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A comprehensive evaluation of intelligent classifiers for fault identification in three-phase induction motors

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ABSTRACT

Three-phase induction motors are the key elements of electromechanical energy conversion for a variety of industrial sectors. The ability to identify motor faults before they occur can reduce the risks in decisions regarding machine maintenance, lower costs, and increase process availability. This article proposes a comprehensive evaluation of pattern classification methods for fault identification in induction motors. The methods discussed in this work are: Naive Bayes, k-Nearest Neighbor, Support Vector Machine (Sequential Minimal Optimization), Artificial Neural Network (Multilayer Perceptron), Repeated Incremental Pruning to Produce Error Reduction, and C4.5 Decision Tree. By analyzing the amplitudes of current signals in the time domain, experimental results with bearing, stator, and rotor faults are tested using different pattern classification methods under varied power supply and mechanical loading conditions.

1. Introduction

Three-phase induction motors (TIMs) are frequently used in various industrial sectors. These machines are characterized by their low acquisition and maintenance costs, adaptability to different mechanical loads, and robustness in harsh working environments. They consume more than 60% of the electricity in the industrial sector [1] and are the primary means of transforming electrical energy into mechanical driving [2].

Like all electrical machines, these motors need proper maintenance, as faults can adversely affect production processes and cause substantial losses for the industries where they are used. According to [3], the correct diagnosis and early detection of incipient faults in TIMs results in quick unscheduled maintenance, whereby the machines are offline for brief periods only.

Operational faults related to TIMs may be divided into two major groups: electrical and mechanical faults. Electrical faults are mainly characterized by problems regarding the stator winding, rotor winding (found on some motor models), broken rotor bars, broken rotor rings, and faulty connections, while mechanical faults include problems with bearings, eccentricity of the shaft or rotor, and wear coupling misalignment [3]. Of the faults reported in the literature, the work of [4,5] states that the bearing, rotor, and stator are responsible for about 78–88% of breakdowns in electric motors.

Various intelligent approaches for pattern recognition have recently been used to identify faults in induction motors. Intelligent techniques such as Naive Bayes (NB), k-Nearest Neighbor (KNN), Support Vector Machine with Sequential Minimal Optimization (SVM), Artificial Neural Network (ANN), Repeated Incremental Pruning to Produce Error Reduction (RIP), and C4.5 Decision Tree (C4.5) have been effective at pattern recognition in many applications reported in the literature.

Some works in the literature are related to pattern identification based on the Bayes theorem. The research conducted by Hajiaghajani et al. [6], where the current signals in the frequency domain were used as input to supply the system, proposed using this method to detect eccentricity faults in a DC motor. In the research presented in [7], the NB, KNN and SVM pattern recognition methods are tested to check induction motor faults such as broken rotor bars, tilted rotors, unbalanced rotors, short-circuits in the stator winding, and bearings flaws. Analysis is based on the motor current data to extract the frequency domain (Hilbert transform), statistics (RMS,

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skewness, kurtosis, entropy, and crest factor), and feature selection (such as PCA and ICA). The authors specified that these tests were conducted under different load variations and by using an inverter fed.

The KNN method has been employed in several pattern recognition studies. For diagnosing faults in TIMs, the work developed by Ondel et al. [8] proposed a solution to detect broken bars under various levels of mechanical load, based on voltage and current signal in the frequency domain. In [9] the authors sought to diagnose eccentricity faults in synchronous motors by using wavelet decomposition and principal component analysis. This approach analyzed the stator current signature in the frequency domain, using a frequency inverter for speed control and torque variation for the bench tests. The KNN and FSVM (Fuzzy Support Vector Machine) methods were used to classify the fault.

The SVM method is recognized in the literature as an effective method for solving problems which require pattern recognition. In recent years several works have been published about detecting flaws in induction motors, such as that presented by Konar and Chattopadhyay [4], where a system was developed to identify bearing faults by using SVM plus Wavelet. Motor vibration signals were used as SVM input, which performs the classification conditions. The methodological structure comprised a frequency inverter, while the experiments were conducted under three separate loading conditions: no load, half of the rated load, and nominal load. The experimental results also demonstrated the results compared with SVM and ANN. Another recent work [10] developed a method for using magnetic signals to identify faults such as unbalanced currents and short-circuits in the stator windings of TIMs. The results used the numerical finite element method and Artificial Neural Networks to generate simulation and experimental data. The SVM method was also used to collect data from the vibration signal, with sinusoidal supply, for detecting bearings faults (balls, inner race, and outer race) [11]. This research did not consider the imbalance of supply voltages in the machine or load variation in its experiments.

