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**HYBRID SYSTEM USING ACOUSTIC EMISSION AND ELECTRIC
CURRENT FOR FUZZY DIAGNOSIS OF SURFACE WEAR IN GEARBOX
COUPLED TO INDUCTION MOTOR**

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Abstract. *This work proposes a hybrid system that uses data collected by current sensors and acoustic emission for the diagnosis of incipient failures in gearboxes coupled to Three-phase Induction Motors, searching for an alternative and non-invasive analysis by signs of vibration. The decomposition of the signals from the Wavelet Packet Transform (WPT) made it possible to evaluate the frequency bands characteristic of the failure by the spectral analysis and the calculation of the entropy. The spectral patterns were initially used to verify the effects caused by surface wear on the signals. In the sequence, the signals were processed by the wavelet transform, to be used as input of a Fuzzy inference system. Experimental results were obtained by testing the system at different wear levels due to lack or insufficient lubrication. The electromechanical set was driven directly from the electrical network and by frequency inverter at 20Hz, 30Hz, 40Hz and 50Hz in order to evaluate the sensitivity of the strategy in a wide rotation range. For each drive at 60Hz, the conditions of nominal load, at no load, with 40% and 70% of the load were imposed in order to evaluate the effects of the load in the calculation of the wavelet entropy.*

Keywords: *failure analysis, surface wear, gearbox, fuzzy logic, wavelet packet.*

1. INTRODUCTION

A strategy that emerged as an alternative to vibrational analysis for the detection of gearboxes failures explores the intrinsic capacity of electric motors and generators to act as transducers (Silva, 2008). This strategy is particularly useful in situations where usual methods such as the installation of accelerometers are inadequate or infeasible (Benghozzi et al., 2012). A failure in the gearbox such as a surface wear produces a torsional vibration in the charge conjugate, causing changes in the flux interaction between the stator and the rotor, resulting in changes in the stator current (Benghozzi et al., 2012). Acoustic signals have generally been used to aid current or vibration signals to detect failures in electric motors or mechanisms, respectively, in order to increase the reliability of the analysis system, mainly due to the fact that audible alterations are identified earlier. However, adequate instrumentation is required to minimize unwanted audio sources.

Kia, Henao and Capolino (2007) presented by means of mathematical model, a set of frequencies that can undergo changes in the electric current due to a surface wear in gearboxes coupled to an induction motor. In this work, the spectral analysis was used to analyze the torsional vibration caused by the surface wear on the gear teeth. The authors concluded that a higher load dampens mechanical vibration and oscillation torque.

Boshkoski and Urevc (2008) investigated the potential and the sensitivity of electric current associated with acoustic emission. In the research the wavelet detail signal power was monitored with the growth of the contact fatigue in a

gearbox coupled to a DC motor. The authors concluded that the combination of signals increases the reliability of detection. In this research it was possible to observe that the process of formation of the contact fatigue presents strong variations of torque and a gradual increase of the vibration of the system over time.

Kia, Henao and Capolino (2012) simulated a dynamic model for the electromechanical assembly in order to compare different strategies for the diagnosis of tooth surface wear. The acoustic pressure and vibration diagnostics capabilities are analyzed by the envelope technique and the coupled induction motor stator current signals are analyzed by current power spectrum density.

In Sena (2015) the author developed a methodology to diagnose the levels of surface wear severity caused by the lack of lubrication in a gearbox coupled to an induction motor. The methodology consisted in the application of the calculation of the wavelet entropy in electric current signals, with severity classification being performed by a Fuzzy inference system.

2. METHODOLOGY

A high noise level at the gear frequency is characteristic of problems that divert the contact surfaces of the teeth from their ideal pattern, such as wear. The gear frequency, f_{eng} , is expressed by the ratio between the number of teeth of a gear and the rotational frequency of its axis, according to Eq. (1). The frequency of the crown gear, f_{cor} , is defined by the gear ratio.

$$f_{eng} = Z_{pin} f_{pin} = Z_{cor} f_{cor}, \text{ where } f_{cor} = (Z_{pin} / Z_{cor}) f_{pin} \quad (1)$$

Where: Z_{pin} is the number of teeth of the pinion gear, Z_{cor} is the number of teeth of the crown gear and f_{pin} , f_{cor} and f_{eng} the rotations in Hz.

