient sensors on the frame outside the yoke or around the shaft [21]–[23], as depicted in Fig. 2.

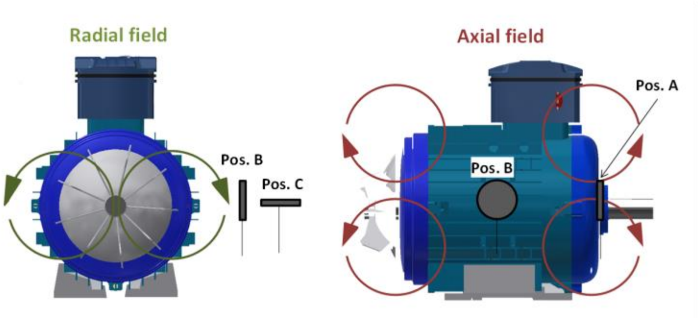

Fig. 2. Nature of the stray flux acquired at each sensor position.

Magnetic airgap and stray fluxes have typically been measured by using coil-based sensors [6], [8], [13], [17]–[19], [22], [24]–[54] and Hall-effect sensors [10], [55]–[60]. Although less widely used, magnetic flux measurement has also been performed by using commercial Emerson flux probes [23], which are essentially an air coil without nonlinear magnetic materials. This characteristic confers them the advantage of yielding linear amplitude readings and exhibiting very stable parameters in time. Likewise, some works such as [14], [61] use fluxgate sensors, which basically rely on a winding around a magnetic circuit. These sensors can be practically installed on the frame of any electric machine;

however, the addition of undesired frequencies may limit their usage. Some recent works have reported the application of the so-called Fibre Bragg Grating (FBG) magnetorestrictive sensors [62], [63], which are small-size devices optimal for air-gap flux measurements. Yet, their feasibility to acquire low amplitude magnetic flux signals (e.g., stray fluxes) has not been demonstrated.

Coil-based sensors have usually circular shapes and incorporate wire windings (with or without ferromagnetic core), based on a low number of turns, commonly between 10 and 3000 depending on the application (air gap or stray flux measurement) and dimensions [7], [13], [22]. A great advantage of coil-based sensors is their simple construction, which allows their easy fabrication. In [64], [65], the authors show an analysis of the impact of the number of wires and diameter, and the core type over the captured signal. There, it is shown that sensors having a large number of turns with smaller diameters are preferred since a decrease and shift toward high frequencies of resonant frequency (F_0) can be obtained. Furthermore, as pointed out by the authors in [75], the nonlinear behavior of the iron due to the permeability, saturation, hysteresis or eddy currents does not affect the fault detection, whereas a significantly greater amplitude of the induced voltage for the same stray flux is obtained (an important feature in noisy environments). This situation reveals that iron core flux sensors seem to provide advantages over air core sensors when acquiring stray flux signals.

The main limitations of coil-based sensors for condition monitoring of electric machines are the following:

- The output signal depends on the frequency of the magnetic field, which therefore limits the frequency bandwidth by resonance of the coil.
- To achieve high sensitivity, the sensor should be rather large, since the sensitivity highly depends on the coil dimensions [65].
- From a practical point of view, coils are often difficult to install in the correct position (in order to ensure acquiring a reliable signal), since the design of the machine and its enclosure sometimes do not allow this.

On the other hand, Hall-effect sensors have been broadly used and installed in numerous electric machines for motion control, initial rotor position estimation, and reliable fault detection and diagnosis. Hall-effect sensors are low cost and small devices (which allows them to be installed in places with reduced space). They have the capability of acquiring constant and variant magnetic fluxes with absolute and linear measurements over a very large field. Since Hall-effect sensors do not require large elements (such as ferromagnetic parts), it is possible generating non-invasive schemes for acquiring magnetic flux signals. Nevertheless, the main disadvantage of this type of sensor is its sensitivity since floor noise can easily disturb the measurements, though these effects can be diminished or nulled by using appropriate electronic circuits.

Recent works have proposed new sensor topologies in order to overcome some drawbacks existing in actual magnetic-sensor designs [10], [33], [62], [66]. The authors of [10] proposed the use of a triaxial Hall-effect-based sensor in order to capture the different stray flux magnetic components at a single point. In [33] a commercial magnetic probe is presented. This probe is comprised of a number of circuit layers printed on a flexible base material, and it is conceived for its installation on a stator tooth. This kind of sensor has provided optimal solutions in machines with small air gaps, since it can be generally installed with the rotor still in place [66]. On the other hand, the use of FBG in combination with a magnetostrictive material is proposed in [62]. This combination gives the sensor advanced features such as small size, immunity to electromagnetic interference (EMI), multiplexing and multi-physical sensing. Nonetheless, the results highly depend on a good calibration, a fact that complicates their reproducibility and flexibility.

III. SIGNAL PROCESSING AND CLASSIFICATION TECHNIQUES

According to the analyzed technical literature, two main signal-processing approaches for electric machine fault diagnosis can be distinguished: 1) steady-state analysis through the conventional use of the fast Fourier transform (FFT) as well as statistical and non-statistical indicators, and 2) transient-based diagnosis through the application of time-frequency decomposition (TFD) mathematical tools.

