Diagnosis of Mechanical Unbalance for Double Cage Induction Motor Load in Time-Varying Conditions Based on Motor Vibration Signature Analysis

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Abstract—**This paper investigates the detectability of mechanical unbalance in double cage induction motor load using motor vibration signature analysis technique. Rotor imbalances induce specific harmonic components in electrical, electromagnetical, and mechanical quantities. Harmonic components characteristic of this category of rotor faults, issued from vibration signals analysis, are closely related to rotating speed of the rotor, which complicates its detection under non-stationary operating conditions of the motor.**

Firstly, experimental results were performed first under healthy and mechanical load unbalance cases, for different load levels under steady-state operating conditions to evaluate the sensitivity of motor axial vibration signature analysis (MAVSA) and motor radial vibration signature analysis (MRVSA) techniques. Secondly, and in order to overcome the limitations of the FFT analysis in time-varying conditions, a simple and effective method based on advanced use of wavelet analysis is proposed, that allows the diagnosis of mechanical load unbalance for a double cage induction machine operating under non-stationary conditions. Experimental tests were conducted for these purposes showing the effectiveness of the presented technique under time-varying operating conditions.

Keywords- Condition monitoring, induction motor, mechnical load unbalance, current signature analysis, vibration signature analysis, wavelet transforms.

I. Introduction

In the last few years, new diagnostic procedures have been investigated mainly focusing on renewable energy sources and power conversion issues. Improving the power conversion efficiency has quickly become the key target even if contrasting with system performances. New challenges arise thus pressing both academic and industrial research towards innovative solutions [1-3].

Fault diagnosis of rotating electrical machinery has received intense research interest. About 40% to 50% of induction motor faults are related to mechanical defects [4]. Mechanical load imbalance is considered as the most potential cause of static or dynamic eccentricities, or bearing faults propagation. Mechanical problems in the load may cause speed oscillations that modulate the motor [5]. More specifically, Rotor unbalances induce specific harmonic components in electrical, electromagnetical, and mechanical quantities [6].

In fact, correct diagnosis and early detection of incipient faults result in fast unscheduled maintenance and short downtime for the process under consideration. They also avoid harmful, sometimes devastating, consequences and reduce financial loss. An ideal diagnostic procedure should take the minimum measurements necessary from a machine and by analysis extract a diagnosis, so that its condition can be inferred to give a clear indication of incipient failure modes in a minimum time. Accurate measurements setup and methods are required [7-11]. Different techniques were proposed for mechanical load faults [6, 12-14]. Based on FFT, Motor current signature analysis (MCSA) is the reference method for the diagnosis of induction machines' rotor faults [6,12-13]. Motor Vibration Signature Analysis (MVSAs) was mainly investigated for limited critical rotor faults and exclusively for rotor broken bars fault detection. In [15] vibrations in axial direction was investigated to evaluate rotor conditions in presence of inter bars currents is steady-state operating conditions. In order to discern cases in which the presence of inter bars currents decreases the sensitivity of the (MCSA), axial and radial vibrations analysis were investigated in [15-21]. More recently, a combined use of current and vibration analysis was developed, by correlating the signal spectra to enhance broken bars detection ability under loaded and unloaded operating conditions of the motor [22]. However, in time-varying conditions, it fails as slip and speed vary and thus the sideband components are spread in a bandwidth proportional to the variation. Techniques based on FFT give satisfactory discrimination between healthy and faulty conditions, but don't provide time domain information, which is mandatory for online fault detection systems. Wavelet transform (WT), on the other hand, provides greater resolution in time for high frequency components of a signal and greater resolution in frequency for low frequency components. In this

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sense, wavelets have a window that automatically adjusts to give the appropriate resolution developed by its approximation and detail signals [23]. A recent time-frequency technique based on improved performance of wavelet analysis was proposed in [24] for high accuracy detection of incipient electrical faults in induction motors. This technique was successfully extended to the analysis of MVSA for the detection of rotor broken bars in steady-state condition in [25], and more recently in time-varying conditions [26]. In this paper, the detectability of mechanical load unbalance, based on motor vibration signature analysis is investigated in steady-state firstly. Then, the fault components characteristic of the fault, evidenced after the above tests, will be tracked under time-varying conditions to evaluate the robustness of the proposed technique. It will be shown that an optimized use of the proposed approach provides the following advantages over existing techniques:

