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A Comparative Study between the adaptive wavelet transform and DWT Methods Applied to a Outer Raceway Fault Detection in Induction Motors based on the Frequencies Analysis

Wafa Bentrach¹, Nouredine Bessous², Salim Sbaa¹

^{1,2}Department of electrical engineering

¹University of Mohammed Khider, Biskra
Biskra 07000, Algeria

²University of El-Oued, Algeria
El-Oued 39000, Algeria

wafaelect@gmail.com, nbessous@yahoo.fr

Remus Pusca, Raphaël Romary

Laboratory of Electrotechnical and Environmental Systems
(LSEE)

University of Artois, France

Béthune, France, Univ. Artois, EA 4025 LSEE, F-62400,
Béthune, France

remus.pusca@univ-artois.fr, raphael.romary@univ-artois.fr

Abstract— This paper presents a new application to diagnose the outer race fault in induction machines based on the three-step nonlinear lifting scheme. The wavelet transform is a powerful and complex tool in the context of diagnosis. The discovery of the lifting schemes structure make a wavelet filters simple, rapid and reversible. This method (lifting) is generally used by researchers in the field of image processing. However we are going in this study to use in order to see its effectiveness in the field of diagnosis in electrical machine in induction motors. In addition, we will exploit the experimental results. This study analyzes the stator current of an asynchronous motor for two conditions: the first is a data acquisition of a healthy machine. The second is a defective machine of an outer race fault and inner race fault. The objective of this work focuses particularly on the frequency analysis of the signal indicators of defects. Moreover, it remains necessary to develop filters for the detection, isolation and estimation of these defects by a certain number of diagnostic methods, techniques and to establish selection criteria for their use. For these reasons, this work compares the three-step nonlinear lifting scheme with the MCA-DWT current analysis method to access a valuable decision based on the experimental results.

Keywords- Lifting schemes; faults; discrete wavelet transform (DWT); fast Fourier transforms (FFT); diagnostic; outer raceway fault

I. INTRODUCTION

In industries, the electric motors especially the induction motor are widely used in many applications because of their low cost, small size, robustness. In order to increase the productivity, reliability and safety of industrial installations,

permanent motor control is very essential. For this reason, research on health monitoring of asynchronous motors has been widely studied and has become a difficult task. In [1-4] the Fault detection and diagnosis methods dedicated to stator winding faults are studied, respectively. These defects may be due to mechanical or electrical forces acting on the induction machine. [5-6].

Principal types of the diagnostic methods for the four major defects are (Air-gap eccentricity fault [7-8-9], bearing fault [10-11-12], broken rotor bar fault [13] and Stator short winding fault).

Fault indicators in the frequency domain are the most popular and best understood because they can be sensibly detected by Fast Fourier Transform. Of all the feedback signals, the current of the induction motor is mainly used because the current sensors are relatively inexpensive and easy to use and are already installed in many applications.

Various fault monitoring techniques for induction motors can be classified in the category of techniques based on processing techniques and soft calculation techniques.

Among these many techniques are mainly studied because of their good diagnostic performance of failures for many machines is the analysis of the stator current signatures by the discrete wavelet transform (MCSA-DWT).

Finally, the analysis of the stator current signatures by the nonlinear adaptive lifting technique in three steps is verified.

II. THE EXPERIMENTAL RESULTS

The outer race defect is one of the faults that cause a problem in torque, rotational speed and stator current. The test

platform has essentially been used until now to detect, analyze and experimentally confirm the theoretical results.

A. Test Bench Details

This test bench is dedicated to analyzing currents, voltages or torque. In another way and according to the acquisition card, it is not possible to record the vibratory signals. Fig. 1 shows an experimental system photo connected with the DSPACE DS1104 real-time map that translates as Matlab under a sampling frequency $f_e = 10000\text{Hz}$.