Many of the proposed works for the steady-state analysis of magnetic fluxes rely on the detection and evaluation of certain frequency components, which are amplified in case of a fault in the FFT spectrum [6], [8], [19], [20], [22], [23], [25], [26], [29], [30], [34]–[38], [40], [43], [46]–[48], [57], [61], [67]–[71]. The wide utilization of the FFT can be mainly attributed to its simplicity, easy implementation in electronic devices, and to the wide variety of faults that can be studied and diagnosed under this diagnosis scheme. However, the FFT has certain drawbacks, especially those related to its intrinsic limitations, namely: sensitivity to low signal-to-noise ratio, overlapping of closely-located spectral components, not suitable for nonstationary signals, spectral leakage, and loss of information related to time [72]. Other works such as [41], [45] propose indicators as the total harmonic distortion (THD) and the correlation coefficient between two sensors; although they are very simple parameters to calculate and allow very fast diagnoses, their reliability is still inexact. In [41], [42], an orbital analysis approach for the analysis of magnetic flux signals is presented. The main advantage of this method is its high sensitivity to low severity faults; however, it requires acquiring the signals from two or more sensors simultaneously. On the other hand, transient analysis relies on time-frequency (t-f) maps obtained from the analyses of flux signals that are captured under transient regimes, especially during the startup transient. The amplified fault harmonics evolve tracing very characteristic patterns that depend on the fault that is present [12]. In this context, the short-time Fourier transform (STFT) has been widely used to obtain a pertinent t-f map of transient magnetic flux signals [10], [12], [16]–[18], [27], [70], [73]–[76].

The benefits of the STFT technique such as reduced computational burden and easy implementation in electronic devices have allowed its wide use. Yet, the main drawback of STFT lies in the fixed time-frequency resolution that is obtained, which depends on the time-window applied. This compromises the diagnosis reliability when there are frequencies that evolve very closely; additionally, parameter optimization is often required. In this context, some works have reported the use of high-resolution techniques such as the short-time multiple signal classification (ST-MUSIC) algorithm [10]. The use of high resolution techniques such as ST-MUSIC provides more regular surfaces, mitigates the effects of noise, and evidences only larger frequency components making it a useful tool for the analysis of noisy signals with time-shifting frequencies [77]. The main disadvantage of high-resolution TFD tools such as ST-MUSIC lies in the high burden and long time that its computation demands. Methodologies based on the Discrete wavelet transform (DWT) have been reported in [12], [13], [24], [51], [78]. The main advantage of DWT-based diagnosis stays in the practicality to generate reliable indicators about the severity of the failure, its low computational burden and its easy implementation in hardware. Nonetheless, this technique is not optimal for the analysis of non-linear signals, and the provided fault component evolution is not very clear.

Additionally, in recent years some flux-based works have put emphasis on complementing the diagnoses using artificial intelligence (AI) techniques. The application of artificial neural networks (ANN), linear discriminant analysis (LDA), principal component analysis (PCA), support vector machines, K-nearest neighbors, fuzzy logic, among others techniques for fault classification purposes have been recently reported [10], [23], [32], [58], [67], [69], [79]. These techniques have favored the decision process and cluster analysis since they enable to provide an automatic classification of the faults. Besides, their use allows generating online and timely diagnostics, providing constant monitoring and diagnosis of the machine, and obtaining indicators of the fault severity. However, since AI techniques often require an initial training stage (a critical aspect for an optimal operation), its generalization for different machines and faults diagnosis is uncertain. Moreover, the training phase requires a large set of samples, which are difficult to setup.

IV. MAGNETIC FLUX ANALYSIS AND ITS APPLICATIONS

The analysis of the magnetic flux has proven to be a useful tool, both for the diagnosis of faults in electric machines by yielding comparable results to those of well-established techniques and as a complement to other fault detection methods. Moreover, this technique has encountered a wide range of applications for different mechanical, electrical, and rotor faults, among others: 1) Broken rotor bars, 2) Stator winding interturn short circuits, 3) Wound rotor short circuits, 4) Winding interturn short circuits, 5) Bearing faults, 6) Permanent magnet demagnetization, 7) Damper bar faults in synchronous motors, 8) Airgap eccentricity faults, 9) Misalignment faults and 10) Coupling system faults.

Additionally, other applications have been reported such as, speed monitoring in synchronous generators [80], load monitoring in induction machines [81], and cutting tool wearing in CNC machines [82].

Due to the wide variety of applications and faults that can be diagnosed through the magnetic flux analysis, the authors conduct a discussion by classifying the main contributions according to the electric machine type.

A. Squirrel cage induction machines (SCIM).

Several works have demonstrated the potential of the magnetic flux analysis for the detection of *rotor faults* in SCIM: [8], [10], [12], [32], [37], [44], [51], [53], [54], [57], [58], [67], [68], [70], [74], [78], [83]. The vast majority of these investigations are been based on the fact that a rotor fault produces an asymmetry in the rotating magnetic field distribution. As shown in [7], broken rotor bars (BRB) yield sidebands of the power supply frequency (f_s) in the radial airgap flux given by (1):

$$f_{flux} = f_s \pm k \cdot f_r = f_s \cdot \left(1 + k \cdot \frac{(1-s)}{p}\right) \tag{1}$$

where p is the number of pole pairs, s is the slip, and k is the harmonic order ($k = 1,2,3,\ldots$), and f_r is the rotor rotational frequency.