- monitoring the fault degree over time under any transient operating conditions
- a low sampling frequency is used to reduce the memory requirement;
- repeated sampling operation is avoided in order to reduce latency in time processing:
- the contribution of most relevant fault frequency components under time-varying conditions are clamped in a single frequency bandwidth, avoiding confusions with other components and false interpretations;

In the following, the principle of the proposed approach, and the results conducted on mechanical unbalanced load of double cage induction motor are presented and commented, showing the validity of the proposed diagnosis technique under time-varying conditions.

II. FREQUENCY DOMAIN FAULT CHARACTERISATION

A. *Experimental setup*

Mechanical load unbalance is investigated for 5.5-kW double cage induction motor. The characteristics of the induction motor used in our experiments are listed in Appendix I. In order emulate a realistic mechanical fault; a revolving mass m is fixed on a disk mounted on the motor shaft as presented in Fig. 1 (right). A three-phase autotransformer of 30 kVA, 0-380 V is used as motor regulated supply.

A four quadrants 7.83-kW dc electrical drive is adopted to reach the different planned load conditions. Two piezoelectric accelerometers Brüel & Kjær, model 4507 B 005, mounted for measuring radial and axial vibrations of the core motors as presented in Fig. 1 (left). A NEXUS 2693 model as a signal-conditionner is used. In this section, the detectability of mechanical load unbalance using vibration signature analysis in frequency domain, is presented and discussed. A sampling rate of 3.2 kHz is adopted with a data acquisition window of 10 seconds, for steady-state and under large speed transient conditions.

B. *Motor radial vibration signature – steady-state condition*

In this sub-section, radial vibration signature analysis results are presented and discussed. Figure 2 shows the spectra

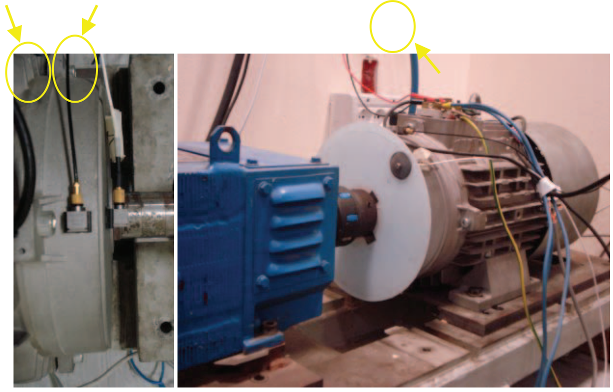

Figure 1. Test bench details; (left) positions of the two accelerometers, (right) load unbalance introduced on the disc mounted on the motor.

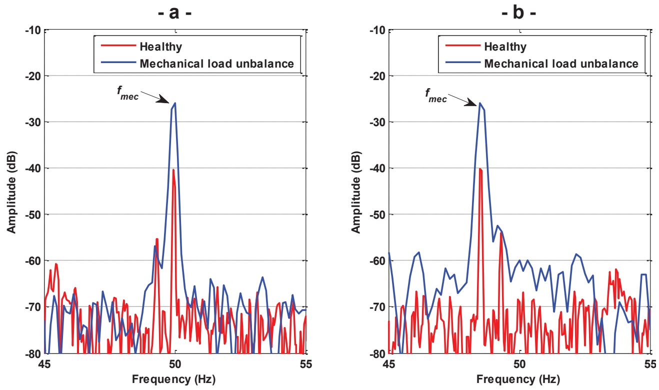

Figure 2. Radial vibration spectra at a) unload, and b) full load conditions.

