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International Journal of
Electrical and Electronics Research (IJEER)
Research Article | Volume 11, Issue 4 | Pages 966-972 | e-ISSN: 2347-470X

Analysis Optimization and Comparison to Detect Failures in the Squirrel-Cage Rotor using High-Level Wavelets

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ABSTRACT- The methods and tools used for signal analysis extracted from the induction motors, such as the motor current signature analysis (MCSA) used for data collection on a non-invasive basis, the multi-resolution analysis (MRA) and discrete wavelet transform (DWT), are efficient tools for the signal analysis at different levels or resolutions, these tools have been applied together to improve detection of failures in the rotor of induction motors in condition of no-load. This work focuses on the study of rotor cage end ring, in a condition with lower-load or no-load where uncertainty predominates, this area of study is complicated to analyze correctly with conventional methods, but in these circumstances, the analysis using TDW has better performance. The article presents an alternative way of detecting failures in three phases induction motors in no-load state method with an optimized method and a comparison between results of the analysis with two different levels of the high-order Wavelet Daubechies, studying and evaluating its performance for the detection of broken ring, all this supported with a specific signal pre-processing and post-processing to improve the results of detection in incipient faults.

Keywords: Fault detection, current analysis, induction motor, squirrel cage rotor, broken ring, DWT.

ARTICLE INFORMATION

Author(s): Martínez García Irving I and Peña Cabrera J. Mario;

Received: 01/08/2023; **Accepted**: 16/10/2023; **Published**: 30/10/2023;
e-ISSN: 2347-470X;
Paper Id: IJEER0108RC;
Citation: 10.37391/IJEER.110413
Webpage-link:
https://ijeer.forexjournal.co.in/archive/volume-11/ijeer-110413.html

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1. INTRODUCTION

At present, most activities have become more immediate, and processes are required to be in real time, the industry is not the exception, people in charge want to know what is the conditions of the equipment in the processes being carried out, if there were any failure in some equipment, it is desired to know as soon as possible what the cause is in order not to affect the operation of a process, ideally, this detection in early stages must be carried out without the need to have the motor to be under some type of load for the faults to be visible. In the field of signal analysis with current and voltage to detect motor failures, many techniques and methods have been used [1-4], known as MCSA [5-14], this method is the most widely used since it is a non-invasive technique and quite simple to collect signal data.

When the type of electrical signals extracted of current analysis in electric motors is explored, an open field of research appears to find new methods and tools that are better adapted to what is currently required, so far there are several methods that use the Wavelet Transforms in their discrete version that show the ability to work with signals that can be generated from the use of faulty alternating current induction motors as [15-27].

In this paper, a method optimized for the diagnosis of broken end ring during operation motor in no-load steady-state was applied, this area of study is very difficult to analyze correctly because an electrical direct connection does not exist and the proximity of the associated signals to the faults are very close to the line frequency value, which compared with frequency motor signals is of much greater magnitude, also comparison performance using two high-level wavelets for the analysis of the stator current in steady-state operation was realized. Several experiments were developed to validate the applied pre-processing with different cases and conditions in the induction motor, cases such as raw signal, healthy no-load motor, fault no-load motor and signal with pre-processing, healthy no-load and fault no-load were done.

This work addresses the detection of failures in the final ring of the rotor of squirrel cage induction motors by applying a new method that increases the precision of the results of the signal analysis with the motor in a steady-state and with low-load condition in which it is very complicated to analyze for conventional methods such as the analysis of the current signature, Fourier transform and the short-time Fourier transform, this method also increases the accuracy in determining the state in which it is found the motor greatly reducing uncertainty, regardless of the amount of motor load. The method provides an analysis with a more stable signal and is capable of being used to carry out a study of the engines over time through trends in their condition.

