Mechanical Systems and Signal Processing 92 (2017) 278–292

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

journal homepage: www.elsevier.com/locate/ymssp

Three-phase electrical signals analysis for mechanical faults monitoring in rotating machine systems

Georgia Cablea, Pierre Granjon *, Christophe Bérenguer

Univ. Grenoble Alpes, GIPSA-Lab, F-38000 Grenoble, France
CNRS, GIPSA-Lab, F-38000 Grenoble, France

ARTICLE INFO

Article history:
Received 1 July 2016
Received in revised form 19 January 2017
Accepted 22 January 2017
Available online 3 February 2017

Keywords:
Instantaneous symmetrical components
Three-phase electrical signals
Electrical rotating machines
Bearing faults
Condition monitoring

ABSTRACT

The current paper proposes a method to detect mechanical faults in rotating machines using three-phase electrical currents analysis. The proposed fault indicator relies on the use of instantaneous symmetrical components (ISCs), followed by a demodulation step enhancing the small modulations generated in electrical signals by mechanical faults. The limitations due to the multi-component nature of electrical signals, as well as to the noise naturally present in the measured signals are studied and taken into account in order to elaborate a proper and efficient algorithm to compute a mechanical fault indicator. It is theoretically shown that the ISCs based approach results in an increase of the signal-to-noise ratio compared to a single-phase approach, finally leading to an improvement of early fault detection capabilities. This result is validated using both synthetic and experimental signals where the proposed method is used to detect bearing faults and the obtained results are compared to single-phase results.

1. Introduction

Nowadays, three-phase rotating machines are widely used in most industries like manufacturing plants (e.g. paper mills), transportation (e.g. electric vehicles) or power generation (e.g. wind turbines). Particularly, three-phase induction machines are most commonly used due to their robustness and lower price. Either used as electric generators to convert mechanical energy to electrical energy, or as electric motors to convert the energy in the other direction, three-phase rotating machines are a connecting component between a mechanical system and an electrical one. Such electro-mechanical systems are subject to both electrical and mechanical faults. In this paper the focus is set on mechanical faults generating load torque oscillations on the machine shaft. Such faults consist for example in bearing faults or gearbox faults, and can be located in the machine itself, as well as in a connected mechanical system, i.e. in the drive-train.

Several condition monitoring methods have been developed in order to detect mechanical faults using electrical quantities involved in such machines. In particular, condition monitoring through stator current analysis, also known as motor current signature analysis (MCSA), is now well developed for single-phase currents [1]. This method relies on the fact that such faults generate amplitude and phase modulations in stator currents [2,3]. One important point concerning single-phase approaches is that the information contained in each stator current is slightly different from phase to phase due to initial phase shifts, amplitude and/or phase unbalance, high frequency components, measurement noise, etc. Therefore, methods

* Corresponding author at: Univ. Grenoble Alpes, GIPSA-Lab, F-38000 Grenoble, France.
E-mail addresses: Georgia.Cablea@gipsa-lab.grenoble-inp.fr (G. Cablea), Pierre.Granjon@gipsa-lab.grenoble-inp.fr (P. Granjon), Christophe.Berenguer@gipsa-lab.grenoble-inp.fr (C. Bérenguer).

http://dx.doi.org/10.1016/j.ymssp.2017.01.030
0888-3270/

based on the analysis of single-phase currents use only one part of the whole information available in the three-phase system.