Some works as in [11], [12], [53], [61], [68] have proven that BRB faults also generate twice slip frequency sidebands of f_s and f_r in the radial stray flux, which are given by (2):

$$f_{BRB(radial)} = \begin{cases} f_s \cdot (1 \pm 2 \cdot k \cdot s) \\ f_s + f_r \pm 2 \cdot k \cdot s \cdot f_s \end{cases} \tag{2}$$

Additionally, as reported in [8], [12] rotor faults amplify slip frequency components given by (3) which are found in the axial flux:

$$f_{BRB(axial)} = \begin{cases} s \cdot f_s \\ 3 \cdot s \cdot f_s \end{cases} \tag{3}$$

Conventional methodologies rely on the evaluation of the abovementioned frequency components, which are amplified in case of BRB faults [8], [11], [37]. In other works as [83], the authors propose to excite rotor fault modes at standstill (s=1) with a special power signal in order to perform an early detection of BRB and porosity defects.

Since BRB fault-amplified frequency components are dependent on slip, some works as in [74] have proposed to study the transient of the machine after power supply disconnection by using TFD tools, more specifically, the STFT. This methodology gives a better interpretation of spectrum compared to the FFT. More recently, there has been a clear trend to study the evolution of these faulty frequency components under the start-up transient as in [10], [12], [17], [32], [51], [78]. The investigations carried out in [51], [78] propose the use of the DWT to identify BRB fault patterns in stray flux signals captured during start-up. The use of discrete TFD tools allows an easy introduction of fault severity indicators; however, the patterns are difficult to be discerned. Other works such as [10], [12], [17] propose the use of the STFT to identify the patterns raising during the startup. Fig.3 shows pictures of the testbench used in [12]. The main limitation of this technique relies in the possible overlapping of closely-located spectral components, which complicates the reliable detection when noisy signals are involved. A very recent work [32] proposes the use of the ST-MUSIC, which mitigates effects of noise, and evidences only larger frequency components; nonetheless, the computational burden and time requirements are high compared to the STFT. These works have evaluated and demonstrated the feasibility of transient magnetic flux analysis for BRB fault detection.

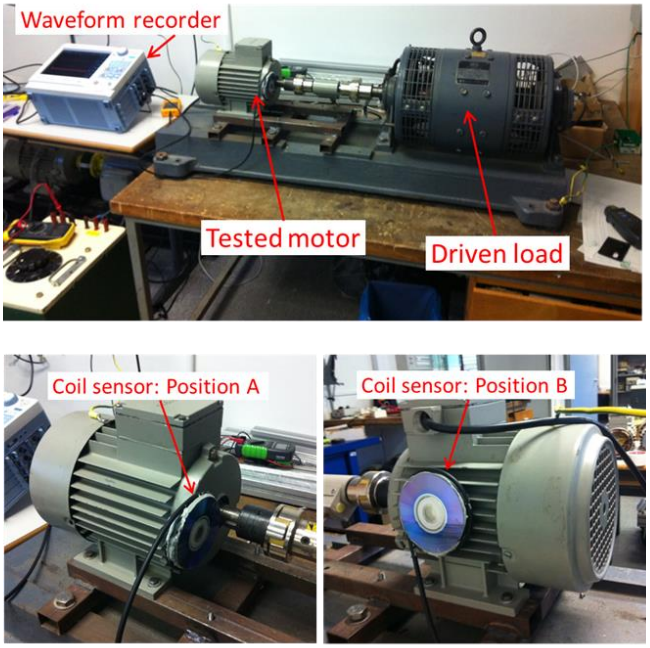

Fig. 3. Pictures of the testbench used in [12].

Due to the large number of false indications reported in conventional methodologies such as motor current signature analysis (MCSA), recent investigations have been focused on reliability aspects. In this context, magnetic flux analysis has become an excellent technique able to avoid some false diagnosis such as electrically symmetrical nonadjacent BRB [18], [29], [36], [53], [70], BRB false indications due to load oscillations [31], [69], and rotor faults under the influence of rotor axial air ducts [6].

In [29], [36], a frequency spectral subtraction of the power spectrum is proposed to detect BRB regardless of their relative position. The paper presented in [53] effectively diagnoses nonadjacent BRB by a time-domain analysis. However, the installation of several sensors is required. Recent works such as [18] proposes the monitoring of the f_r sidebands of f_s and odd harmonics in the internal and external search coil measurements during steady state and motor starting as an indicator for detecting broken bars. There, it was shown that internal airgap flux measurements produce superior reliability diagnosis than stray flux signals.

Regarding false diagnosis related to load oscillations, the authors of [69] present the use of an ANN fed by the magnitude of the odd multiple of power supply frequencies. For similar purposes, the work presented in [31] proposes to analyze the time between successive zero crossings (TSZCs) of the airgap flux, since TSZC should remain constant if the rotor does not have any asymmetry as demonstrated there.