Figure 1. Experimental setup for outer race defect

The tested induction motor characteristics are presented in Table 1:

Table.1. Induction motor parameters of the experimentation

Rated frequency	50 Hz
Number of pole pairs	2
Number of rotor bars	28
Rated Voltage	380V
Rated Power	3kw

III. APPLICATION OF THREE-STEP NONLINEAR LIFTING SCHEME TECHNIQUE

A. A Three-Step Nonlinear

Consider the lifting scheme [15] illustrated in Fig. 2.

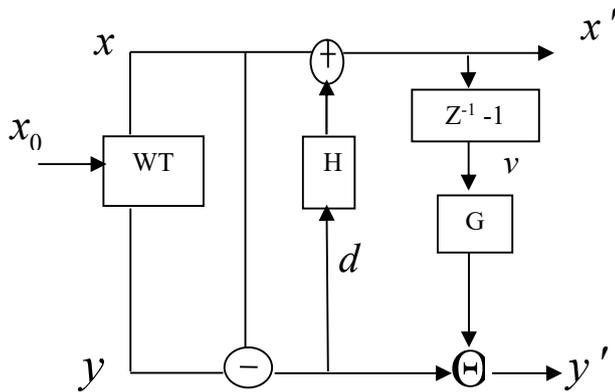


Figure 2. The three steps of the Lifting Scheme

Where WT is the lazy wavelet transform.

$$x(n) = x_0(2n), \quad y(n) = x_0(2n-1)$$

and H, G are thresholding operators defined for all $u \in \mathbb{R}$ as:

$$H(u) = \begin{cases} 1/2 u & \text{if } |u| < T \\ \alpha T / 2 \text{sign}(u) & \text{otherwise} \end{cases} \quad (1)$$

$$G(u) = \begin{cases} u & \text{if } |u| > T' \\ \alpha' T' & \text{otherwise} \end{cases} \quad (2)$$

Where T, T' are positive threshold values and $\alpha, \alpha' \in \{0,1\}$ constants which determine the kind of thresholding (hard or soft-thresholding) applied.

The approximation signal x' is deduced from the following relation:

$$x'(n) = x(n) + H(d(n)) \quad (3)$$

Where: $d(n)$ is a first signal equal at:

$$y(n) - x(n) \quad (4)$$

As shown in Fig. 2, the detail signal y' is obtained through a non-additive prediction lifting step. Note that the standard subtraction "-" has been replaced by a nonlinear operator " \ominus " defined as:

$$t \ominus u = \frac{t}{B + |u|} \quad B \geq 1 \quad (5)$$

For all $t, u \in \mathfrak{R}$ the detail signal y' is presented by:

$$y'(n) = \frac{d(n)}{B + |G(v(n))|} \quad (6)$$

Where $v(n) = x'(n-1) - x'(n)$

If we apply this scheme to the one-dimensional signal, we get the following relation: [15]

$$x'(n) = \begin{cases} \frac{x(n) + y(n)}{2} & \text{if } |y(n) - x(n)| < T \\ x(n) & \text{otherwise} \end{cases} \quad (7)$$

$$y'(n) = \begin{cases} y(n) - x(n) & \text{if } |x'(n-1) - x'(n)| < \bar{T} \\ \frac{y(n) - x(n)}{1 + |x'(n-1) - x'(n)|} & \text{otherwise} \end{cases} \quad (8)$$

B. Experimental Results Dedicated To The Outer Race Defect:

Many mechanical types' faults cause oscillations in the load torque applied to the asynchronous machine [16]. We

therefore study the effects of periodic variations caused by the outer race fault in the load torque.

The spectrum of the stator current of the asynchronous machine, in absence and in the presence of a defect is very rich in harmonics. Indeed, the frequencies presented in this spectrum are mainly the spectral rays related to the frequency of the outer race defect by [15-16]:

$$f_{charac-or} = |vf_s \pm kf_{or}| \quad (9)$$

With $f_{charac-or}$ is the characteristic frequency of the outer race defect in the stator current spectrum. f_s is the supply frequency and f_{or} is the characteristic frequency of the outer race defect.

