Measurement 43 (2010) 887–900

Contents lists available at ScienceDirect

Measurement

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

Estimation of frequency components in stator current for the detection of broken rotor bars in induction machines

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ARTICLE INFO

Article history:
Received 11 August 2008
Received in revised form 19 December 2009
Accepted 12 March 2010
Available online 19 March 2010

Keywords:
Induction machine
Broken rotor bar
Prony
Frequency estimation

ABSTRACT

The limitation of data window length in induction machine broken rotor bar diagnostics is a real challenge in practice. Sideband frequencies which are used as broken rotor bar indicators are very close to the fundamental frequency and have low magnitude. Traditional spectral analysis approach such as Discrete Fourier Transform (DFT) can be inaccurate in these conditions due to its inherent drawbacks such as the requirement of long data window for high resolution and the side lobe leakage in frequency domain. In this paper, a high-resolution spectral analysis technique, Prony Analysis (PA), is proposed for broken rotor bar detection in induction machines. The method is described and demonstrated in detail, validated by experimental data, and compared with DFT. Results clearly indicate the advantages of PA over DFT in terms of maintaining a high resolution with a much shorter window and a better frequency estimate accuracy with the same window length.

1. Introduction

Induction machines (IM) play a vital role in industry. Internal machine faults such as broken rotor bars are potential hazards to the reliability and safety of industrial operations, and also increase the operational costs. Therefore, induction machine condition monitoring and fault diagnostics has been an important research topic in the last decades, and many of them are with great respect to broken rotor bar detection [1–4].

Motor Current Signature Analysis (MCSA) is a widely adopted technique for on-line diagnostics of induction machine broken rotor bars. Research has found that when broken bars occur in the machine rotor, the induced anomaly of the electromagnetic field will cause two sideband frequency components, $(1 \pm 2s)f$, to appear in the stator current spectrum [5], where f is the supply frequency and s is the machine slip. Identification of these sideband frequencies can be used as a convenient and reliable approach to broken rotor bar fault diagnostics [3].

In an induction machine, the slip s is usually below 10%. If the machine load gets lighter, the slip gets smaller. As a consequence, the two broken rotor bar sideband frequencies become quite close to the fundamental frequency. This appears in the stator current spectrum as two small peaks in the vicinity of a high peak. Combined with low signal to noise ratio, the task of selecting a spectral analysis method is difficult.

Discrete Fourier Transform (DFT) is a classical technique for spectral analysis. Fast Fourier Transform (FFT), which is a fast computation algorithm of DFT, has been previously adopted in the implementation of MCSA [5,3]. However, inherent disadvantages of using DFT limit its applicability in practice. The two broken rotor bar sideband frequency components are very close to the fundamental frequency when the machine load is light. This requires the data window used for DFT to be long for sufficient frequency resolution [6]. Another major disadvantage of DFT is that the impact of side wiggles (Gibbs oscillations). The implicit windowing process when using DFT causes side lobe leakage in spectral domain, obscuring and distorting other spectral response in its vicinity [7]. There are also other limitations such as that the time domain noise in the signal is distributed uniformly by DFT in the frequency domain,

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doi:10.1016/j.measurement.2010.03.006

which limits the certainty of computing frequency widths, magnitudes, and phases [8] and, it is also known that DFT may cause spurious spectral components in the spectrum, which will confuse the detection on desired frequency components. Additionally, DFT requires the values of the frequencies in the target signal to be constant.

These limitations of DFT can be particularly troublesome in real induction machine condition monitoring situations. Short data records are usually required because the instability of machine load condition may cause time-varying broken rotor bar sideband frequencies. However, on the other hand, a high resolution is required to observe the two broken rotor bar sideband frequencies when the machine is operating with light load. This means longer data acquisition time. Moreover, in practice, sometimes only restricted data records are available. This also makes enlarging the data window to obtain a high resolution impossible. Thus, trade-offs among leakage suppression, resolution and tracking changes are difficult to fulfill. The detection of broken rotor bars using DFT can be difficult and unauthentic. Failures have been reported in [5,9]. In most applications reported in the literature, where DFT is used for the signal processing stage of MCSA, the machine load is usually fixed at near full load.