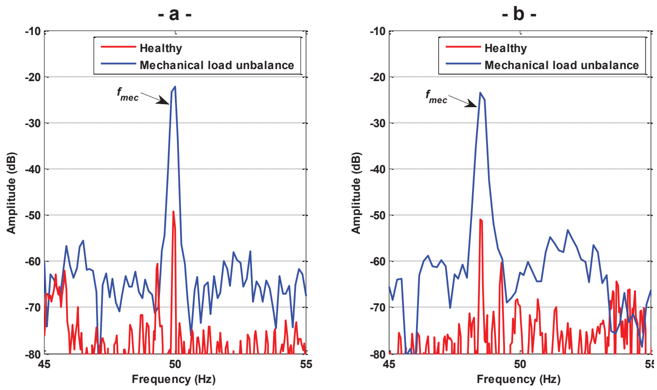

Figure 3. Axial vibration spectra at a) unload, and b) full load conditions.

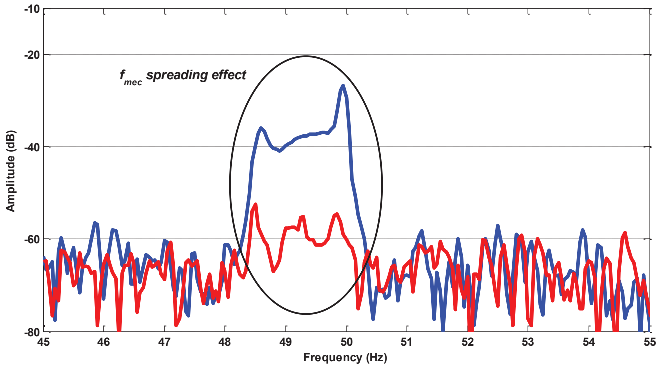

Figure 4. Axial vibration spectra under large speed transient. Healthy (Red), and unbalanced load (Blue).

centered on the rotational frequency f_{mec}, issued from experimental tests for unloaded (Figure 2-a) and full loaded (Figure 2-b) operating conditions. The spectrum for the healthy machine is considered as reference in comparison to the faulty case. For unloaded motor condition, under mechanical load unbalance the rotational component f_{mec} shows a significant increase from -40,45 dB under healthy condition, to -26,04 dB for the faulty case (Figure 2-a).

The same observation is valuable for full load condition; the rotational component f_{mec} shows a significant increase from -40,24 dB under healthy condition to -25,94 dB for the motor with unbalanced load (Figure 2-a). After several tests under different load conditions, the magnitude of the fault component f_{mec} remains equal to ≈-26 dB and ≈-40 dB under healthy and faulty conditions respectively.

As a preliminary conclusion, the signature issued MRVSA is quite robust versus load levels in steady state condition, with relevant variation from healthy to faulty conditions.

C. Motor axial vibration signature – steady-state condition

In this sub-section, axial vibration signature analysis results are investigated. Figure 3 shows the spectra centered on the rotational frequency f_{mec}, issued from experimental tests for unloaded (Figure 3-a) and full loaded (Figure 3-b) operating conditions. As already mentioned, the spectrum for the healthy machine is considered as reference in comparison to the faulty case. For unloaded motor condition, under mechanical load unbalance the rotational component f_{mec} shows a significant increase from -49,20 dB under healthy condition, to -22,19 dB for the faulty case (Figure 3-a).

The same observation is valuable for full load condition; the rotational component f_{mec} shows a significant increase from -50,89 dB under healthy condition to -23,48 dB for the motor with unbalanced load (Figure 2-a). After several tests under different load conditions, the magnitude of the fault component f_{mec} remains equal to ≈-22.5 dB and ≈-50 dB under healthy and faulty conditions respectively.

The signature issued from MAVSA is quite robust versus load levels in steady state condition, with relevant variation from healthy to faulty conditions. By comparing the relevance of the rotational component f_{mec} issued from MRVSA and MAVSA corresponding to the healthy and faulty cases, the sensitivity of axial vibration signature is higher than the observed on radial one.

