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Simplified detection of broken rotor bars in induction motors controlled in field reference frame

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ABSTRACT

In this paper, a simple method for additional on-line detection of broken rotor bars in a squirrel cage induction motor controlled in rotor field co-ordinates using existing hardware is presented. Based on a previously presented approach, an algorithm for on-line calculation of the variance of stator voltage reference, which depends on the number of broken bars, has been developed. Due to its simplicity, it could run in parallel with a standard control algorithm in field reference frame using contemporary fixed- and floating-point processors, thus requiring minimum processing time. The algorithm uses internal reference values of the stator voltage; therefore no additional dedicated measurements are needed. Results were obtained at different operating points on an induction motor with gradually damaged rotor. Comparison with commonly used diagnostic method confirms the validity of the approach.

1. Introduction

Motor drives provide flexible, reliable, versatile, and high efficient source of mechanical energy. Their on-going progress enabled not only vast improvements in purely industrial applications, but also sparked growth of numerous consumer products. In recent years, field of motor drives is playing a vital part in the development of certain emerging technologies such as electrical vehicle or alternative energy sources.

As any type of device the motor drives are also subject to various faults. Generally, three groups of causes can be distinguished. Firstly, there are design issues. Each drive comprises stationary as well as moving parts made of various materials linked by different types of junctions. When design configuration is too complex the drive itself becomes more prone to fault. Secondly, modes and conditions of operation such as frequent changes in speed and torque, overloading, non-adequate installation and maintenance, and invasive environment induce fault occurrence as well. Last but not least the drive is also open to usual wear and tear during its lifetime.

Proper error handling of the drive has always been an important issue in engineering. Two basic mechanisms of fault development depending on its progression can be discerned. In cases where fault occurs suddenly, without notice, one must rely solely on protection elements in the drive. Conversely, when fault develops gradually, during time span of a day, a week or a month, it is possible to detect it at an early stage, thereby timely enabling to undertake proper measures to avoid further aggravation.

In general, detection methods utilized in electrical drives are tailored to the specific type of erroneous state, thus various diagnostic methods differ in many aspects. For example, methods can be intrusive or interfere with regular operation, demand additional (analysis) equipment and/or special sensors, etc. Consequently, diagnostic feature, when integrated with the drive, most likely raises its immediate application cost. This is especially true for classic approaches to diagnostics using temperature, chemical or vibration analyses which are consequently limited to the larger units (power supply transformers and generators). In order to overcome this cost factor, trend of conceiving non-invasive, on-line diagnostic methods has emerged. Their goal is to establish health state of the drive using solely signals already available during normal operation (Combastel, Lesecq, Petropol, & Gentil, 2002).

In past, diagnostic methods were primarily designed for open-loop systems, i.e. not taking into consideration possible impact of a control loop. Its introduction generally makes detection ability more difficult as fault expression becomes unclear and nonconsistent. Therefore, detection in closed-loop drives calls for an upgrade of existing approaches or conceiving new detection methods. Number of proposals in contemporary scientific literature proves that there is a growing interest in solving the problems that closed-loop systems pose to detection and diagnostics.

Among several possible irregularities of induction motor drives, electrical asymmetry due to broken bars in rotor squirrel

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cage is often discussed in scientific and research literature (Mehrjou, Mariun, Marhaban, & Misron, 2011). The effects of one or more broken rotor bars propagate in several ways: as a distortion of magnetic field distribution, generation of particular side-band components in the stator current and an increase in torque and speed ripple. Thermal and mechanical stresses found in motors subjected to frequent start–stop operation constitute a major factor leading to broken or cracked rotor bars. The cracking usually occurs at the junction with the end ring. The damage impairs the torque of the motor and introduces low-frequency harmonic components. Healthy bars in imminent vicinity must conduct extra current, thus increasing the possibility of cracking due to increased stress. Many authors presented different approaches to modeling and detecting such fault due to the impossibility of direct measurements of rotor currents. A number of papers have been published discussing different techniques of broken bar detection (Bellini, Filippetti, Tassoni, & Capolino, 2008; Zhang, Du, Habetler, & Lu, 2011). The fault is irreversible so laboratory tests on induction motors with intentionally broken bars (mostly by drilling through the aluminum) have limited practicability and must be very carefully planned as return to the unimpaired state is impossible. To extend possibilities of laboratory tests some authors even developed specially designed induction motor rotors (Bruzzese, Honorati, & Santini, 2006). The majority of laboratory tests are performed on low-power induction motors, so an additional problem in motor diagnosis is to extend the conclusions to the large power motors in industrial practice.

