Experimental detection of defects in variable speed fan bearing using stator current monitoring

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Abstract

This article presents an experimental contribution to detect and diagnose mechanical faults, including bearing faults, which are the cause of most faults in single or variable speed fan motor systems. For this, we proceed to the extraction of the characteristics appearing in the supply current signal of the diagnostic system, by the application of three complementary approaches. During our experimental study, we found that one of the best methods for diagnosing single or multiple mechanical faults in induction motor systems is MCSA (Motors Current Signature Analysis), to which we applied the FFT (Fast Fourier transform) spectral analysis completed by the park vector approach orbital (OPVA) applied to the components of the current stator vector. In order to confirm the reliability of our diagnosis, these two approaches have been supplemented by the Gabor spectrogram (STFT). The practical validation of this plural methodology, in the case of a bearing degradation, was carried out on a variable speed fan motor of 0.25 HP. The results obtained by this fault detection technique are satisfactory and interesting because they make it possible to anticipate breakdowns and, therefore, to program and control the maintenance costs of industrial systems without affecting production.

Keywords Fan motor · Bearing defects · Motor current signature analysis · FFT · STFT · Gabor spectrogram

1 Introduction

The monitoring of electromechanical systems composed of an induction motor and a fan in an industrial environment is a fundamental task, considering their importance in the animation of technological processes [1–3]. Following mechanical alterations (loss of fin, erosion or fouling of the blades, etc.), these systems are often subject to unbalance faults which are generally at the origin of the deterioration of the bearings. In the presence of these mechanical faults, significant pumping of the supply current is observed, as well as vibrations and torque fluctuations which have very critical consequences for the safety of the equipment and the personnel.

The fact of detecting and correctly characterizing these failures at an early stage is necessary to anticipate the definitive shutdown of the system, whose cost has a significant financial impact. Vibration analysis is one of the best diagnostic methods especially for the study of mechanical failures on rotating machines [4]. Nevertheless, these approaches have shown their limits when it comes to defects inducing torque variations or incipient defects that are almost imperceptible. To accurately extract information about these failures, research was particularly directed to the MCSA (Motors Current Signature Analysis) [5–9].

The contribution to this work lies primarily in the simultaneous application of the FFT, OPVA and STFT. Compared to other studies, our goal is to combine the advantages of

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spectral, orbital and temporal signatures in order to allow reliable detection and interpretation of bearing defects in a variable speed fan motor system. Moreover, besides the fact of requiring simple and low-cost equipment, this set of signatures has the advantage of being able to be used by non-expert operators. [10], [11].

The results obtained highlight the added value provided by this technique compared to other detection techniques. This is because it is fast, easy to interpret and does not require a large budget for online maintenance. This technique can also serve as a basis for establishing an automatic approach by adding a decision-making tool that would allow a reliable diagnosis and improve the management of system maintenance.

2 Structure of system

It is known that any air-gap eccentricity products anomalies in the air-gap flux density, which is reflected on the stator current. In the case of a mechanical damage, the characteristic frequencies are modulated by the electrical supply frequency at a predictable frequency [12–16].

$$f_d = (f_s \pm m \cdot f_r) \quad (1)$$

f_d : characteristic frequency of the defect; f_s : frequency of the supply current; f_r : rotation frequency; $m = 1, 2, 3 \dots$

In the case of bearings, Schoen et al., [17] show that the relation between the vibration of the bearing and the spectrum of the stator current is expressed by the following relation:

$$f_{bng} = (f_s \pm m \cdot f_v) \quad (2)$$

Where: f_s is the electrical supply frequency, f_v is one of the fault frequencies defined by Eqs. (3) and (5) and $m = 1, 2, 3 \dots$

On the other hand, Blodt [18] suggests a characteristic expression of the ball defect defined as follows:

$$f_{bng} = (f_s \pm f_{cage} \pm k \cdot f_{ball}) \quad (3)$$

Approximations to estimate the frequencies of the defects have been proposed [19], [20]:

$$f_{ball} = f_r \cdot (0.2 - 1.2/N_b) \quad (4)$$

$$f_{ball} = f_r \cdot (0.5 - 1.2/N_b) \quad (5)$$

2.1 Signature of the direct component of the Park vector

The spectrum approach via the FFT of the direct component of the Park vector gives a more significant spectrum than that obtained by the conventional spectral analysis (FFT) of the induction motor and records a cumbersome representation of the spectra of the three phase currents (I_a, I_b, I_c) [21], [22].

