Conditioning of a statistical indicator for the detection of an asynchronous machine rotor faults

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Received 21 December 2011, Accepted 23 June 2012

Abstract – In this paper, the cyclostationary characteristics of electrical signals will be exploited in order to detect the rotor faults of an asynchronous machine. These defects are the most complex in terms of detection since they interact with the 50 Hz carrier with a weak band occupied in frequency. The testing ground used includes an industrial three-phase wound rotor asynchronous motor of 400 V, 6.2 A, 50 Hz, 3 kW, 1385 rpm characteristics. The rotor fault has been carried out by adding an extra 40 mΩ resistance on one of the rotor phases (i.e. 10% of the rotor resistance value per phase, $R_r = 0.4 \Omega$). From the stator voltage and current acquisition, and by application of the Time Synchronous Averaging (TSA) method to the stator current, the electrical signal will be conditioned in order to obtain a sensitive indicator allowing to easily distinguish the healthy cases from defective ones.

Key words: Cyclostationarity / time synchronous averaging (TSA) / monitoring / rotor fault / asynchronous motor

Résumé – Conditionnement d'un indicateur statistique pour la détection de défauts rotoriques d'une machine asynchrone. Dans cet article, les caractéristiques cyclostationnaires des signaux électriques vont être exploitées pour détecter les défauts rotoriques d'une machine asynchrone. Ces derniers, sont les plus complexes au niveau de la détection car ils interagissent avec la porteuse à 50 Hz avec une faible bande occupée en fréquence. Le banc d'essai utilisé comprend un moteur asynchrone triphasé industriel à rotor bobiné, de caractéristiques 400 V, 6,2 A, 50 Hz, 3 kW, 1385 tr.min⁻¹ et le défaut rotorique est réalisé par adjonction d'une résistance additionnelle de 40 mΩ sur une des phases du rotor (soit 10 % de la valeur de la résistance rotorique par phase $R_r = 0,4 \Omega$). À partir de l'acquisition des signaux électriques (tension et courant) et par application de la méthode de Moyennage Synchrone (TSA : Time Synchronous Averaging) au courant statorique, le signal électrique sera conditionné afin d'obtenir un indicateur sensible permettant de distinguer aisément les cas sain et défectueux de la machine.

Mots clés : Cyclostationnarité / moyennage synchrone / surveillance / défaut rotorique / moteur asynchrone

1 Introduction

The electrical drives using asynchronous machines are very common within industrial applications due to their low costs, high performance and robustness. However, there are various reasons, related to the stator or rotor, which can sometimes affect the well-functioning of

these machines [1–3]. The appearance of a fault in the drive modifies its operation, which affects its performance. There are mainly two approaches for the monitoring of the electrical-drive system: the mechanic's, based on the vibration, speed and torque measures and the electro-technician's, based on the current and voltage measures.

Within a predictive maintenance framework, the proposed method is dedicated to the monitoring of asynchronous machines based on a statistical approach by

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Nomenclature

f_{samp}	(Hz)	Sampling rate (25.6 kHz in this paper)
$I_{\text{res}}(t)$	(A)	Residual current
I_{resRMS}	(A)	Residual current RMS
$I_s(t)$	(A)	Stator current
$I_{\text{savg}}(t)$	(A)	Synchronous averaged current
$I_{\text{sh}}(t)$	(A)	Stator-current harmonic component
$I_{\text{smec}}(t)$	(A)	Mechanical-structure-related stator current
$I_{\text{srand}}(t)$	(A)	Stator-current random component
I_{sRMS}	(A)	Stator current RMS
N		Number of samples
N_{samp}		Number of samples (512 per period in this paper)
T_{samp}	(s)	Sampling period ($T_{\text{samp}} = 1/f_{\text{samp}}$)

development of an indicator resulting from the electrical signals of the machine (current and voltage). Indeed, the current signal presents a nonstationary behavior related to the machine operating process and the electrical phase fluctuations [4]. Very little work has been done to exploit the electrical-signal cyclostationary characteristics [4], and it seems interesting to adapt these signal treatment tools to the electrical signal case. We are particularly interested in the rotor failures. Those generally lead to an increase of a one-phase rotor resistance value [1,2,5–7]. Therefore, a rotor defect has been created by adding a 10% value extra resistance on one phase of the rotor, and acquired the stator voltage and current signals.