In the wavelet packet (WPT) decomposition, the detail coefficients are divided into approximation coefficients and details, decomposing the signal into a binary tree (Crovato, 2004). The calculation of the WPT coefficients of Eq. (2) is the resultant sequence of the internal product of a signal $s(t)$ with the wavelet packet functions.

$$\lambda_{m,f}(n) = \langle s, w_{mf} \rangle = 2^{-m/2} \sum_n s(t) w_f(2^{-m}t - n), f \geq 0 \quad (2)$$

Where: $\lambda_{m,f}(n)$ are the expansion coefficients of $s(t)$ in wavelet packet functions; $w_{mf}(t)$ are the basic wavelet packet functions, f is the frequency index, t is the time, m is the scale coefficient and n is the translation coefficient.

The translate, dilated and normalized wavelet packet functions are obtained by Eq. (3).

$$w_{mf}(t) = 2^{-m/2} w_f(2^{-m}t - n) \quad (3)$$

There are several wavelet functions that can be used as the mother wavelet (w_f), and among the most usual discrete wavelets, it is possible to mention the families of Daubechies, Coiflets and Symlets (all orthogonal). A detailed presentation of wavelets theory can be found in De Oliveira (2007) and Addison (2002).

Entropy is related to the degree of disorder of a system. The greater the degree of entropy, the greater the dispersion of energy in a process. Entropy-based methods allow the comparison of system properties in numerical terms by means of a probability distribution, since entropy can be used as a measure of dispersion. The wavelet energy spectrum in the m scale is defined by Eq. (4).

$$E_{mf} = |\lambda_{m,f}(n)|^2 \quad (4)$$

Therefore the wavelet energy spectrum for a given time window in the m scale can be calculated according to Eq. (5), and the total energy by Eq. (6).

$$E_m = \sum_n E_{mf} \quad (5)$$

$$E = \sum_m E_m \quad (6)$$

The relative energy value, which corresponds to the energy of each wavelet packet, is given by Eq. (7). On what $\sum_m p_m = 1$.

$$p_m = \frac{E_m}{E} \quad (7)$$

The total entropy is defined as the sum of the entropy computed over the full extent of the frequencies.

$$WPE_{tot} = \sum_m WPE_m \quad (8)$$

On what $WPE_m = -p_m \ln(p_m)$.

Depending on the phenomenon to be studied, there will be a need for scale harmonization through the normalization of entropy values.

$$(WPE_m)_N = \frac{WPE_m - WPE_{mmin}}{WPE_{mmax} - WPE_{mmin}} \quad (9)$$

Where: WPE_m is the measured entropy in a given condition, WPE_{mmin} is the minimum measured entropy and WPE_{mmax} is the maximum measured entropy.

3. EXPERIMENTAL RESULTS

3.1 Experimental Assembly

The experimental assembly is composed of Three-phase Induction Motor of 0,5 CV, nominal voltage of 220/380VAC-60Hz, 4 poles, 1,720 RPM. The load is simulated by electrodynamic braking by Foucault currents, where the force applied to the motor axis is controlled by a DC power supply (potentiometer), and this same mechanical force is measured by a coupled digital dynamometer (load cell) to the brake system and retransmits the analog signals standardized and proportional to the braking force and the speed of the disc. The system is operated by direct start or by means of WEG® CFW-08 frequency inverter.

The coupled gearbox was designed and manufactured during the project period, consisting of a pinion (21 teeth) and crown (38 teeth) of module 2 and a gear ratio of 1,8. The currents are obtained from linear Allegro ACS712ELC-30A Hall effect sensors with a sensitivity of 66mV/A, low current conductor resistance and low offset. For the acoustic analysis a KY-038 sound module is used, with operating voltage between 5V, with digital and analog output, sensitivity adjustable via potentiometer and has a condenser microphone. For the conditioning of the sensor signals to the specifications of the acquisition board, it was necessary to amplify using operational amplifiers (LM358).

The A/D converter used is the NI-6289 Data Acquisition Module (DAQ), which has 18 bits of resolution, and can handle a sampling rate of up to 625ks/s (samples per second). The NI USB-6289 module offers 32 analog inputs, programmable acquisition levels per channel, with voltages ranging from $\pm 0.1V$ to $\pm 10V$. From the signals obtained from the A/D converter will perform the failure analysis by an algorithm in LabView®. The experimental assembly for failure analysis is shown in Fig. (1).

