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A fault detection scheme based on minimum identified uncertainty bounds violation for broken rotor bars in induction motors ☆

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ABSTRACT

In this paper, a novel method for broken bars fault detection in the case of three-phase induction motors and under different payloads will be presented and experimentally evaluated. In the presented approach, the cases of a partially or full broken rotor bars are being also considered, caused by: (a) drilling 4 mm and 8 mm out of the 17 mm thickness of the same rotor bar and (b) fully drilled (17 mm) one, two and three broken bars. The proposed fault detection method is based on the Set Membership Identification (SMI) technique and a novel proposed minimum boundary violation fault detection scheme, applied on the identified motor's parameters. The system identification procedure is being carried out on the simplified equivalent model of the induction motor, during the steady-state operation (non-fault case), while at the same time the proposed scheme is able to calculate on-line the corresponding safety bounds for the identified variables, based on a priori knowledge of the measuring corrupting noise (worst case encountered). The efficiency, the robustness and the overall performance of the established fault detection scheme is being extensively evaluated in multiple experimental studies and under various time instances of faults and load conditions.

1. Introduction

With the rapid advancement in the heavy industry, rotating machineries and especially the induction machines are becoming more and more complex, while since their size and cost are constantly increasing, these machines require a continuous attention in all the aspects of their operation. Although, induction machines from their manufacturing inherit robust properties such as high efficiency, good reliability, operational stability, robustness, durability, and power-to-weight ratio (Henao et al., 2014), still many types of faults might occur, leading to subsequence economical expenses, increases in the maintenance cost and further failures that might lead to complete system breakdowns. Moreover, it is widely well known, that a sudden motor failure may reduce the current productivity of the industrial system and thus it is of paramount importance to create proper and fully functional fault detection schemes, being able to diagnose and detect the incipient faults exactly on the time of their occurrence (Group, 1985).

Regarding the various faults that might arise, in the area of induction machines, the most common types are faults in the bearings, the stator, the rotor (broken bars or end ring) and eccentricity faults (Aydin, Karakose, & Akin, 2007; Kim, Youn, Wang, Sun, & Kang, 2013). From all these faults, the broken rotor bar faults are causing serious disruption on the motor, while this condition is an important fault, since even though broken bars do not cause motor failures initially, they can significantly lower the efficiency and shorten the lives of induction machines. In general, a defect out of the bars does not induce a machine stop, because the current flowing through the broken bar is spread over the adjacent bars. However, these defected bars are being overloaded, which can lead to a broken bar, and so on, until failure of a sufficiently large number of bars leads to switch off the machine. The presence of broken rotor bars causes an unbalance to the rotor magnetic flux, while during this stage, the current cannot flow through the broken or cracked bar/end ring (Gyftakis & Spyropoulos, 2013) and the rotor resistance of an induction motor will increase when a rotor bar breaks (Said, Benbouzid, & Benchaib,

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☆ Preliminary results and limited to one broken bar case at full load conditions have been presented in the 39th Annual Conference of the IEEE Industrial Electronics Society, IECON 2013.

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2000). The reasons for the occurrence of broken rotor bar failures are various and mainly depend on the large starting currents in an induction motor. On the other hand, the heating and cooling cause thermal stress (Garcia-Escudero, Duque-Perez, Morinigo-Sotelo, & Perez-Alonso, 2011), as well as an increase in the corresponding magnetic, residual, dynamic, and environmental stresses (Abbaszadeh, Milimonfared, Haji, & Toliyat, 2001). All these issues during the fault creation have a straight forward effect on the physical properties of the motor and a corresponding effect on the mathematical model that describes the whole operation, while this is the main idea that inspired the work presented in this paper.

In the related literature, several modeless methods and techniques have been proposed to detect broken bar faults, such as Wavelet-based techniques (Bouzida et al., 2013; Llinares, Daviu, Guasp, Sanchez, & Alarcon, 2013), Instantaneous Power Spectra analysis (Liu, Yin, Zhang, & Chen, 2004; Said et al., 2000), Model based methods (Combastel, Lesecq, Petropol, & Gentil, 2002; Loparo, Horattas, & Adam, 1997), and the Motor Current Signature Analysis (MCSA) (Ilonen et al., 2005; Thomson & Fenger, 2001). At this point it should be mentioned that the MCSA technique is still used as a first diagnostic approach, but the real conditions of industrial applications are such that it cannot be the only support for the development of diagnostic tools (Henao et al., 2014). Also, this technique has significant limitations mainly due to the increased complexity of the electric machines and drives (Henao et al., 2014). As an example, MCSA is the optimal choice for electrical machines under steady-state conditions and rated load. Furthermore, the Wavelet Transform (WT) was introduced with the intention of overcoming the difficulties mentioned above. WT analysis allows for the use of long time intervals if one would prefer a more precise low-frequency information and shorter regions in high-frequencies (Benbouzid, 2000; Kia, Mabwe, Henao, & Capolino, 2006). Instantaneous Power Spectra Analysis can be used for the detection of the most common motor damages in induction motors. To perform the method, it is only needed data from the current and voltage measurements in two phases (Liu et al., 2004). Consequently, it requires more sensors, form the MCSA method, but hypothetically, gives satisfactory results because the power harmonics amplitudes are greater than the current harmonics and the power spectra contain more diagnostic information, while the power harmonics, related to damages, have higher amplitudes. Conversely, artificial intelligence approaches have been introduced using concepts such as fuzzy logic, genetic algorithms, and neural networks (Said et al., 2000). The large amount of numerical data from the system is also an essential requirement for training a NN in these cases. Difficulties occur in these methods regarding the creation of a reliable network, and if there are not enough measurements available from all operation states of the process. Recently, identification and prediction techniques have also been utilised to perform diagnosis for the occurred faults (Gaeid & Mohamed, 2010).

