ELECTRIC MOTOR FAULT DIAGNOSIS BASED ON THE ADVANCED ANALYSIS OF THE STRAY FLUX

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Abstract - This paper presents the most novel research concerning the application of modern technologies for condition monitoring of electric motors based on the advanced analysis of the stray flux. The analysis of the magnetic field in the vicinity of the motor has proven to provide very useful information for the diagnosis of several failures. This technique has drawn recent attention due to the advance in the technology of the necessary sensors, simplicity, non-invasive nature and low cost. The paper presents the different variants within this technology, including the classical method based on the stationary analysis of the flux as well as recent techniques relying on the advanced analysis of transient flux signals. The paper includes experimental results in motors with different failures and proves the potential of this technology for becoming a reliable source of information for the determination of the motor health.

Index Terms — Induction motor, Fault diagnosis, Stray flux, Transient analysis, Reliability, Rotor, Eccentricity.

I. INTRODUCTION

Electric motor reliability is a matter of increasing concern in the industry due to the vast participation of these machines in processes and applications which are often critical in the plants where they take part [1]. Therefore, proper maintenance strategies must be adopted to maintain these machines in suitable conditions in order to prevent unexpected outages and subsequent production downtimes. According to some surveys [2], maintenance costs may account for 15-40% of total cost of production for petrochemical industries. This gives an idea of the relevance of this area in petrochemical facilities, where electric motors play an especially prominent role due to the critical nature as well as to the safety requirements of the processes taking place at these sites.

Different types of failures may occur in an electric motor. Rotor faults, eccentricities, bearing damages, degradation of the stator insulation or core faults are some of the failures that may take place in induction motors [1], the most widespread type of electric motor in industry. The consequences of the occurrence of these faults are very negative leading even to catastrophic effects on the machine itself that may have severe repercussions for the process where they operate. Fig. 1 shows some examples of catastrophic faults that led to forced motor outages [3]. Most of them are referred to H.V. motors.

Fig. 1 Catastrophic faults in induction motors [3]

Over recent decades, many researchers both in academia and in industry have worked in the development of reliable techniques able to diagnose the previous faults when they are still in their early stages of development, so that proper maintenance actions can be adopted before the machine collapses. These techniques rely on monitoring specific motor quantities and on their subsequent analysis to detect possible evidences of the presence of the failure. In this regard, electrical monitoring (currents, voltages), mechanical monitoring (vibrations), thermal monitoring (internal temperature, infrared data), partial discharge monitoring or even acoustic (noise, ultrasounds) and chemical monitoring have been proposed as a basis of the developed techniques [3]. In spite of this dynamic activity, one of the most important conclusions derived from this vast work is that none single technique or quantity has proven to be enough reliable to diagnose, alone, the condition of the whole motor. In other words, each specific quantity is valid for diagnosing certain faults but not for others. And, even for the faults that it can better diagnose, there may be cases in which false alarms or erroneous diagnostics can be derived from the use of a specific quantity [4]-[6]. Therefore, the best solution seems to be to combine the information coming from different diagnosis methods, so that a more reliable conclusion on the motor condition can be obtained. At the same time, investigation of new techniques that enable to overcome the diagnosis provided by the already existing ones is another way to reach a more reliable diagnostic of the motor health.

In this context, the analysis of the external magnetic field and, more specifically, of the stray flux at the vicinity of the electric motor is drawing the attention of many researchers and companies worldwide, due to the interesting advantages that this diagnosis technique provides [7]–[9]: on the one hand, it is a non-invasive approach, since the registration of the necessary data can be carried out without perturbing the normal operation of the motor. Moreover, the necessary equipment for the registration of this quantity is simple, it has low cost and it has had a spectacular development over recent years with regards to the features of the necessary flux sensors [8]. Furthermore, previous works have proven the potential of the stray-flux-based technique for obtaining relevant information for the diagnosis of certain faults such as stator short-circuits [10]-[11], rotor problems [12]-[13], eccentricities [14]-[15] of even coupling system problems [16]. Some well-known manufacturers have started building coil sensors for fault diagnosis which rely on this technique.