D. Motor axial vibration signature – transient condition

In order to evaluate the detectability of the investigated mechanical fault, experiments were made by analyzing a deceleration transient, starting with mechanical speed of 3000 rpm down 2910 rpm with ramp duration of about 4 seconds. The corresponding instantaneous speed values under healthy and faulty conditions are depicted in Figure 5-a and Figure 6-a. Figure 4 shows the spectrum of axial vibration signals machine in healthy and faulty conditions during the above described transient.

The spectra show that no signature analysis is possible for such cases, because of the large spreading of frequency and speed. Hence the magnitude variation of the rotational component f_{mec} related to the faults is spread across a wide frequency range. Consequently, the use of Fourier transform in these conditions can lead to an erroneous diagnosis. Then, a more appropriate technique is needed for providing a reliable diagnosis procedure. In the next section, a simple and effective new technique is proposed, providing accurate information in time-frequency domain about the investigated mechanical unbalance.

III. Time-Frequency Analysis – The proposed approach

Wavelet analysis is signal decomposition, using successive combination of approximation and detail signals [27]. The procedure is repeated until the original signal is decomposed to a pre-defined J level decomposition. With the well known dyadic down sampling procedure, frequency bands of each level of decomposition are related to the sampling frequency.

Hence, these bands can't be changed unless a new acquisition with different sampling frequency is made. This fact complicates any fault detection based on DWT, particularly in time-varying condition. In this paper, an efficient solution to overcome this limitation is proposed. With a sampling frequency f_s=3.2kHz, an eight level decomposition ($J=8$) was chosen in order to cover the frequency bands in which the frequency component characteristics of the fault will be tracked (see Table I). Under steady state operating condition, for healthy or faulty case, the rotational component f_{mec} takes only one single position in the spectra as shown in Figure2 and Figure 3. However, in time varying conditions, as can be seen in Figure 4, the magnitudes of f_{mec} can't be detected through a frequency analysis since the rotational component is spread in a wide frequency range.

A simple processing of the motor vibration signal v_{AX} (t), allows shifting f_{mec} to the frequency band corresponding to the 8th approximation signal. In such a way, all the information related to the fault is isolated and confined in a single frequency band. More in detail, a frequency sliding with f_{sl} is applied at each time slice to the axial vibration signal as in (1), so that the harmonic component of interest is moved to the desired frequency band. Then the real part of the shifted signal is analyzed by means of DWT.

$$V_{sl}(t) = \mathrm{Re}\left[v_{AX}(t) e^{-j2\pi f_{sl} t} \right] \quad (1)$$

The choice of f_{sl} is made by taking into account the speed range of the transients. The evaluation of f_{sl} is made in such a way that the contribution of the fault frequency component, for the whole considered slip range, is shifted into one of the intervals [0, $2^{-(J+1)} f_s$] or [$2^{-(J+1)} f_s$, $2^{-J} f_s$] and consequently the DWT can be applied to analyze only the frequency band of interest. In this way, fault detection and quantification becomes easier.

As illustrated in Figure 7, the DWT analysis divides the signal into logarithmically–spaced frequency bands. From Fig. 2, it is possible to realize that the smallest frequency band width for both approximation and detail signals is equal to $f_{sam}/2^{J+1}$, but approximation a_J is less subjected to the overlapping effect than that of d_J due to its proximity to 0Hz [18], [24]. For this reason, approximation a_8 has been chosen for extracting the contribution of the rotational frequency.

Once the state of the machine has been qualitatively diagnosed, a quantitative evaluation of the fault degree is necessary. For these purposes a dynamic multiresolution mean power indicator mPa_j at different resolution levels j was introduced as a diagnostic index to quantify the extent of the fault as:

$$mPa_j = \frac{1}{N}\sum_{n=1}^{N}\left|a_j(n)\right|^2 \quad (2)$$

Where N is the number of samples and j is the level decomposition. In fact, the MRA analysis decomposes the signal in different frequency levels. This choice reduces the feature dimension and consequently the computational time. The fault indicator is periodically calculated (every 150 samples) using a window of 6400 samples as depicted in Figure 1, where δn=150 samples and Δn=6400 samples. The n sequences are indexed by a Time Interval Number (TIN).