Moreover, Discrete Fourier transform (DFT) has been utilised successfully to detect a broken rotor bar, when the motor operates near its full load. However, as it has been proved, the DFT method in the case of a light load such as 25% of full load, cannot produce robust enough results especially for the detection of an incipient rotor fault (Didier, Ternisien, Caspary, & Razik, 1997; Gu et al., 2015). In addition, broken-bar fault diagnostic techniques, based on the motor's magnetic-field space-vector pendulous oscillation concept, have also been introduced in (Mirafzal & Demerdash, 2006), while various attempts have been made for proposing diagnosis methods based on current measurements and pattern recognition analysis, for detecting and localising failures in induction motors (Ondel, Boutleux, & Clerc, 2006).

On the other hand, thermal and vibration monitoring has been alternatively utilised for decades (Thomason & Orpin, 2002). Transient approaches based on the acquisition of start-up currents and voltages have been also utilised as means to detect stator, rotor bar and end ring faults (Elder, Watson, & Thomson, 1989; Georgoulas et al., 2008; Penman & Stavrou, 1996; Supangat et al., 2006). Finally, machine learning techniques such as fuzzy logic (Zidani, Diallo, Benbouzid, & Said, 2008), genetic algorithms (Cristaldi, Lazzaroni, Monti, & Ponci, 2004), neural network (Filippetti, Franceschini, & Tassoni, 1995), Bayesian classifier (Haji & Toliyat, 2001), and Support Vector Machine (SVM) (Matic, Kulic, Sanchez, & Kamenko, 2012), have been introduced for motor fault's detection and classification. However, as a general remark, the area of fault detection and especially in the cases of broken bars, is still an open area of research, where multiple methods exist but still there is not a single one that could be optimal and applicable in all the cases and for all the desired outcomes. As a major contribution in this paper, the presented model based fault detection scheme is aiming in establishing another fault detection and isolation methodology that can be easily tuned and applied online in induction motors.

Recently, system identification based on time domain prediction techniques has been utilised to perform model based fault detection and diagnosis and more specifically, the theory of Set Membership Identification (SMI) has been efficiently applied in simulated studies in order to detect and diagnose faults in the cases of stator windings and broker rotor bar faults (Mustafa, Nikolakopoulos, & Guastafsson, 2012). Moreover, in Mustafa, Nikolakopoulos, and Guastafsson (2013) the authors have demonstrated an experimental verification of the SMI technique with respect to the detection of one broken bar fault in induction motors. The results depicted in that article have been very promising and set the basis for further investigations and formal establishment of a fault detection and isolation scheme for the case of various types of broken bar failures, which is the main focus of the presented research approach and extended theoretical and experimental results.

The main contribution of this paper is dual. Initially, a novel and complete fault detection framework based on the SMI scheme for partial or full broken bars is being established. Secondly, the proposed detection scheme is being experimentally evaluated in multiple different test cases of broken rotor bars faults, such as gradually or partially drilled rotor bars and related extended discussions and insights for the established fault detection method are being depicted. Based on the best of author's knowledge, this is the first time that a system identification scheme based on SMI has been experimentally verified and analysed in the field of fault detection in induction motors. As it will be presented in the following sections, the proposed scheme is able to identify the fault in due time after the fault occurrence, while the method has been applied on-line and can be easily tuned based on the characteristics of the motor under study.

The rest of the paper is structured as it follows. In Section 2, the SMI scheme is being presented, followed by the proposed fault detection conditioning framework in Section 3. Section 4 contains multiple experimental results that prove the efficacy of the proposed SMI based fault detection scheme, while the conclusions are drawn in Section 5.

2. Set Membership Identification

Set Membership Identification (SMI) refers to a class of techniques for estimating parameters of linear and non-linear systems (Deller, 1989; Milanese & Novara, 2004). The objective of the SMI technique is the determination of the feasible parameter set that contains the nominal parameter vector, the measurement data and the a priori known bounded noise-error. Due to the complexity in computing the feasible parameter set, the majority of the SMI