Note that, due to the recent dynamic research activity, the former approaches for stray-flux data analysis that were based on the Fourier analysis of stationary signals [10]-[15] are being complemented by more modern and robust technologies that rely on the advanced analysis of the stray-flux data under transient operation of the machine (e.g. the motor startup). Recent works have proven the potential of transient analysis of the stray flux which has provided excellent results for enhancing the diagnosis of some of the aforementioned failures in several types of electric motors, such as cage induction motors or wound rotor induction motors [17]-[19], avoiding some drawbacks of the conventional methods. The application of transient analysis requires the use of more advanced and sophisticated signal processing tools that are suitable for the analysis of non-stationary quantities (time-frequency transforms).

This paper reviews the different fault diagnosis approaches relying on stray flux analysis, including both the classical methods based on steady-state analysis as well as the recently introduced technologies that rely on the analysis of stray flux data under transient regimes. The paper includes several experimental cases that demonstrate the suitability of both approaches for the detection of certain faults in induction motors.

II. STRAY FLUX DATA ANALYSIS FOR FAULT DETECTION

In its more widespread modality, the diagnosis technique based on stray flux data analysis relies on installing a coil sensor on the external part of the motor frame [7], [12]. The dispersion flux created by the motor during its operation (stray flux) induces an electromotive force (emf) in the sensor; the waveform of this emf can be easily registered with the aid of an oscilloscope or waveform recorder. The proper analysis of that emf signal enables to detect evidences of the presence of faults in the motor. To this end, suitable signal processing tools must be applied, depending on the operation regime under which the emf has been captured (steady-state or transient).

One of the most important characteristics of this diagnosis technique is that its results are strongly influenced by the sensor position. This is due to the fact that, depending on the position of the sensor, a higher portion of axial or radial flux will be captured and, hence, the corresponding fault components (axial or radial) will be better observable when the emf signal is analyzed. Fig. 2 depicts three typical locations of the flux sensor on the motor frame [7],[20]: at position A, a higher portion of axial flux is captured and, therefore, fault components with axial nature will be better noticeable in the results of the analyses. On the contrary, at position C, the captured stray flux is primarily radial and, consequently, the radial components will be better observed. Finally, at position B, a mixture of axial and radial flux is captured by the sensor and all components can be observed in a certain level.

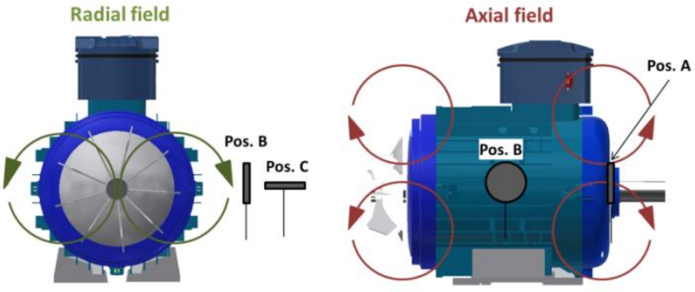


Fig. 2 Nature of the flux captured at each coil sensor position [20].

A. *Classical method (steady-state)*

In the early 2000's several authors proposed the analysis of the stray flux data under stationary conditions as a way to detect several faults in induction motors [11], [13], [21]. The idea of these methods was to analyze the data representative of the stray flux (e.g. the emf induced in an external sensor) at steady-state by applying the Fast Fourier Transform (FFT). It is well-known that this transform extracts the frequency components present in the analyzed signal as well as their corresponding amplitudes (in other words, the FFT is an amplitude vs. frequency representation of the analyzed signal). The idea of this conventional approach is that, when a certain fault is present in the motor, specific frequency components will be amplified in the FFT spectrum. Therefore, the evaluation of the amplitudes of these components enables to diagnose the presence of the failure in the machine.

More specifically, several authors proved that, in the case of rotor damages, the components given in Table I are amplified in the FFT spectrum of the emf [7], [21] (f=supply frequency and s=slip). Note that, according to that table, some of the rotor fault components have an axial nature, while others have a radial nature. Hence, depending on the location of the flux sensor that is employed, one or the other will be better observed in the resulting FFT spectrum of the registered emf signal.

TABLE I
FREQUENCY COMPONENTS AMPLIFIED BY ROTOR DAMAGES IN THE FFT SPECTRUM OF STRAY FLUX

Component	Nature	Comments
$f\cdot(1\pm2\cdot s)$	Radial	
$s\cdot f$	Axial	May be also amplified by eccentricities/misalignments
$3\cdot s\cdot f$	Axial	May be also amplified by eccentricities/misalignments

On the other hand, other authors stated that, in the event that eccentricities are present in the motor, the components given in Table II are amplified in the FFT spectrum of stray flux data [14]. In the expression written in that table, p stands for number of pole pairs and m=1,2,3…Hence giving values to m, different pairs of frequency components are obtained, the most relevant being those for m=1.