$$[I_{0dq}]_i = p(\theta) [I_{abc}]_i \quad (6)$$

When Concordia transform is applied to the mains, (d) and (q) components of the stator current are obtained. This transform is expressed by:

$$\begin{cases} x_d(t) = \sqrt{\frac{2}{3}} x_a(t) - \frac{1}{\sqrt{6}} x_b(t) - \frac{1}{\sqrt{6}} x_c(t) \\ x_q(t) = \frac{1}{\sqrt{2}} x_b(t) - \frac{1}{\sqrt{2}} x_c(t) \end{cases} \quad (7)$$

However, this FFT technique of (I_d) may have limits because some elements of the system can couple in the spectrum and their frequency components will be masked, which will make the different defects difficult to isolate.

2.2 Orbital signatures of the Park vector

Generally, when the system is operating under ideal conditions, this approach gives a circular representation. This orbit will serve as a reference for detecting degradations that can affect the engine by monitoring deviations and degree of deformation of the obtained patterns.

$$x_s(t) = \sqrt{x_d^2(t) + x_q^2(t)} \quad (8)$$

2.3 Signatures of the Gabor transform spectrogram (TG) carried by the signal

The Gabor spectrogram is used to estimate the frequency content of a signal. It represents, as indicated on Eq. (9), a signal of the time domain $s(t)$ with the linear combination of elementary functions [23]:

$$s(t) = \sum_{m=0}^{m-1} \sum_{n=0}^{n-1} c_{m,n} h_{m,n}(t) \quad (9)$$

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

The idea of the spectrogram of the Gabor transform is simple and can be a good alternative because it offers better time–frequency resolution (TFR) for diagnosis and predictive faults detection.

The exploitation of OPVA and GT (Gabor Transform) can complement the spectral analysis of the direct vector component of the stator current. The results of these simultaneously applied approaches help, on the one hand, to provide a solution for the separation of signatures of near defects overlapping in time and/or frequency and, on the other hand, to make detection and diagnosis of multiple mechanical degradations affecting the variable speed electromechanical system more reliable. We have carried out an experimental validation, on a test bench, of these complementary techniques for analyzing the stator current signatures absorbed by the variable speed fan-motor system, for the healthy and degraded state.

3 Experimental context

The experiment required a test bench consisting essentially of an asynchronous cage motor linked to a fan V63L1 N°3727578; $P = 180$ W; 3 ph; 2800RPM; Δ/Y 220/380 V; 0.85A/0.5A; It is equipped with ball bearings whose characteristics: number of balls = 8; $D = 3.5$ cm (Fig. 1).

We proceeded by acquiring the current signal of the fan motor for different speeds using Altivar 28, during operation in the healthy state and in the event of voluntary degradation of the bearing (balls and cages), caused by a drill used to create micro cracks and breaks.

For the acquisition of the signal, we use a current sensor connected to a HAMEG507 oscilloscope which allows the acquisition of an 8 bit signal with a sampling frequency between 1 kHz and 2.5 MHz. The signal is transferred to the

computer using SP107 E software and data processing is done using MATLAB software for signal analysis.

Lastly, the results of FFT, OPVA and STFT obtained from operations on healthy and degraded systems, at different speeds, are compared in order to detect and evaluate the degree of failure which results in amplitudes variations of the corresponding frequencies.

4 Expérimental results

4.1 Approaches of the park vector spectrum

The system has been previously tested in the healthy state during its operation for the different selected speeds (Fig. 2), in order to use it as a reference for the cases of operation in the presence of degradations (Fig. 3).

4.2 Orbital approaches of the Park vector: $I_d = f(I_q)$ for different speeds

Figure 4 represents the orbits generated by the Park vector approach (OPVA) of the current during the variable speed operation of the fan-motor, in the presence of bearing defect. The orbits are distinguished above all by the ellipsoid of revolution (lengthened or narrowed) according to the ratio of major and minor axes where: $k_a = R/r$, signifying the presence of degradation (Fig. 5).

4.3 Spectrogram approaches of Gabor (STFT)

Figure 6 shows the spectrogram of the healthy fan-motor which will serve us as a reference for the comparison with the degraded case (Fig. 7), in order to detect and confirm the presence of the fault by analyzing the signatures of the stator current absorbed by the induction motor during variable speed operation.

5 Discussions

5.1 Approaches of the Park vector spectrum

Figure 2 illustrates the spectrum (FFT) of the I_d component of the Park vector of the current subjected to the speeds of 1400RPM (Fig. 2a), 2000RPM (Fig. 2b) and 2800RPM (Fig. 2c).