A simple comparison between the stator current RMS in the healthy and defective modes of the no-load machine does not allow us to detect the failure (the variation is about 1% only). The stator current RMS cannot thus be used as a sensitive rotor defect indicator. A preliminary conditioning of this indicator will precisely make it possible to exploit the stator current cyclostationarity. By application of the TSA method [8,9], the residue related to the machine mechanics is obtained by subtraction. After conditioning, the new energy indicator will allow the easy distinction of the healthy and defective cases (the variation of the indicator value being clearly higher).

2 Cyclostationarity

2.1 Strict-sense stationarity

Strictly speaking, it is said that a random process $\{x(t)\}$ is stationary [10] if its statistical properties are invariant by translation in time, particularly its probability density:

$$p(x_1, \dots, x_n; t_1, \dots, t_n) = p(x_1, \dots, x_n; t_1 + \tau, \dots, t_n + \tau) \quad (1)$$

for all n , for all τ and for any vector time $\{t_i\}_{i=1,\dots,n}$; $\{x_i\}_{i=1,\dots,n}$ being a realization.

So every moment of this random process is invariant by temporal translation.

2.2 Wide-sense stationarity

Broadly speaking, a random process is stationary if:

- Its average is constant:

$$m_x(t) = m_x \quad (2)$$

- Its covariance function depends only on the temporal variation:

$$K_x(t_1, t_2) = K_x(\tau) \quad \text{where} \quad \tau = t_1 - t_2 \quad (3)$$

When the process is not stationary, its probability density can vary randomly. A very particular class of nonstationary signals is referred to as the cyclostationary signals. A signal is known to be cyclostationary [11] if periodicities are found in some of its statistics. Thus, each period (or cycle) of this signal could be regarded as the realization of the same random process.

2.3 Strict-sense cyclostationarity

A random process $\{x(t)\}$ is known as strict-sense cyclostationary, of T cycle, if its probability density is periodic of T period:

$$p(x_1, \dots, x_n; t_1, \dots, t_n) = p(x_1, \dots, x_n; t_1 + T, \dots, t_n + T) \quad (4)$$

2.4 First-order cyclostationarity

The basic, or first-order, cyclostationary signal is the one with a T -period moment of order 1 (or average):

$$m_x(t) = E\{x(t)\} = m_x(t + T) \quad (5)$$

$E\{x(t)\}$ is the overall statistical average (not to be confused with the temporal average). In practice, only one realization is often available, so the overall average is replaced with a cycle average called **synchronous average** [4].

2.5 Second-order cyclostationarity

A second-order cyclostationary signal is a signal whose 2nd order moments are periodic. In particular, the function of autocorrelation $C_x(t, \tau)$ is a T -periodic function:

$$C_x(t, \tau) = E\{x(t)x^*(t - \tau)\} = C_x(t + T, \tau + T) \quad (6)$$

where $x^*(t)$ is the transposed conjugate of $x(t)$.

2.6 Wide-sense cyclostationarity

Wide-sense cyclostationary signals are the signals which are both first and second order cyclostationary.

3 Signal synchronization

The asynchronous motor operating process and the electric supply fluctuations cause the non-stationary behavior of the stator current signal. Previous research [12–14] has applied time/frequency representation techniques with an aim of identifying the signatures of the faults not in the frequential field, but in the time/frequency domain.

However, there has been very little work [4] exploiting the electrical-signal cyclostationary characteristics to identify the faults which occur in an asynchronous-motor drive. The idea is to extend the application of these signal-processing tools to the case of electrical signals.

In this work, the first-order cyclostationarity of stator current and voltage is largely exploited. However a problem of cycle drift from one electric cycle to another occurs, due to the electrical supply fluctuations. Figure 1 represents the superposition of 1000 electric cycles acquired in a temporal way and it clearly illustrates the shift between the 1st and the 1000th voltage signal cycle. The sampling rate taken is 25.6 kHz, so the number of samples per average cycle of 50 Hz is 512 ($25\,600/50 = 512$).

The cyclic statistic rules cannot be directly applied to these signals to extract desired information, except if a way to compensate these fluctuations is proposed.

A preliminary stage is needed: the current and voltage signals must be re-sampled according to a reference which “follows” these fluctuations: it’s “the synchronization of the current and voltage signals”. Therefore, a re-sampling algorithm which allows synchronizing the acquired signals (stator current and voltage) is developed. Synchronization is operated by compensation of the delay between the various electric cycles.