The development of data-acquisition techniques is also investigated. The purpose of article [12] was to employ a low-cost technique using multi-sensor and wireless transmission in order to monitor the condition of faults in bearings and eccentricity under motor-fed induction with variable frequency drive. For this, the authors used the stator current and acoustic signs at frequency domain (FFT and Hilbert–Huang transform) and QDA (quadratic discriminant analysis), where the SVM method performs the classification. The inner race, outer race, cage, and bearing lubrication were investigated for bearing failure problems. Other important studies related to using SVM to identify faults with induction motors appear in [13–15].

Decision trees are simple representations of knowledge. They can be applied to learning systems and are widely used in classification algorithms. In the research of TIM faults, some recent studies [16] describe an investigation of bearings faults in TIMs by using methods based on decision trees, called Random Forest and C4.5 Decision Tree. Mechanical vibration signals are used as the input of these methods in the time frequency domain and considering sinusoidal supply. To complete the pre-processing system, the Principal Component Analysis (PCA) and Linear Discriminant Analysis (LDA) are used to reduce the size and complexity of the feature set. The results indicate that the Random Forest method is the most efficient for this work. The research presented in [17] proposed a method that uses the measurement of a phase current signal, through the Hilbert transform, to build a representation of a graphic image, allowing the detection of edges in images and pattern recognition of faults related to broken rotor bars and connectors in TIMs with sinusoidal supply and disregarding loading variation. This same study evaluated the following classifiers methods: C4.5, Artificial Neural Networks, Gaussian mixture models, negative selection algorithm based on genetic algorithm, and artificial immune classifier with learning particle swarm.

ANNs are computational techniques which present a model inspired by the neural structure of intelligent organisms, and which acquire knowledge through experience. This method is characterized by its flexibility and range of architecture. Several studies [18] regarding fault classification in induction motors have recently been published. The authors presented two ANN-based schemes in order to identify and diagnose faults in induction motor rotors through the use of self-organizing maps. The first scheme used a single phase current signal in the frequency domain to diagnose the load unbalance and shaft misalignment. This neural network was trained and validated using data generated through simulation. The second scheme was carried out by analyzing the frequency of active and reactive instantaneous power in order to detect and classify broken rotor bars and oscillating loads faults. The research conducted by Ertunc et al. [5], the authors presented a new methodology for monitoring the condition of the bearings in a three-phase induction motor. The tests presented in this paper used the ANN and Neuro-Fuzzy (ANFIS) models, in the time and frequency domain, to generate data resulting from the vibration and stator current of an induction motor with sinusoidal supply. The authors inserted predefined bearing flaws into the internal and external tracks in order to detect the severity of the fault. In [19], proposed a set of hybrid intelligent models for condition-monitoring of induction motors under the following mechanical load conditions: 25%, 50%, 75%, and nominal torque, considering the sinusoidal supply. To classify the faults, the authors used the Neural Network Fuzzy Min-Max (FMM) and Random Forest (RF) with inputs fed by the stator current signals through the MCSA (Motor Current Signature Analysis) method in the frequency domain. The experimental results also considered noisy environment situations. One recently employed technique, found in [20], applied the analysis of acoustic data from an induction motor, captured simultaneously by multiple microphones. Correlations and analysis based on signal processing by wavelet transform are used in the current study as the inputs to extract features. The pattern classification method used is based on Konohen self-organizing maps, and faults in bearings, broken rotor bars, and short-circuits in the stator are investigated. Other ANN-related investigations of induction motors appear in [21–23]. Recently in Ref. [24], researchers focused on the development of a solution to identify stator inter turn short-circuit in a permanent magnet synchronous motor. A Multilayer Perceptron network was used for the diagnosis and classification of different levels of short-circuit and check its severity under variable speed and load torque conditions. The pre-processing in the frequency domain is processed via FFT.

Furthermore, statistical methods are also studied as an alternative to intelligent systems as can be observed in the work of [25] where this tools were tested to diagnose rotor broken bars faults in three phase induction motors (0.75 and 1.1 kW) by means of features extracted from the stator current by the power spectral density (PSD) using the FFT. For the experiments, the motors were driven by frequency inverters under different load torque conditions.

Image-based methods are also currently being investigated for fault identification in induction motors such as Ref. [26] which presents a methodology based on segmentation of thermographic images for fault diagnosis in induction motors. According to the authors, this methodology diagnoses broken bars in the rotor, bearings, mechanical unbalance, misalignment and also unbalance voltage.

The primary purpose of this study is to analyze the behavior of the Naive Bayes, C4.5, RIPPER, KNN, SVM/SMO, and ANN/MLP classification methods under various operating conditions and induction