The most common approach to detect broken rotor bars is based on motor current spectral analysis (MCSA). MCSA takes the advantage of correlation between specific fault type and its frequency component (Didier, Ternisien, Caspary, & Razik, 2007). This feature has provoked an ongoing research and produced many diagnostic methods which extend and upgrade the basic idea of MCSA. In due time, it has become an industrial standard, employed in various types of drives. In Nandi, Toliyat, and Li (2005) it was demonstrated that magnitude of the side-band components at specific frequencies can be used as an appropriate diagnostic index and that increase in number of broken bars raises its magnitude. The magnitude is also risen by increase of load, therefore for accurate broken bar detection several parameters have to be considered simultaneously.

Today, modern electric drives are equipped with inverter stage, which greatly enhances their flexibility and enables various additional tasks. On the other side, the detection potential of stator current, as most often used fault indicator, becomes somehow encumbered. More specifically, signal-to-noise ratio (SNR) of the current signal decreases significantly, which hinders appropriate distinction of specific fault frequencies. Moreover, as modern drives supplied by inverter are often used in applications with variable operating point, the fault frequency components are not fixed and the transients can affect fault signatures. In consequence, traditional methods of detection used for grid supply become ineffective and call for an upgrade. Detection task in closed-loop drives raises additional considerations. Effect of the type of the controllers and their parameters, as well as specific control method must be properly accounted for (Pires, Pires, Martins, & Pires, 2009). There is however a slight advantage the inverter supply brings to detection, as additional components arise in low frequency spectrum. This new set of information can subsequently enhance detection (Akin, Orguner, Toliyat, & Rayner, 2008).

Methods have been developed enabling on-line detection of various types of faults (Tavner, 2008). However, most of them rely on additional hardware components and sophisticated software. Evidently, logical step forward is to combine control and detection process in just one processor (nowadays usually digital signal processors—DSP), thus ensuring significantly lower cost of diagnostic monitoring/protection. Obvious challenge in this respect is overcoming computational burden and coping with numerous data, which are to be processed. Therefore, a detection algorithm designed for real-time DSP application should be fast and simple, without vast, time consuming calculations and/or need for large storage space. In other terms, this implies avoiding classic frequency analysis (through fast Fourier transform—FFT) where sufficient resolution could be attained only using large amount of data.

In this paper, a new method for detecting broken rotor bars in induction machine is presented. It was designed following next guidelines: simple implementation without additional measuring equipment, no interference with normal operation of the machine, diagnostic algorithm capable of extracting a fault in real-time and using solely existing computational resources of a microcontroller. Fulfilling these criteria offsets most of the causes, which prohibited the implementation of diagnostics in standard drives (mainly cost factor, invasiveness, etc.). Control signal of a closed-loop scheme is used to detect broken rotor bar fault instead of analyzing stator currents. Method previously presented by the same authors (Nemec, Drobnič, Nedeljković, Fišer, & Ambrožič, 2010) is modified and implemented in real-time on a DSP applying conventional Field oriented control (FOC). Considering that FOC is the most widely used approach in control of demanding drives, the proposed detection method gains conspicuous practical value. Differing from the original approach, the new one does not require any measurement of stator voltages, thus reducing the necessity of additional sensors. Instead, reference voltages are used, as being already offered by the standard control algorithm. These signals are then filtered and evaluated through their variance, a variable correlated to the number of broken bars.

The diagnostic algorithm is simple and short enough to be run on-line in parallel with a control algorithm on almost every processor on the market dedicated to machine control. In addition, RAM requirements are very small (1 kWord), which is very likely available without a need for any hardware modifications. In this paper, the results are reported for a machine using FOC, with different number of broken bars. Results are very promising, giving a distinct pattern for different fault conditions at almost all operating states.

With regard to the proposed method, there are certainly some important considerations when applying it to the high-power drives. Most of high-power motor run with low switching frequency, which makes detection more difficult (Nemec et al., 2010). Thus proposed fault indicator could become less pronounced subsequently hindering overall detection procedure. However, the proposed method is specifically aimed at small power motors, where low cost is paramount. With an addition of costless detection ability, one could improve the reliability of the drive.

2. Theoretical background

As already known broken rotor bars in induction motor (IM) cause additional harmonics in stator currents, which then transpose to the torque, causing ripple and speed oscillations (Fišer & Ferkolj, 2001). This effect is correlated to the number of broken bars and their location, as well as the operating point of the machine, particularly to the torque.

2.1. Previous work

In fast closed-loop control systems, such as FOC with current regulated space vector modulation (SVM), or predictive torque