The new method uses the multispectral analysis based on the Discrete Wavelet Transform applied to the analysis of the stator current in steady-state, a comparison between the results of analysis applying the Daubechies Wavelet of level 44 (db44) used for some authors in [19, 22, 24, 25] and 45 (db45) presented as a new focus was made, under the hypothesis that the higher the order the better the results will be get and

Research Article | Volume 11, Issue 4 | Pages 966-972 | e-ISSN: 2347-470X

according to the conclusions in [28], and according to the theoretical behaviour of these and in which a comparative study of performing different mother wavelets was also carried out. The new method focuses on the study of the energy of the coefficients of the resulting signal from the decomposition of a high-level, as a way of detecting the presence of the left sideband component at the corresponding level the detail frequency band in which the associated signals to the fault are expected to appear, the energy of these coefficients shows a clear difference when a breakage of the rotor end ring has occurred, the signal used to determine the existence of the fault in the end ring is through the left side band generated by it.

1.1 Method of Side Bands

It has been known since the first two decades of the 20th century that an asymmetrical rotor winding, whether in a three-phase cage or slip-ring induction motor, will induce a voltage in the stator winding at a frequency of $f(1-2s)\ Hz$ and therefore conduct a current at that frequency in the stator. The cyclical variation in current caused by a broken rotor bar produces a torque variation at twice the slip frequency and this produces a speed variation that is a function of driveshaft inertia. This normally reduces in the magnitude of the current component $f_1 * (1-2s)$ and a new current component appears in $f_1 * (1+2s)$ and its magnitude can be improved by modulating the third harmonic flow of time in the stator. The greater the inertia of the drivetrain, the greater the resistance to oscillation of torque and speed at $2sf_1$ and therefore the smaller the magnitude of the upper sideband at $+2sf_1$ compared to the lower sideband $-2sf_1$ around *f*, the supply or fundamental component. Therefore, the cage winding breaks produce two sidebands at $\pm 2sf_1$ around *f*, and given by the aforementioned equation, the magnitude of the supply frequency component can be 20 to 1000 times greater than the magnitude of the sidebands according to [5], [20], [27].

1.2 Continuous Wavelet Transform

Wavelet Transform [31-34] is a technique using windows with regions of variable size, it represents the next logical step to the STFT [29], [30], since the analysis by the Wavelet Transform allows the use of large time intervals in those segments in which greater precision is required at low frequency, and smaller regions where information is required at high frequency, for the detection of failures in induction motors, this idea is shown in *figure 1*. Wavelet Transform has been widely used in signal processing fields and is also applied to distinguish and extract signal and fault characteristics in electrical machines, it can generally be divided into continuous and discrete transforms based on the Wavelet orthogonally.

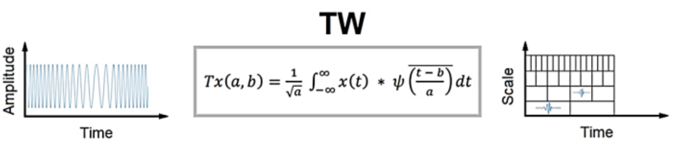

Figure 1: Continuous Wavelet Transform

1.3 Discrete Wavelet Transform

To apply the wavelet-transform to a series of numerical data, it is necessary to implement a Discrete Transform [34], [35]. Considering the Wavelet Transform of a continuous signal x(t), but with translation and scaling discrete parameters *a* and *b*. A natural way to sample the parameters a is by using logarithmic discretization of the scale *a* and binding it to the step size of *b*, that is, moving in discrete steps to each location of *b* which is proportional to the scale *a*. This discretization of the Wavelet has the following form:

$$\psi_{m,n}(t) = \frac{1}{\sqrt{a_0^m}} \psi\left(\frac{t - nb_0 a_0^m}{a_0^m}\right) \quad (1)$$

where *m*, *n* ∈ ℤ control the scaling and translation respectively, a_0 is the fixed expansion step size greater than 1 and *b* is the location parameter that must be greater than zero.

2. MULTI-ESPECTRAL ANALYSIS

2.1 First approach: Conventional analysis based on the Discrete Wavelet Transform

First analysis is carried out with the conventional 1-D discrete Wavelet Transform *figure 2*, analyzing the spectrum resulting from the study signal after data acquisition, the raw signal is analyzed using the Matlab toolbox Wavelet Analyzer DWT-1D application to get the spectra of the different levels also known as multi-spectral analysis or multi-resolution.