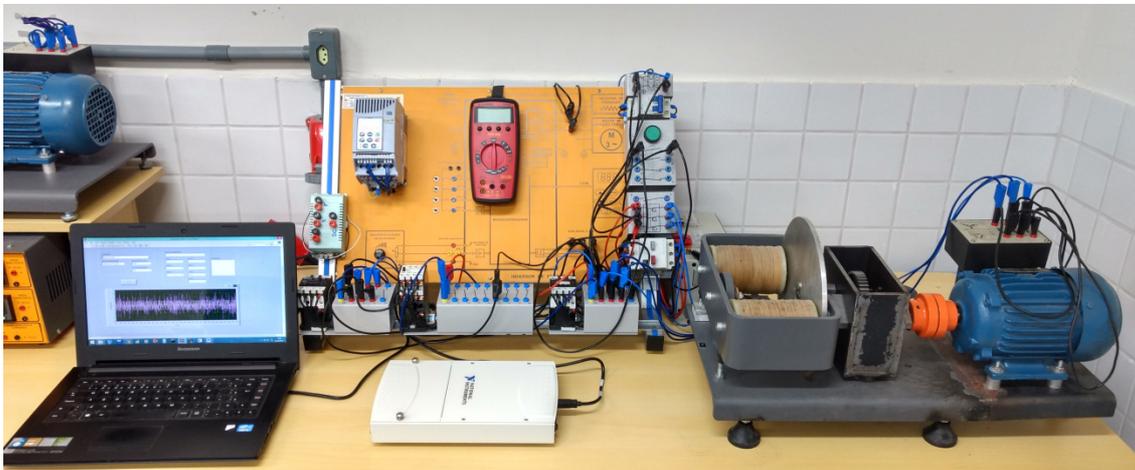


Figure 1. Experimental assembly for failure analysis. Source: Author.

wear tests, except for the acoustic emission signals in the condition of severe wear on the empty drive, which is classified as mean dispersion ($15\% < \text{coefficient of variation (CV)} < 30\%$) according to the classification proposed by Correa (2003). Tab. (1) shows a statistical summary of the calculation of the entropy with motor at 40% of the nominal load (direct from the electrical network). In Tab. (2) a statistical summary of the entropy calculation with motor at nominal (direct from the electrical network) is presented.

