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Evaluation of stator winding faults severity in inverter-fed induction motors

Wagner Fontes Godoy [a,b], Ivan Nunes da Silva [a], Alessandro Goedtel [b,*], Rodrigo Henrique Cunha Palácios [a,b]

[a] University of São Paulo (USP), São Carlos School of Engineering, Department of Electrical Engineering, Av. Trabalhador São Carlense, 400, Centro, 13.566-590, São Carlos, SP, Brazil

[b] Federal Technological University of Paraná (UTFPR), Department of Electrical Engineering, Av. Alberto Carazzai, 1640, Centro, 86.300-000, Cornélio Procópio, PR, Brazil

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ABSTRACT

Three-phase induction motor are one of the most important elements of electromechanical energy conversion in the production process. However, they are subject to inherent faults or failures under operating conditions. The purpose of this paper is to present a comparative study among intelligent tools to classify short-circuit faults in stator windings of induction motors operating with three different models of frequency inverters. This is performed by analyzing the amplitude of the stator current signal in the time domain, using a dynamic acquisition rate according to machine frequency supply. To assess the classification accuracy across the various levels of faults severity, the performance of three different learning machine techniques were compared: (i) fuzzy ARTMAP network; (ii) multilayer perceptron network; and (iii) support vector machine. Results obtained from 2.268 experimental tests are presented to validate the study, which considered a wide range of operating frequencies and load conditions.

1. Introduction

Three-phase induction motors are now the primary means for industry to transform electrical energy into mechanical driving. Offering robustness and low cost, they can be used in most industrial applications, particularly in the production of components and accessories. As a result, these machines have widespread applications in various industrial processes [1,2].

Although typically robust and well constructed, these motors have an inherent possibility of failure when in the operation. Incipient defects inside the machines usually affect their performance even before significant failures occur, which can cause losses in the industrial process. The application of methods for reliable fault diagnosis allows for effective maintenance and a consequent reduction in operational costs [3].

According to [4] major faults found in three-phase induction motors are derived from electrical or mechanical problems. Stator faults represent approximately to 36–40% of the electrical problems associated with undesired stops in electric motors [4,5], and these figures were recently confirmed in [6–8].

Traditional non-invasive techniques can be used to diagnosis this type of fault. These strategies are based on the analysis of quantities such as vibration, voltage, current, torque and speed [4,7,9,10].

Currently, motors driven by using frequency inverters are an integral part of many production processes, due to their characteristics of speed regulation, fast dynamic response and allowing the incorporation of direct torque control schemes. Fault diagnosis in motors driven by frequency inverters has attracted the attention of many researchers in recent years [11]. Diagnostic technology currently available includes in several commercial models overvoltage/undervoltage, overcurrent, motor overload, short-circuit faults on the outputs, and protection against overheating.

The literature discusses how faults detection in inverter-fed induction motors is influenced by the dynamics control as well load changes [4,12,13]. In the work [14] stator short-circuit faults in an inverter-fed induction motor were detected by reconstructing the stator current. Constant switching of the inverter voltage source contributed to a temperature increase and consequent wear of the winding insulation, leading to stator faults.

In the work of [15] it was proposed the application of voltage tests, with the aid of the frequency converter, to evaluate the degradation of stator insulation in induction motors. These tests were performed when the motor was turned off. Additionally, the work

* Corresponding author. Tel.: +55 4335204096.
E-mail address: agoedtel@utfpr.edu.br (A. Goedtel).

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of [8] suggests the diagnosing of stator faults in motor feeds either line connected or by inverters by comparing the analysis signature of instantaneous active and reactive potency obtained through current and voltage measures in the frequency domain.

Computational methods have been widely studied for the diagnosis and classification of faults in electrical machines [9,16], and are able to classify and determine the origin of faults which are still evolving [17,18].

The area of pattern recognition is based on the automatic discovery of data regularities through the use of computational algorithms, and them using these regularities to take actions such as classification these data in different categories [19].

In the work of [20], stator winding fault detection in an inverter-fed motor is performed by analyzing the harmonic content of the stator current signature. The authors analyze a motor working with no load, 50% and 100% of rated load at frequencies of 30, 50 and 60 Hz, using a low sampling rate to acquire the signals, which were subsequently interpolated.

More recently, [6] developed a method for stator short-circuit fault diagnosis through the use of magnetic signals, by using the numerical finite element method in association with Artificial Neural Networks (ANN).

Although the ANN and fuzzy logic have been presented separately as potential candidates for various approaches and pattern recognition applications, hybrid systems that combine fuzzy logic and ANN have been investigated for their pattern recognition and classification properties due to high adaptability and excellent generalization ability [21–23].

