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Analysis of fault signatures for the diagnosis of induction motors fed by voltage source inverters using ANOVA and additive models

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ABSTRACT

Condition monitoring of voltage source inverters-fed induction motors is challenging since the influence of the supply complicates the use of methods valid for utility fed motors. Analysis of variance is performed over data obtained in a controlled laboratory experiment where a hole was progressively drilled into a rotor bar. Additive models are obtained to stand out the influence of the operating conditions and the supply on the amplitude of the fault signatures. Useful conclusions for the design of diagnosis systems for the detection of broken bars in induction motors are drawn from the analysis.

1. Introduction

Induction motors are essential in many industries. Their simplicity and ruggedness are outstanding advantages and make them by far the most commonly used type of motor in sizes ranging from fractional horsepower to grades of industrial applications [1]. However, owing to the thermal, electrical and mechanical stresses, industry is confronted with unexpected faults and lifetime reduction of these motors [2].

The need to increase reliability against possible faults has attracted considerable interest in fault diagnosis of induction motors in recent years [3–7]. The main aim of a condition monitoring system is to detect incipient faults before a potentially harmful machine failure occurs with low missed and false alarms rates, in order to discriminate among various machine conditions, classifying faulty modes from normal modes.

Motor current signature analysis (MCSA) is currently considered as a standard in preventive maintenance basically due to the advantages of using non-invasive sensors [8,9]. Nevertheless, the introduction of VSI-fed (voltage source inverters) motors in applications where variable speed and torque are needed has produced significant changes in the field of diagnostics needing further research in order to overcome various challenges such as higher noise level (inherent floor noise reduces the possibility of true fault signature recognition using line current spectrum) [10,11], dynamically changing excitation frequency and the fact that fault signatures can significantly change from open-loop to closed-loop VSI operation. All these effects complicate the utilization of frequency analysis methods [12]. VSI-fed motor faults have been analyzed and initial results are given in literature [13–19] but further investigation is still required [20].

The amplitude of fault harmonics is also affected by the supply voltage, making any of these anomalies more noticeable as the supply voltage increases, provided that the machine is not working under saturation condition. This is very important, and it must be taken into account, particularly, with controlled-speed induction motors, when this control is based on voltage regulation, keeping constant the voltage/frequency ratio. Therefore, to develop a generic condition monitoring method valid for any supply and

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Table 1
Specifications of the tested motors.

Motor	Rated power (kW)	Rated voltage (V)	Rated current (A)	Rated speed (rpm)	Pole pairs
M1	0.75	3 × 230/400	1.9	1395	2
M2	1.1	3 × 230/400	2.6	1415	2

at different operating conditions, further considerations must be taken into account.

Considering this goal, in this paper it is analyzed the suitability of a number of fault signatures obtained from the stator current to diagnose rotor faults in induction motors fed by different supplies. First, statistical tools such as boxplots and analysis of variance (ANOVA) are used to analyze the data obtained from a case study in which a cage fault condition has been produced by drilling a hole in one of the bars of an induction motor. Different fault conditions have been obtained by progressively making the hole deeper.

Secondly, additive models are obtained, which are easy to interpret but are more powerful analysis tools than linear models, as it is shown in Section 5. The aim of this analysis is to evaluate the potential and suitability of the data, composed by the aforementioned fault signatures, to be used in a condition monitoring task and to study the influence on the diagnosis of the type of motor (two motors of different rated powers have been tested), the motor supply (five supplies have been used, utility supply and four different frequency inverters with different types of control) and the motor load level (the motors have been tested from low load to full load). It is also evaluated the capability to distinguish among four different rotor bar states: healthy, incipient fault (corresponding to a 6 mm depth hole), half-broken bar and full broken bar.