The research carried out in [6] shows that radial stray flux spectrum can provide reliable detection of rotor faults immune to the influence of rotor axial air ducts. Furthermore, a very recent paper [84], demonstrates that the 2nd rotor rotational frequency of the airgap flux can provide reliable detection of rotor faults under load varying conditions, low slip operation, and with non-adjacent broken bars.

Another fault that frequently occurs in SCIM is the presence of *stator interturn short circuits*. This type of fault is considered one of the most dangerous since it can suddenly lead to a shut-down of the machine. The degradation of the insulation system can be mainly caused by overheating, vibration or aggressive ambient. In order to perform an incipient interturn fault detection, the authors of [19], [22], [26], [52] propose to use several search coils around the shaft of the machine to detect and locate interturn short circuits. In [18] and [21] an array of 4 search coils is installed around the shaft and internally. On the other hand, in [52], the authors propose to use a fusion technique in order to increase the diagnosis efficiency. The work presented in [22] uses two sensors installed on the frame at 180° apart. The main advantage of this method is that it does not require knowledge about the healthy state. The main drawback of these methods is the requirement of several sensors. The research carried out by [85] shows that stator faults generate magneto-motive force space harmonics given by (4).

$$f_{stator\_fault} = k_{odd} \cdot f_s \pm n \cdot f_r \qquad (4)$$

where k_{odd} is an odd integer and n is an integer different than $6 \cdot j \pm 1$ (j is an integer). Some investigations such as [20], [30], [37], [47] have ratified these findings and concluded that the harmonic in the lower part of the spectrum ($f<500$Hz) are not very sensitive to the fault. Other works, as [49], propose to analyze the start-up transient by using the DWT, and a fault index based on the energy evaluation of the external magnetic field is introduced there. In [41], it is demonstrated that stator short circuits also produce an increment in the THD of the axial stray flux. Other works such as [34] use statistical analyses to detect faults at incipient stages by comparing the standard deviation of faulty and healthy machines. On the other hand, [43] proposes to combine the information obtained of vibration and magnetic flux analysis. The research developed in [24] has been focused on the estimation of the healthiness state of the insulation, before a interturn short-circuit develops. A DWT-based severity level indicator is proposed. There it is shown that high temperatures deteriorate the final diagnosis. In [86], the analysis of thermal images and magnetic flux is suggested. This scheme was capable of tracking and localizing the fault; however, several internal sensors are required. Other woks such as [28], [42] have proposed an orbital analysis. The main advantage of this is the sensitivity to low severity faults; yet, it is necessary to use several sensors.

The magnetic flux analysis has also demonstrated potential to diagnose mechanical faults such as eccentricity faults [8], [17], [35], [40], [44], [87], misalignment faults [10], [12], [17], [32], [42], [78], bearing faults [23], [46], [87], [88], and gearbox faults [71], [89].

Regarding *eccentricity faults*, [87] demonstrates that dynamic eccentricity produces f_r sidebands of f_s given by (1). The works presented in [90] also investigate the frequencies related to the slotting effect (given by (5)) to diagnose dynamic and static eccentricity faults.

$$f_{ecc} = f_s \pm (k \cdot N_r \cdot \pm n_d) \cdot f_r \tag{5}$$

where N_r is the number of rotor slots, $n_d = 0$ for the static eccentricity and $n_d = 1,2,3$ for dynamic eccentricity. In [8] it is pointed out that machines considered as perfect also present $s \cdot f_s$ frequency with a low value due to manufacturing processes. Reference [12] evaluates the stray flux analysis under the starting transient and demonstrates that $s \cdot f_s$ fault components appear due to inherent eccentricity. In [12], [17] it is shown the possibility of discriminating between eccentricity, misalignment and BRB by means of STFT analysis of the startup transient. Since BRB amplifies similar frequency harmonics as eccentricity faults, the research in [44] is focused on the reliable diagnosis and classification of these faults by means of airgap and radial stray flux monitoring.

With respect to *misalignment faults*, it has been shown that f_r sidebands of f_s (given by (1)) are sensitive to misalignments [17][78][78][12]. In [10], the use of AI algorithms is proposed to automatically detect mechanical faults by means of statistical and non-statistical parameters obtained from STFT t-f maps when analyzing the startup transient. The main disadvantage of this approach relies on the potential false diagnostics produced due to noise. In [32], high resolution transforms (ST-MUSIC) are used in order to mitigate the effects of noise on the results. Other works [42] proposes an orbital analysis to determine misalignments faults; nevertheless, it is required to install two sensors, which is not always possible due to spatial restrictions.

Bearing failures can be detected by analyzing stray flux signals harmonic components given by (6), which are similar to those found on current signals and that appear with a low amplitude [87].

$$f_{bng} = |f_s \pm k \cdot f_v| \tag{6}$$

where f_v is vibration frequency associated with the corresponding bearing failure (outer race, inner race, ball or cage defect).

Nevertheless, as stated by [87], the feasibility of applying the stray flux analysis to bearing fault detection is controversial since amplitudes of these components are very low both in the stator current and the stray flux. In [46][46] statistical analyses are proposed; however, these methods need an initial data set to be used as the healthy reference.