To spot the differences between the conditions of the rotor the resulting spectrum was used analyzed Matlab, same is it the energy of the detail coefficients is calculated focusing on the level that contains the characteristics where signals linked to faults condition are found, which because of the specific characteristics of this study is the level four (cD4). The obtained results between the analysis using the Daubechies Wavelet order 44 and 45 are compared to evaluate your performance, with the motor in a healthy-state and with fault with a broken end ring.

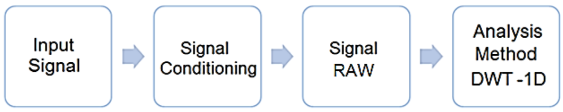

Figure 2: Conventional analysis diagram

2.2 Second approach: Analysis with new method optimized

Second analysis in the same Matlab tool with the 1-D Discrete Wavelet Transform was carried out, simulation was done and implementing an optimized method for the detection of failures with the motor no-load, by applying a specific pre-processing and post-processing which eliminate the signals that may affect the analysis. The pre-processing establishes a limit where only the signals are found of interest, besides applying a line filter and anti-aliasing, this is done since it is necessary for the signal resulting from the analysis to be as stable and with very low variations for the proper performance of the method (Figure 3). This special filter, together with the elements in charge of signal acquisition, is called the signal conditioning pre-processing system one-sideband (SCPS-1SB). After having finished the conditioning of the signal, this signal is used to apply the multi-

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Research Article | Volume 11, Issue 4 | Pages 966-972 | e-ISSN: 2347-470X

resolution or multi-spectral analysis based on the fast wavelet transform algorithm *figure 3*.

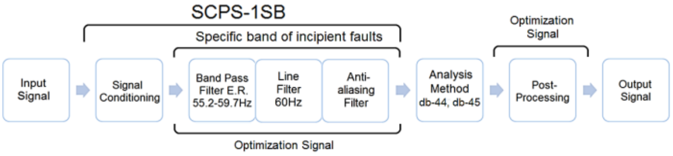

Figure 3: Analysis with new method optimized diagram

For this, some important aspects are considered, the first is the choice of a mother wavelet considering its correlation with the study signals based on the results of the works where the comparison of different types of wavelets and their performance is carried out, starting from this, the performance is evaluated and the results between two wavelets of the same family but different levels were compared. Another aspect that must be calculated is the levels of necessary decomposition, Matlab use its own expressions to calculate the limit of decomposition levels, in this case uses fix(log2(length(x))) where (x) is the data from the study signal. There are multiple variations of the equation to determine the limit of the decomposition levels according to the main purpose and the specific data for this work, in our case, we work with a fundamental frequency of 60 Hz and a sampling frequency of 720 Hz. The choice of the mother wavelet is very important and in this work the Daubechies-44 (db44) wavelet used in severals studies and Daubechies-45 (db45) as new view are applied, the results got are compared in both analyzes. It's are selected as the mother wavelet since it is known that higher levels provide a more precise signal detail with lower harmonics since as the wavelet is higher in level it is less localized in time and oscillates less, for the nature of dilation of Wavelet Transform, this means that at a higher level it behaves like a more ideal filter, according to this would mean that the mother wavelet db-45 would behave better, but let's not forget that the correlation with the study signal is also important. The equation chosen to calculate the levels of decomposition or branches is:

$$N_{n+1} = int\left(\frac{log\left(\frac{f_s}{f_l}\right)}{log(2)}\right) + 1 \qquad (2)$$

According to this equation, the result of the calculation is of 4 levels, one thing that must be mention is that this decomposition tree has a decimated dyadic structure, this type of structure optimizes the characteristics of the system since it avoids having redundancy in the data of output (coefficients C_A, C_D).