As a consequence, current research in the field of condition monitoring of three-phase systems focuses on developing methods taking into account three-phase quantities. In order to efficiently combine and process the information contained in the three phases as a whole, several three-phase transforms have been used such as the Fortescue transform [4] or the Clarke/Concordia transform [5]. In [6], all these transforms are shown to be equivalent, finally leading to the instantaneous symmetrical components (ISCs). More particularly, the positive-sequence ISC of the stator currents is generally demodulated to detect mechanical faults in three-phase rotating machines. For example, the so-called Extended Park's Vector Approach (EPVA) [7] computes the squared modulus of this component in order to estimate and analyze its instantaneous amplitude to detect bearing failures. In [8], the instantaneous frequency of the positive-sequence ISC is estimated and used to monitor mechanical faults inducing load-torque oscillations on the machine shaft. The positive-sequence ISC obtained with a Concordia transform is amplitude and frequency demodulated in [9–12], and the obtained results are compared to several other demodulation techniques. In all these studies, two major points have been identified as limitations. Firstly, while the noise naturally present in measured signals may hide incipient fault signatures and deteriorate early fault detection capabilities, none of the previous study investigate its specific influence on the ISCs. Secondly, the demodulation steps of the positive-sequence ISC proposed in the previous papers assume that this signal is a monocomponent analytic signal, which is generally false. Indeed, the presence of harmonics and/or electrical unbalance in three-phase signals leads to the presence of different components with positive and negative frequency in the positive-sequence ISC, and finally to extra-oscillations in the demodulated quantities. These problems have been identified and partly solved in [13,14], where a technique dedicated to the adaptive estimation of the fundamental frequency of balanced or unbalanced three-phase signals has been proposed. Another interesting approach relying on a principal component analysis (PCA) directly applied to three-phase electric signals has been proposed in [11,12]. This method has been studied under the assumptions of three-phase signals unbalanced in amplitude only and without any additive noise, and properly demodulates the signals in this particular case. The main drawback of [11] is that the PCA method assumes monocomponent signals (no harmonics or other frequency components).

The previous observations lead to the two major contributions of this paper. The first one is a detailed study of the content of the ISCs in terms of periodic components as well as noises. The second contribution is to propose a mechanical fault indicator relying on a correct implementation of an amplitude and phase demodulation of the positive-sequence ISC, even in the presence of harmonics, electrical unbalance, and white or colored additive noises in electrical data. Beyond these two contributions, another interesting point is also addressed: while for electrical faults the advantage of using symmetrical components methods for condition monitoring is stated as the separation of balanced and unbalanced components [15], what is the real advantage of using three-phase approaches over single-phase ones for mechanical faults detection? Some answers are provided to this important question throughout the current paper, where it is shown that the proposed method improves early faults detection capabilities by increasing the signal-to-noise ratio in the positive-sequence ISC compared to single-phase currents. This last result is confirmed by simulated and experimental results obtained by comparing the proposed mechanical fault indicator relying on a three-phase approach with the same indicator computed from single-phase currents only.

The next section of this paper gives the definition of the instantaneous symmetrical components, their interpretation and argues their advantages compared to single-phase quantities. In Section 3, a single-phase current model for mechanical fault signature in electrical signals is extended to three-phase current signals. A mechanical fault indicator relying jointly on the proposed three-phase signal model and on instantaneous symmetrical components is then developed with the corresponding estimation algorithm. Its performance is illustrated in Section 4 on experimental data acquired at the stator of a three-phase generator located on a test-bench emulating a wind turbine, and compared to single-phase results. Finally, the last section of this paper presents the overall conclusions of this research work.

2. Effect of the instantaneous symmetrical components transform

In this section, as well as in the rest of the paper, a complex-valued three-phase signal model was used for the theoretical development, while a real-valued signal formulation was used for the simulations. The choice of using a $\mathbb{C}$-valued model is justified by the need for clarity and to simplify computations. However, since real world signals are $\mathbb{R}$-valued, such a formulation was used for the simulations.

2.1. Three-phase electrical signal model

In order to study the effect of the ISC transform on three-phase signals, we consider the three-phase currents signals formulation as in Eq. (1), where the complex-valued formulation of the signals model was chosen in order to simplify further theoretical computations.

$$\mathbf{i}(t) = \mathbf{a} \cdot e^{j2\pi f_0 t} + \mathbf{n}(t) \tag{1}$$