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Multiple Impairments Mechanical Detection of a System Engine - Reducer by a Plural Approach of The Stator Current

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***Abstract*— Unbalance and damage to the gear denutre are among the most likely causes of breakdowns electromechanical systems breakdowns which consist of a motor coupled to a mechanical gearbox. Analytical modeling of these complex systems to the degraded state is not easy. An experimental alternative was considered as a contribution to the diagnosis and early detection of the mechanical damage. Only the specific designation of the nature of the detected fault remains an unfinished task. To this end, a plural resolution making use of a series of advanced approaches of the stator current analysis (STFT, Gabor Spectrograms and CWT) has been introduced to complement the FFT. The practice validation of multiple signatures targeting the aforementioned damage involved a motor-reducer system 3kW.**

***Keywords*— induction motor, mechanical defects, MCSA, non-stationary currents, STFT, Gabor spectrogram, CWT**

I. Introduction

The majority of industrial applications based on rotating machines, especially those high powers (metallurgy, transport, handling, drilling ...), use of drive systems consist of an actuator coupled to a gear box for the purpose of transmission of mechanical power and speed as recorded in the book drop. Faced with relatively high mechanical stresses during transient (start, speed variation and loads, braking ...), these complex systems are often subject to mechanical defects such as mass imbalance or "unbalanced" and wear gear denture. Moreover, these aforementioned defects are the cause of the degradation of bearings that ranks amongst the first identified faults in industry [1]–[3]. Seeing the importance of these systems in the animation process technology, a necessity is then required for predictive detection of these failures and an anticipation of the final shutdown of the system which cost has a huge financial impact. The vibration and acoustic approaches [4]–[6] have shown their limits when it comes to defects inducing torque variations or incipient faults that are almost imperceptible. To accurately extract information about such defects, research has been especially directed to the spectral analysis of stator currents of the induction motor by means of the Fast Fourier Transform (FFT) [7], [8]. MCSA (Curent Motors Signature Analysis) was the work of many research results throughout the last decade [9]–[14] and was successful. Fluctuations of the amplitudes of the stator currents at the start of the electromechanical drive systems are very important, particularly, for larger calibers. Therefore, the analysis of these currents, even in vacuum is carrying valuable signatures for system health.

This experimental work has a plurality of signatures from the treatment of stator transients by advanced techniques [15]–[17] as the spectrograms of the STFT (Short Time Fourier Transform), spectrograms Gabor and scalograms of CWT (continuous wavelet transform), in addition to the FT (Fourier transform) in order to have a proper and robust predictive diagnosis of single and multiple mechanical defects. Practice validation was performed on an induction motor 3KW coupled to a mechanical gearbox. The implementation of this multifaceted approach is simple and not expensive. The results obtained are satisfactory. They can serve as a reliable automatic diagnosis by introducing a technical decision-making.

II. Mechanical Failures Signatures of the Gear Box Motor System via the Stator Current

A. Transfer of Mechanical Damage to the Stator Current

Careful exploration of the instantaneous stator current induction motor is a very significant contribution to the detection of mechanical defects in the training complex mechanical system engine – reducer. It has been proven in [18]–[20] that internal or external mechanical damage to the induction actuator oscillations cause the load torque which, consequently, will alter the variation of the stator current of the motor. The surface current distribution, is generally sinusoidal for an ideal machine, and will be phase modulated i_{to}(t) for an arbitrary phase:

$$i_{to}(t) = i_s(t) + i_s(t) = I_s \sin(\omega_s t) + I_r \sin(\omega_s t + m\cos(\omega_c t - \phi_A) - \phi_r) \quad (1)$$

where φ_A denotes the modulation phase angle.

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B. Stator Current Analysis Techniques Adopted for Diagnosis of Mechanical Defects in the Engine-Gearbox System

Fig. 1, Fig. 2 and Fig. 3 present principles of processed technical signal.