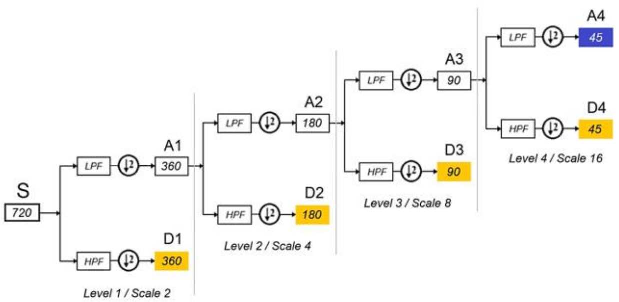

Figure 4: Tree of decomposition multi-level

Figure 4 shows the four levels of the multi-level decomposition tree with the respective outputs of the detail coefficients and the output for level four of the approximation coefficients of this.

To improve the results show in the *figures 9* and *10* , with the determination of the status of the rotor a post-processing of the signal resulting from the coefficients of the level of interest (cD4) is carried out, which aims to improve the performance in the detection of failures in the rotor end ring, for this the window border effects are considered and eliminate, having specific criteria for this to avoid deviation in the result of the coefficients because of atypical values or of big variation in magnitude, only the values are considered where the convolution of the signals completely overlaps and values outside the signal boundary are not considered.

For this, three criteria were applied: in the first the energy contained in the output signal of the analysis complete with edge of signal included is got (related to the Energy 1), in the second the elimination of the edge of the signals is carried out in an amount the size of the kernel, that is to say, where signal and kernel completely overlap (related to the Energy 2), and in the third the evaluation of the signal is carried out, eliminating the border of the windows in an amount of the size of the kernel plus 14 values (related to the Energy 3), this was established through a study and statistical analysis of the resulting signal, since from these the resulting signals are more uniform searching with this increase the precision more in fault detection and differentiation.

3. MATERIALS AND EXPERIMENT

(a) (b) (c)

Figure 5: (a) Healthy rotor, (b) Ring and bar failure simulation, (c) Rotor broken

The validation of the method with several tests on 2Hp, 4-pole squirrel cage induction motors was carried out. Initially, the motors were tested first in a healthy-state, next the brakes rotor end ring was performed in the laboratory. After finishing the tests in a healthy-state, the simulation of the failing to carry out material was artificially removed to generate a slot in the end ring *figure 5*, the activation of the motor was through a switch and the data was obtained after 10 seconds of having started the motor. The motor was connected in a star configuration with a 220V supply voltage and data on the study's motors nameplate are: brand: WEG, model: 00218ET3EM145TCW, star connection, nominal voltage: 230 V, nominal primary current:

5.52 A, rated power: 2Hp, 4 single poles, rated speed: 1755 rpm, service factor: 1.25, insulation class: F.

Was selected the line where the data would get to the analysis of the stator current, in this, the primary current was measured during the steady-state for the different cases, for this condition samples were taken after 10 seconds of starting the motor thus ensuring the integrity of data get.

To capture the data, an analog-to-digital converter was used with a theoretical sample rate of 860 SPS with programmable gain and 16-bit resolution, following the path of high resolution and not the path of high sampling, unlike all the work that has been done so far. The detection failures in the rotor of the squirrel cage induction motor using both the conventional methods and the new method optimized of signal was made, comparing motor results in a healthy and faulty state, a decomposition of 4-level was performed using the wavelet mother Daubechies-44 and Daubechies-45 to compare and evaluate their performance.

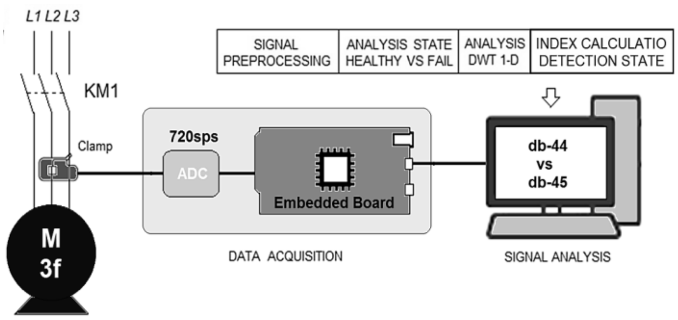

Figure 6: Data acquisition and processing

4. SIGNAL ANALYSIS MRA

4.1 Analysis and comparison of the signal

Table 1 shows the bandwidth with which each level remains for the details or high-frequency signals, as well as for the approximations or low-frequency signals of the decomposition tree. In this table, we can see that the area of interest focuses mainly on the level four of details understanding as an area of interest, the range where the signals linked to the fault are expected to appear.