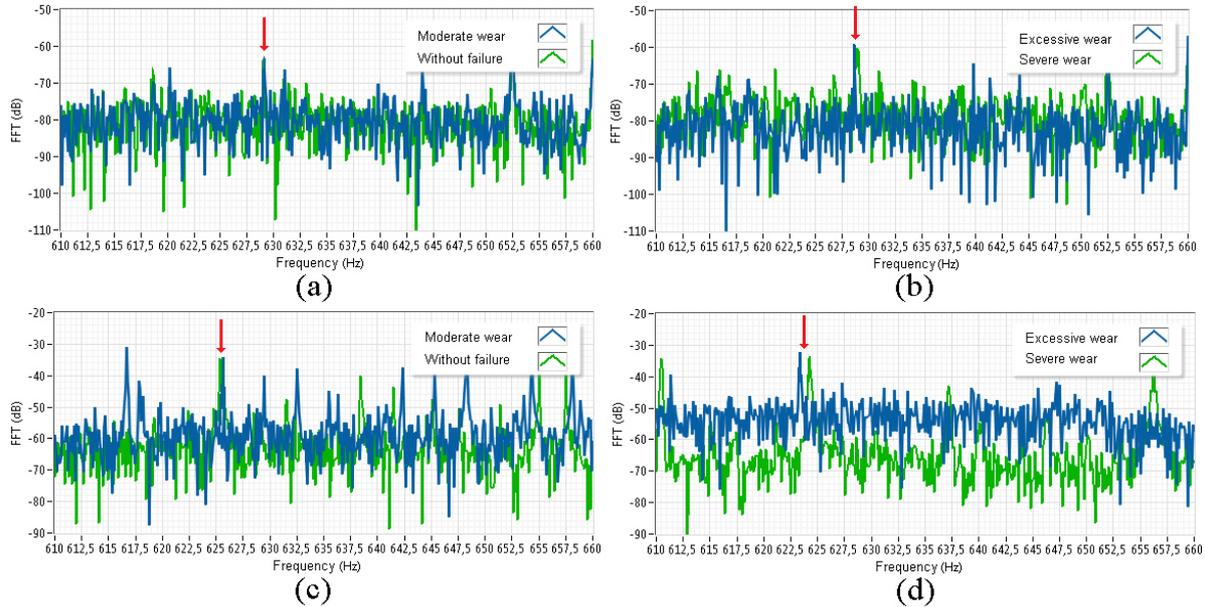


Figure 4. Spectral analysis of the wavelet detail: (a) current signal without failure and moderate wear, (b) current signal with severe and excessive wear, (c) acoustic signal without failure and moderate wear, (d) acoustic signal with severe and excessive wear. Source: Author.

Table 1. Summary of wavelet entropy with motor operating at 60Hz (40% of nominal load). Source: Author.

Wavelet Entropy (nats) - Electric current								
Sample	1	2	3	4	5	Mean	Deviation	CV (%)
Without Failure	2,93	2,81	3,01	2,85	2,97	2,914	0,083	2,846
Moderate Wear	3,39	3,24	3,51	3,25	3,34	3,346	0,111	3,319
Severe Wear	4,00	4,11	4,18	4,19	4,20	4,136	0,084	2,027
Excessive Wear	4,08	4,59	4,42	4,33	4,16	4,316	0,204	4,722
Wavelet Entropy (nats) - Acoustic Emission								
Sample	1	2	3	4	5	Mean	Deviation	CV (%)
Without Failure	111,95	112,52	107,33	110,09	112,69	110,916	2,254	2,033
Moderate Wear	166,85	158,81	160,56	166,78	168,62	164,324	4,343	2,643
Severe Wear	172,64	165,57	165,34	179,95	178,99	172,498	7,017	4,068
Excessive Wear	184,38	181,81	175,96	188,2	192,28	184,526	6,213	3,367

Table 2. Summary of wavelet entropy with motor operating at 60Hz (nominal load). Source: Author.

Wavelet Entropy (nats) - Electric current								
Sample	1	2	3	4	5	Mean	Deviation	CV (%)
Without Failure	5,62	5,14	5,37	5,42	5,48	5,406	0,176	3,251
Moderate Wear	5,83	6,02	5,98	5,51	5,48	5,764	0,256	4,438
Severe Wear	6,71	6,75	6,60	6,55	6,41	6,604	0,135	2,047
Excessive Wear	6,82	7,11	7,35	7,84	7,32	7,288	0,374	5,135
Wavelet Entropy (nats) - Acoustic Emission								
Sample	1	2	3	4	5	Mean	Deviation	CV (%)
Without Failure	142,82	143,88	144,24	138,32	138,61	141,574	2,888	2,040
Moderate Wear	161,82	150,43	147,06	155,98	143,60	151,778	7,236	4,768
Severe Wear	177,07	176,90	176,13	173,07	170,28	174,690	2,945	1,686
Excessive Wear	178,86	185,22	180,60	167,05	174,83	177,312	6,841	3,858

The behavior of the normalized wavelet entropy is shown in Fig. (5) according to the observed wear and the imposed load for the direct drive of the electrical network.