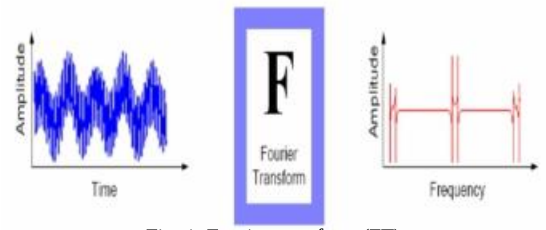

Fig. 1 Fourier transform (FT)

$$x(f) = \int_{-\infty}^{+\infty} X(f) \cdot e^{j2\pi ft} df \quad (2)$$

$$x(f) = \int_{-\infty}^{+\infty} x(t) \cdot e^{-j2\pi ft} dt \quad (3)$$

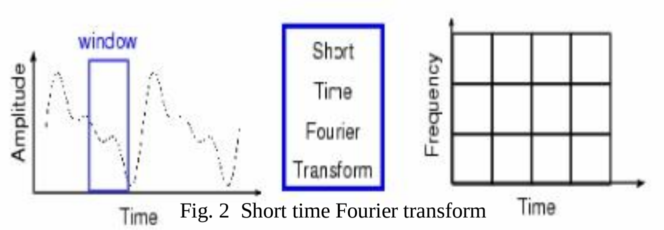

Fig. 2 Short time Fourier transform

$$STFT_x^w(\tau, f) = \int_t x(t) \cdot w^*(t-\tau) \cdot e^{-j2\pi ft} dt \quad (4)$$

x (t): represents the sampled time signal.
w (t): the time window of width and centered at τ which allows extracting a portion of signal.
w *: denotes the conjugate complex of w.

Fig. 3 Continuos wavelet transformer

$$CWT_x^{\psi}(\tau, s) = \frac{1}{\sqrt{|s|}} \cdot \int_t x(t) \cdot \psi^*\left(\frac{t-\tau}{s}\right) dt \quad (5)$$

τ : translation factor.
s: Scal factor; ψ (t): Mother wavelet.
$CWT_x^{\psi}(\tau, s)$: Wavelet coefficient; ψ^*: Complex conjugate of ψ.

Spectral analysis of the stator current is one of the methods that are mostly used and mostly established for the identification of signatures from frequency torque oscillations during the degraded operation of the electromechanical system. Frequency torque oscillations f_{osc} induce lateral components of stator current. Typically, the characteristic frequencies of mechanical defects are given by the following formula:

$$f_d = f_1 \{ k \pm n / p (1 - s)\} \quad (6)$$

where p: Pole pairs; s: The slip; f_1: Fundamental frequency (Hz); f_d: The fault characteristic frequency (Hz); k = 1, 3, 5 ... and n = 1, 2, 3…

This technique provides information on the quantities of existing frequency but not the time of their presence. It is not convenient for the treatment of the starting current of our system. In addition, the FFT analysis showed restrictions in the case of an assembly of several mechanical parts. Some elements of the system can be coupled in the spectrum and frequency components will be hidden. However, the STFT spectrogram and Gabor and the scalograms WCT of the induction motor of the feed stream may be both a complementary and an alternative to the traditional Fourier analysis. They help to make a clarification for the separation of close vibratory signatures which overlap in time and / or frequency [21]–[24].

The spectrogram of the STFT (Short Time Fourier Transform) also known as the Fourier transform sliding window rather exposes the spectral distribution of the surge current over time and which the colour corresponds to the energy of the signal. However, it is impossible to simultaneously obtain the temporal resolution and frequency because of the Heisenberg uncertainty principle. However, the simple evaluation of the spectrogram Gabor can act as a good alternative to the STFT spectrogram. The spectrogram Gabor estimates the frequency content of a signal and is as shown in equation (7) a signal from the time domain s (t), with the linear combination of elementary functions:

$$s(t) = \sum_{m=0}^{M-1} \sum_{n=0}^{N-1} c_{m,n} h_{m,n}(t) \quad (7)$$

where $h_{m,n}(t)$ is the elementary function of the time of frequency, $c_{m,n}$ are the Gabor coefficients. The Gabor transform calculates the coefficients $c_{m,n}$ for the signal s (t).

However, with the STFT, precision time and frequency are the same for high and low frequencies. These limitations of the STFT can be overcome by applying the technique of wavelet transform. CWT (Continuos Wavelet Transform) not only allows local analysis but, in addition, a variable temporal resolution.

III. Experimental Context

The experiment involved a test bed in Fig. 4 consisting essentially of a cage induction motor (3KW; 2p = 6; 960rpm; 220V / 380V; 12.5A / 7.2A) coupled to a gearbox 3-stage parallel gear and helical teeth right (Figure 1a) with Z_1 = 26 and Z_2 = 73 teeth.