Table 1: Frequency bands in Hz for DWT with Fs=720 Hz

Level	Approximations [Hz]	Details [Hz]
1	A1: [0, 360]	D1: [360, 720]
2	A2: [0, 180]	D2: [180, 360]
3	A3: [0, 90]	D3: [90, 180]
4	A4: [0, 45]	D4: [45, 90]

The multi-resolution analysis was carried out with the Matlab tool, the comparative graphs were obtained with the Matlab toolbox Wavelet Analyzer DWT-1D tool, the data of the signals obtained and stored were loaded one by one for analysis, in this the behavior was observed of the tests of the healthy motor and with the failure, as well as the signal with preprocessing and without it, in the Matlab editor the different levels of decomposition of the detail coefficients and approximations were generated through code, subsequently the postprocessing was carried out of the signal and the calculation of the energy of level of detail four (cD4) using three different criterio.

Figure 7 shows the analysis done to the raw signal motor no-load in healthy-state, while *figure 8* shows the analysis done to the raw signal no-load but in a faulty-state with a broken end ring, both using the mother wavelet db-44 and db-45. In the analysis carried out on conventionally (related to the signal raw) shown in *figures 7* and *8*, a variation in magnitude the coefficients can be observed in the level of interest (cD4) using the db-44 or db-45, being higher when a fault occurs regardless of the wavelet used, in both cases either using the db-44 or db-45 the energy contained in the signal is lower when the motor fault occurs, although this can be a sign that could be taken and related to the presence of the failure at the cD4 level, it is difficult to maintain an accurate trend because of the variations present in the signal of the coefficients, since not it is all certain that this is because of the failure or some effect as load variation motor.

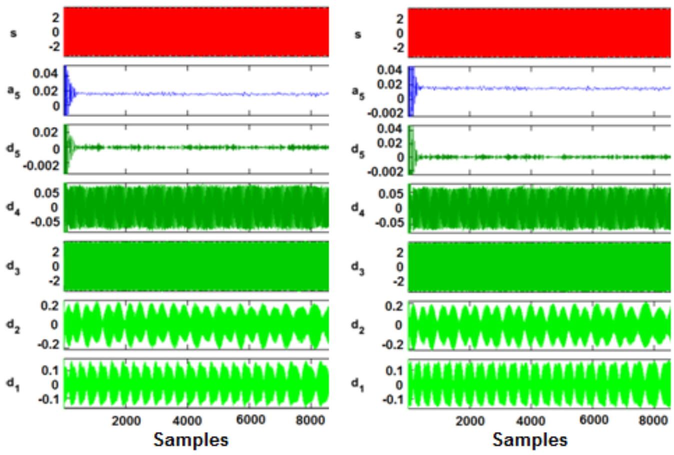

Figure 7: Raw signal healthy no-load motor, comparison MRA with mother wavelet db-44 and db-45

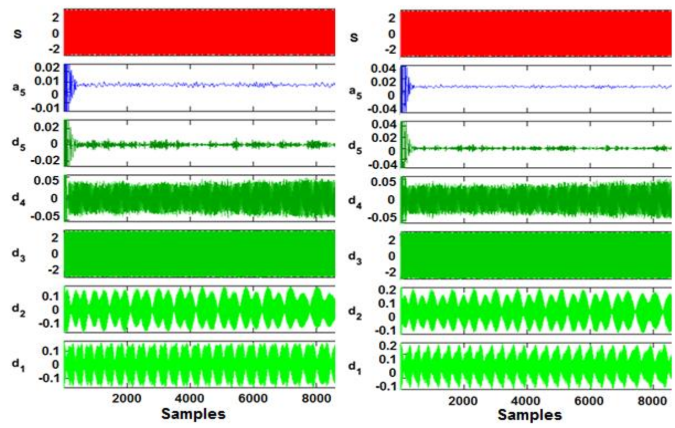

Figure 8: Raw signal fail no-load motor, comparison MRA with mother wavelet db-44and db-45

