Electric Power Systems Research 152 (2017) 18–26

Contents lists available at ScienceDirect

Electric Power Systems Research

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

Analysis of various inverters feeding induction motors with incipient rotor fault using high-resolution spectral analysis

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ARTICLE INFO

Article history:
Received 5 December 2016
Received in revised form 21 June 2017
Accepted 22 June 2017

Keywords:
Condition monitoring
Fault detection
Induction motor
Inverter
Multiple signal classification
Spectral analysis

ABSTRACT

Recently, there has been an increased interest in fault detection on electrical machines in steady-state regimes. Several frequency estimation techniques have been developed to assist the early detection of faults in induction motors, especially in line-fed motors. However, in modern industry, the use of inverters is increasingly present. This paper presents an analysis for comprehending the challenge in detecting incipient rotor faults using the stator current signal under different inverter supplies. The approach is based on the high-resolution technique known as multiple signal classification (MUSIC). In this study, incipient rotor faults in a squirrel-cage rotor, prior to the complete breaking of a rotor bar, are better identified in some inverters than others. The proposed approach finds the adequate MUSIC order that facilitates identification of bar breakage frequencies for early fault detection in each case studied from a wide set of trials. The study has been developed to detect incipient rotor bar breakages in an inverter-fed three-phase induction motor under varying load situations.

1. Introduction

Induction motors (IM) are considered the workhorse of industry, mainly because of their robustness, reliability, and low price. Despite these advantages, they are susceptible to failures and require condition monitoring to carry out effective predictive maintenance practices [1]. Researchers have devoted considerable efforts in the area of Motor Current Signature Analysis (MCSA) [2–5] for IM fault detection (FD) under different conditions that are commonly present in industrial environments. MCSA has many advantages such as being non-invasive, it does not interfere with motor operation, and it is less affected by environmental noise compared to vibration signals. Therefore, MCSA-based approaches provide a reliable monitoring of rotor health. Since spectral analysis techniques are useful to identify faulty patterns in frequency domain, Fast Fourier Transform (FFT) has been widely used [6]. FFT makes use of Discrete Fourier Transform (DFT) using a computationally efficient algorithm [7]. However, it has some drawbacks: it suffers from spectral leakage, lacks a good frequency resolution, and it also produces a noisy spectrum, especially in inverter-fed IM [8], which limits its reliability [9]. Certainly, FFT can be a useful tool when the normal situation of the IM is in steady state. Yet, the current signal is in fact time varying, which makes it more difficult to achieve the steady-state condition for FFT computation, also demanding a long acquisition period and is impractical for low slip applications [10]. Nevertheless, MUSIC and ESPRIT are suited methods for analyzing signals with low SNR [11]. In [10], the Hilbert transform is combined with ESPRIT to perform fault detection on IM operating at low slip to improve BRB fault detection and to overcome the limitations of the FFT. Authors in Ref. [10] stated that ESPRIT has the capacity to avoid spectral leakage and its combined application with the Hilbert transform has given good results to detect a broken rotor bar (BRB) when the fault components are close to the fundamental component [10]. Unlike FFT, MUSIC algorithm can be computed from a much shorter acquisition period and with lower memory requirements to locate BRB frequencies, producing comparable results to those FFT-based methods [12], and this is because the technique can be applied to a narrow frequency band where the BRB components are present. Through decimation on that frequency band, the required sampling rate is reduced and thus, computation time is decreased.

Some key papers in the field [10,13–21] deal with the fault of a BRB. For instance, Kim et al. [18] introduced an axis transformation and average method for detecting a BRB using the current spectrum in an inverter driven induction machine. The results proved to be more effective compared to FFT regarding fault diagnosis sys-

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http://dx.doi.org/10.1016/j.epsr.2017.06.021
0378-7796/

tem costs. Other researchers [16] investigated the generation of specific frequency components related to induction motor faults in inverter-supplied electric drive systems. Also, the authors in Ref. [19] dealt with the diagnosis of rotor faults in closed-loop IM drives. Their main contribution was the use of the inverter to perform an offline test, equivalent to a single-phase rotation test. Ghorbanian et al. [20] reviewed suitable techniques for FD, addressing fault diagnosing procedures with different kinds of supply. This study was focused partly on BRB considering motor supply and condition changes. However, although the detection of a BRB is a milestone in the detection of IM rotor faults, the determination of an incipient BRB still remains a challenging situation in the literature. Early FD is even more difficult in inverter-fed IM [20–22]. Since there are no studies that consider the influence of various types of inverters for dealing with early FD, a wrong conclusion may be drawn by generalizing from the behavior of the hitherto proposed techniques by limiting themselves to only one power supply. Thus, the diagnosis technique utilized must be applied under different supply conditions to show its potential to deal with incipient faults. FD complications in inverter-fed IM may be explained by noise level introduced by the inverter [16–18], which is originated by pulse width modulation (PWM) technique, the control mode [21], and the inverter model or brand. Each inverter model introduces different power conversion harmonics into the stator current spectrum [22]. They contribute to the generation of inter- and sub-harmonics in the stator current, negatively affecting the diagnosis. Consequently, in the case of a partial BRB, differences among inverters may be observed, and it is worth reporting some conclusions about the detectability of this fault in these situations.

