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Fault diagnosis in induction machines using the generalized structured singular value

D. Henry*, A. Zolghadri, M. Monsion, F. Cazaurang

Laboratoire d'Automatique et de Productique, UMR CNRS 5131, Université Bordeaux I, 351 cours de la Libération, 33405 Talence Cedex, France

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Abstract

A model-based approach for off-line fault diagnosis in induction machines is presented. The class of faults to be diagnosed is restricted to broken rotor bars, asymmetry in the rotor cage and asymmetry in the stator, arising due to an inter-turn fault resulting in an opening or shorting of one or more circuits of stator phase windings. The method is based on model invalidation tools and $\mathscr{H}_\infty/\mu$-framework models. The experimental model consists of a nominal model estimated by means of a subspace identification algorithm, together with linear fractional norm-bounded perturbations and norm-bounded unknown inputs.

Keywords: Induction motors; Stator failures; Broken rotor bars; Subspace-based identification; Generalized structured singular value

1. Introduction and problem setting

In recent years, research has picked up an important part in the area of fault diagnosis of induction drives. The manufacturers of these drives are more and more keen to include diagnostic features in the control software to decrease machine down time and improve maintenance schedule and repair actions. Critical stator and rotor faults have been identified and classified by some authors (see for example, Toliyat, Arefeen, & Parlos, 1996). In this content, the main challenge is to detect and isolate:

- inter-turn fault resulting in the opening or shorting of one or more circuits of a stator phase winding,
- abnormal connection of the stator windings,
- broken rotor bar or cracked rotor end-ring, caused by a combination of various stresses such that overloading,
- static and/or dynamics air-gap irregularities,
- a rub between the rotor and stator which can result in serious damage to the stator core and windings.

To achieve the above objectives, different techniques have been proposed in the last decade. Based on spectrum processing, motor current signature analysis (MCSA) approaches have been used as a medium for induction machine faults classification (see Elkasabgy, Eastham, & Dawson, 1992; Benbouzid, 2000; Arthur & Penman, 2000 for surveys). However, the MCSA techniques success depends not only on the accuracy of measurements, but also on the ability to discriminate between normal and faulty conditions. As an example, if the load torque varies with the rotational speed, then the motor current spectral harmonics produced by the load, overlap the harmonics caused by broken bars, making the fault detection task difficult. To overcome this problem, recent efforts include electro-magnetic field monitoring, temperature measurement, infrared recognition, vibrations monitoring, acoustic noise measurements and chemical analysis. Some developments in the field of diagnosis of electrical machines have also been carried out using artificial intelligence. In Filippetti, Franceschini, Tassoni, and Vas (2000) and Li, Chow, Tipsuwan, and Hung (2000), the benefits of artificial neural networks and fuzzy logic techniques are also discussed.

Another class of fault diagnosis techniques, which has recently received attention in the rotating machine literature, is the model-based techniques (Cho, Lang, & Umans, 1992; Toliyat & Lipo, 1995; Loparo, Adams, Lin, Abdel-Magied, & Afshari, 2000; Moseler & Isermann, 2000). Model-based fault detection and isolation (FDI) schemes may also be thought of testing the applicability of a model set of the process being

*Corresponding author. Tel.: +33-556842400; fax: +33-556846644.
E-mail address: david.henry@lap.u-bordeaux.fr (D. Henry).

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Nomenclature

v_s	stator line-to-neutral voltage and i_s is the stator line current
v_a, v_b, v_c	stator voltages in the three-phase system
i_a, i_b, i_c	stator currents in the three-phase system
$\mathscr{P}$	Park transformation matrix linked to the stator reference
v_{sd}, v_{sq}	Park stator voltages linked to the stator reference
i_{sd}, i_{sq}	Park stator currents linked to the stator reference
θ	used to represent the rotor shaft angle
$\omega_s, \omega_r, \Omega$	stator and the rotor electrical and the rotor shaft angular velocity
R_s, L_s	stator resistance and inductance
R_r, L_r	rotor resistance and inductance
M	mutual inductance
σ	represents the total leakage factor $(1 - M^2/L_sL_r)$
s	slip $(\omega_s - \omega_r)/\omega_s$
R_{pf}	models the ferro-magnetic leakages