Other papers [71], [89] investigates the frequencies amplified by *gearbox-related faults*. There, it is demonstrated that the gear fault frequencies (given by (7)) depend on the number of gearbox teeth, and can be clearly identified in the stray flux spectrum.

$$f_{gear} = \left|f_S \pm (N_d \pm k_{gear}) \cdot f_r\right| \tag{7}$$

where N_d is the number of teeth and $k_{gear} = 0, 1, 2, \ldots$

B. *Wound rotor induction machines (WRIM).*

A fewer number of research works have been focused on this type of machines, in comparison to those dealing with SCIM. This situation can be mainly attributed to the fact that they are less widespread in the industry due to the more complex configuration of their rotor circuit, which requires slip-ring/brushes systems to access the rotor winding. Clearly, this characteristic makes them prone to suffer from different types of faults such as occasional defective contacts between slip-ring and brushes, uneven wear of the brushes in the three phases, high-resistive joints, and inadequate or uneven tightening of the springs [13]. Despite this, WRIM present some advantageous characteristics such as capabilities to develop high starting torques at standstill while maintaining low start-up currents (by inserting external resistors in series with the rotor winding). More recently, a renewed interest on WRIM has emerged since they are being extensively used as generators in wind turbine units, as they can provide a high energy output with a low rating of the power converter connected to the rotor side [91]. The main failures that usually occur in this type of machine are those due to stator and rotor winding faults, and rotor eccentricities. They can manifest itself in an increase in rotor resistance, a short circuit or an open circuit [13]. It is known that an electrical failure of the rotor in a WRIM induces a phase dissymmetry and the magnetic flux can be useful to detect it. In [92], it is proposed to analyze the stray flux to detect and determine the fault severity level of rotor winding asymmetries by using the STFT and DWT under the startup transient. It is shown that fault frequency components dependent on f_s and s, which are given by (8) are amplified in case of rotor asymmetries, and the amplitude of such components can be used to determine the fault severity. In this way a DWT-based fault severity index is proposed.

$$f_{asymmetry} = f_s \cdot (1 - 2s) \tag{8}$$

The authors in [25] propose to use pole-specific search coils to determine rotor eccentricity faults. The practical applicability of the method is linked to large machines with low critical speeds. The main disadvantage of the method is that search coil voltages are largely dependent on loading.

In [92], a technique for detecting stator interturn faults in a DFIGs is presented. This technique is based on rotor-phase current and validated by the rotor search-coil voltages. The main disadvantage of this methodology is related to its invasiveness since it is required an extra winding that must be wound on the rotor.

C. *Permanent magnet machines (PMM).*

Nowadays, permanent magnet machines (PMM) have received special attention as they represent an excellent alternative to induction machines in many applications. This situation can be mainly attributed to its excellent benefits such as high efficiency, power density, ease of control, torque–current ratio, among others [93]. The most common failures reported in permanent magnet synchronous machines (PMSMs) are rotor eccentricities, permanent magnet (PM) demagnetization, and load alignment/unbalance-related failures. Rotor eccentricity faults can be caused by imperfections introduced during manufacturing or assembly, imperfections in the rotor, worn bearings, bent shaft, etc. [94]. Global demagnetization can lead to a decrease of the average torque, and local demagnetization can produce an increase of the torque ripple, motor vibration, and acoustic noise [95]. Irreversible local demagnetization in the PMs can be caused by a combination of thermal stress, demagnetizing magneto-motive force, mechanical stress (chipping or cracking), or disintegration due to corrosion/oxidation. As shown by [94], the interaction between the signatures produced by rotor and load defects could cause false indications when conventional motor current signature analysis (MCSA) is employed. The authors in [96] presented and validated (through experimental results) a time-stepping finite-element method (TSFEM) analytical model for the analysis of eccentricity faults in PMSM. There is shown that the magnetic field in PMSM under eccentricity faults results in the amplification of particular frequency components (which can be used as an index for proper fault recognition) given by (9):

$$f_{PMSM} = \left(1 \pm \frac{m}{P}\right) f_s = f_s \pm f_r \tag{9}$$

where m is an integer and P is the number of pole pairs.

Furthermore, inherent problems related to the PMSM drive system (i.e., misalignment, load unbalance, or other mechanical asymmetries) produce sideband components identical to f_{PMSM} [97]. Certainly, this situation makes the fault classification a challenging task. In this regard, the focus of very recent researches has been directed towards reliability and fault classification aspects. The study of the magnetic flux in PMSMs has turned out to be an excellent technique for the online diagnosis of faults such as demagnetization [14], [56], [62], [94], [98], and rotor eccentricities [94], [96]. In [12] it is proposed to use fluxgate sensors to study the demagnetization severity level through fault-related harmonics. Dominant fault signatures, such as the 0.25th and 0.5th harmonics in the radial direction show better sensitivity results for demagnetization defects. The work presented in [62] analyzes the air-gap magnetic flux using its proposed FBG-Magnetostrictive sensor; moreover, an easy-to-compute index based on the observed pulse shaped flux density measurement is proposed. Although these investigations have shown to be capable of generating diagnoses of the demagnetization fault severity, their reliability has yet to be proven. In this context, some works have been developed to achieve a more reliable diagnosis.