Fig. 3, Fig. 4 and Fig .5 respectively show the detail number 2 "d2" of stator current spectrum obtained by lifting method in healthy and faulty machine at no load ($s=0.004 \approx 0$). We notice clearly, the presence of harmonics due to the outer race defect in the spectrum of the stator current in the healthy or faulty case. As well we have seen the existence of series of harmonics characterizing the outer race defect in the spectrum of detail number 2 such as: 44.2 Hz, 55.7Hz, 144.1Hz, and 148.5Hz.

The spectrum is easily confirms the faulty state of the motor by noticing the characteristic frequencies of the mixed eccentricity defect $f_s - f_r$ and $f_s + f_r$ are located approximately in half of the fundamental supply frequency. The variation of the slip from no load operation to full load operation gives the amplitude -61.31dB and -58.15dB. The characteristic frequency components of the mixed eccentricity defect in the interval [0- 150 Hz] are presented in Fig. 3. We can notice precisely the presence of some peaks centered on the fundamental frequency. The frequency values are in concordance with the formula of the characteristic frequencies of equation (9). The values can be written as follows:

$$f_{charac-or} = |vf_s \pm kf_{or}|$$

$$f_{charac-or} = f_s + 0.4 N_b \cdot f_r \text{ With } f_s = 50 \text{ Hz, } N_b = 9,$$

$$f_r = \frac{1-s}{P} f_s = 25 \text{ Hz because } (s=0.004 \approx 0) \text{ and } P=2,$$

$$f_{charac-or} = 50 + (0.4) \cdot 9 \cdot (25)$$

$$f_{charac-or} = 140 \text{ Hz}$$

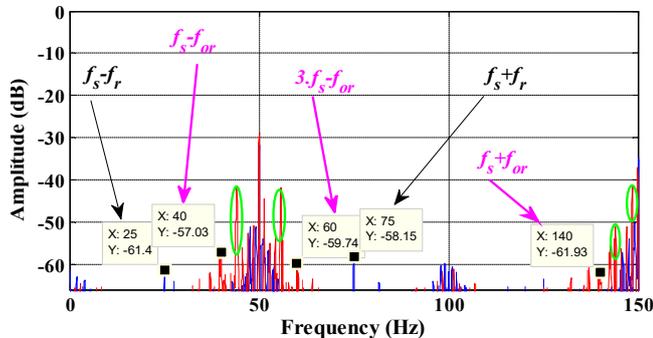


Figure 3. d2 of stator current spectrum of healthy (blue) and faulty (red) motor by the lifting method at no load ($s \approx 0$) for the frequency band: 0-150 Hz

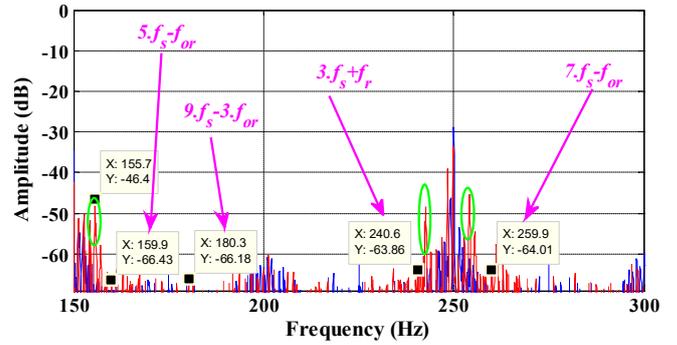


Figure 4. d2 of stator current spectrum of healthy (blue) and faulty (red) motor by the lifting method at no load ($s \approx 0$) for the frequency band: 150-300 Hz