Research on transient signals of induction motors has also attracted recent attention. Based on techniques for signal processing, [24] addressed the concept of fault identification by using Wavelet to analyze the current during the start-up transitional regime.

Reference [2] developed an application based on analysis of the current signal during the transitional regime of the machine. The current signals were decomposed into individual components by Fourier-Bessel expansion, followed by application of generalized discriminant analysis to reduce the dimensionality of the original features of the signal. Finally, the simplified fuzzy ARTMAP classifier is used to identify motor conditions. The authors performed a comparative study with the SVM method.

In reference [25] it was examined experimental results for the monitoring of small short-circuit faults by using signal processing techniques and data reduction tools which combined the Park transform and the continuous Wavelet transform. The SVM technique is used to characterize failures based on the fault characteristics extracted by using the Wavelet. In [11], it was investigated the use of vibration signatures to diagnose multiple faults in inverter-fed motors, combining the wavelet transform with the SVM classifier and also k-nearest neighbor (k-NN).

Accordingly, the purpose of this work is to present an alternative strategy to traditional methods based on intelligent systems for the diagnosis and classification of faults in the stator winding of an induction motor driven by three distinct inverter models. This is performed by monitoring the amplitudes of the currents signal in the time domain, using the waveform to classify faults of 1%, 3%, 5% and 10% of short-circuit between the turns of the stator winding. A total of 2.268 tests with 1 and 2 HP motors, at steady state are performed by varying the frequency range between 12 Hz to 60 Hz, under load conditions ($10\% < Tn < 110\%$), where Tn is the nominal torque. The high dimensionality of the input vectors is solved by a discretization signal capable of translating the information needed without mischaracterizing the waveform, thereby reducing the computational classification complexity. This leads to an accurate diagnosis of motor conditions, which includes detecting incipient defects and predicting the induction mode if the induction motor.

Table 1
Fault types.

Electrical	Mechanical
Stator winding	Wear coupling
Rotor windings	Misalignment
Rotor broken bars	Eccentricity
Broken rings	Bearings
Connections	-

This work also compares the performance of three supervised learning machine techniques: (i) the network Multilayer Perceptron (MLP), (ii) the network Fuzzy ARTMAP (FAM), and (iii) Support Vector Machine (SVM/SMO).

This paper is organized as follows: Section 2 describes of the main faults in electric motors, with a focus on the stator faults. Section 3 presents selected approaches of intelligent systems. Section 4 discusses the proposed methodology for network performance evaluation and presents the experimental data results, while the conclusions appear in Section 5.

2. Aspects associated with stator faults

The monitoring of the operating conditions of an induction motor, in order to diagnose faults and predict operating conditions, has attracted the attention of many researchers in recent years. This is due to the considerable influence of these motors on the continued operation of numerous industrial processes [2–4]. The detection and accurate early diagnosis of incipient faults can minimize damage to an industrial process, increasing the availability of equipment and consequent maintenance of financial performance.

Electric motors are subjected to various types of failures or faults, which can be divided into (*i*) electrical; and (*ii*) mechanical [4,5]. Table 1, shows the classification of the main types of induction motors faults.

Any type of fault that causes an unbalance is reflected in characteristics such as torque, the field flux, and stator currents, among others. By analyzing these signals, faults can be detected between the stator windings [23]. The most common faults associated with the stator windings are short-circuit between phase-earth, phase-to-phase, short-circuits between the winding turns of same or different phases [2]. Stator insulation deterioration usually begins with a short-circuit involving just a few turns; however, its evolution is rapidly prejudicial to motor operation [4,8,23]. The situation becomes even worse in the case of inverter-fed motors [18].

Reference [26] states that the short-circuit current was approximately twice of the blocked rotor current, causing local heating which rapidly extended to other winding sections. Also, [18] contend that an incipient insulation defect among the stator windings, if not identified, may eventually cause irreversible motor damage.

Failure isolation is due to various reasons, but primarily for excessive temperature increases [23], as the temperature in the electric machines windings exerts essential influence on the performance of the insulation. According to [27], an increase of 10 °C above the specified threshold can reduce the estimated useful life of a motor by about half. Drives in low frequency ranges associated with high load torque can result in temperature increase in the motor windings, leading to a reduced life span. Other reasons for isolation faults includes voltage surges, aging, vibration, inadequate mechanical handling procedures during maintenance, excess lubrication during replacement of damaged bearings, and also the inevitable natural degradation of the insulation [15,27,28].

Fault evolution time is hard to estimate and depends on the operating conditions of a motor. However, the evolution is know to