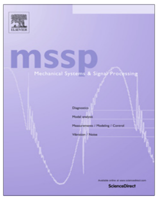
Mechanical Systems and Signal Processing 98 (2018) 63–77

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

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



Fast and accurate spectral estimation for online detection of partial broken bar in induction motors

Anik Kumar Samanta [a,*], Arunava Naha [b], Aurobinda Routray [b], Alok Kanti Deb [b]

[a] *Advanced Technology Development Centre, Indian Institute of Technology Kharagpur, 721302, India*
[b] *Dept. of Electrical Engineering, Indian Institute of Technology Kharagpur, 721302, India*

ARTICLE INFO

Article history:
Received 8 December 2016
Received in revised form 14 April 2017
Accepted 24 April 2017
Available online 3 May 2017

Keywords:
Autocorrelation matrix
Broken rotor bar
Closely spaced sinusoids
Empirical cumulative distribution function
Fault diagnosis
MCSA
MUSIC
Rayleigh-quotient
Simulink real-time
Squirrel cage induction motor

ABSTRACT

In this paper, an online and real-time system is presented for detecting partial broken rotor bar (BRB) of inverter-fed squirrel cage induction motors under light load condition. This system with minor modifications can detect any fault that affects the stator current. A fast and accurate spectral estimator based on the theory of Rayleigh quotient is proposed for detecting the spectral signature of BRB. The proposed spectral estimator can precisely determine the relative amplitude of fault sidebands and has low complexity compared to available high-resolution subspace-based spectral estimators. Detection of low-amplitude fault components has been improved by removing the high-amplitude fundamental frequency using an extended-Kalman based signal conditioner. Slip is estimated from the stator current spectrum for accurate localization of the fault component. Complexity and cost of sensors are minimal as only a single-phase stator current is required. The hardware implementation has been carried out on an Intel i7 based embedded target ported through the Simulink Real-Time. Evaluation of threshold and detectability of faults with different conditions of load and fault severity are carried out with empirical cumulative distribution function.

1. Introduction

A condition monitoring system for early detection of squirrel cage induction motor (SCIM) faults like broken rotor bar (BRB) can significantly enhance the operation efficiency of any industry. As reported, BRB accounts for about 5–10% of all induction motor faults [1]. BRB is initiated when small cracks develop at the junction between the bars and the end ring. The resultant signatures for cracked and broken rotor bars on the current spectrum are the effect due to rotor circuit asymmetries [2–4] giving rise to multiple frequency components around the fundamental as

$$f_{brb} = (1 \pm 2ks)f_o \tag{1}$$

where s is the slip, k is any integer, and f_o is the fundamental frequency. High-resolution spectral estimators like multiple signal classification (MUSIC) [5,6] and estimation of signal parameters via rotational invariance technique (ESPRIT) [7,8] have gained prominence over the classical method of the power spectrum because of its robustness and resolution capacity for detecting BRB under low load conditions. Still there are concerns over critical issues related to computational complexity and accurate amplitude estimation of the detected fault components. Use of parametric spectral estimators for fault

---

[*] Corresponding author.
E-mail address: ece.anik@gmail.com (A.K. Samanta).

http://dx.doi.org/10.1016/j.ymssp.2017.04.035
0888-3270/© 2017 Elsevier Ltd. All rights reserved.

diagnosis using maximum lilkihood estimation with a particular signal model can be found in [9]. Spectral estimation based on total least square methods was developed by [10] for fault detection.

Fault diagnosis can be accomplished by analyzing a variety of signals of the motor such as vibration [11–13], current [14–16,7,17], magnetic fields [18,19], supply voltage modulation [20], active-reactive power [21,22], acoustics [11], thermal field [23], thermal imaging [24], slot harmonics [25], torque [26], low-voltage offline testing [27], etc. Signals like flux [19] and instantaneous power factor with phase [22] were used to alleviate the problems faced by motor current signature analysis (MCSA) due to load-torque. Indicators of BRB, which are independent of load-torque oscillations were proposed in [28–30]. In [31], a low sampling rate of 200 samples/s was used for improved resolution in detecting BRB under low load conditions. Transient and non-stationary signal processing using the wavelet decomposition of the startup current [32,12,16], adaptive slope transform [33] are also popular. Effect of simultaneous occurrence of static eccentricity, BRB, and speed ripples were studied analytically and experimentally in [15]. A winding function model based method with parameter estimation using current, rotor speed, and torque is shown in [34]. The authors in [35] have used empirical mode decomposition for direct, and inverter-fed motors to detect BRB. A comprehensive review of recent advances for detection of BRB can be found in [36].