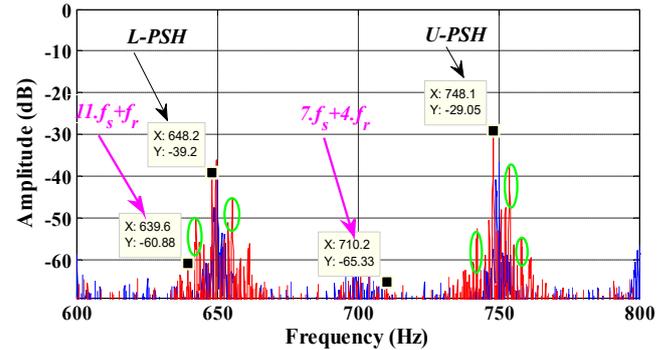


Figure 5. d2 of stator current spectrum of healthy (blue) and faulty (red) motor by the lifting method at no load ($s \approx 0$) around the PSHs

The table below represents some comparison values between the theory and the experimental at no load state ($s \approx 0$).

Table.2. The characteristic frequencies of outer race defect at no load

The characteristic frequency formula $f_{charac-or} = vf_s \pm kf_{or} $	T.V (Hz)	Lifting method	
		E.V (Hz)	Am (dB)
$ f_s - f_{or} $	40	4	-
		0	57.03
$ f_s + f_{or} $	140	1	-
		40	61.93
$ 3f_s - f_{or} $	60	6	-
		0	59.74
$ 5f_s - f_{or} $	160	1	-
		59.9	66.43
$ 9f_s - 3f_{or} $	180	1	-
		80.3	66.18
$ 3f_s + f_{or} $	240	2	-
		40.6	63.86
$ 7f_s - f_{or} $	260	2	-
		59.9	64.01
$ 11f_s + f_{or} $	640	6	-
		39.6	60.88
$ 7f_s + 4f_{or} $	710	7	-
		10.2	65.33

It is also possible to indicate the *PSHs* in the d2 of stator current spectrum so the rotor slot harmonics can be calculated theoretically by the following table:

Table.3. The values of the PSHs

(s=0.004) $\nu = 1$ and $\lambda = 1$ $PSH_s = \left(\frac{\lambda n_b (1-s)}{P} \pm \nu \right) f$	T.V (Hz)	Lifting method	
		E.V (Hz)	Am (dB)
$PSH_1^- = (14(1-s)-1)f_s$	647. 2	648. 2	- 39.2
$PSH_1^+ = (14(1-s)+1)f_s$	747. 2	748. 1	- 29.05

with:

T.V: Theoretical values.

E.V: Experimental Values.

Am: Amplitudes

This successful comparison of the experimental results with the characteristic frequency formulas of the outer race defect allows ensuring the effectiveness of the diagnostic method by the application based on an adaptive wavelet transform which is constructed with a three-step nonlinear lifting scheme especially at the amplitudes level, we notice that the analysis of the healthy experimental spectra shows the absence of the characteristic frequencies fault in the spectrum of the d2 of stator current.

In case of full load, we analyze the current of the stator in healthy machine (blue) and defective (red). Fig. 6, Fig. 7 and Fig .8 show the spectrum of the detail number 2 "d2". The new harmonics are: 15.4 Hz, 84.6 Hz, 115.4 Hz, 159.6 Hz and 184.6 Hz around of the fundamental. In addition, the series of harmonics is verified by the equation (9) on the bands illustrated.

The diagnostic operation by the adaptive wavelet transform of the current makes it possible to follow acceptable indicators of the outer race defect. The detail number 2 "d2" of stator current spectrum of the induction machine, as we have seen, in the presence of a defect is very rich in harmonics. The current diagnostic operation by this method will allow an acceptable follow-up of the outer race fault indicators. Furthermore, depending on the spectrum of the stator current and equation (9), we give some examples of the frequencies characteristics.

Table 4 summarizes and compares the theoretical frequency of this defect if it exists experimentally.

Table.4. Theoretical and practical characteristic frequencies of the outer race defect (s = 0.044).