The main objective of this paper is to prove the potentiality of high-resolution spectral analysis to detect a BRB at an early stage for different inverter feedings. The analysis is performed by using a considerable number of trials of various inverters to supply an IM, considering several load conditions, ranging from medium to high. Given these load levels, MUSIC has been selected as the analysis method to locate the characteristic spectral components, present at the incipient rotor fault in an inverter-fed IM. The analytical methodology consists of basically three stages: a preprocessing stage that selects the most relevant samples; a high-resolution spectral estimation of the BRB frequencies based on MUSIC; and a third stage for quantifying the fault severity. Experimentation is performed to test the feasibility of this method using an IM and three different inverters.

2. Application of MUSIC to the detection of incipient broken bar fault

As is well known, the BRB-related components are given by Eq. (1), resulting in sidebands around integer harmonics [22]:

$$f_{BRB} = (k \pm 2ns)f_s,\ n = 1, 2, 3, \ldots \quad (1)$$

where s is the per-unit motor slip, and k is the harmonic order.

The MUSIC algorithm estimates the frequency content of a signal using eigenvector decomposition of the autocorrelation matrix. In this method, it is assumed that $x[n]$, the discrete time stator current signal, is a sum of M complex sinusoids with white noise and it can be expressed as follows:

$$x[n] = \sum_{i=1}^{M} \bar{A}_i e^{j2\pi f_i n} + e[n] \quad (2)$$

with

$$\bar{A}_i = |A_i| e^{j\phi_i} \quad (3)$$

and n = 0,1,2,. . ., $N-1$ where N is the number of sampled data, $|A_i|$ is the magnitude, f_i is the frequency, ϕ_i is the random phase of i-th complex sinusoid, and $e[n]$ is white noise with zero mean and variance σ^2. $\boldsymbol{R_x}$ is the MxM autocorrelation matrix of $x[n]$ and can be expressed as the sum of signal and noise autocorrelation matrices $\boldsymbol{R_s}$ and $\boldsymbol{R_n}$ respectively, as follows:

$$\mathbf{R_x} = \mathbf{R_s} + \mathbf{R_n} = \sum_{i=1}^{m} |A_i|^2 e(f_i)\, e^H(f_i) + \sigma^2 \mathbf{I} \quad (4)$$

where m is the number of frequency components, the exponent H denotes the Hermitian transpose, $\mathbf{I}$ is the identity matrix, and $\boldsymbol{e}^H(f_i)$ is the signal vector given by:

$$\boldsymbol{e}(f_i) = [1 e^{j2\pi f_i} e^{j4\pi f_i} \ldots e^{j2\pi (N-1) f_i}]^T \quad (5)$$

From the orthogonality condition of both subspaces, the MUSIC pseudo-spectrum Q is given by:

$$Q^{MUSIC}(f) = \frac{1}{|\boldsymbol{e}^H(f_i)\, \boldsymbol{v}_{m+1}|^2} \quad (6)$$

$$\boldsymbol{v}_{m+1} = \sum_{k=m+1}^{M} \boldsymbol{v}_m \boldsymbol{v}_m^H \quad (7)$$

where $\boldsymbol{v}_{m+1}$ is the noise eigenvector and is expressed as in Eq. (7). This expression exhibits the peaks that are at exact frequencies of the principal sinusoidal components, where $\boldsymbol{e}(f)^H \boldsymbol{v}_{m+1} = 0$.

The scalar integer and tuning parameter m, also known as the MUSIC order, is the signal subspace dimension. The performance of the MUSIC algorithm depends on this value, and it determines the dimension of the autocorrelation matrix, which is unknown *a priori*. Indeed, there is no theoretical basis for computing the exact value of m, but a multi-objective optimization method, to address this question, has been proposed in Ref. [15]. Mainly, in the analysis of different inverter feedings, the corresponding autocorrelation matrices should contain high enough eigenvalues for the noise space and should be low enough not to highlight spurious frequencies, all of which performed with a reduced computational time.

3. Methodology and signal processing

A block diagram of the proposed methodology is shown in Fig. 1. First, a one-phase stator current signal is acquired for each power supply and rotor state. Then, band-pass filtering, for limiting those frequencies outside a specific bandwidth, is applied before using the FFT and MUSIC algorithms. Once a sizeable dataset of signals is built from the laboratory experiments, the MUSIC algorithm is tuned, applying it to those signals obtained under different motor loads and rotor conditions.

The band-pass FIR filter designed is based on the Parks–McClellan optimal filter order estimation, which is implemented in the signal processing toolbox of MATLAB©. The band-pass filter parameters are defined as follows: (1) The band-pass frequencies are set at 42 Hz and 58 Hz, respectively, considering that at higher loads, the BRB faulty components are further separated from the fundamental frequency [23], and the maximum slip of the trials at high loads has a per-unit value of 0.065, which corresponds to values of LSH = 43.5 Hz and RSH = 56.5 Hz. The frequencies are chosen based on the highest load level since it is the limiting factor of the frequency band of interest for locating the BRB components within that range; (2) the first and second stop-band frequencies are assigned to be 30 Hz and 70 Hz, respectively. This step rejects those frequencies related to lower and higher harmonics than the fundamental, and (3) the attenuation at the stop-band is set at 40 dB, which requires an order of 32 for the FIR filter. This FIR filter has been designed to allow the observation of the frequencies of interest and to eliminate the switching frequencies of the inverters located in the kHz region.