The investigation presented in [56] shows an accurate PM demagnetization detection method based on the measurements from Hall-effect sensors, and it relies on the total harmonic distortion (THD) and the peak-to-peak value of the magnetic flux density complex vector. Since the implementation strongly depends on the angle of the Hall-effect sensors used, any variation in the sensor gains, assembling tolerances, offsets in the sensors, and stator current effects can lead to accuracy-related issues. Another paper [98] investigates the possibility of overcoming such drawbacks by using simple metrics as the peak-to-peak value or the mean value of the zero-sequence magnetic flux density. Although reliable estimations of the magnetization state are achieved, this technique still shows a sensitivity for the same aspects but it is less affected. Besides, according the authors, all these implementation concerns virtually disappear, if incremental instead of absolute measurements are used.

A very recent research carried out in [94] examines the signals from analog Hall-effect field sensors (which are commonly available in the motor) for detecting and classifying eccentricity and local demagnetization defects. This method does not require motor model information, and it is immune to the influence of motor design, ambient or operating conditions. This technique is able to reliably classify eccentricity, local demagnetization, and load unbalance conditions with high sensitivity. Most of the proposed works to detect demagnetization faults and eccentricities in PMM use Hall-effect sensors since many PMM include this type of sensors for motion control and initial rotor position estimation. This allows the use of these techniques with low or no additional hardware cost. Moreover, some methodologies have reported the effectiveness of magnetic flux signals for improving the estimation of rotor position for sensorless control applications and PM temperature monitoring. In [99], it is shown the superiority of Hall-effect magnetic signals for the control of PMM since speed/position sensors as encoders or resolvers are not required, which avoids moving parts or coupling to the machine shaft. Also, in [100] a nonintrusive estimation of the PM temperature based on magnetic flux signals is presented. The method is not influenced by changes in the thermal characteristics, and does not require prior knowledge of motor parameters.

All these remarkable applications have demonstrated the potential of analyzing magnetic flux signals for the condition monitoring of PMMs. However, in practical terms, further research for non-invasive fault classification methodologies is needed to extend the capabilities of the available techniques.

D. *Wound field synchronous machines.*

Wound field synchronous machines (WFSM) have the advantage of delivering higher efficiency and power factor regulation capabilities, in comparison to the broadly used induction machines. Nonetheless, WFSM are less widely used mainly due to the high costs and maintenance required for similar power ratings, as these machines have a complex rotor structure and excitation components [101]. The most common failures reported in WFSM are those related to bearings, damper bar damages and rotor field winding faults. Damper bar breakages are mainly generated by thermo-mechanical stresses due to uneven thermal expansion during the starting transient, where high amplitude currents develop [102]. On the other hand, faults in the field winding are usually caused by gradual deterioration of the insulation between turns, mainly due to thermal stresses and mechanical wear caused by centrifugal forces [66], [75]. Online detection of these faults is a complex task: on the one hand, the damper bars are active only under the starting or load transients. On the other hand, shorted field winding turns slightly increase rotating asymmetry (especially when the machine has several winding turns per pole). Finally, field winding turn shorts can be intermittent and unobservable at standstill or under an steady state operation [76]. Besides, it is known that conventional methodologies based on the increase study of the rotor rotational frequency (1x), such as vibration or current analysis monitoring do not produce reliable results since other types of defects in the motor, coupling, or load can mask the identical 1x sidebands and there is no known way of identifying the source [103].

In this context, magnetic flux analysis has shown very good results for detecting and discriminating damper and field winding faults in WFSM [16], [27], [38], [66], [75], [76]. In order to confirm or discard the presence of any of these electric faults, in [38] it is proposed to study the stray flux and the external frame vibrations (EHV) by analyzing the correlation between the external field and the EHV. The advantage of this, as reported by the authors, lies in that the method can be applied to detect other types of faults as turn to ground fault or eccentricities, since they appear in the external magnetic field. However, in this methodology there is still a need for separating the different types of faults. In [27], the authors propose the study of the airgap flux during the starting transient to detect damper bar faults in salient pole synchronous motors (SPSM). This proposal follows the most favorable conditions for the detection of this fault, since the damper winding is active during the startup transient (with maximum current). As shown by [27], rotor failures produce frequency components at f_r sidebands of the power supply frequency (f_s), depending on the number of pole pairs (p), rotor slip (s), and k multiples of ± 1 that are not multiples of $k = \pm 2p$, given by (1) (same as rotor faults in SCIM).

The work presented in [76] proposes a method that analyzes the airgap flux under the starting transient for the detection of shorted turns in field windings of SPSM. As shown in [76], f_{flux} fault components (given by (1)) appear in the induced voltage of a search coil installed on the stator tooth surface. In this way, f_{flux} components not overlapping with saliency related components (which appear regardless of the fault) can serve as an indicator of field windings faults and they can be observed when $k \neq 2p \cdot k_1$ where k_1 is an integer.