The purpose is to synchronize all electric cycles according to the same reference, so all cycles must be superimposed after the synchronization process.

To do this, voltage signal is first cut out in slices, each one corresponding to one period ($T = 20$ ms), and each period containing an integer number of samples N_{samp} . In our case:

- The acquisition duration T_a is 20 s, so the number of voltage periods is $N = T_a/T = 1000$;

Fig. 1. 1000 voltage cycles before synchronization.

Fig. 2. 1000 voltage cycles after synchronization.

- The sample rate is 25.6 kHz, so $N_{\text{samp}} = 512$ samples per period ($512 = 25.6 \text{ kHz} \times 20 \text{ ms}$).

The shift between the first voltage period, taken as a reference, and the others is estimated: for this purpose, the first-period zero abscissa and the k th-period zero abscissa (for $k = 2$ to N) are determined; the shift corresponds to the difference between these two abscissas. Then, each period is shifted to make it coincide with the first one (reference). If the two periods are already synchronous, the shift is then null. The obtained signal is represented in Figure 2.

The current signal will be similarly synchronized; but by using the voltage-shift values: the fluctuations due to the supply frequency will be compensated.

Figures 3 and 4 illustrate the superposition of 1000 stator current cycles, respectively in healthy and defective cases before synchronization.

Fig. 3. 1000 current cycles – healthy case (before synchronization).

Fig. 5. 1000 current cycles – healthy case (after synchronization).

Fig. 4. 1000 current cycles – defective case (before synchronization).

Fig. 6. 1000 current cycles – defective case (after synchronization).

Figures 5 and 6 show the superposition of 1000 synchronized stator current cycles respectively in healthy and defective cases.

Once all cycles are synchronized, the signal is rebuilt by setting these cycles end to end. Figure 7 illustrates synchronized current in healthy (a) and faulty (b) cases.

All cycles are now synchronous and the “synchronous averaging” can be carried out.

4 Time Synchronous Averaging (TSA)

A rotor fault can be detected by highlighting a stator-current amplitude or phase modulation. However, the

modulated-signal weak frequency band makes it too difficult to detect modulation. An alternative to overcome this difficulty is proposed by [8]: the Time Synchronous Averaging (TSA) method. It's a way to reshape the signal before its processing. The TSA method allows the separation between the excitation sources and, consequently, fault identification.

The stator current $I_s(t)$ can be decomposed as follows:

$$I_s(t) = I_{sh}(t) + I_{smec}(t) + n(t) \quad (7)$$

where $I_{sh}(t)$, $I_{smec}(t)$ and $n(t)$ are respectively the stator-current harmonic component, the mechanical-structure-related stator current and the noise.

Fig. 7. Synchronized stator current. (a) Healthy case. (b) Defective case.

In fact, the asynchronous motor monitoring consists of supervising the signal harmonic part. So the harmonic frequency (50 Hz) which is related to electrical phenomena and the mechanical structure-related frequency must be separated.

For this purpose, the TSA method will be applied to the stator current. In fact, the stator current is the sum of a determinist signal ($I_{sh}(t)$) and a random signal (sum of $I_{smec}(t)$ and $n(t)$); whose average value is zero:

$$I_s(t) = I_{sh}(t) + I_{srand}(t) \quad (8)$$

$I_{srand}(t)$ is the stator-current random component.

The synchronous averaging of N stator-current samples for each sample time n is done by:

$$I_{savg}^N(n \cdot T_{smp}) = \frac{1}{N} \sum_{k=1}^{k=N} I_s^k(n \cdot T_{smp}) \quad (9)$$

where:

- $T_{smp} = \frac{1}{f_{smp}}$, where f_{smp} is the sampling rate (25.6 kHz);
- I_s^k is the k th synchronized stator current cycle;
- n is the sample row ($n = 1$ to 512; $512 = 25.6 \text{ k}/5$; 512 is the number of samples per 50 Hz cycle).

For the large value of N

$$\lim_{N \rightarrow \infty} I_{savg}^N(t) = I_{sh}(t) \quad (10)$$

Note that only the harmonic part $I_{sh}(t)$ corresponding to 50 Hz frequency remains in the averaged signal; since the random-component average value is zero.

Thus, the synchronous averaging allows an effective separation between electrical-related and mechanical-related components.

Fig. 8. TSA stator current. (a) Healthy case. (b) Defective case.