TABLE II
FREQUENCY COMPONENTS AMPLIFIED BY ECCENTRICITIES IN THE FFT SPECTRUM OF STRAY FLUX

Component	Nature	Comments
$f\cdot(1\pm m\cdot(1-s)/p)$	Radial/axial	May be also amplified by rotor faults

Other authors provided similar expressions for the components amplified by other faults and anomalies such as bearing faults, gear problems or even stator short-circuits [10]-[15].

B. New approaches (transient)

Recently, an alternative diagnosis approach relying on the analysis of stray-flux data has been introduced [17]-[18]. Unlike the previous FFT-based method, the new approach relies on the analysis of stray-flux data that are registered under transient operation of the motor. More specifically, the recent works that propose this new methodology have been focused on the analysis of the emf signals captured during the startup transient (i.e. the connection of the motor). It has been demonstrated that under a direct-on-line startup of an induction motor, due to the characteristic variation of the slip s (from s=1, when the motor is connected, to $s\approx 0$ at steady-state), the fault-related frequencies described in Section II.A (which are slip-dependent) will also change. Therefore, they will follow characteristic variations over time. The identification of these evolutions is a reliable evidence of the presence of the corresponding failure. As an example, Fig. 3 shows the characteristic time evolutions during a direct-on-line startup of the fault frequencies related to rotor damages and eccentricities (described in the previous section) [20]. If these evolutions are detected, the corresponding faults can be properly diagnosed in the motor.

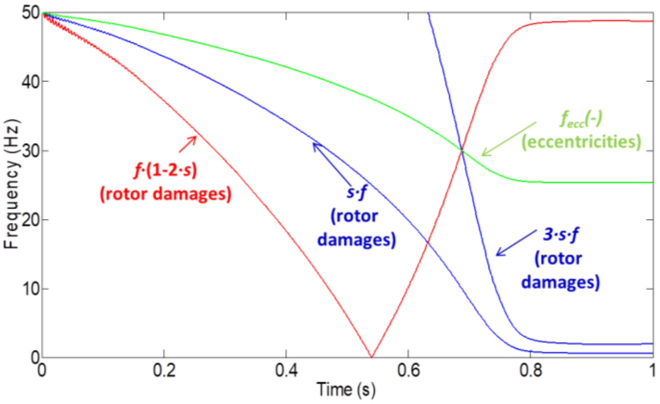


Fig. 3. Expected t-f evolutions of the emf fault harmonics during a direct-on-line startup of the motor.

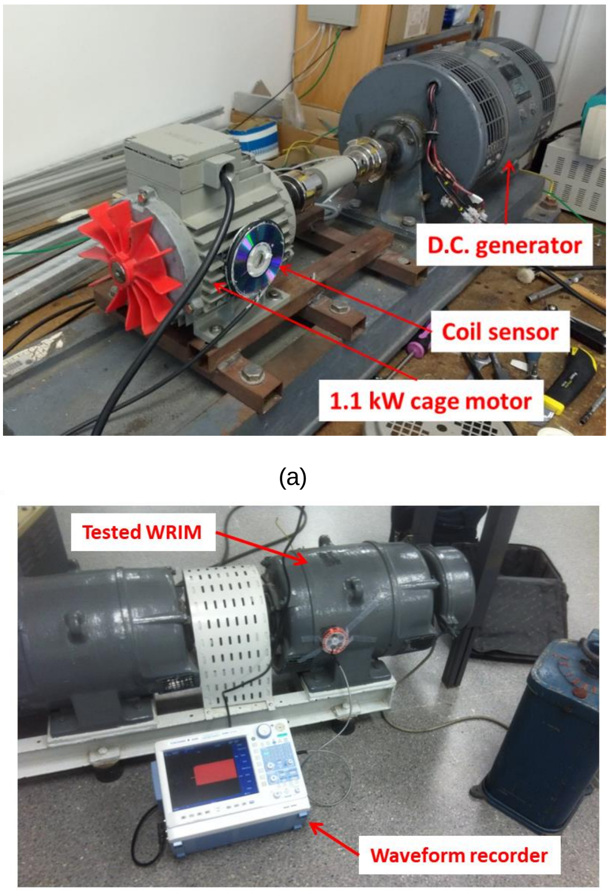
The detection of the evolutions of the aforementioned components under a startup requires the application of sophisticated signal processing tools that are capable to represent not only the frequency components present in the analyzed signal but also how they change over time. These tools are known as time-frequency transforms since they provide, as a result, a time-frequency map that depicts the time evolutions of all frequency components present in the signal. There are several time-frequency transforms that have been optimized and applied in the area of transient analysis (wavelet transforms, Hilbert-Huang-transform, Wigner-Ville Distributions…) [17]. In this paper, the Short Time Fourier Transform (STFT) will be applied since it gives a good tradeoff between computational burden and user availability, despite it requires the previous optimization of the parameters needed for its application. The STFT performs a time-frequency decomposition of the analyzed signal by multiplying this signal by a window function that is moved over time and by computing the FFT at each location of that function. The window function length must be selected by the user depending of the considered problem. In this particular work, a suitable window length has been selected so that the frequency harmonic's evolutions of interest can be properly tracked.

