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Baptiste Trajin, Jérémie Regnier, Jean Faucher. Bearing fault detection improvement using several stator current measurements in asynchronous drives. International Conference on Condition Monitoring and Diagnosis (CMD 2010), Sep 2010, Tokyo, Japan. pp.0. hal-02094382

HAL Id: hal-02094382

<https://hal.science/hal-02094382>

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To cite this version:

Trajin, Baptiste and Regnier, Jérémie and Faucher, Jean
Bearing fault detection improvement using several stator
current measurements in asynchronous drives. (2010) In:
International Conference on Condition Monitoring and
Diagnosis (CMD 2010), 6 September 2010 - 10 September
2010 (Tokyo, Japan). (Unpublished)

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Bearing Fault Detection Improvement Using Several Stator Current Measurements In Asynchronous Drives

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Abstract—This paper focuses on rolling bearings monitoring in induction motor, based on stator current measurements. Bearing defects induce slight load torque oscillations and then, specific fault sideband harmonics on stator currents. As stator current fault components are also of small amplitude, signal to noise ratio has to be considered. In order to implement an efficient automatic detection scheme of frequency fault components, based on energy extraction in the frequency domain, the signal to noise ratio of stator currents has to be increased. Using convolution theory, it is demonstrated that the use of several stator currents measurements allows to increase the signal to noise ratio and reduce the spectral estimation variance. Then, an intercorrelation of several stator currents is used to correlate spectral signatures. This method is assumed to be the most efficient one to improve the fault harmonics detection. An automatic detection scheme is proposed, based on the use of one or more stator current signals. Consequently, the advantages of taking into account more than one stator current measurements are analysed using simulation results and experimental measurements.

Keywords: *Cross-correlation; Harmonic detection; Power spectral density; Bearing faults*

I. INTRODUCTION

Faulty operations could appear during the lifetime of electrical drives. To improve the availability and reliability of the drives, a condition monitoring could be implemented to favour the predictive maintenance. Many studies deal with the detection of rolling bearing defects using stator current monitoring [1]. However, stator spectral components induced by bearing faults are hardly detectable using automatic detection scheme. Consequently, some methods are used to improve performance of monitoring applications [2].

This paper deals with the use of cross-correlation of two measurements to increase the detection capability of stator current harmonics due to bearing defects. First of all, in section II, a theoretical analysis recalls statistic distribution of spectral noise and signal to noise ratio considerations. In section III, it is demonstrated that cross-correlation allows to increase the SNR of noisy signals. Finally, section IV validates the proposed approach with the detection of spectral components on simulated signals and experimental measurements dedicated to bearing faults detection.

II. THEORETICAL ANALYSIS

In an asynchronous drive, stator current measurements may be considered, with simplicity, as the sum of a deterministic signal (real stator current) and a random one (measurement and electromagnetic noises).

A. Autocorrelation and Cross-correlation Functions

The autocorrelation and cross-correlation functions, respectively $R_x(\tau)$ and $R_{xy}(\tau)$, are defined for finite energy signals using the convolution product $*$ in (1) and (2) and for finite power signals using the mathematical expectancy E in (3) and (4) [3]

$$R_x(\tau) = x(\tau) * x(-\tau) = \int_{-\infty}^{+\infty} x(t)x(t-\tau)dt \quad (1)$$

$$R_{xy}(\tau) = x(\tau) * y(-\tau) = \int_{-\infty}^{+\infty} x(t)y(t-\tau)dt \quad (2)$$

$$R_x(\tau) = E[x(t)x(t-\tau)] \quad (3)$$

$$R_{xy}(\tau) = E[x(t)y(t-\tau)] \quad (4)$$

Consider two signals $x(t)$ and $y(t)$, expressed as sums of sinusoidal components with an additive white noise. It can be demonstrated that, with an approximation, if $x(t)$ and $y(t)$ have the same frequency contents, the cross-correlation function has also the same frequency content [4].