Figure 9 shows the analysis done to signal with pre-processing the motor no-load in healthy-state, while *figure 10* shows the analysis done to signal with pre-processing the motor no-load

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Research Article | Volume 11, Issue 4 | Pages 966-972 | e-ISSN: 2347-470X

in a faulty-state with a broken end ring, both using the mother wavelet db-44 and db-45, in both this a smaller variation is observed in the values of the signal of the level of interest (cD4) in comparison with the conventional analysis show in *figure 7* and *8* of the raw signal in the same conditions.

In the analysis of the signal applying pre-processing, it is shown that the stability of the resulting values at the level of interest (cD4) is greater and the remain stable regardless of the condition of the motor and the wavelet used, besides increasing the magnitude of the energy contained in the signal of the coefficients. This behavior is extremely important for the developed method since any minimal increase in the magnitude's trend of the signal indicates the presence of the fault. For this application, it is required to have a lower number of variations to reduce the deviation when calculating the energy of the coefficients of the resulting signal at the cD4 level; this will increase the accuracy in detecting faults.

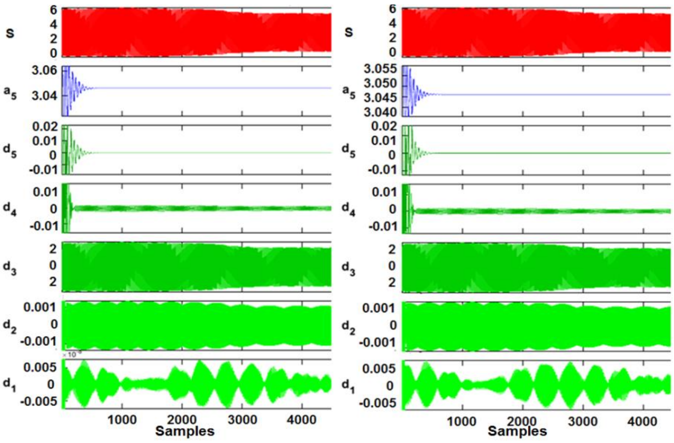


Figure 9: Signal SCPS-1SB healthy no-load, analysis with mother wavelet db-44 and db-45

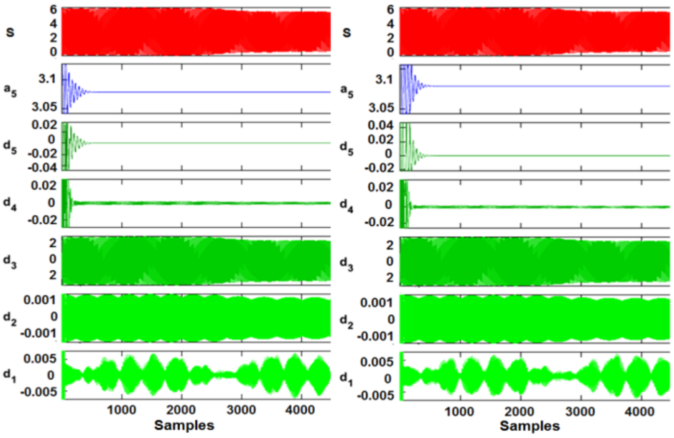


Figure 10: SCPS-1SB failure no-load, analysis with mother wavelet db-44 and db-45

The calculation of the energy of the coefficients was carried out having three criteria; this is shown in the *figure 11*. The basis that was taken to establish the accuracy and deviation was a measure of central tendency among all the tests carried out from the calculation of the concentrated energy in each spectrum in the entire selected range with the help of MATLAB.