monitored, with respect to an experimental input–output data (see for example Frank, 1990; Zolghadri, 1996; Patton & Chen, 1997). If no element of the model set accounts for the observed behavior of the physical system, then one can conclude that a fault has occurred in the monitored process. The major advantage of model-based approaches is the capability to take into account various disturbances and perturbations in the model set describing the monitored process behavior. This key feature includes robustness constraints and thus the enhanced possibility to distinguish between faults and various operating conditions of the supervised system. For the induction machine case, the core element is to obtain a not too complicated model set, which is able to describe the machine dynamics, as well as the internal and external perturbations. The Lens law combined with the Park transformation (see for example Barbier, Nogarede, & Meyer, 1996) can also be used in order to obtain reduced machine models. However, it is a very hard task to determine how the effect of disturbances such that magnetic saturations and temperature variations, can be included in the models. To overcome this problem, the concept of $\mathscr{H}_\infty/\mu$-framework robust models is used. The modeling formalism also includes nominal model with linear fractional norm-bounded perturbations and norm-bounded unknown inputs.

The method proposed in this paper for fault diagnosis can be summarized as follows:

First, based on the electrical mode on the machine, a subspace system identification procedure is used to estimate a nominal discrete-time model of the induction machine. The Park transformation linked to the stator is applied to the stator voltages and currents, in order to reduce model's complexity. Next, using the linear fractional transformation (LFT) framework and based on the concept of the generalized structured singular value μ_g, frequency fault indicating informations are generated. Fig. 1 illustrates the proposed scheme. Note that, due to its implementation in the frequency domain, the proposed approach cannot be used as an on-line FDI method, but as an off-line integrity monitoring procedure.

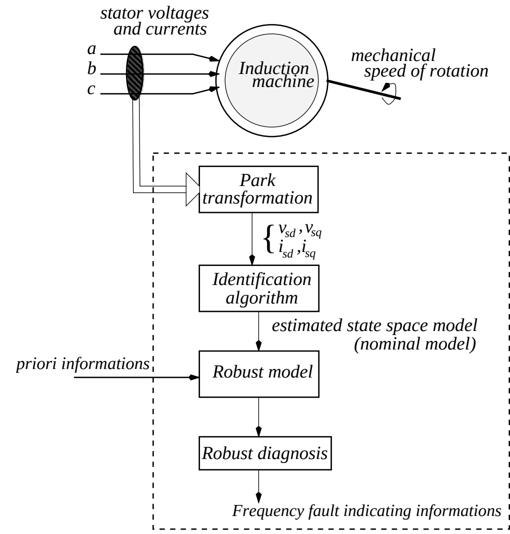

Fig. 1. The proposed diagnostic scheme.

2. Description of the benchmark

The experimental study[1] is based on a four-pole, 1.1 kW, rotor cage induction machine with 18 rotor bars, manufactured by "Leroy Somer" industry. Numerical values of electric parameters of the equivalent single-phase model of the machine are listed in Fig. 2.

The three stator voltages v_a, v_b and v_c are assumed to be measured using voltage sensors with an isolating amplifier. Three Hall sensors are also used in order to measure the three stator currents i_a, i_b and i_c. Both voltages and currents are filtered using a fourth-order anti-aliasing filter, with cross over frequency fixed to 500 Hz. The mechanical position θ is taken using a 2048 points incremental coder. Fig. 3 shows a diagram of the experimental set-up. To generate various operating modes, three configurations corresponding to different type of load, are considered: the full-load experimenta-

[1] The benchmark is located at the "Laboratoire d'Automatique et d'Informatique Industrielle" in France ("http://laii.univ-poitiers.fr/diagnost/").