B. Frequency Analysis of Random Variables

The frequency content of a noisy signal $x(t)$ is estimated through the Power Spectral Density (PSD) [3], defined as the Fourier Transform (FT), along the frequency ν , of the autocorrelation function (5)

$$PSD_x(\nu) = FT_\nu\{R_x(\tau)\} = \int_{-\infty}^{+\infty} R_x(\tau)e^{-j2\pi\nu\tau} d\tau \quad (5)$$

The PSD of a zero-mean white gaussian noise with a σ_n^2 variance is theoretically a constant equal to the noise power $P_n = \sigma_n^2$ [3]. Let a sampled zero-mean white gaussian noise,

considered as a random variable X , following a normal distribution $N(0, \sigma_n^2)$, with a Probability Density Function (PDF) $\phi(x)$ expressed in (6). It is demonstrated in [5] that the PDF $\phi_\nu(x)$ of the PSD of the random variable X is a χ^2 function with k degrees of freedom (7), where Γ is the Gamma function [6].

$$\phi(x) = \frac{1}{\sqrt{2\pi\sigma_n^2}} e^{-\frac{x^2}{2\sigma_n^2}} \quad (6)$$

$$\phi_\nu(x, k) = \frac{1}{\sigma_n^2 2^{\frac{k}{2}-1} \Gamma\left(\frac{k}{2}\right)} \left(\frac{2x}{\sigma_n^2}\right)^{\frac{k}{2}-1} e^{-\frac{x}{\sigma_n^2}} \quad (7)$$

As the PSD is estimated through the Welch periodogram with a rectangular window, without meaning or zero-padding, there is $k=2$. Thus, considering properties of Gamma functions [6], the PSD of a zero-mean white gaussian noise has a σ_n^2 mean and a $(\sigma_n^2)^2$ variance.

C. Signal to Noise Ratio

Signal-to-noise ratio (SNR) is defined as the power ratio between meaningful information of a signal and the background noise (unwanted signal) [7]. The meaningful information of a signal is generally unknown. An alternative definition of the SNR is based on the power of the measured signal P_s and the power of the background noise P_n (8), where P_i is the power of the meaningful information of the signal

$$SNR = 10 \log_{10} \left(\frac{P_i}{P_n} \right) \approx 10 \log_{10} \left(\frac{P_s}{P_n} - 1 \right). \quad (8)$$

D. Evaluation of SNR

Consider a signal $x(t)$ composed of an harmonic of amplitude A at frequency f_i with an additive zero-mean white gaussian noise $n(t)$ of power $P_n = \sigma_n^2$, such as given in (9)

$$x(t) = A \cos(2\pi f_i t) + n(t). \quad (9)$$

As it can be seen in the PSD of $x(t)$ in Fig. 1, with $A=0.1$, $N=10^5$, $\sigma_n^2=0.02$ and $f_i=50\text{Hz}$, the frequency component at f_i has an amplitude equal to $NA^2/4 + \sigma_n^2$, where N is the number of samples of $x(t)$ considered for the PSD estimation. As the power of the meaningful information part of $x(t)$ is well-known ($P_i=A^2/2$), a relation is set between the power P_{crest} of the component at frequency f_i , the power of the meaningful information and the noise power (10)

$$P_{crest} = \frac{N}{2} P_i + P_n. \quad (10)$$

Using (8) and (10), the SNR of $x(t)$ is estimated through its PSD (11)