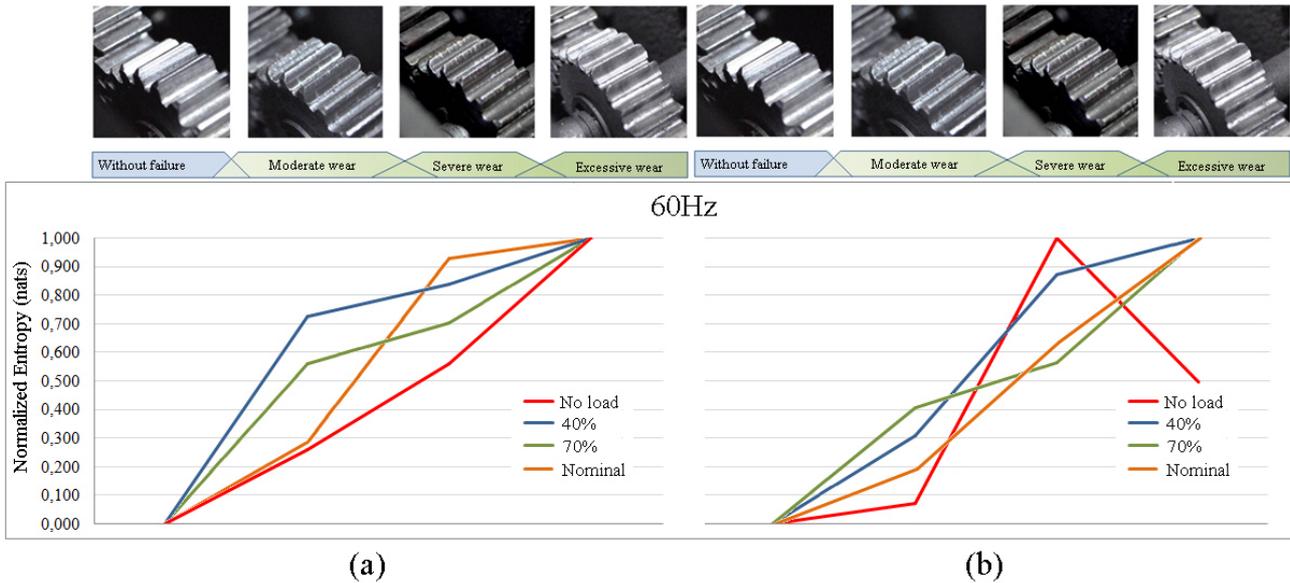


Figure 5. Behavior of wavelet entropy: a) acoustic emission signals and b) electric current signals. Source: Author.

The entropy calculation presented a reliable analysis for the differentiation between the severity levels, because as shown in Fig. (5), the entropy was presented as increasing according to the visual observation of the failure, except for the empty condition in the signal electric current. However, it was observed (spectral analysis) in current signals with excessive wear at no load, a considerable increase of the effect of slack. It is interpreted that in high rotation and in the empty condition there was no adequate contact between the crown and pinion teeth (fluctuations), damaging the sensitivity of the current to failure. In Fig. (6) and (7) the normalized wavelet entropies are shown according to the wear observed for the drives with inverter. For each drive with frequency inverter, the load conditions were imposed and without load, due to nominal motor decharacterization.