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Fig. 4 Test bench of the electromechanical drive system engine – reducer

The measurement and processing of the current three-phase motor-induction system power to gear from the starting time were taken until its steady state for healthy and degraded operations. The test procedure was as follows:

- The first stage involved the measurement during the operation of the non-degraded system (healthy).
- The second stage relates to the damage due to the presence of an unbalance created by attaching a weight on the mechanical shaft of the induction motor.
- The third step was dealing with the damage by a pelting at angles of three adjacent dents of the dentured wheel Z_2.

The acquisition of signals for the diagnosis was carried out using a HAMEG507 oscilloscope connected to a current sensor. This unit allows the acquisition of the signal of 8 bits with a sampling frequency of between 1kHz and 2.5MHz. The acquisition of the stator current signal and its display on the PC screen, is made using the SP107E software and integrated capture card to the oscilloscope.

The data processing is done using the MATLAB software for signal analysis purposes.

IV. Experimental Results and Discussions

A. Motor-Reducer System in the Absence of any Voluntary Degradation

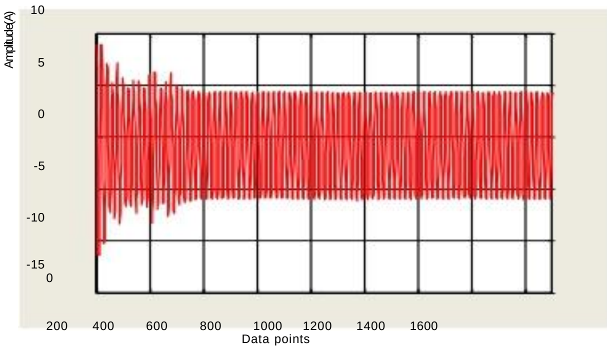
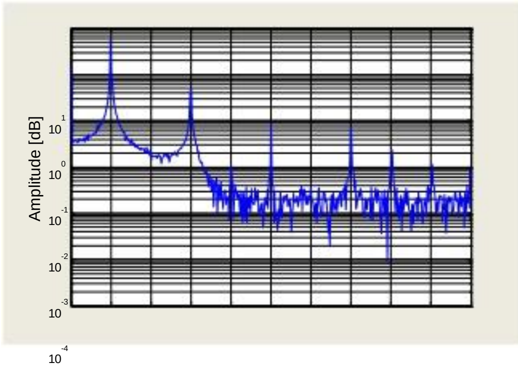