Figure 3 represents, respectively, the spectra of the I_d component of the Park vector (or Concordia) of the current as a result of the deterioration of two balls and a portion of the cage of the fan-motor bearing operating at the following speeds: 1400 RPM (Fig. 3a), 2000RPM (Fig. 3b) and 2800RPM (Fig. 3c).

Fig. 1 Test bench of the fan-motor system

Fig. 2 Spectrum of Park vector component of healthy fan-motor system current: **a** 1400 RPM; **b** 2000 RPM; **c** 2800 RPM

The results obtained are compared and analyzed in order to detect faults. We notice a remarkable increase in the amplitudes of the components of the current vector in the case of the degraded engine as soon as the speed is reduced. Table 1 summarizes the results expressed by the characteristic frequencies which represent the signatures of the defect.

Fig. 3 Spectrum of the Park vector component I_d of the failed fan-motor system current: **a** 1400 RPM; **b** 2000 RPM; **c** 2800 RPM

Table 1 Signals of Bearing fault affecting the variable speed fan-motor

Current supply	Rotation Speeds	F_{balls} defect	F_{cages} defect
50 Hz	2800 RPM	36.32 Hz; 98.99 Hz 96.66 Hz; 103.97 Hz 136.32 Hz; 203.97 Hz	31.34 Hz 68.66 Hz
35 Hz	2000 RPM	26.6 Hz; 68.33 Hz 70 Hz; 74.11 Hz 145.89 Hz	21.67 Hz 48.33 Hz
25 Hz	1400 RPM	28.16 Hz; 48.33 Hz 48.38 Hz; 51.96 Hz 78.16 Hz; 101.96 Hz	15.67 Hz 34.33 Hz

Fig. 4 Patterns obtained for the healthy fan-motor system **Fig. 5** Bearing failure at speeds: 1400 RPM **(a)**; 2000 RPM **(b)**; 2800 RPM **(c)**

Fig. 6 Spectrogram for the healthy case of fan-motor

5.2 Orbital approaches of the Park vector: $I_d = f(I_q)$ for different speeds

Figure 4 shows that under ideal conditions and when the system operates in the absence of degradation (healthy), the pattern obtained is an almost perfect circle $k_a = 1$, since the amplitudes of the components of the current vector are equal $I_d = I_q$.

Figure 5 shows that the presence of bearing defects is manifested by the deformation of the pattern of Park current vector; this deformation provides information on the severity of the degradation because it is directly proportional to the thickness of the ring. We note in our case that the ellipse tends towards a narrowing accompanied by a thickening of its ring, which indicates the presence of degradation. The variation of the speed is clearly indicated by the displacement of the axes and the division of the orbits.

5.3 Spectrogram approaches of Gabor (STFT)

By comparison with the spectrogram of the healthy fan-motor (Figs. 6,7a) which illustrates the spectrogram in the case of the degradation of two balls and the corresponding part of the bearing cage, when the engine is running at 1400 RPM, we detect the presence of the defect which results in a shock every 41.6 ms with amplitude peaks of 20 dB. At 2000 RPM (Fig. 7b), we see the increase in the number of shocks with a continuous noise of 20 dB which

Fig. 7 Bearing failure at speeds: 1400 RPM (a); 2000 RPM (b); 2800 RPM (c)

Fig. 8 Diagnosis flowchart

becomes unstable and oscillating between 16 and 20 dB when the fan passes at 2800 RPM (Fig. 7c).

5.4 Diagnosis flowchart

The flowchart shows the steps taken to diagnose mechanical degradations of the variable speed fan-motor system (Fig. 8). Confirmation or denial of degradation and identification of its nature are made by the successive application of the three approaches.

6 Conclusion and future directions

This article focused on an experimental study conducted on the diagnosis and detection of bearing defects of the variable speed fan-motor system, using the simultaneous application of the FFT of the real component of the Park vector, OPVA and STFT Gabor.

Current signatures through this pluralistic approach do not compete with the performance of conventional

Fourier analysis but are rather complementary for the early detection of bearing degradation.

The experimental results obtained by this multiple technique are satisfactory. They provided us with a predictive detection of the most widespread mechanical defect affecting the different variable speed motor systems which is the bearing defect.

In the future, we plan to explore the application of this technique in several directions. These results can contribute to a reflection on the implementation of an automated system capable of providing a reliable diagnosis and maintenance management in case of mechanical or electrical failure, single or multiple, affecting industrial systems.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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