The characteristic frequency formula $f_{charac-or} = \nu f_s \pm k f_{or} $	T. V (Hz)	Lifting method	
		E.V (Hz)	A m (dB)
$ f_s - f_{or} $	6.04 ³	5.8 ³	- 65.02
$ f_s + f_{or} $	36.04 ¹	36.2 ¹	- 63.79
$ 11f_s - 6f_{or} $	3.76 ³	4 ³	- 64.16
$ 5f_s - 4f_{or} $	4.16 ⁹	3.3 ⁹	- 49.69
$ 3f_s - 3f_{or} $	08.12 ¹	07.8 ¹	- 60.59
$ 5f_s + f_{or} $	63.96 ¹	63.9 ¹	- 64.4
$ 9f_s - 3f_{or} $	91.88 ¹	91.9 ¹	- 65.88
$ 11f_s + 4f_{or} $	05.84 ²	06.6 ²	- 55.45
$ f_s + 3f_{or} $	08.12 ²	07.9 ²	- 62.76

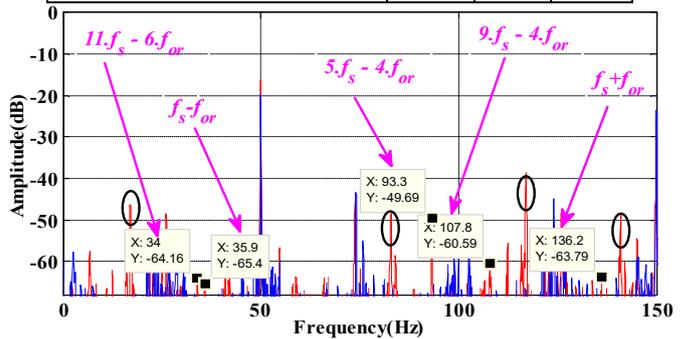


Figure 6. d2 of stator current spectrum of healthy (blue) and faulty (red) motor by the lifting method at full load (s = 0.044) for the frequency band: 0-150 Hz

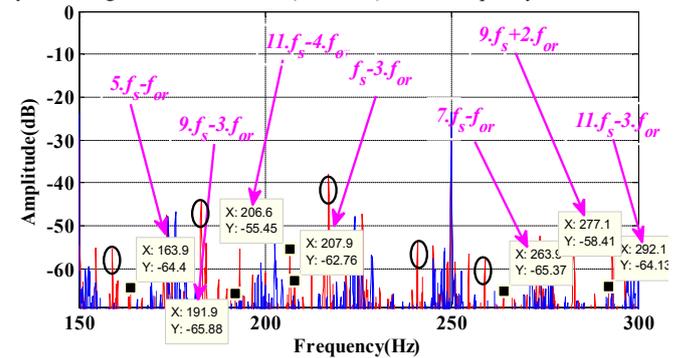


Figure 7. d2 of stator current spectrum of healthy (blue) and faulty (red) motor by the lifting method at full load (s = 0.044) for the frequency band: 150-300 Hz

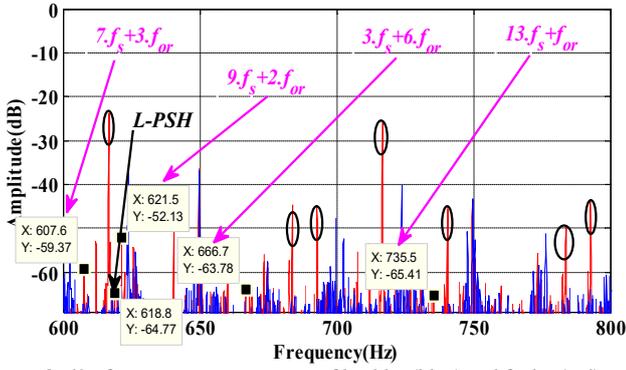


Figure 8. d2 of stator current spectrum of healthy (blue) and faulty (red) motor by the lifting method at full load ($s = 0.044$) around the PSHs.