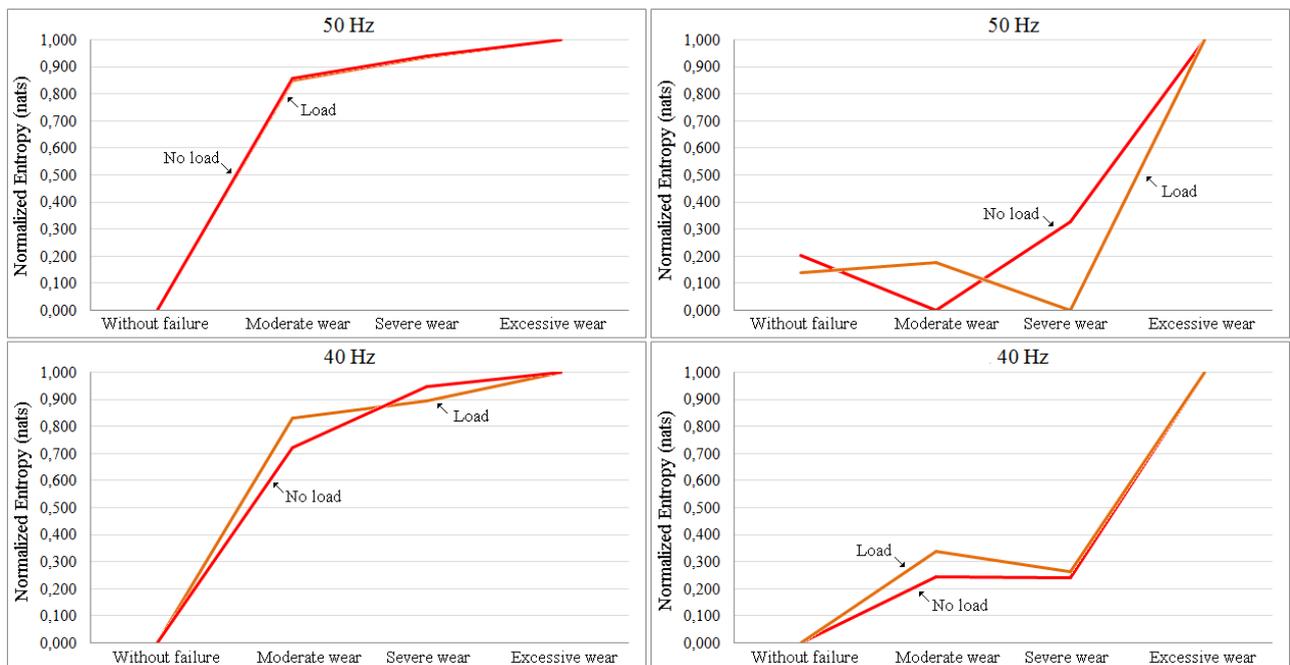


Figure 6. Normalized wavelet entropy behavior for drives with frequency inverters at 50Hz and 40Hz: on the left side the acoustic emission signals and on the right, the electric current signals. Source: Author.

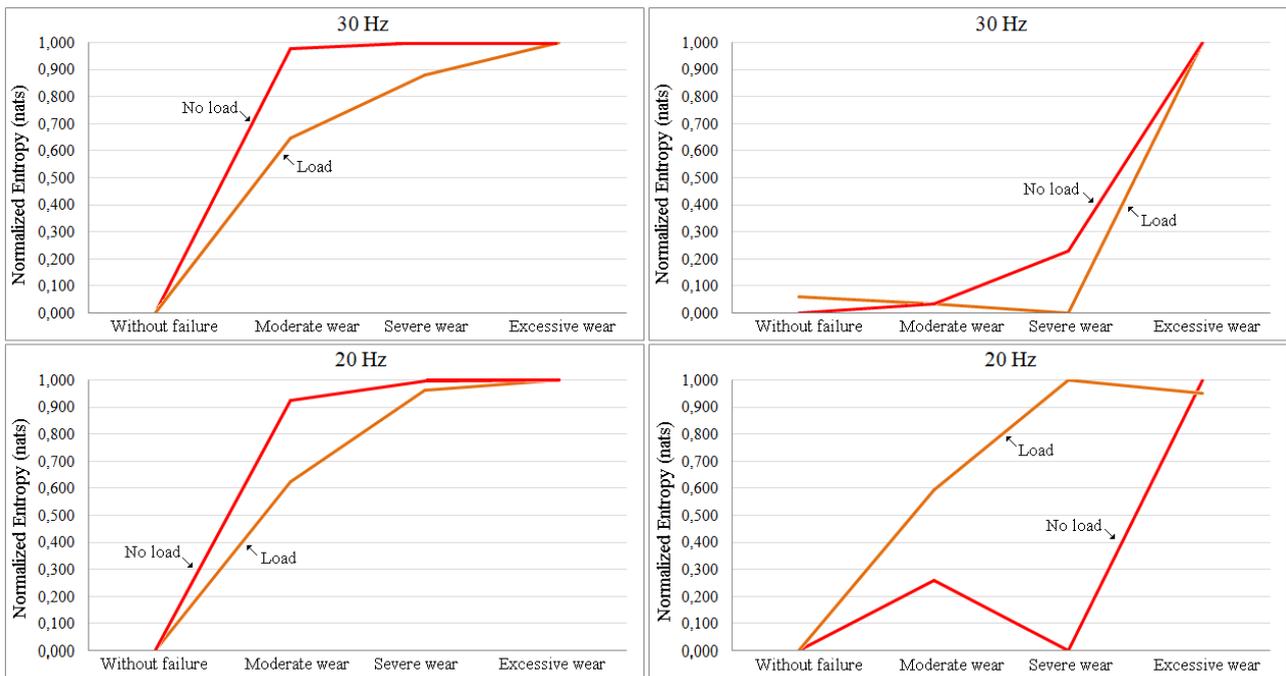


Figure 7. Normalized wavelet entropy behavior for drives with frequency inverters at 30Hz and 20Hz: on the left side the acoustic emission signals and on the right, the electric current signals. Source: Author.