Nevertheless, since broken damper bars and shorted field windings can be detected by monitoring the presence of f_{flux} components that are not multiples of $k = \pm 2p$, the two faults cannot be discriminated by just analyzing f_{flux}. To this end, in [16] it is proposed to analyze the "change" in the "z-axis magnitude" of the saliency-related components ($k = \pm 2p$) of f_{flux} for reliable identification of the fault origin. The main disadvantage of airgap approaches lies in the fact that airgap flux probes are not available in all motors. Furthermore, methodologies based on the analysis of the air gap are considered to be intrusive (as they require installation of internal air gap flux sensors). In this regard, some investigations have been based on the analysis of the stray flux. In [104] it is shown that damper cage damages also amplify the frequency components at the rotor rotational frequency f_{flux} in the stray flux under starting. Furthermore, there it is demonstrated how the effect on the remnant magnetism in the rotor may complicate the diagnosis since it can make the startup much shorter, enabling a faster synchronization of the machine. A comparison of time-frequency analysis between current and stray flux signals is carried out in [105]. There it is shown that current analysis can be complemented by high-order harmonics of stray flux in order to get more reliable diagnosis.

In [75] a non-intrusive method for detecting and distinguishing damper and field winding faults under motor starting is proposed by studying the time and frequency domain analysis of stray flux and current. There, it is shown that the presence of an open damper bar or shorted field winding turns produce an asymmetry, which in turn generates a nonzero net axial flux. The frequency of the axial leakage flux is identical to that of the rotor winding induced currents given by (10):

$$f_{fault,\ ax} = s \cdot f_s \tag{10}$$

In order to classify the origin of the fault, the authors in [75] propose to use the time required to achieve steady state operation (t_{start}), since t_{start} decreases due to a low impedance shorted turn loop and it can be determined from the stator current during the starting transient. The main disadvantage of methods relying on stray flux analysis is the lack of sensitivity when the number of turns per pole is large.

Due to the complexity of the asymmetry failure in synchronous machines, as well as the fact that this type of failure is visible in transient states, the study of this type of machine represents a big challenge, and it requires further research. Based on the limitations of existing test methods in the field and according to the technical literature, there is still work to be done in terms of generating a timely diagnosis on a continuous basis and providing indicators of the fault severity.

V. Comparative of Magnetic Flux Analysis with other Techniques and Pending Issues

In this section it is presented a summary about the main advantages and disadvantages of the different available techniques for the diagnosis of faults in electric machines. A comparison is provided according to the fault origin and location; i.e., mechanical (bearing, coupling, misalignment, eccentricity), stator (inter-turn short circuit, asymmetries, insulation), and rotor (broken rotor bars, asymmetries). Table I is intended to provide a quick insight about the different technologies currently available; more details can be found on the references cited there. Additionally, Table II specifies some relevant pending issues concerning the application of magnetic flux analysis to the fault diagnosis of electric machines.

TABLE I
MAIN FAULT DIAGNOSTIC METHODS COMPARISON: ADVANTAGES AND DISADVANTAGES

Acquired Signal / **Fault origin**	**Stray/airgap flux**	**Stator/rotor currents**	**Vibrations/acceleration**	**Others (partial discharges, acoustic signals)**
Mechanical: bearing, coupling, misalignment, eccentricity.	✓ Able to distinguish among different faults that arises identical fault harmonics [17]. ✓ Immune to low load variations [7].	✓ Nonintrusive and remote technique [106]. ✓ Signal directly tied to the fault [107].	✓ Considered to be more reliable for bearing, eccentricity, or load defects [106]. ✓ The primary effect of bearing failures is in vibration [108].	✓ Useful for the diagnosis of bearings faults (acoustic signals). [109]. ✓ Remote diagnosis (acoustic signals) [109]. ✓ Time effectiveness, which can improve the efficiency of fault diagnosis and maintenance scheduling[110].
	× Controversial usage for bearing fault diagnosis [87]. × Low amplitude fault-related harmonics [87].	× False diagnosis due to low load variations [7]. × Relatively low sensitivity due to attenuation [106].	× Sensitivity influenced by the sensor position [107].	× Indirect relation to the fault (acoustic signals). × Background noises may cause distortion of signal (acoustic signals) [111]. × Frequency bandwidth limited by the used sensor (acoustic signals) [111].
Stator: inter-turn short circuit, asymmetries, insulation.	✓ Sensitivity superior than line currents [107]. ✓ Location of the short circuited turn [19].	✓ Nonintrusive and remote technique [106].	✓ Diagnose capabilities under varying supply-frequency and load conditions [112].	✓ Capable of generating online diagnosis (partial discharges) [106]. ✓ Widespread application (partial discharges) [106].
	× Low sensitivity for a small number of shorted turns for the case of WFSM [106]. × Several sensors required to locate interturn short circuits [19], [22], [26], [52]. × Influence of high temperatures over the results [24]. × High-frequency resolution is required [108].	× High-frequency resolution is required [108]. × Other causes may induce a negative sequence component [108].	× Difficult to confine the exact location of the fault [111]. × Often, there are evidences when the level of fault is severe.	× Influence of pulse-like electrical “noise” on stator partial discharges [106]. × Influence of switching noise on stator partial discharges [106]. × Difficult to diagnose machines rated at voltages below 6 kV (partial discharges) [107].
Rotor: broken rotor bars, asymmetries.	✓ Able to detect non-adjacent broken bars [18]. ✓ Immune to rotor axial air ducts [6]. ✓ Direct indication of the asymmetry [106]. ✓ Superior sensitivity of airgap flux monitoring [106].	✓ Widely accepted and applied in the field [106]. ✓ Suitable to obtain a diagnostic index and a threshold between faulty and healthy conditions [107]. ✓ Well-established method [107].	✓ Inexpensive diagnostic technique [111]. ✓ Detection of deterioration and incipient faults [111].	✓ Immediate and non-invasive measurement of acoustic signals [113].
	× Considered as an invasive technique (airgap flux) [7]. × Lack of measurement of the operational quantities, such as voltage or currents [111]. × Physical access to the motor is required.	× Half pole pitch apart broken bars are not observable [7]. × False diagnosis due to non-adjacent broken bars [106]. × False diagnosis due to low load variations [106]. × False indications due to rotor axial air ducts [6]. × Indirect relation to the fault [106].	× Indirect relation to the fault.	× Acoustic signals are mixed together (e.g., reflections, waves overlapping)[113].