III. EXPERIMENTS

In order to illustrate the operation of the two approaches based on stray-flux analysis described above, different emf signals obtained from experimental tests will be analyzed. The tests were carried out on two different types of induction motors in order to show the validity of the method for a variety of constructive characteristics. More specifically, a cage induction motor (motor 1) and a wound rotor induction motor (motor 2) were tested. The characteristics of these machines are shown in Table III. The test benches used for testing both motors are depicted in Fig. 4(a) and (b). Three different positions of the coil sensor were considered (corresponding to those depicted in Fig.2). Moreover, different types of faults were forced in each of the machines: in motor 1, different levels of rotor damage were forced by drilling holes in the corresponding bars and, also, a certain level of eccentricity was created. In motor 2, different levels of rotor asymmetry were forced by inserting external rheostats in series with the rotor winding, simulating a high-resistance connection of the rotor circuit (this would correspond, for instance, to an uneven contact between brushes and slip rings or a high resistance connection between rotor coils).

TABLE III
CHARACTERISTICS OF TESTED MOTORS

	Motor 1	Motor 2
Type	Cage IM	Wound rotor IM
Rated power	1.1 kW	11 kW
Rated frequency	50 Hz	50 Hz
Rated voltage	400 V	400 V
Rated current	2.7 A	23 A
Rated speed	1410 rpm	1425rpm
Connection	Star	Star
Number of poles	4	4
Rotor slots	28	24
Stator slots	36	36



(a)

(b)

Fig. 4. Experimental test benches for the stray flux data acquisition: a) cage induction motor (motor 1), b) wound rotor induction motor (motor 2).

IV. RESULTS

In this section, the results obtained with the test benches described above are discussed. These results illustrate the usefulness of the approach to detect a diversity of failures both in cage and wound rotor induction motors.

A. Motor 1: cage induction motor

Fig. 5 shows the application of the conventional method based on stray-flux analysis to the cage induction motor [17]. This figure shows the FFT analyses of the emf signals (only the low frequency region is depicted) captured at steady-state, considering three different positions of the sensor (shown in Fig. 2) and three different fault cases: 1) healthy motor, 2) misalignment and 3) motor with 2 broken bars and misalignment. Note how the expected fault components are amplified in the analyses when the corresponding fault is present in the machine. However, these components have different amplitudes depending on the location of the sensor. This is due to the fact that, depending on the nature of the corresponding fault component (axial/radial), its increment when the fault is present will be more evident at the sensor position that enables capturing the flux portion in which it appears.