The subtraction between the stator current $I_s(t)$ and the synchronous averaged current $I_{savg}^N(t) \approx I_{sh}(t)$ (for the large value of N) gives the residual current $I_{res}(t) = I_{srand}(t)$ where only mechanical-related frequencies remain.

The TSA current has the same shape as the current signal. Figures 8a and b respectively show the healthy and defective TSA currents.

The residual signal is obtained by subtraction of the TSA signal from the synchronized signal. This action reduces the electrical contribution, and, consequently, makes the extraction of mechanical-related information easier.

5 Conditioning of an indicator

We are now interested in signal conditioning for the development of an asynchronous motor monitoring indicator. Three tests are carried out:

- test n°1: No-loaded motor. This particular case allows the detection of an inherent motor fault, without load influence;
- test n°2: Motor with a 65% nominal load;
- test n°3: Full-loaded motor.

The simple comparison of the stator current RMS in the healthy and defective modes does not allow us to detect the failure. Indeed, in the first 2 tests, there is practically no difference; whereas in the 3rd test, this difference is of hardly 8%. A first indicator K_1 is defined, such as the stator current RMS, according to the relation:

$$K_1 = \frac{I_{sRMS}(\text{healthy}) - I_{sRMS}(\text{defective})}{I_{sRMS}(\text{healthy})} \quad (11)$$

Table 1 recapitulates the values for the 3 tests.

There is too little variation of the K_1 indicator between the healthy and defective cases. It cannot be used

Table 1. Stator current RMS values – healthy & defective cases.

	Stator current RMS		K_1 indicator
	Healthy case	Faulty cas	
Test n°1	2.61 A	2.63 A	1.05%
Test n°2	3.72 A	3.76 A	1.25%
Test n°3	5.58 A	6.02 A	7.93%

Fig. 9. No-loaded motor.**Table 2.** Residual current RMS values – healthy & defective cases.

	Residual current RMS		K_2 indicator
	Healthy case	Faulty cas	
Test n°1	0.0748 A	0.0914 A	22.07%
Test n°2	0.1584 A	0.3858 A	143.6%
Test n°3	0.2389 A	0.8790 A	267.9%

like a sensitive indicator of rotor defect. The idea now is to compare the residual current RMS obtained after the TSA of the stator current. The residual current RMS is calculated according to the relation:

$$I_{\text{resRMS}} = \sqrt{\frac{1}{N_{\text{samp}}} \sum_{n=1}^{n=N_{\text{samp}}} I_{\text{res}}^2(n \cdot T_{\text{samp}})} \quad (12)$$

where N_{samp} corresponds to the number of current samples ($N_{\text{samp}} = 512 \text{ samples per cycle} \times 1000 \text{ cycles} = 512000$).

Figures 9, 10 and 11 show the healthy and defective residual stator currents respectively for the 3 tests (no load, 65% nominal load and full load).

The electrical signal is conditioned in order to obtain a second indicator K_2 , obtained from the residual stator current RMS, according to the relation:

$$K_2 = \frac{I_{\text{resRMS}}(\text{healthy}) - I_{\text{resRMS}}(\text{defective})}{I_{\text{resRMS}}(\text{healthy})} \quad (13)$$

Table 2 recapitulates the values for the 3 tests.

Fig. 10. Motor with a 65% nominal load. **Fig. 11.** Full loaded motor.

The conditioned indicator K_2 , on the other hand, allows an easy distinction of the healthy and defective cases (the variation is from 22% for the no-loaded motor to nearly 270% in the case of a full-loaded motor).

B Conclusion

In this paper, the proposed method of asynchronous-motor-failure monitoring has two major advantages:

- First, it is a method which is based on the analysis of the “current” and “voltage” signals. We can therefore apply it even to the inaccessible engines (such as the engines immersed in the motor-driven pump groups), unlike the methods based on the analysis of the accelerometer signal, where a direct access to the engine is necessary to be able to place the sensors there.
- Besides, the approach is relatively simple: the monitoring of the residual current RMS makes it possible to clearly detect the defective case. In fact, with a

Appendix: Experimental device photos

Fig. 12. Wound rotor asynchronous motor associated to DC generator.

Fig. 13. Electrical load of the DC generator.

Fig. 14. Data acquisition system.

Fig. 15. Additional resistance (40 mohms).

no-load engine, where the fault is hardest to detect, the K_2 indicator already shows a difference between healthy and faulty cases that exceeds 20%, to go beyond 250% for the full-load engine case.

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