Control Engineering Practice 52 (2016) 15–23

Contents lists available at ScienceDirect

Control Engineering Practice

journal homepage: www.elsevier.com/locate/conengprac

# Detecting broken rotor bars in induction motors with model-based support vector classifiers ☆

Mohammed Obaid Mustafa [b], Damiano Varagnolo [a,*], George Nikolakopoulos [a], Thomas Gustafsson [a]

[a] Department of Computer Science, Electrical and Space Engineering, Division of Signals and Systems, Luleå University of Technology, Sweden
[b] Department of Electrical Engineering, Collage of Engineering, University of Mosul, Mosul, Iraq

ARTICLE INFO

*Article history:*
Received 30 June 2015
Received in revised form
11 February 2016
Accepted 29 March 2016
Available online 19 April 2016

*Keywords:*
Fault detection
Model based methods
Broken rotor bar
Three phase asynchronous motors
Statistical characterization
Support vector classification
Motor current signature analysis

ABSTRACT

We propose a methodology for testing the sanity of motors when both healthy and faulty data are unavailable. More precisely, we consider a model-based Support Vector Classification (SVC) method for the detection of broken bars in three phase asynchronous motors at full load conditions, using features based on the spectral analysis of the stator's steady state current (more specifically, the amplitude of the lift sideband harmonic and the amplitude at fundamental frequency). We diverge from the mainstream focus on using SVCs trained from measured data, and instead derive a classifier that is constructed entirely using theoretical considerations. The advantage of this approach is that it does not need training steps (an expensive, time consuming and often practically infeasible task), i.e., operators are not required to have both healthy and faulty data from a system for checking it. We describe what are the theoretical properties and fundamental limitations of using model based SVC methodologies, provide conditions under which using SVC tests is statistically optimal, and present some experimental results to prove the effectiveness of the suggested scheme.



## 1. Introduction

The interests in the on-line Fault Detection and Diagnosis (FDD) of faults in induction motors are given by the fact that more than 79% of the industrial electromechanical converters are Induction Motors (IMs) (Henao et al., 2014). Despite being highly reliable, these electromechanical devices are also subject to many types of faults. Early detection is then crucial to reduce maintenance costs, prevent unscheduled downtimes for electrical drive systems, and prevent risks for humans. Early isolation is important too, since different faults generally demand different countermeasures/actions on the plant.

Among the various possible faults in IMs, several of them occur in their rotor and/or stator. The most common faults are openings or shortings of one or more of the stator's phase windings (Nandi, Toliyat, Nandi, & Toliyat, 2005), broken rotor bars or cracked rotor's end-rings (Santos & Lubiny, 2010), static or dynamic air-gap irregularities (Acosta, Verucchi, & Gelso, 2004), and bearing failures (Anel, Azenol, & Benbouzid, 2007).

Many faults appear gradually, and sometimes it can be very difficult to detect them before they induce faults in connected processes. To ease the detection of these faults, a variety of sensors can be used to collect meaningful information. The most common sensors are measurements of stator voltages and currents (Acosta et al., 2004), external magnetic flux densities (Sushma, Samaga, & Vittal, 2010), rotor position and speed (Arif, Imdadullah, & Asghar, 2011), output torque (Arif et al., 2011), internal and external temperatures (Bacha, Henaob, Gossa, & Capolino, 2008), and vibrations (Thomason & Orpin, 2002).

The main objective of on-line FDD schemes is to detect and isolate the fault in its early stages. The aim of this paper is instead to develop and analyze a model-based scheme for the detection of broken bars in IMs that is endowed with some optimality properties, described in our statement of contributions.

*Literature review*: FDD schemes aim at distinguishing potential failure conditions from normal operating ones (Gao & Dai, 2013). The main dichotomy separates the existing schemes in:

**model-based methods,** where one first determines analytically mathematical models from first-principles, and then checks if the information obtained from measurements

☆This work is supported by the Framework Programme for Research and Innovation Horizon 2020 under Grant agreement no. 636834 (DISIRE), and the Swedish Research Council Norrbottens Forskningsråd.

* Corresponding author.
*E-mail addresses:* mohammed.obaid@ltu.se (M.O. Mustafa), damiano.varagnolo@ltu.se (D. Varagnolo), george.nikolakopoulos@ltu.se (G. Nikolakopoulos), thomas.gustafsson@ltu.se (T. Gustafsson).

http://dx.doi.org/10.1016/j.conengprac.2016.03.019
0967-0661/

comply with these models or not (Johansson, Bask, & Norlander, 2006). These methods do not need observations from *both* fault-free and faulty systems (that might not be available) and can thus be implemented in already existing plants;

**model-based methods,** where one gets measurements from a fault-free, a faulty and a to-be checked motors, and then decides whether the motor is healthy or faulty considering if the to-be checked measurements are (statistically) closer to the fault-free or the faulty ones. These methods potentially do not suffer of model imprecisions that may arise due, e.g., to simplifications, construction tolerances and wear of the machine. At the same time these methods come with the difficulty of obtaining data, and suffer for the absence of generalization capabilities: indeed training a method using a specific motor does not guarantee that that method will work for other motors.

Here we propose a method that exploits a model-based strategy, more precisely Support Vector Classifications (SVCs) and evaluations of the sidebands of the harmonics of the stator current (also known as Motor Current Signature Analysis (MCSA)). In the next bulleted paragraphs we thus review the literature on model-based methods, the literature on model-free methods based on SVC strategies, and the literature on model-free methods exploiting properties of the stator current.