The results of Fig. (6) and (7) present an increasing behavior of the acoustic emission for all the drives, crediting this variable as reliable for analysis of the failure levels. However, the electric current presented variations in the entropy of moderate and severe wear, and it is not possible to distinguish. Possibly the electric current was greatly influenced by the noise generated by the frequency inverter. In general, the electric current presented a considerable increase of entropy for the condition of excessive wear, affirming the sensitivity of this variable to the failure.

3.3 Fuzzy Diagnosis

The Fuzzy diagnosis was only set up for the direct drive of the network in the load conditions, where the detection results were more reliable. The following nomenclatures were used: CE40 (electric current with 40% of nominal load), EA40 (acoustic emission with 40% of nominal load), CE70 (electric current with 70% of nominal load) and EA70 (acoustic emission with 40% nominal load), CENO (electric current with nominal load) and EANO (acoustic emission with nominal load). The following parameters were used for the inference system: Operator and (Zadeh), then operator (minimum), aggregation operator (maximum) and defuzzification method (area center method). Tab. (3) presents the rules bases used for inference.

Table 3. Rules basis for Fuzzy diagnosis. Source: Author.

		EA40						EA70						EANO			
		GI	GII	GIII	GIV			GI	GII	GIII	GIV			GI	GII	GIII	GIV
CE40	GI	SA	IN	IN	IN	CE70	GI	SA	IN	IN	IN	CENO	GI	SA	IN	IN	IN
	GII	IN	DM	IN	IN		GII	IN	DM	IN	IN		GII	IN	DM	IN	IN
	GIII	IN	IN	DS	IN		GIII	IN	IN	DS	IN		GIII	IN	IN	DS	IN
	GIV	IN	IN	IN	DE		GIV	IN	IN	IN	DE		GIV	IN	IN	IN	DE

Fig. (8) presents the pertinence functions of the input variables used. The language terms used were: GI (signal without failure), GII (signal with moderate wear), GIII (signal with severe wear) and GIV (signal with excessive wear).