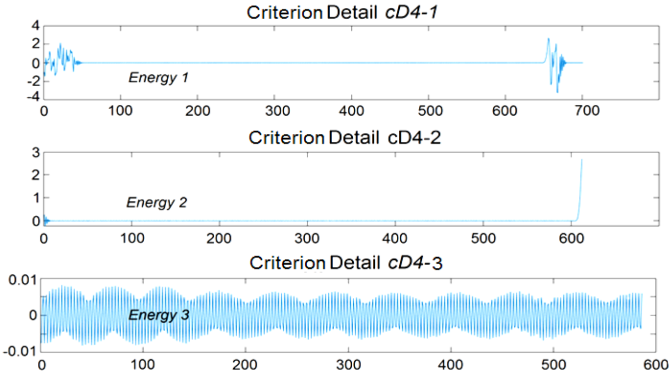


Figure 11: Graph of the signal post-processing criteria

5. RESULTS AND DISCUSSION

5.1 Analysis and Comparison of Signal

The results get with the analysis carried out on the signal with pre-processing *figures 8, 9* show that the signal treated with it is more stable regardless of the condition of the motor or the mother wavelet used so as less variations in comparison with the results of the analysis carried out on the signal without pre-processing. The get results show differences in the magnitudes between the state without failure and state with failure in signal the level of interest cD4 and when the highest order wavelet (db45) applies to the signal analysis, the magnitude of the energy contained in the signal is lower regardless of the state of the motor, confirming that higher levels provide a more precise detail signal, according to with that at a higher level it behaves like a more ideal filter.

Figure 12 shows the trend of the tests of signal with pre-processing apply and analyzed with the wavelet lower order db-44 and db-45, where the tendency of the energy corresponding to the new method that applies a post-processing to completely eliminate the effects of the edge of the window is related to the criterion called *Energy 3*, comparing its performance with the motor in a healthy-state and with fault.

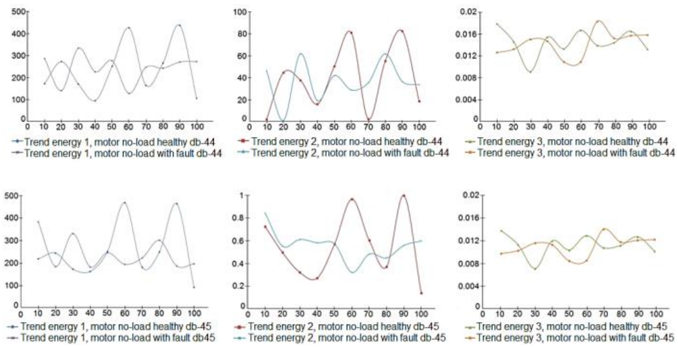
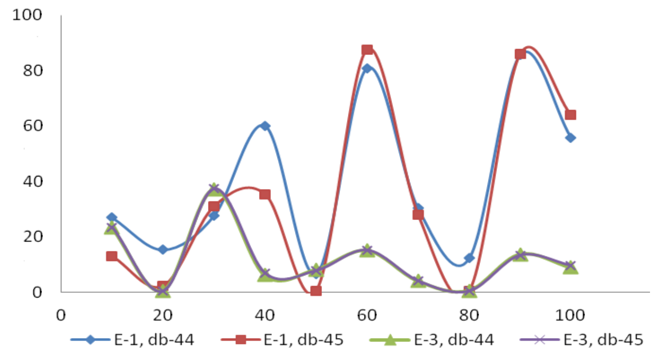


Figure 12: Trend motor no-load healthy and failure using mother wavelet db-44 and db-45

