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Research article

Discrete wavelet transform and energy eigen value for rotor bars fault detection in variable speed field-oriented control of induction motor drive

Tarek Ameid[a,*], Arezki Menacer[a], Hicham Talhaoui[a,b], Youness Azzoug[a]

[a] LGEB Laboratory, Electrical Engineering Department, Biskra University, Algeria
[b] University of Bordj Bou Arreridj, Algeria

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ABSTRACT

This paper presents a methodology for the broken rotor bars fault detection is considered when the rotor speed varies continuously and the induction machine is controlled by Field-Oriented Control (FOC). The rotor fault detection is obtained by analyzing a several mechanical and electrical quantities (i.e., rotor speed, stator phase current and output signal of the speed regulator) by the Discrete Wavelet Transform (DWT) in variable speed drives. The severity of the fault is obtained by stored energy calculation for active power signal. Hence, it can be a useful solution as fault indicator. The FOC is implemented in order to preserve a good performance speed control; to compensate the broken rotor bars effect in the mechanical speed and to ensure the operation continuity and to investigate the fault effect in the variable speed. The effectiveness of the technique is evaluated in simulation and in a real-time implementation by using Matlab/Simulink with the real-time interface (RTI) based on dSpace 1104 board.

1. Introduction

In industry, drive applications require high performances, the squirrel-cage induction motor (IM) takes an important place due to its rigidity, and works more efficiently compared to the wounded rotor. In addition, it adjusts to several service applications, where the speed should closely follow a trajectory specified reference that is independent of any external load disturbance. The operation modes of the IM are vulnerable to a variety of unwanted conditions, which make it susceptible to different types of defaults. In this respect, these faults in the machine can be classified into two categories: on the one hand, External, such as: overload, poor mounting, the voltage and the environmental phenomena. On the other hand, Internal, such as: interturn short circuit [1,2], eccentricity of the rotor [3,4] and broken rotor bars [5,6]. The broken rotor bars fault causes fluctuation and decreases torque's amplitude; therefore, more fluctuation and mechanical vibrations can be produced, and then these problems can lead to the damage of the machine. Ultimately, the rotor bars fault effect becomes more obvious by the increase of the broken bars number, especially, in the open-loop drives [7]. To avoid such problems, the fault diagnosis and detection process become highly necessary step to protect this type of electrical components [8].

The purpose of the field-oriented control is to have good performance flux and torque decoupled control, this technique has led to a radical change in control of the IM [9]. The recommended machine model for closed-loop FOC design takes into account the effective geometry of the rotor based on multi-winding model for diagnosis purpose considering the broken rotor bars fault [10].

In recent years, several techniques for the fault detection have been proposed in the literature; they focused on the diversity of the encountered problems, and have made it a challenging topic for many researchers. Furthermore, it is usually known that the developed techniques for IMs diagnosis in open-loop drives are not so effective when the motor's control structure becomes more complex, particularly, the closed-loop vector controlled motors [11–14].

The use of signals approach for diagnosis has a great importance for the broken rotor bars detection. It's necessary to employ different analysis to interpret the acquired signals for the detection process, such as stator voltage, current, speed, temperature, and vibration signals [13,14]. The monitoring and diagnosis based on motor current signature analysis (MCSA) are widespread used methods, whereas, they present many advantages like requiring only one current sensor per machine, and is based on straightforward signal processing such as Fast Fourier Transforms (FFT) [15,16]. The FFT analysis method has been proved to be a good technique for fixed frequency supply, such as the connected machines to the electrical grid (steady-state), where it is used to determine the spectral signatures by investigating components around the fundamental frequency [17]. However, the effectiveness

* Corresponding author.
E-mail address: tarek-gnr@hotmail.fr (T. Ameid).

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and accuracy of the FFT are affected by the amount of time domain data. In addition this can be more affective in cases of inconstant load or speed, since both of them make a variation on the motor slip or time-frequency. Therefore, this assumption may be considered as a limitation of this approach and the FFT analysis cannot be applied by consequence. For this reason, the wavelet decompositions becomes our main focus in this paper which will be proposed in order to overcome the aforementioned difficulties [18–21].

The wavelet transform is a window technique with a variable size. It is used in order to improve the stator phase current analysis in steady and transient states. The wavelet transform is a new description of spectral decomposition via the scaling concept. Wavelet theory offers a unified framework for many techniques, which have been developed for different applications in the field of signal-processing. Moreover, it can provide information in both of time and frequency domains [22,23].

In Ref. [24], the authors present a method for the broken rotor bar fault detection based on discrete wavelet coefficients, when the induction motor operates with load variation. Others [25] use the DWT for the current space vector magnitude or the instantaneous magnitude of the stator phase current analysis, the energy associated to the rotor fault in the frequency bandwidth is computed, this energy allows to evaluate the fault severity without any slip estimation. The DWT is used in Refs. [18,26] for the analysis of stator current to detect the rotor bars fault in steady and start-up transient states, the calculation of the energy Eigenvalue of the stator current signal proves its importance as a good fault severity indicator. In most cases, the diagnostic methods are used for open-loop machine operation. However, in closed-loop drives, the control-loop masks and compensates the fault effect [10]. As a consequence, they cause a difficulty in fault detection using stator current analysis. Some attempts can be found in literature which uses other quantities for fault analysis. For instance, in Refs. [27,28], d (direct) and q (quadratic) current axis components have been used for broken rotor bars detection in closed-loop drive. Nevertheless in case of variable speed drive, the continuous speed variation between two reference values causes a non-stationary state in the signals and confusion in the DWT spectrum, consequently a more difficulties in the fault diagnosis process.