TABLE II
PENDING CHALLENGES RELATED TO THE USE OF MAGNETIC FLUX FOR ROTATING ELECTRIC MACHINES FAULT DIAGNOSIS

Type of machine	**Fault**	**Pending challenges**
SCIM	Adjacent broken rotor bars [6], [8], [10]–[12], [17], [31], [32], [37], [44], [51], [53], [54], [57], [58], [61], [67], [69], [74], [78], [83]	• Generation of indicators and thresholds to identify the fault and determine the fault severity level under transient analysis. • In the case of stray flux analysis, determine the optimal sensor position that provides the highest sensitivity. • Automation of the diagnosis process. • Study of the applicability and sensitivity of high-resolution and empirical TFD tools. • Study of the applicability of transient analysis for the reliable detection of mechanical-related faults such as coupling system faults and bearing faults. • Enhance the discrimination between different faults.
	Non-adjacent broken rotor bars [18], [29], [36], [53], [70]	
	Intern-turn Short circuit [11], [19], [20], [22], [24], [26], [28], [30], [34], [37], [39], [41]–[43], [45], [47], [49], [50], [52], [59], [60], [73], [86]	
	Eccentricity [8], [17], [35], [40], [44], [87]	
	Misalignment [10], [12], [17], [32], [42], [78]	
	Bearing failures [23], [46], [87], [88]	
	Coupling system failures (Gearbox) [71], [89]	
WRIM	Rotor winding asymmetries [13]	• Development of reliable diagnostic techniques. • Incorporation and optimization of indicators and thresholds to identify the presence and determine the severity of the fault. • Development of methods able to generate automated final diagnosis.
	Stator inter turn short circuit [92]	
	Rotor eccentricity [25]	
PMM	Rotor eccentricity [94], [96]	• Development of techniques capable of generating non-invasive diagnosis. • Evaluation of the applicability of transient analysis for the reliable fault detection. • Classification of the different fault conditions.
	Permanent magnet demagnetization [14], [55], [56], [62], [94], [98]	
WFSM	Broken damper bar [16], [27], [38], [75]	• Development of techniques capable of generating a continuous online diagnosis. • Development of fault severity indicators in order to obtain additional information. • Study of the applicability to detect non-adjacent broken damper bars. • Optimizing the methods for their practical implementation in the field.
	Winding faults [16], [38], [48], [75], [76]	

VI. CONCLUSIONS

This paper presents the review of different aspects related to the application of magnetic flux analysis for condition monitoring of rotating electric machines. A study of the different sensors used to measure airgap and stray fluxes in different electrical machines has been carried out by discussing the uses, advantages and disadvantages of each type of sensor. It is concluded that coil-based and Hall-effect sensors have been widely used in this area, although recently printed circuit sensors and fiber-optic-based sensors have been recently proposed due to their good responses over time and reduced sizes.

Moreover, a comprehensive review of the different signal processing techniques adopted for the study of magnetic flux signals has been developed. Methodologies based on the FFT analysis were found to be broadly used for diagnosing a wide variety of faults in different types of machines. Nevertheless, over recent years, there has been a clear trend to employ time-frequency decomposition (TFD) techniques during transient states of the machine, especially under the starting, where frequency components amplified by a specific fault develop yielding particular patterns. Additionally, very recent methodologies propose the use of high-resolution TFD tools such as ST-MUSIC that allow obtaining clearer and more concise time-frequency maps, evidencing only larger frequency components. Similarly, discrete transforms like DWT have demonstrated practicality to generate reliable indicators informing on the severity of the failure.

On the other hand, there has been a clear trend toward the development of methodologies that yield diagnosis techniques with greater reliability, capable of generating timely diagnoses where conventional techniques produce false indications, in such a way that some recent approaches have been directed towards the analysis of higher order harmonics. These harmonics have been shown to be less distorted by noise and other non-fault related phenomena. Thus, the analysis of the magnetic flux has proven to be a significant tool, both for the diagnosis of faults in electric machines by yielding comparable results to those of well-established techniques and as a complement to other fault detection techniques.

One field that opens an interesting research area in relation to the stray-flux analysis relies on the classification, extraction of fault severity indicators and reliable identification of fault patterns. The ultimate objective is to build intelligent systems capable of providing reliable and robust diagnoses in an online basis. In addition, the examination of the feasibility of using modern TFD tools, such as high-resolution and empirical transforms to obtain clearer results and reliable diagnosis is still pending. A compendium of the pending challenges for each specific type of fault and machine typology is included in Table II.

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