It is also possible to indicate the *PSHs* in the d2 of stator current spectrum so the rotor slot harmonics can be calculated theoretically by the following table:

Table.5.The values of the PSHs

$(s=0.044)$ $\nu = 1$ and $\lambda = 1$ $PSH_s = \left(\frac{\lambda n_b (1-s)}{P} \pm \nu \right) f_s$	T.V (Hz)	Lifting method	
		E.V (Hz)	Am (dB)
$PSH_1^- = (14(1-s)-1)f_s$	619 .2	618.8	- 64.77

IV. APPLICATION OF THE MCSA-DWT TECHNIQUE FOR FAULT DETECTION

The usual methods for extracting a fraction of the noisy signal or a set of harmonics are filters in order to cancel and preserve the most interesting part of the signal. The DWT method is one of the currently techniques applied in the field detection of faults in MAS. Recently, this technique and its derivatives have been the subject of a large number of searches [18-20].

In practice, the choice of the wavelet is not crucial, indeed we are looking for a wavelet that offers a good compromise between temporal and frequency resolution, such a choice depends very much on the objective of the proposed subject. Additional criteria such as regularity, symmetry, fast decay to infinity may be needed [30].

Tests have been done by [17] for different orders and types of mother wavelet lead us to take the choice of Daubechies (Db43) for all analyzes concerning this part of application.

A. Energies and frequency bands for DWT

Raising the original signal from the stator current, or any signal, requires a preprocessing platform. Our study is based on the MCSA by DWT under a sampling frequency equal to 10000Hz. Although the diagnosis of defects is based on a finite analysis and a comparison between the decomposition levels

(a_i or d_i) that contain the fault information for different machines to diagnose.

[21-22] have explained the cause of this choice. The number of decomposition, advisable for the sampling frequency $f_e = 10$ KHZ is calculated as follows:

$$N_{sA} = \text{int} \left[\frac{\log \left(\frac{10^4}{50} \right)}{\log(2)} \right] + 2 = 9 \text{ levels} \quad (10)$$

Another indicator of the defect, is the energy of the details, we can calculate the energy associated with each decomposition level. The proper value of energy of each detail according to the frequency band is defined by:

$$E_j = \sum_{n=1}^N |d_j(n)|^2 \quad (11)$$

As j is the decomposition level, and N is the total number of samples in the signal.

Fig.9 presents the energy in each detail level for the outer race defect for healthy and faulty state and at full load. The effect of the outer race fault on the energy stored in the levels 5 and 6 is clearly visible and is more sensitive compared to the others; this increase differs according to the severity of the fault and the load of the motor. It is also noted that the energy of detail 3 was influenced by the conditions of the tests.

The fault indicator can be in any level and detail. Frequency bands of such d_i are considered as an orientation to the important detection zone. Table 6 shows the frequency bands of each level.

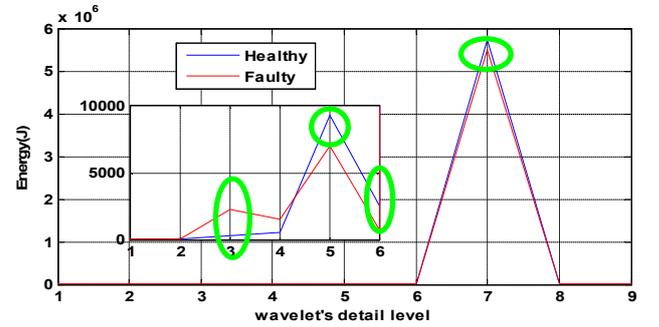


Figure 9. Energy levels (1 to 9) evolutions for stator current at full load.

Table.6. Frequency bands at different decomposition levels

Details	Frequency bands of levels (Hz)
d_1	5000-10000
d_2	2500-5000
d_3	1250-2500
d_4	625-1250
d_5	312.50-625
d_6	156.25-312.5
d_7	78.12-156.25
d_8	39.06-78.12
d_9	19.53-39.06

B. Detection of the outer race defect

This try to clarify the difference between stator current signatures analysis using the nonlinear adaptive lifting technique in three steps and the analysis of the stator current signatures using the discrete wavelet transform (DWT). We obtained the detail number d2 from the DWT signal analysis of experimental stator current in faulty and healthy state with outer race, at full load (Fig .11).