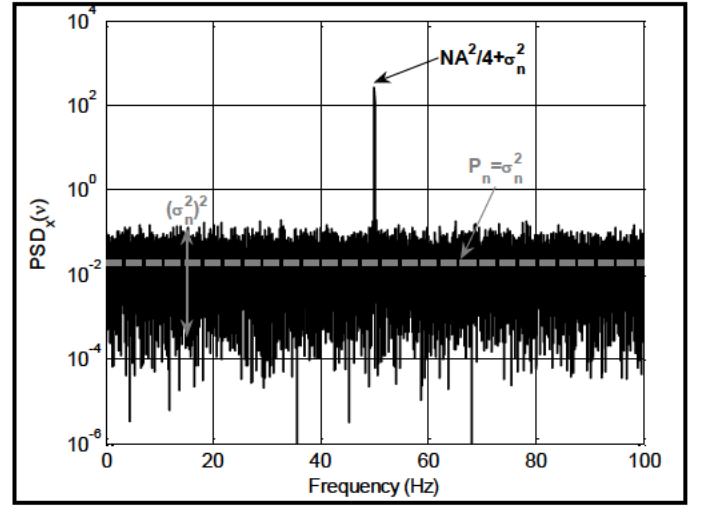


Figure 1. PSD of a monocomponent signal with additive noise

$$SNR = 10 \log_{10} \left[\frac{2(P_{crest} - P_n)}{NP_n} \right]. \quad (11)$$

Consequently, the SNR of $x(t)$ in (9) is evaluated in (12), using given parameters

$$SNR_x = 10 \log_{10} \left[\frac{A^2}{2\sigma_n^2} \right] \approx -6.02 \text{dB}. \quad (12)$$

III. SNR IMPROVEMENT

A. PSD of Cross-correlation Function

Consider two signals $x(t)$ and $y(t)$ (13), with the same frequency component, a phase shift $\psi = -2\pi/3$ and additive zero-mean white gaussian noises, respectively $n_x(t)$ and $n_y(t)$, following a normal distribution $N(0, \sigma_n^2)$

$$\begin{cases} x(t) = A \cos(2\pi f_i t) + n_x(t) \\ y(t) = A \cos(2\pi f_i t + \psi) + n_y(t) \end{cases} \quad (13)$$

Using the definition of the PSD in (5), autocorrelation and cross-correlation functions definitions, it is demonstrated that the PSD of the cross-correlation of $x(t)$ and $y(t)$ expresses as the product between PSD of $x(t)$ and $y(t)$ (14)

$$\begin{aligned} PSD_{R_{xy}}(\nu) &= FT_\nu \{ R_{R_{xy}}(\tau) \} \\ &= FT_\nu \{ R_x(\tau) \} FT_\nu \{ R_y(\tau) \} \\ &= PSD_x(\nu) PSD_y(\nu) \end{aligned} \quad (14)$$

B. Cross-correlation of White Gaussian Noises

Now considering two sampled independent zero-mean white gaussian noises, considered as random variables X and Y , following a normal distribution $N(0, \sigma_n^2)$, it is clear that the PSD of the gaussian noises are also two independent random

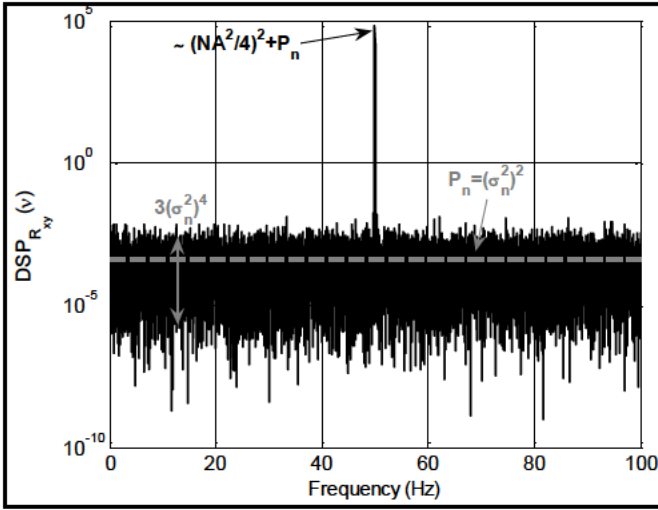


Figure 2. PSD of cross-correlation of two monocomponent signals with additive noise

variables with the properties given in II.B (7). As two independent variables, the product of the PSD of the two noises has a mean equal to $(\sigma_n^2)^2$. Moreover, it can be demonstrated that the variance of the product expresses as $3(\sigma_n^2)^4$ [8].