Fig. 5 Time significance of the stator current



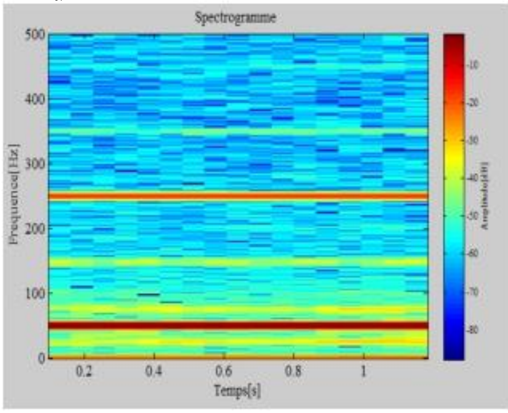


Fig. 7 STFT of healthy system

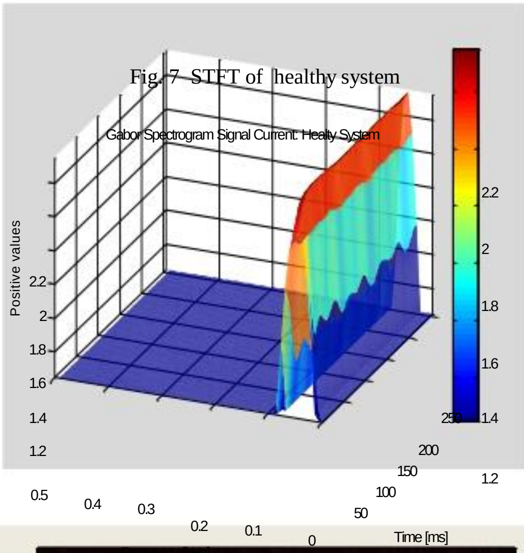


Fig. 8 Gabor spectrogram of healthy system

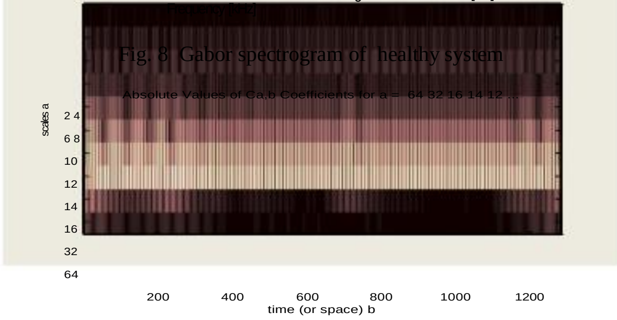


Fig. 9 CWT of healthy system

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The results from the treatment of transient stator current by applying the various conventional and advanced techniques when the engine – reducer system is not affected in any intentional damage (Healthy). This is primarily the characteristic of the feed stream Fig. 5 and its FFT in Fig. 6. Fig. 7, Fig. 8 and Fig. 9 present respectively the spectrogram of the STFT, the Gabor spectrogram and scalogram of CWT when healthy electromechanical system is starting up.

B. System Degraded Motor-Reducer Following an Unbalance

Fig. 10 includes the representation of the spectrogram, on the left the spectrum of the amplitude of the stator current and above its temporal characteristic. The spectrum obtained by applying the TF current amplitude reveals lateral stripes on both sides of the fundamental frequencies. $f_{imb} = f_s \pm 1f_r = 50 \pm 16.5$ to be 33.5Hz and 66.5Hz ; knowing that the vacuum speed measured during the tests is 990rpm ($f_r = 16.5$Hz). The time-frequency representation in 2D obtained through the spectrogram of the STFT current shows the appearance of frequency bands with bright red colors similar to f_{imb} frequency characteristics. $f_s = \pm 1f_r = 50 \pm 16.5$ to be 33.50Hz and 66.50Hz and the 3rd and 5th harmonics. On the colour scale of the spectrogram, the bright red colour indicates that the intensity of the energy at these frequencies is high. Compared to the spectrogram obtained for the current healthy state, reddish bands validate the signature of unbalance.

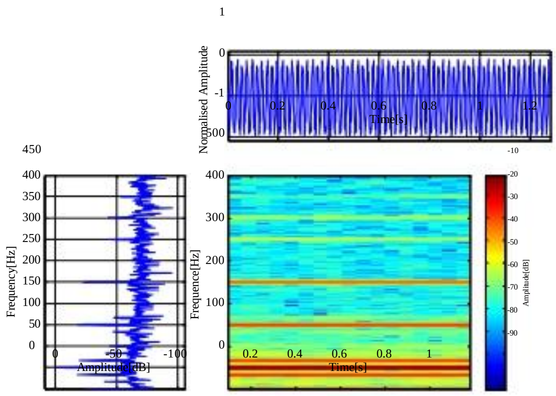

Fig. 10 Spectrogram of the system degraded motor - reducer following an unbalance

On the Gabor spectrogram in Fig. 11, highest peak succession cyclically every 50ms with substantially the same amplitudes. They change from yellow to bright red every blows caused by the passage of the mass of unbalance during rotation of the system.

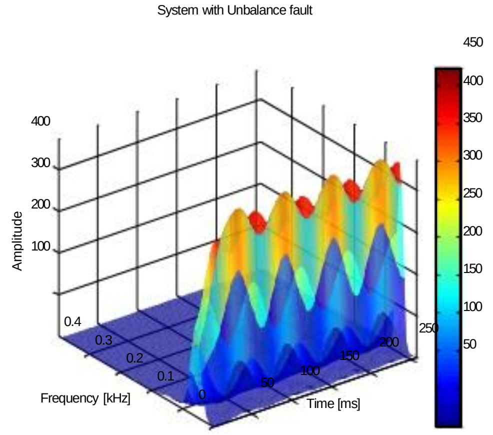

Fig. 11 Gabor spectrogram of the system degraded motor - reducer following an unbalance

Fig. 12 shows scalogram of CWT applied to the stator transient current. Interference (striations) on scales 16 and 32 for short period of time through the dynamic regime marks the onset of degradation of the electromechanical system. The intensity of the energy represented by the color scale justifies the importance of decibels due to vibrations introduced by the unbalance fault.