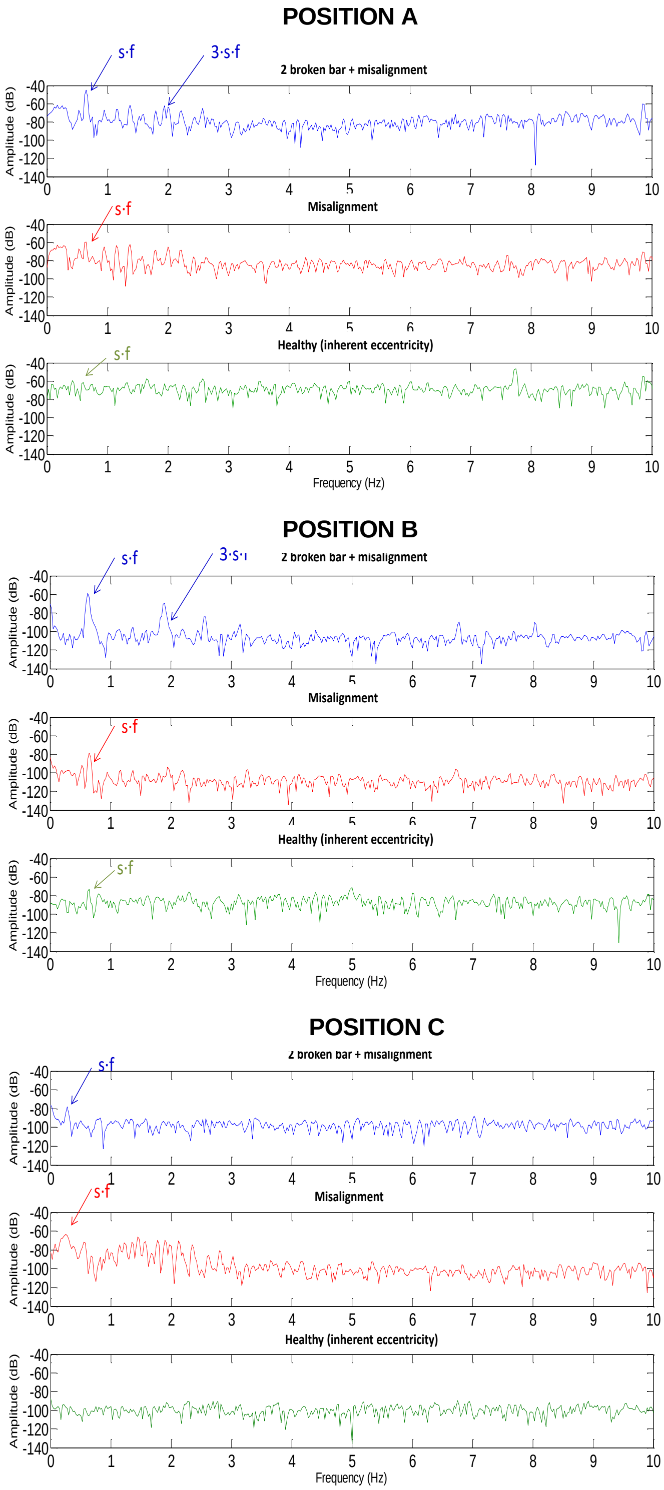


Fig. 5 FFT analyses of the coil sensor signal for the three fault cases and for the three considered positions of the sensor (motor 1).

For instance, in case of rotor damages (broken bars), the axial components $s \cdot f$ and $3 \cdot s \cdot f$ will be amplified, among others. As observed in the graphs, these increments are more evident in position A and position B since, at these positions, a higher portion of axial flux is captured. At position C, the captured flux is primarily radial and, hence, these components show little increments when the fault is present. These analyses prove that the technique is able to detect the fault but the sensor location plays an important role on the components amplified by the failure.

On the other hand, Fig. 6 shows the STFT analyses of the emf signals (motor 1) captured during the startup for the three fault cases and sensor positions commented before [17]. Note that the transient evolutions of the fault components (depicted in Fig. 3) are clearly observable in the resulting time-frequency maps: on the one hand, we can clearly observe the evolution of the axial component s·f associated with rotor damages, which is significantly amplified as the fault gets worse (compare healthy motor and motor with misalignment + 2 broken bars). In addition, the evolution of the component f_{ecc} caused by eccentricities/misalignments is clearly observed and, finally, the radial component $f_{sb}=f\cdot(1-2\cdot s)$ evolution is also identifiable at position C, in which a predominantly radial flux is captured. In conclusion, these fault signatures can be used as reliable evidences of the presence of these failures.

B. Motor 2: wound rotor induction motor

Fig. 7 shows the FFT analyses of the emf signals captured at steady-state for the wound motor induction motor, considering three different rotor asymmetry levels and two positions of the sensor (positions A and C). In this figure, the region around the fundamental frequency is depicted. Note the clear increment of the amplitude of the fault component f·(1-2·s) when the fault gets worse. This is visible for both positions of the sensor since this component is radial and at both positions of the sensor a certain amount of radial flux is captured.