Using (14) and previous results, the power of the component at frequency f_1 is estimated to $P_{crest} = (NA^2/4)^2 + (\sigma_n^2)^2$. Fig. 2 depicts the PSD of the cross-correlation of $x(t)$ and $y(t)$ given in (13), with $A=0.1$, $N=10^5$, $\sigma_n^2=0.02$ and $f_1=50\text{Hz}$.

C. SNR Improvement using Cross-correlation

Results of section II.D and III.B are recalled in Table I. Moreover, corresponding SNR evaluated through the PSD are given. It can be clearly seen in Table I that, if (15) is satisfied by the number of points N of the sampled signals, the PSD of the cross-correlation of two monocomponent signals with additive zero-mean white noise allows to improve the SNR

$$N > \frac{4\sigma_n^2}{A^2}. \quad (15)$$

One can note that, in order to evaluate the advantages of the PSD of cross-correlation of two signals with similar frequency contents for spectral harmonic detection, the notions of SNR and spectral noise variance have to be extended to limited spectral bandwidth analysis [9].

IV. IMPROVEMENT OF SPECTRAL HARMONIC DETECTION

A. Simulated Signals

Simulated sampled signals such as those given in (13) are considered, with $A=0.01$ or $A=0$ (no harmonic), $\sigma_n^2=0.02$, $f_1=50\text{Hz}$, $\psi=-2\pi/3$ and $N=10^5$ samples. A spectral frequency range centered on f_1 , with a bandwidth $\Delta f=10\text{Hz}$ is chosen. It can be asserted that, for sampled signals considered as ergodic processes, these are weakly stationary with a finite energy [8]. Then, the PSD content is comparable to spectral energy.

TABLE I. EVALUATION OF SNR USING PSD

	$PSD_x(\nu)$	$PSD_{Rxy}(\nu)$
$P_{crest}-P_n$	$NA^2/4$	$(NA^2/4)^2$
P_n	σ_n^2	$(\sigma_n^2)^2$
Spectral noise variance	$(\sigma_n^2)^2$	$3(\sigma_n^2)^4$
SNR	$10 \log_{10} \left[\frac{A^2}{2\sigma_n^2} \right]$	$10 \log_{10} \left[\frac{NA^4}{8(\sigma_n^2)^2} \right]$

TABLE II. PERFORMANCES OF SPECTRAL HARMONIC DETECTOR ON SYNTHESIZED SIGNALS

	A=0		A=0.01	
	PSD_x	PSD_{Rxy}	PSD_x	PSD_{Rxy}
M_{detec}	≈ 0	≈ 0	12.3	1080
σ_{detec}	3.1	4.57	3.39	187.6
σ_{detec}/M_{detec}			0.27	0.17

Consequently, the spectral energy is extracted in the specified band using the sum of the PSD terms. Then, to built a detector, the spectral energy is compared to a referenced one obtained with $A=0$, using a relative difference expressed in %. Finally, in order to statistically characterize the detector, 100 values of the detector are computed for $A=0$ and $A=0.01$.

The detector values are then compared for $A=0$, $A=0.01$ and for the PSD of $x(t)$ and the PSD of the cross-correlation of $x(t)$ and $y(t)$, using the mean M_{detec} and the standard deviation σ_{detec} of detectors. Results are summarized in Table II. It can be seen that the performances of the detector increase using the PSD of the cross-correlation of two signals. Indeed, the confidence rate of the detector increases with the use of cross-correlation (the ratio σ_{detec}/M_{detec} decreases). In this case, the detector principle is similar to a Nuttall detector [10].

B. Experimental Setup and Effects of Bearing Faults

6208-type bearings are modified using electro-erosion to create an outer or inner race 3mm-large single point defect comparable to the effect of spalling due to a severe ineffective lubrication [11]. Thus, faulty bearings are mounted in a 3-phases, two-pole-pair, 5.5kW induction machine supplied by a variable frequency inverter. An acquisition board is used to sample the stator currents. Characteristic frequencies of faulty bearings in the vibration spectrum are theoretically well known [12]. Moreover, low frequency harmonics due to defects could appear as combinations of characteristic and mechanical rotating frequencies [13]. All theoretical combinations do not appear and the frequency content of mechanical and electrical variables cannot be theoretically predicted. As a consequence, the detection of bearing faults has to take into account the stochastic nature of fault harmonics.