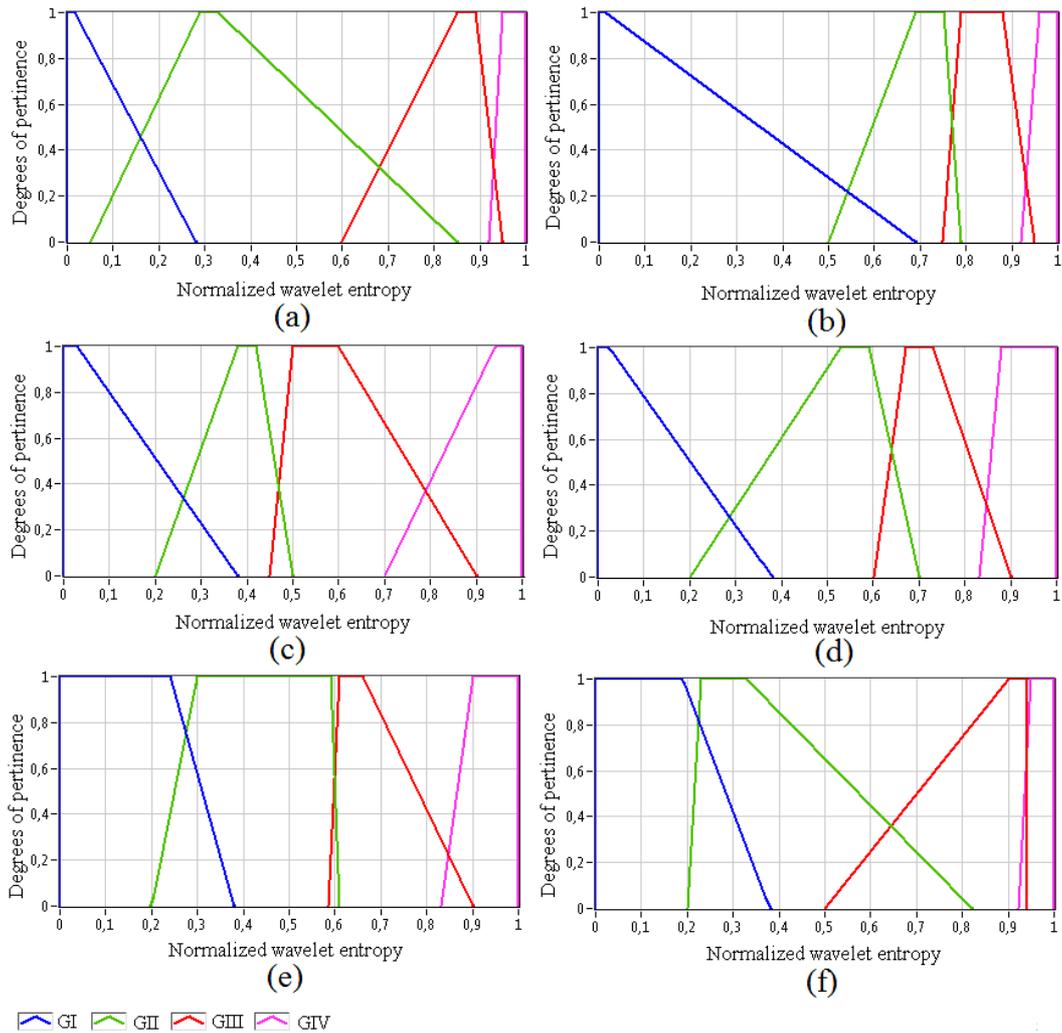


Figure 8. Pertinence functions and their respective language terms: a) CE40 input, b) EA40 input, c) CE70 input, d) EA70 input, e) CENO input, f) EANO input. Source: Author.

For the proposed system, variable DA40 was defined for the diagnosis of failures with drive at 40% of load, DA70 for the diagnosis of failures with drive at 70% of load and DANO for the diagnosis of failures with drive at nominal load. The language terms used for the outputs were: SA (Without Failure), DM (Moderate Wear), DS (Severe Wear), DE (Excessive Wear) and IN (Inconsistency of result). Therefore, there are 16 rules for the implication of each output. Each of these bases have been implemented in different programs due to the limitations of the Labview® Fuzzy Logic Toolkit, that is, there is a program to analyze the failures with 40% of the load, another for 70% of the load and another one for nominal load. Fig. (9) presents the pertinence functions of the DA40 output and their respective linguistic terms.

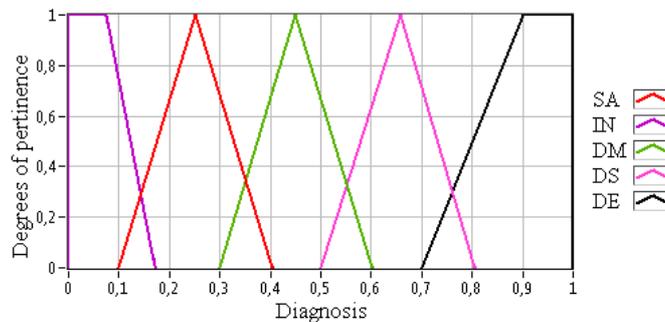


Figure 9. DA40 output pertinence functions and their respective language terms. Source: Author.

4. CONCLUSIONS

The proposition of entropic wavelet decomposition patterns was presented as a source of reliable information to the limitations of the spectral analysis. The calculation of the wavelet entropy enabled the quantification of the transient effects of the failures in the region of the gear with low dispersion of the samples in the direct drive of the network under the same condition of the gear and engine operation (variation of load and rotation). The analysis of the drives with frequency inverter was also reliable for the acoustic emission analysis, however the electric current was affected, only being able to be distinguished the conditions without failure and excessive wear. In general, the electric current was less sensitive to detect the levels of wear compared to the acoustic emission. The increase of the load caused a low damping of the vibrational effects in the entropy calculation. The reduction of rotation caused a lower noise level; however, it was still possible to distinguish the stages of wear.

In this sense, the Fuzzy diagnosis was set up for the direct drive of the network in the conditions of the motor in 40%, 70% and with nominal load, where the results of the detection were presented in a satisfactory way. The Fuzzy system presented a coherent behavior of the wear severity, allowing a reliable hybrid diagnosis.

The main conclusion of this work was the observation of the severity of the superficial wear as a gradual increase of the entropy in the region of the gear in the signals of acoustic emission and electric current.

The results produced in this research can be considered satisfactory; however, they suggest some improvements for future work, such as: the improvement of the relation between the sampling rate and the effects of the failure, the greater number of samples for each studied condition and the assembly of an algorithm unique to the Fuzzy rule bases.

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