The severity of BRB is indicated by the magnitude of the fault component [37,17]. However, subspace-based methods cannot give exact information about the amplitude of the fault components. Hence, simulated annealing algorithm was used to determine the correct amplitude and eventual fault severity in [8]. In [7,38] the amplitude was estimated using least square estimation, which is equivalent to computing the discrete Fourier transform (DFT) for a single frequency. However, DFT is not suitable for estimating the amplitude of closely spaced sinusoids [39,40]. Moreover, these methods require extra computational resources for their execution when used in conjunction with MUSIC and ESPRIT. Modulation of the stator current due to partial BRB is weak, and its detection in a light load condition is challenging as the fault components are very close to the fundamental [17] and have low amplitude [41]. Detecting weak faults require the fundamental frequency to be suppressed effectively without affecting the closely spaced fault components. Commonly, this is achieved by using a sharp notch filter [31]. But, variable frequency operation with load changes require the central frequency of the notch filter to track the fundamental frequency, and its cutoff bandwidth to be adaptive to the slip. In developing unsupervised fault detectors, implementing notch filter with these characteristics is inconvenient. Therefore, an extended Kalman filter (EKF) based signal conditioning method is adopted to remove the fundamental component. This method tracks and attenuates only the fundamental component to improve the detection of close sidebands. Detection of faults in low load condition was accomplished by Hilbert modulus with FFT (0.2% slip) [42], Hilbert modulus with ESPRIT (0.33% slip) [43], Fourier analysis (1.38% slip) [44], Teager - Kaiser energy operator (0.4% slip) [45]. In [46], Fourier analysis of stator current envelop is carried out to detect BRB under a low slip of 0.11%. However, a high initial sampling of 50 kHz makes it disadvantageous for low-cost hardware implementation. The majority of the research focussed on detecting single and multiple BRB. Detection of partially BRB were demonstrated in [47,4,3]. However, detecting partial BRB in low-slip applications especially for the inverter-fed motor is yet to be addressed. In the proposed paper, detection of a partially broken bar for the inverter-fed SCIM has been achieved with 0.2% slip.

The major contribution of this paper can be enumerated by (a) Development of a novel spectral estimator which can

1. estimate the location of fault frequency components with very high accuracy in noisy environment and has a lower computational complexity than MUSIC,
2. estimate the magnitude of fault frequencies accurately unlike subspace-based methods like MUSIC, ESPRIT, etc.,
3. avoid spurious peaks as it doesn't require the information about the number of sinusoids. This decreases the chance of false-alarms and missed detections,

(b) An elegant fault detection algorithm is developed using the novel spectral estimator having the following attributes:

1. can detect single BRB fault with different levels of damage under low-slip. The lowest slip for the medium-sized motor to detect a partially broken bar has been found to be 0.2% under 1.9% of the rated load,
2. a novel EKF-based signal conditioner is developed to estimate and remove the fundamental supply frequency component from the input. The detectability of closely spaced fault frequencies due to partial BRB under low slip has been improved by this conditioning. Moreover, being a time-domain based sequential technique, it can also be used for non-stationary applications,
3. the overall system is implemented on an embedded hardware platform for online and real-time (RT) fault detection with only a single phase stator current as input.

2. The proposed spectral estimator

The signal model used for developing the spectral estimator is represented by

$$x[n] = \sum_{i=1}^{P} a_i e^{j(\omega_i n + \phi_i)} + v[n], \quad n = 0, 1, \ldots, (N-1) \tag{2}$$