Fig. 8 shows the STFT analyses of the emf signals (motor 2), captured during the startup, for the three different levels of rotor winding asymmetry. Note that the components associated to the different faults are clearly visible in the resulting time-frequency maps. Particularly evident is the evolution of the component f·(1-2·s) that increases its amplitude when the fault gets worse, at all positions of the sensor. The axial component s·f is also detectable, especially at position A, that captures the axial flux. Finally, the evolution of the eccentricity/misalignment component at f_{ecc} is also detectable and reveals the existence of a certain level of misalignment between the tested motor and the driven load.

V. CONCLUSIONS

This paper describes the currently existing approaches for condition monitoring of electric motors relying on stray flux data analysis: on the one hand, the classical methods based on the analysis of the steady-state flux data using the FFT and, on the other hand, the new technologies relying on the advanced analysis of stray flux data captured under transient operation of the motor by applying time-frequency tools.

The analysis of the experimental data obtained in the paper enables to illustrate the operation of each approach. Whereas the conventional methods enable the detection of the different faults through the assessment of the amplitudes of the fault harmonics present in the FFT spectrum, the new transient-based technologies rely on the detection of characteristic patterns that are caused by the evolution of the fault components. These latter methods increase the reliability of the diagnosis since these patterns cannot be caused by other phenomena different than the failure, thus avoiding false indications that may appear with the classical methods.

The paper intends to be a first approximation to show the state-of–art in the use of this diagnosis technology which is drawing the attention of certain manufacturers that have recently developed integrated sensors embedded on the motor frame with the aim of providing self-diagnostics capability to the motor. The inherent advantages of this technique, some of them proven in recent works (non-invasive nature, simplicity, higher sensibility for detecting certain faults…) makes it a very interesting option. However, as it is shown in the paper, some issues are still under study, such as the influence of the sensor position on the results or the necessity of further massive validation that enables to set objective fault severity thresholds valid for a wide number of cases.

The method is planned to be applied in the near future to detect damper bar damages in synchronous motors in the range of MW, which are largely used in the Petrochemical industry.