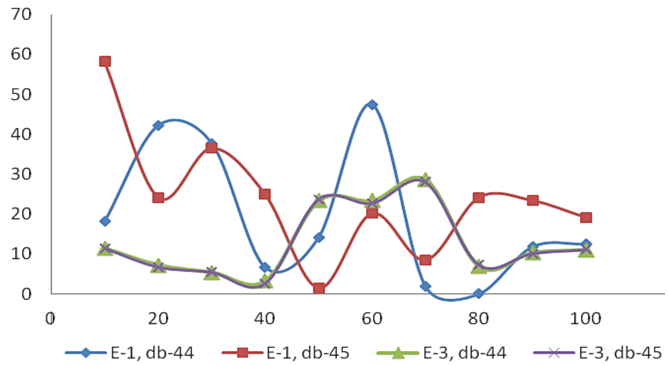
In the analysis made at the level of interest for this study (level cD4), was made the elimination of the edges of the signal for the different tests under different criteria, among the three ways of carrying out the analysis of the signal a greater stability is presented in the results of energy 3, regardless of the state of the motor and the mother wavelet used, this is confirmed with the get results from the absolute deviation, this should be understood as the standard deviation but taking its value absolutely. This is the signal totally clean under the special criteria where removal of the window borders plus 14 points, this characteristic being of great importance in order to reduce the uncertainty in the detection of incipient failures in the squirrel-cage rotor with motor no-load, since it is a fundamental part for a good result in the detection of the different states of the motor, this can be observed in the results get of the tests where the results are shown between the three selected criteria of calculating the energy of level 4.

The results get of the absolute deviation of the tests realized whit the three selected criteria to calculating the energy of level 4 are shown. First results are with the motor in healthy-state no-load, using the wavelet db-44 for the analysis of the signal with pre-processing. Taking as reference a measure of central tendency *ta* calculate the resulting absolute deviation, the results show that the average of the absolute deviation for the calculation of the first criteria or energy 1 is 40.2%, for the second criteria or energy 2 it is 61.02% and for the third criteria or energy 3 it is 11.8%, this being the lowest among the three different ways of performing the tests, this is directly related to and indicates the accuracy of rotor state detection. Second results are with the motor in fault-state no-load, using the wavelet db-44 for the analysis of the signal with pre-processing. The calculation of the absolute deviation of the resulting energy is on average for the calculation of energy 1 of 19.2%, for energy 2 it is 35.8% and for energy 3 of 13.09%, Third results are with the motor in healthy-state no-load, using the wavelet db-45 for the analysis of the signal with pre-processing. The calculation of the absolute deviation of the resulting energy it has an average of 34.8% for the calculation of energy 1, for energy 2 it is 41.7% and for energy 3 it is 11.8%, this being the lowest among the three different ways of carrying out the analysis. Fourth results are with the motor in fault-state no-load, using the wavelet db-45 for the analysis of the signal with pre-processing. The calculation of the absolute deviation of the resulting energy is on average for the calculation of energy 1 of 24.04%, for energy 2 of 15.3% and for energy 3 of 11.1%, being again the lowest among the three different ways of the tests carrying out.



(Healthy)

Figure 13 shows the results of absolute deviation motor no-load healthy and motor no-load failure, where the results get from the analysis with the mother wavelet db44 and db-45 are compared, between the conventional method associated to *Energy 1* and the optimized method associated to *Energy 3*.



(Failure)

Figure 13: Absolute deviation motor no-load healthy and failure

6. CONCLUSIONS

In this paper, it is presented as an optimized method for the early detection of broken rings and bars in induction motors in permanent-regime no-load. The experiments made, is concluded that the proposed method reduces uncertainty and considerably increases the possibility of detecting incipient failure conditions of broken end rings in conditions with the motor no-load compared to conventional or classical DWT analysis, as well as that it has a greater stability, regardless of the mother wavelet and its level used, confirming the more selective behavior when a mother wavelet of higher order is used, increasing the precision by differentiating regardless of whether there is an incipient failure. However, no significant improvement is observed between the results get with the application of db-44 and db-45, if the computational load is considered. Therefore, this leads to the assumption that a lower order wavelet could be used without significantly losing the precision and accuracy that is gained with the application of the proposed method for the detection of failures in the rotor ring, generating much less computational load and increasing the speed of processing and detection in real time.

Author Contributions: Authors individual contributions are in conceptualization, methodology, formal analysis, investigation, data curation, writing—original draft preparation, resources, visualization, supervision, project administration, Martínez García Irving I., and validation, resources, writing—review and editing, Peña Cabrera J. Mario. All authors have read and agreed to the published version of the manuscript.

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