These values were regulated experimentally to reduce variations that can lead to false alarm in healthy operating conditions of the motor. When the fault occurs, the energy distribution of the signal is changed at the resolution levels related to the characteristic frequency bands of the default. Hence, the energy excess confined in the approximation is considered as an anomaly indication in case of motor-load unbalance faults.

IV. EXPERIMENTAL RESULTS

The proposed approach was applied to the to the axial vibration signal with f_{sl}=-46Hz, to isolate the contribution of the f_{mec} component. Hence, with respect to the frequency bands reported in Table I, the frequency band of interest is the 8th DWT level decomposition. The corresponding experimental results, under healthy and unbalanced load conditions, are presented respectively in Figure 7-b and Figure 8-b.

It is possible to notice that the 8th approximation signal, issued from wavelet decomposition for the healthy machine (Figure 7-b), does not show any variations. This indicates low contribution of the rotational frequency, allowing diagnosing the healthy condition of the motor-load under time-varying operating condition. On the contrary in faulty condition, the approximation a_8 shows significant variation in amplitude, as can be seen from Figure 8-b. Effectively, the large amplitude variations reflect the relevant magnitude variation of f_{mec} in presence of the motor- load fault. Despite the speed transient, the oscillations reproducing the fault presence are still significant. The mean power calculation results, issued from the approximation signal *a6*, which have been obtained in Figures 7-b and 8-b, are depicted in Figure. 9. In healthy condition, the calculated *mPa6* indicator doesn't show any significant changes. Consequently, the indicator values for the healthy motor response are considered as a baseline to set the threshold for discriminating healthy from motor-load unbalance conditions. These results show a clear detection of the investigated fault, leading to an effective and accurate motor-load unbalance diagnosis under time-varying conditions.

TABLE I
FREQUENCY BANDS AT EACH LEVEL

Approximations «a_j»	Frequency bands (Hz)	Details « d_j »	Frequency bands (Hz)
a_8	: [0– 6.25]	d_8	: [6.25– 12.5]
a_7	: [0– 12.5]	d_7	: [12.5– 25]
a_6	: [0– 25]	d_6	: [25– 50]
a_5	: [0– 50]	d_5	: [50– 100]
a_4	: [0 – 100]	d_4	: [100 – 200]
a_3	: [0 – 200]	d_3	: [200 – 400]
a_2	: [0 – 400]	d_2	: [400 – 800]
a_1	: [0 – 800]	d_1	: [800 – 1600]

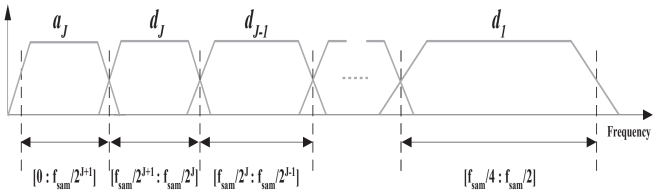

Figure 5. The DWT filtering process.

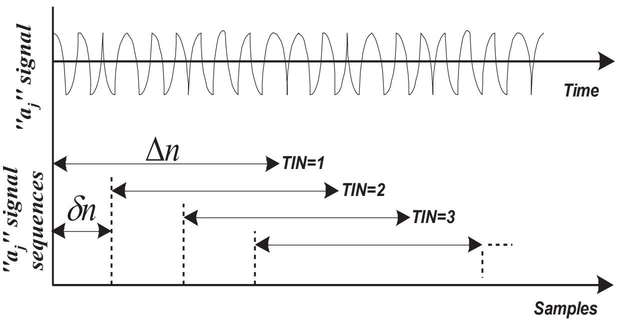

Figure 6. Principle of time interval calculation, *TIN: Time Interval Number*.