Previous studies on mechanical failures in induction motors have shown that load torque oscillations appear with bearing faults. Moreover, these oscillations induce phase modulations (PM) on stator current [14]. Considering that load torque is

composed of a constant plus a sum of n slight harmonics of frequencies f_n and amplitudes Γ_n , the Fourier transform of the stator current $i(t)$ can be approximated by (16), where I_s is the rms value of stator current, I_r is the rms value of rotor current, f_s is the fundamental frequency, β_n is the PM index depending on Γ_n and f_n , and δ is the Dirac function [2]

$$|FT_v\{i(t)\}| = \sqrt{2}(I_s + I_r)\delta(v - f_s) + \sqrt{2}I_r \sum_n \frac{\beta_n}{2} \delta(v - (f_s \pm f_n)). \quad (16)$$

C. Stator Current Indicator

The stator current detector for bearing faults S is defined by extracting energies in the PSD of measurements, on frequency ranges corresponding to the sideband components at $f_s \pm n f_{def}$ where f_{def} is either the inner or the outer theoretical mechanical fault frequency [13]. The proposed indicator takes into account the probabilistic nature of stator current harmonics due to bearing defects. This allows to consider the possible appearance of numerous harmonics on stator currents related to bearing faults by analysing a global energy increase in frequency ranges. Thus, the frequency ranges are extended to include modulations linked to the cage and mechanical rotational frequencies [15]. Chosen frequency ranges are given in (17) where $n \in [1;5]$,

$$\begin{cases} |f_s \pm [n f_{def} - f_c; n f_{def} + f_c] \\ |f_s \pm [n f_{def} - f_r - f_c; n f_{def} - f_r + f_c] \\ |f_s \pm [n f_{def} + f_r - f_c; n f_{def} + f_r + f_c] \end{cases} \quad (17)$$

Then, the proposed indicator uses the relative error of energy between the current spectrum in faulty and healthy cases in the specified frequency ranges. Thus, the relative errors of energy extracted from frequency ranges are added in order to obtain a unique value considered as the detector value S [15].

As stator currents theoretically have identical frequency contents plus uncorrelated zero-mean white Gaussian noise, the cross-correlation of two measurements can be applied to improve the detection of harmonics due to bearing faults. Thus, the indicator S is first applied on one stator current (PSD_{i1}) and then on the cross-correlation of two synchronised measurements (PSD_{Ri1i2}). Ten values of S are computed in each case with a faulty bearing mounted in the asynchronous drive. Mean M_s and standard deviation σ_s of detectors are given in Table III. It can be clearly seen that the detection efficiency is improved using the PSD of the cross-correlation of two measurements due to an increase of the M_s . Moreover, the confidence rate of the detection scheme also increases due to a decrease of the ratio σ_s/M_s .

V. CONCLUSION

In this paper, the cross-correlation of two noisy signals with similar frequency content has been presented. Spectral properties of white Gaussian noise and cross-correlation of white Gaussian noises have been recalled. Then, SNR

TABLE III. BEARING FAULT DETECTOR

	PSD _{i1}	PSD _{Ri1i2}
M_s	277.6	1035.8
σ_s	249.8	850.02
σ_s/M_s	0.899	0.8206

properties of noisy signals have been introduced. It has been shown that the use of two signals with the same frequency content plus uncorrelated noises allows to improve the SNR and consequently the detection of harmonics using spectral energy extraction. This method has been tested on simulated signals. Finally, a detection scheme has been proposed to improve the efficiency of the detection of bearing faults using the PSD of the cross-correlation of two stator currents using spectral energy extraction.

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