The main objectives of this paper are the diagnosis of the broken rotor bars fault and the evaluation of the fault severity when the IM operates in closed-loop drive with continuous speed change. The FOC control strategy is presented to preserve a high performance decoupled control. The used method for the fault detection is DWT analysis which will be applied to output signal of the speed regulator and stator phase current. The choice of this technique has been done to ensure a good diagnosis during the continual variation of speed. The evaluation of the stored energy in each level of the active power energy allows both, to evaluate the fault severity (break or fissure), and to distinguish between fault and normal variation.

The effectiveness of the control scheme with diagnosis method will be investigated in simulation and experimentation using the Matlab/Simulink software and hardware implementation using Real-Time interface (RTI) environment based on dSpace 1104 board. The realization of the control strategy is done by Digital Signal Processor with graphical programming platform (Matlab/Simulink/Control Desk). The simulation and experimental validation has shown a good dynamic control under rotor bars fault, wherein, the same signatures of the fault are proved in both results.

This paper is structured as follows: Section 2 presents the dynamic modeling of the IM taking into account the rotor bars fault. Section 3 describes the vector controlled IM. In section 4, the discrete wavelet transforms method is proposed. Section 5 illustrates and discusses the simulation results of the proposed control technique with diagnosis method. Then, the experimental validation is presented in Section 6.

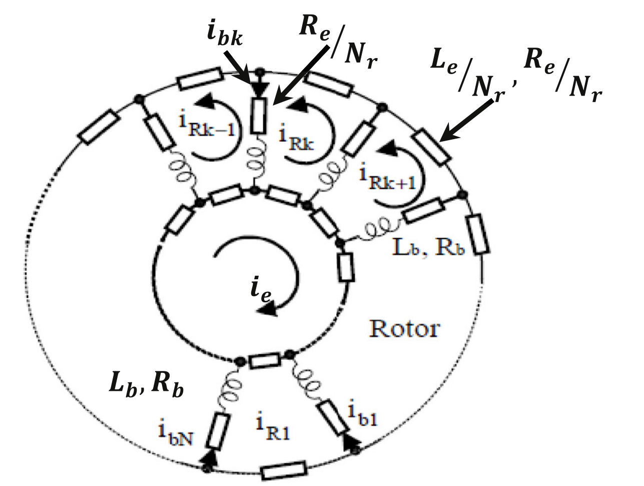

Fig. 1. Rotor cage equivalent circuit of induction machine.

2. Modeling of the induction motor with taking into account the rotor bars fault

The development of the reduced model which is dedicated for closed-loop control is inspired by the multi-winding model of the induction machine. This proposed model takes into account the rotor geometry which is considered as a squirrel-cage. The modeling is based on the equivalent scheme of the rotor which is shown in Fig. 1. It can be noticed that each bar of the rotor cage is represented by a resistance R_b, in series, with a leakage inductance L_b. The short-circuit ring portion between the two bars, as well, is represented by a resistance R_e in series with a leakage inductance L_e. A mesh is composed of two bars and two portions, hence, the cage is modeled by q number of meshes where each mesh represents one of the two rings of the short circuit, which are located on the rotor periphery. Therefore, with N_r number of bars, the cage contains $2N_r$ nodes and $3N_r$ branches based on the theory of electrical circuits. As a result, the number of independent currents in the cage is: $3N_r - (2N_r - 1) = N_r + 1$ [29,30].

The modeling steps are presented in details in Refs. [14] and [15] in order to highlight the effect of the broken rotor bar fault. This model presents a difficulty in the control implementation, due to the big number of equations. To transform the system in N_r phases into *(d, q)* system, the extended Park's transformation of the rotor will be applied.

The system is put in canonical form:

$$[L]\frac{d[I]}{dt} = [V]-[R][I] \tag{1}$$

where:

$$[L] = \begin{bmatrix} L_{sc} & 0 & -\frac{N_r}{2}M_{sr} & 0 & 0 \\ 0 & L_{sc} & 0 & -\frac{N_r}{2}M_{sr} & 0 \\ -\frac{3}{2}M_{sr} & 0 & L_{rc} & 0 & 0 \\ 0 & -\frac{3}{2}M_{sr} & 0 & L_{rc} & 0 \\ 0 & 0 & 0 & 0 & L_e \end{bmatrix};\ [R] = \begin{bmatrix} R_s & -\omega_r L_{sc} & 0 & \frac{N_r}{2}\omega_r M_{sr} & 0 \\ \omega_r L_{sc} & R_s & -\frac{N_r}{2}\omega_r M_{sr} & 0 & 0 \\ 0 & 0 & [R_{rdd} & R_{rdq}] & 0 \\ 0 & 0 & [R_{rqd} & R_{rqq}] & 0 \\ 0 & 0 & 0 & 0 & R_e \end{bmatrix};$$

As:

The total cyclic inductance of a stator phase which is given by the following equation:

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