APPENDIX .I
DATA OF THE DOUBLE ROTOR CAGE MOTOR

Data	Value	
Rated Power	kW	5.5
Rated stator voltage	V	400
Rated current	A	13
Rated frequency	Hz	50
Rated speed	rpm	2870
Rotor diameter	mm	110
Axial length of the rotor	mm	90
Air gap length	mm	0.5

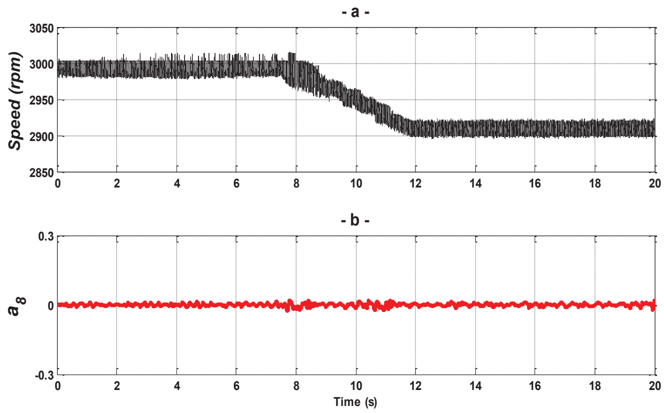

Figure 7. Experimental results: Instantaneous values of the mechanical speed (a), and the eight approximation signal "a_8" (b) issued from Wavelet analysis of the axial vibration signal under healthy conditions.

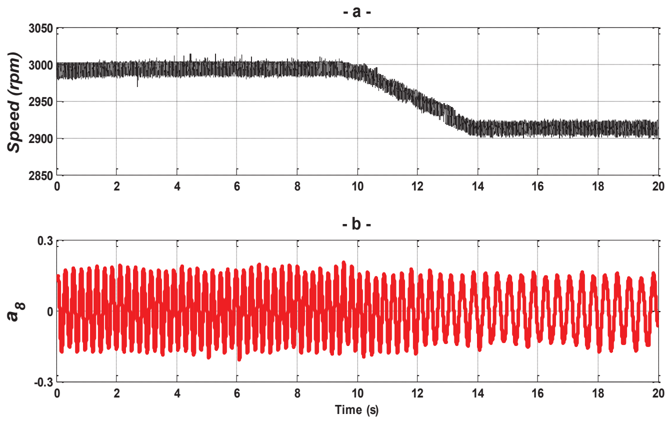

Figure 8. Experimental results: Instantaneous values of the mechanical speed (a), and the eight approximation signal "a_8" (b) issued from Wavelet analysis of the axial vibration signal under unbalanced mechanical load.

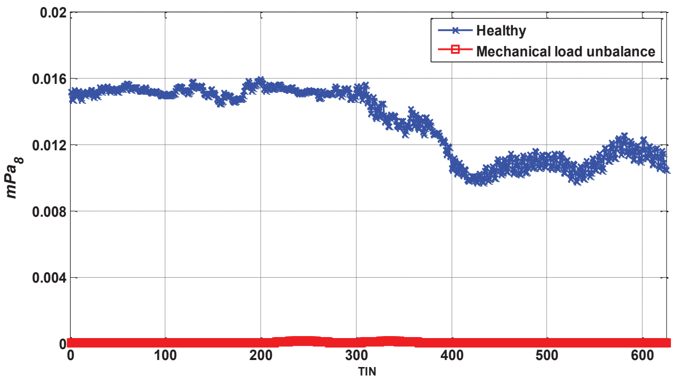

Figure 9. Values of the fault indicator mPa8 (as a function of the TIN) resulting from the eighth wavelet decomposition under healthy and mechanical load unbalance for large speed variation.

I. CONCLUSION

A new technique that allows diagnosis of motor-load unbalance fault in double cage induction motors under time-varying conditions based on an advanced DWT method is presented in this paper. A preliminary experimental study shows that the method can provide reliable and accurate load unbalance under speed transients with reduced computational burden. The results are meaningful considering the analysis issued from MRVSA less sensitive than MAVSA to this case of mechanical fault. A detailed description of the proposed method and more experimental results under a number of transient conditions will be provided in the final paper.

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