We notice that the detail d2 of stator current spectrum at full load using the DWT method does not contain any frequencies of outer race defect.

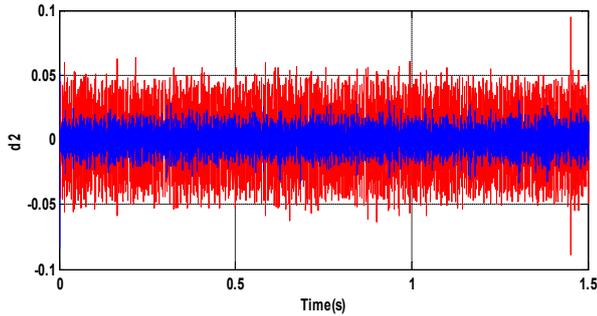


Figure 10. Detail d2 from the DWT signal analysis of experimental stator current in (blue) and faulty (red) with outer race, at full load

The detail d2 of stator current spectrum of healthy and faulty motor by DWT method at full load is presented in Fig.12.

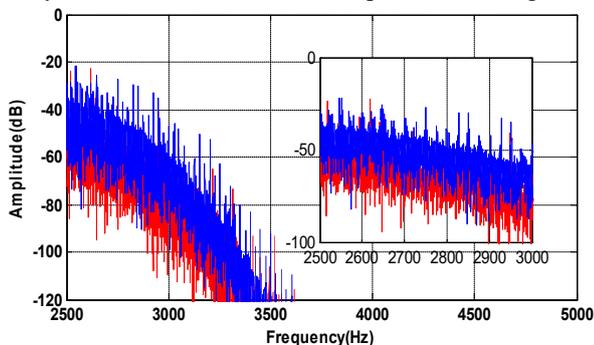


Figure 11. d2 of stator current spectrum of healthy (blue) and faulty (red) motor by DWT method at full load ($s = 0.044$)

Fig. 12 shows the FFT of d6 in healthy (blue) and faulty (red) motor by DWT method at full load ($s = 0.044$).

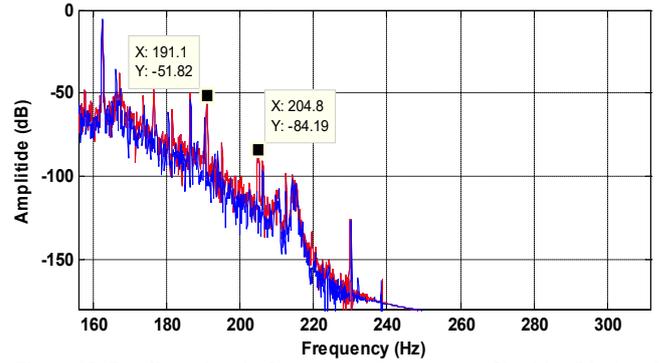


Figure 12. Detail number 6 of stator current spectrum of healthy (blue) and faulty (red) motor by DWT method at full load ($s = 0.044$)

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VI. CONCLUSION

This work presented a frequency analysis in order to detect the outer race fault in induction motor type. The question asked after this study is: what is the most effective technique for detecting defects in IM?

Comparing the two techniques, the three -step nonlinear lifting has shown the best results in identifying and diagnosing of outer race defect. Thus the simulation study, analysis and results presented in this work prove the efficacy of lifting technique in induction motor fault diagnosis.

Using this technique with $\alpha = \alpha' = 1$, $B = 1$ and $T = 2T' = 10$, it is easier to separate typical fault frequencies from neighboring components. On the other hand, we notice that the analysis of experimental spectra shows the presence of the characteristic frequencies fault in the spectrum of the d2 of stator current, in addition, to the series of harmonics witch verified theoretically with a good amplitude values contrary to the DWT.

In conclusion, the lifting technique proved that has a very simple and fast implementation, earlier localizes the fault.

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