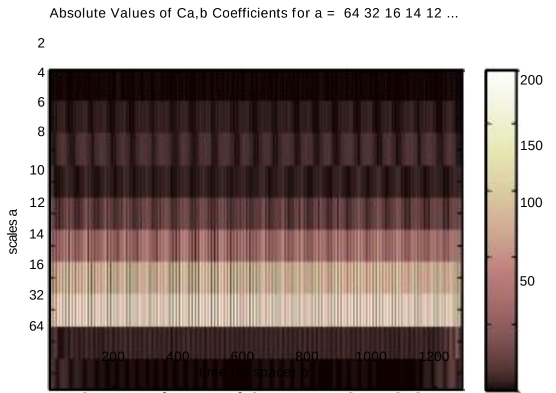

Fig. 12 Scalogram of CWT of the system degraded motor - reducer following an unbalance

C. The System Motor - Reducer Failed Following the partial wear of three adjacent teeth

The spectrogram of the STFT in Fig. 13 showed on both sides of the fundamental (50Hz) very narrow bands, coloured bright red. These bands correspond to frequencies $50 \pm n.f_{r2}$ with no $f_{r2} = 7.5$Hz. There is also the order harmonics 3 and 5. All these bands that emerge with remarkable decibels following the color scale (bright red) clearly indicate a deterioration of the denture.

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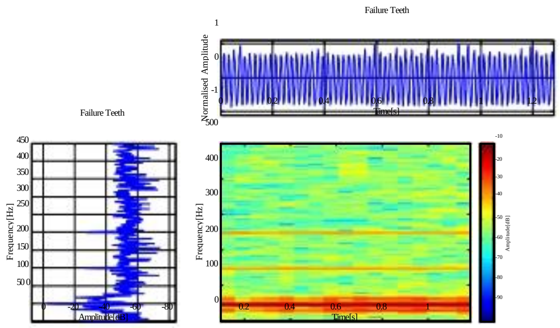

Fig. 13 Spectrogram of the faulty system motor-reducer due to wear of 3 teeth

The degradation of the three teeth of the gear is manifested by periodic shocks. The spectrogram in Fig. 14 show three highest peak of Gabor meaning the number of shocks in each contact 3 of teeth Z_2 with the toothing of the motor sprocket Z_1 during their rotation.

The degree of wear performed on the three teeth is not identical. For this, the attenuation of shock resulted in different degrees of decibel displayed by the colour scale.

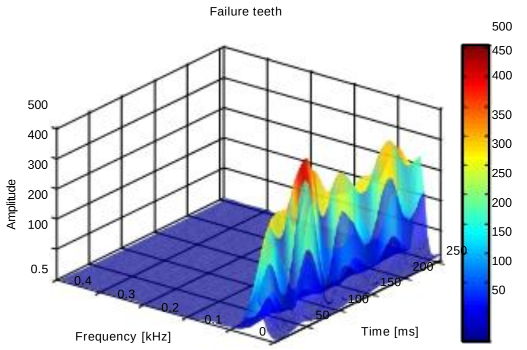

Fig. 14 Gabor spectrogram of the Faulty system motor-reducer due to wear of 3 teeth

The CTW Fig. 15 shows interference with brilliant colours with 16-32 scales and 64. They are the result of blows upon contact of 3 teeth Z_2 with those of Z_1 during the transitional process.

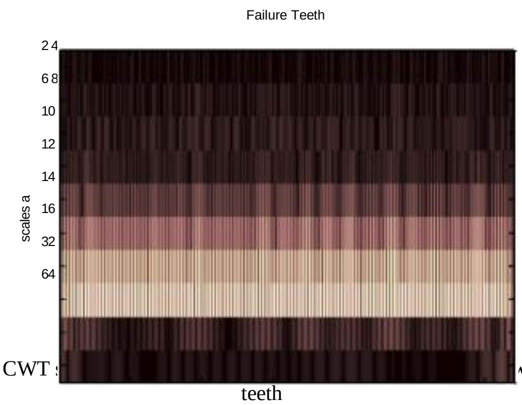

Fig. 15 CWT [illegible] wear of 3 teeth

V. Conclusion

The use of spectrograms of the STFC, Gabor and scalogram of CWT transient current is more complementary rather than competing with the performance analysis of classical Fourier transform (FFT) for the purpose of diagnosis and early detection of defects unbalance, wear of the dents of the gear wheel and motor combination affecting the basic transmission system induction coupled to a gear reducer. The experimental results obtained by the application of plural transformed stator current techniques allow us to decide firmly on the aforementioned mechanical damage.

Therefore, the STFC and CTW added to the FFT can be exploited as robust detection and monitoring tools very early single and multiple mechanical damage for complex systems based on induction motor. This study may help provide food for thought on the automation of diagnostic and predictive detection of multiple mechanical defects of electromechanical drive systems Motor Reducer variable speed currently increasingly spread in industry.

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