VI. ACKNOWLEDGEMENTS

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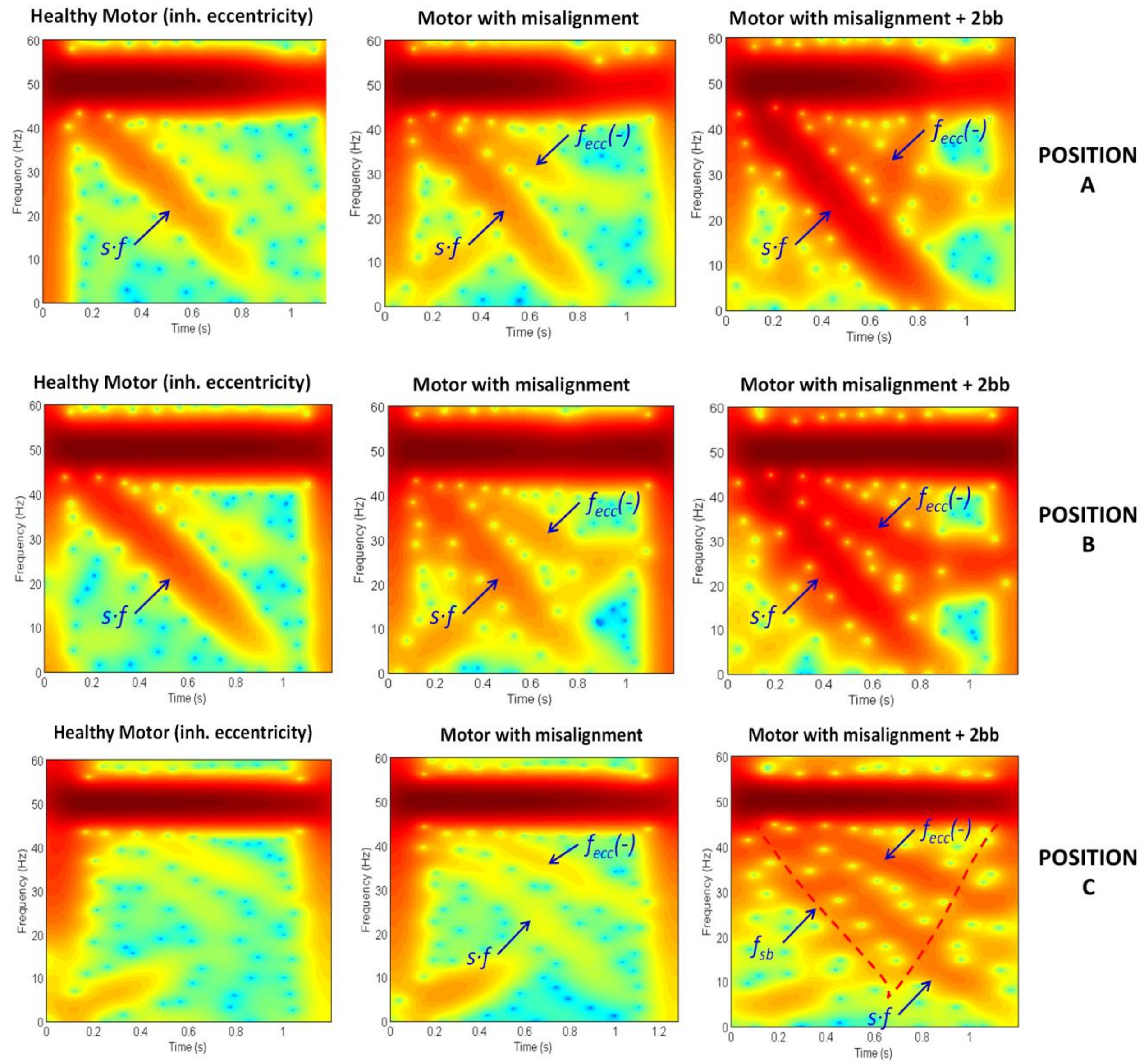
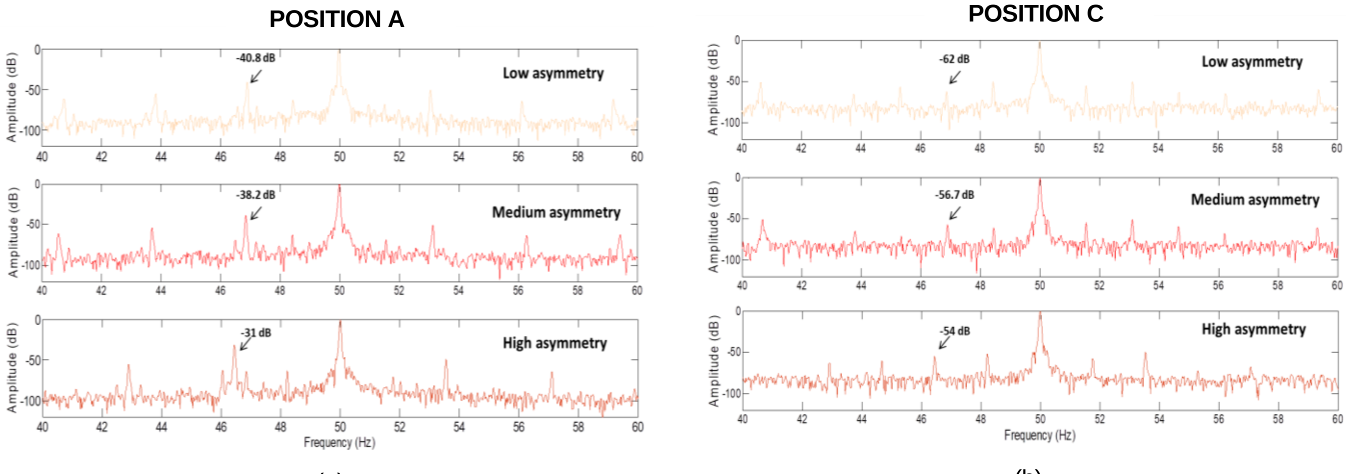


Fig. 6 STFT analyses of the coil sensor signals for the machine (Motor 1) with inherent eccentricity, motor with misalignment and motor with misalignment +two broken bars and for the three considered positions of the sensor (the color denotes the energy density in each point of the time-frequency map, with red=highest density while blue=lowest density).