The results show that the same fault severity produces different fault signature amplitudes depending on the type of the motor, supply and load level. This is critical in the construction of a universal diagnosis procedure. Another significant contribution of this paper is the use of the additive models to quantify the influence of each of these influential variables in the amplitude of the fault signatures, allowing the subtraction of the contribution of a variable in the fault signature value. This way, when constructing a universal diagnosis procedure, the bias produced by any of these variables can be avoided.

2. Detection of broken rotor bars in VSI-fed induction motors

Induction motor failure through broken rotor bars (where cracking is experienced in the rotor conductors) is common in many industrial applications. One of the reasons for this type of failures is that large starting currents occur when cooling is at minimum, resulting in thermal and mechanical stresses being at maximum. The incidence of this failure mode is greatest when the start-up time is relatively long and when frequent starts are required as part of a heavy-duty cycle [21]. Initially, they start as high resistance, causing high temperature, and then progress as cracking or small holes in the rotor bars [22]; healthy bars in imminent vicinity must conduct extra current, thus increasing the possibility of cracking due to increased stresses [23]. To prevent such cumulative destructive process, the problem should be detected as early as possible [24]. Recently, improvements in machine design and manufacturing have been very important in diminishing the occurrence of other types of faults in induction motors but squirrel cage design has only changed slightly [25].

When the cage winding is symmetrical and assuming a purely and balanced sinusoidal voltage supply, there is only a forward rotating field at slip frequency with respect to the rotor. If a rotor asymmetry occurs, there will be a resultant backward rotating field at slip frequency with respect to the forward rotating rotor. This backward rotating field induces a voltage and a current in the stator winding at $(1-2s)f_1$ frequency (known as lower-sideband harmonic, LSH), where s is the motor slip and f_1 is the fundamental frequency. This induced current is the cause of torque and speed pulsations, which at the same time, induce new electromotive forces in the stator, and as a result, new counter currents are produced at frequency $(1+2s)f_1$ (known as upper-sideband harmonic, USH). This process goes on indefinitely, until it is damped and a pair of new sidebands appears around the main frequency f_1 [26].

In VSI-driven induction motors, the line current will contain additional time harmonics whose number, frequency and amplitude will depend on the switching strategy of the semiconductors. These time harmonics will generate new air gap spatial harmonics or will modify the amplitude of the existing ones. That is, in addition to the characteristic motor spectrum, new harmonics will be introduced, related to the fault condition, to the driven load or to the system performance. Therefore, the current spectrum is affected by many factors, including the motor characteristics (stator connection, design and application), the power supply and the fault condition.

When a motor with a cage asymmetry is fed by a non-sinusoidal voltage supply, the process is very similar to a motor fed by a balanced and sinusoidal one [27]. A pair of sidebands around the time harmonics of the line current will appear at frequencies $(k \pm 2\,ns)f_1$, where k is the order of the line current time harmonic and n is any positive integer. The number of sidebands will increase progressively, but their amplitude will decrease as they move away from the main frequency, although the magnitude of this amplitude attenuation will depend on the machine and driven load inertia and the building characteristics of the motor, which, in turn, depend on its purpose or application.

3. Case study

In this work, stator current is the signal measured and processed to determine the condition of the induction motor. Two different motors, star connected, were tested. Each motor was fed from a set of three different sources. The first motor, named M1, was fed from the utility supply (UT), an inverter by Telemecanique (TE) and a laboratory inverter by Lucas Nülle (LN). The second motor, named M2, was also fed from three sources: utility supply (UT) and two frequency inverters by Allen Bradley (AB) and by Siemens (SM). Table 1 shows the specifications of both motors. The control of the TE and SM inverters was of V/f linear type, the AB inverter had sensorless vector control, while the control of the LN inverter permits an independent adjustment of voltage and frequency. All four inverters operated with the slip compensation option off and with an assigned frequency of 50 Hz. In each test, the stator current was measured using a Hall effect current probe by Fluke (i30s) and a DAQ board by National Instruments (PCI-6250M) as data acquisition equipment. The software used was Labview DLLs for data acquisition, Matlab for signal processing and R as statistical software for data analysis.