• *Model-based methods*: Among the few manuscripts in this category, Bachir, Tnani, Trigeassou, and Champenois (2006) perform fault detection and localization of stator and rotor faults in IMs using model structures that are derived from theoretical considerations as in this paper, but using parametric estimation methods instead of SVC strategies. Also Kim and Parlos (2002) develop an empirical model-based fault diagnosis system, but using recurrent dynamic Neural Networks and multi-resolution signal processing methods, and lack describing the theoretical properties of the strategy. Da Silva, Demerdash, and Povinelli (2013) exploit instead models obtained using finite-element methods, and thus techniques and software tools not always available to practitioners. We notice that the current directions in these methods are to assess the existence of incipient/partially broken rotor bars under different load conditions (Garcia-Perez, Ibarra-Manzano, & Romero-Troncoso, 2014; Mustafa, Nikolakopoulos, Gustafsson, & Kominiak, 2016; Rangel-Magdaleno, Romero-Troncoso, Osornio-Rios, Cabal-Yepez, & Contreras-Medina, 2009).

• *Model-free methods based on SVC strategies*: Support Vector Classifications are based on structural risk minimization concepts (Vapnik, 1998), and require selecting opportune *features*, i.e., measurable and quantifiable characteristics to be exploited as benchmarks (see Section 3.5 for more details). In the literature one can find reviews on the generic usage of SVC technologies for the monitoring of machine conditions and for the diagnosis of faults (Widodo & Yang, 2007). Other works instead deal specifically with motors. E.g., Baccarini, Rocha e Silva, de Menezes, and Caminhas (2011) test unbalance, misalignment and mechanical looseness in three phase induction motors using measurements of vibrations as features. Keskes, Braham, and Lachiri (2013) instead detect broken bars by using features that are based on discrete wavelet transforms and wavelet packet transforms of the motor current signatures (the benefit of using these transforms being to require lower sampling rates). Kurek and Osowski (2010) also use spectral information of the phase current and phase voltage.

• *Model-free methods based on properties of the stator current*: Broken bars introduce distortions in the air-gap field that eventually modify the envelope and the spectrum of the current. Faulty spectra have indeed specific sideband components around the main supply frequency; FDD schemes can then act by checking the presence of these specific frequency components (Antonino Daviu, Aviyente, Strangas, & Riera-Guasp, 2013; Benbouzid, 2000; El Bouchikhi, Choqueuse, & Benbouzid, 2015; Kliman & Stein, 1992; Thomson & Gilmore, 2003). One can also exploit analysis of the envelope of the current, since faults cause modulation effects in time that are not present in non-faulty conditions. For example, da Silva, Povinelli, and Demerdash (2008) analyze these envelopes using Gaussian mixture models and reconstructed phase spaces to identify motor faults. On the other hand MCSA is the optimal choice for electrical machines under steady-state conditions and rated load (Henao et al., 2014), while frequency analysis is a generally exploited concept for checking industrial equipment (Cabal-Yepez, Garcia-Ramirez, Romero-Troncoso, Garcia-Perez, & Osornio-Rios, 2013). Other features other than amplitude of the harmonics and their combination could be instead considered starting from the results in Garcia-Perez et al. (2014).

*Statement of contributions*: In a nutshell we propose a model-based SVC methodology with provable optimality properties: more specifically, we propose a method to construct SVCs starting from generic features that are computed from models of fault-free and faulty motors. In this way we therefore do not need collecting training datasets, and thus address the situation in which there is no possibility of collecting data from both fault-free and faulty systems.

Remarkably, even if we explicitly derive the technique for some specific features, we provide and discuss a general framework that can be used also for other features, e.g., the ones surveyed in Ghorbanian and Faiz (2015). We thus propose a methodology rather than simply a method, and apply it to the MCSA case. In other words, we specialize the derivations for that particular case where the selected features are the ones that are currently believed to be the most powerful ones for motor fault classification purposes (i.e., features based on the analysis of the spectrum of the stator current at full load conditions). The method here described thus operates under the same conditions for classical MCSA analyses, even if it can be generalized for other cases.

What we believe is an other important contribution is moreover that we answer the question "*why should one use SVC strategies?*". More precisely, we motivate under which assumptions it is statistically correct to use SVC approaches, and perform experimental evaluations on real case scenarios to prove the validity of the technique for practical purposes.

At the best of our knowledge, thus, our contributions w.r.t. to the existing literature are as follows: (i) we propose for the first time and validate against real data a model-based SVC technique; (ii) we propose a broad methodology that can be applied to generic features and not only the ones that we present here; (iii) we clarify under which assumptions it is statistically optimal to use SVC strategies.

*Organization of the manuscript*: Section 2 starts with describing the effects of broken bars in IMs. Section 3 then introduces in general terms our methodology. Sections from 3.1 to 3.8 detail the specific steps defined by our methodology. Section 3.8 reports also a statistical analysis of the proposed classification rule. Section 4 describes some numerical results on artificially broken IMs. Section 5 then concludes by summarizing some remarks on the findings and by outlining future development lines.

## 2. Effects of broken bars on Induction Motors

Rotor bars break because of thermal, magnetic, residual, dynamic, and mechanical stresses (Kliman & Stein, 1992; Nandi et al., 2005), and constitute a significant part of the problems in induction motors (Motor Reliability Working Group, 1985, 1987).