(a)

(b)

Fig. 7. FFT analyses of the steady-state EMF signals for the sensor at positions A and C for the cases of low, medium and high asymmetry (motor 2).

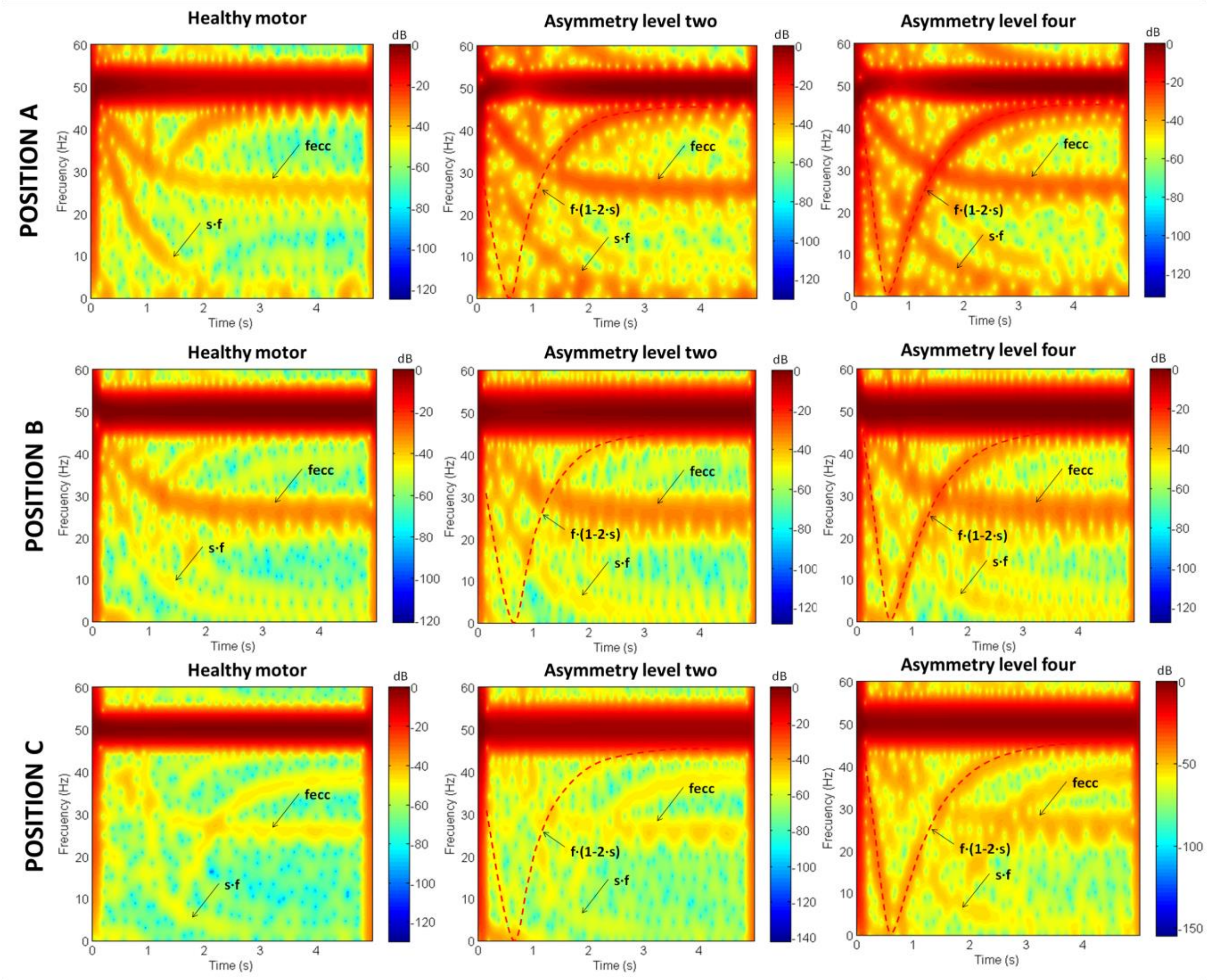


Fig. 8 STFT analyses of the coil sensor signals for the machine (Motor 2) in healthy state, motor with rotor asymmetry level two out of four and motor with rotor asymmetry level four out of four and for the three considered positions of the sensor (the color denotes the energy density in each point of the time-frequency map, with red=highest density while blue=lowest density).

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VIII. VITA

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