Due to those limitations of DFT, other methods for spectral analysis become potential options to the detection of broken rotor bars. Prony Analysis (PA) is a high-resolution spectral analysis method developed on the basis of the original work of the French mathematician, Gaspard de Prony [10]. It is able to achieve high frequency resolution and estimation accuracy using very short data acquisition windows. Such technique overcomes the drawbacks of DFT and has high value in practical implementation in light and variable machine load conditions.

In this paper, firstly, the original Prony's method and the Least Squares (LS) Prony, which is used for dealing with real signals, are reviewed. It is known that the original Prony's method is sensitive to noise [8]. The LS Prony method deals with practical situations but cannot provide satisfied outcomes since it fits the model to any noise present in the data [10]. Therefore, the Iteratively Reweighted Least Squares (IRLS) Prony [11] is then proposed to obtain improved results in the broken rotor diagnosis application. The term PA in this paper refers to the IRLS Prony method, except otherwise indicated. In the following sections, results obtained by PA using both simulated and experimental data are presented and compared with that obtained by DFT, clearly demonstrating the superiority of PA over DFT in terms of using much shorter data windows to achieve high resolutions and obtaining higher precision in frequency estimation with the same length of window. In the end, influential factors to the PA are analyzed.

2. Prony Analysis

2.1. Theory of the Prony's method

The original Prony method seeks to fit a deterministic exponential model to equally spaced data points. It was discussed in detail by Marple [10] and Therrien [12]. Here we will give a brief review of this technique. Assuming signal data $x[n]$ has N complex samples $x[1],\dots,x[N]$, the Prony method will fit the data with a sum of q complex exponential functions

$$\hat{x}[n] = \sum_{k=1}^{q} A_k \exp[(\alpha_k + j2\pi f_k)(n-1)T_s + j\varphi_k] \tag{1}$$

for $n = 1,2,\dots,N$ and $k = 1,2,\dots,q$, where A_k is the amplitude of the complex exponential, α_k is the damping coefficient in s^{-1}, f_k is the sinusoidal frequency in Hz, φ_k is the initial phase in radians, and T_s is the sampling interval in seconds.

The objective is to estimate the frequencies f_k, damping factors α_k, amplitudes A_k and phases φ_k. If these function coefficients are determined correctly, then the plot of the estimation of the signal within the data window should fit the original signal with a high degree of accuracy.

Since only real signals are considered, the signal poles $\exp(\alpha_k + j2\pi f_k)$ must appear in complex conjugate pairs. Thus the q is always assumed to be even for convenience. Then, Eq. (1) can be expressed in form of

$$\hat{x}[n] = \sum_{k=1}^{q} h_k z_k^{n-1} \tag{2}$$

where h_k and z_k are complex parameters defined as

$$h_k = A_k \exp(j\varphi_k)$$

and

$$z_k = \exp[(\alpha_k + j2\pi f_k)T_s]$$

The fitting of a designated signal using (2) is a difficult nonlinear problem as sums involving exponentials must be solved for z_k [10]. No analytic solution is available.

Prony's method addresses this problem by determining the z_k elements separately and then considering Eq. (2) as a set of linear simultaneous equations to solve for h_k. The key of the Prony method is in the fact that to see Eq. (2) as the solution to a homogeneous linear difference equation with constant coefficients. Then the coefficients can be identified by solving the linear prediction equation, as demonstrated below. A polynomial with roots z_k can be formed accordingly

$$\phi(z) = \prod_{k=1}^{q}(z - z_k) = \sum_{m=0}^{q} a_m z^{q-m} \tag{3}$$

The linear difference equation whose homogeneous solution is given by Eq. (3) is

$$\sum_{m=0}^{q} a_m x[n-m] = 0 \tag{4}$$

with complex coefficients a_m such that $a_0 = 1$.

The original Prony method assumes that the number of available data samples is equal to the unknown parameters, so the difference equation is valid for $n = q+1,\dots,2q$. The coefficients a_m form a linear predictive relationship among the available samples and the relationship can be then expressed as the $q \times q$ Toeplitz structure matrix equation [10]