Available online at www.sciencedirect.com

ScienceDirect

Engineering Applications of Artificial Intelligence 21 (2008) 961–973

Engineering Applications of ARTIFICIAL INTELLIGENCE

www.elsevier.com/locate/engappai

FDI based on pattern recognition using Kalman prediction: Application to an induction machine

O. Ondel[a,*], E. Boutleux[a], G. Clerc[b,c,d,1], E. Blanco[a]

[a]*Ecole Centrale de Lyon, CEGELY UMR CNRS 5005, 36 Avenue Guy de Collongue, 69134 Ecully Cedex, France*
[b]*Université de Lyon, Lyon F-69622, France*
[c]*Université Lyon 1, Lyon F-69622, France*
[d]*CNRS, UMR5005, Laboratoire AMPERE, Villeurbanne F-69622, France*

Received 10 March 2006; received in revised form 1 October 2007; accepted 18 November 2007
Available online 11 January 2008

Abstract

A pattern recognition technique associated with a new state estimator is developed in order to supervise electrical process. For this purpose, diagnostic features are extracted from current and voltage measurements for monitoring different operating modes. Then, a feature selection method is applied in order to select the most relevant features which define the feature space. In this frame, the classification is realized by a non-parametric method ("*k*-nearest neighbors" rule) with reject options. However, this method does not take into account the evolution of the operating modes. Thus, it is necessary to enhance the initial knowledge database. For that, a polynomial approach allows characterizing the intermediate states of each operating modes and an original use of Kalman algorithm allows predicting the evolution of the partially known modes. A simple behavioral model is used to describe the evolution of the pattern vector. An estimation step provides the parameter of such model and a prediction step determines the future evolution of the pattern vector.

This approach is illustrated on an asynchronous motor of 5.5 kW, in order to detect broken bars under any load level. The experimental results prove the efficiency of pattern recognition methods in condition monitoring of electrical machines.

Keywords: Pattern recognition; Kalman state prediction; Induction motor; Fault detection and diagnosis; *k-nn* rule

---

1. Introduction

The monitoring and diagnosis of electrical machines have been under focus for at least 20 years with a special interest in squirrel-cage three-phase induction machines (Deleroi, 1982; Penman et al., 1985, 1986; Kliman and Koegl, 1988; Nandi and Toliyat, 1999; Thompson, 1999; Benbouzid, 2000; Bellini et al., 2002; Nandi, 2005). These induction motors present numerous advantages due to their robustness and their power–weight ratio. Most electric motor failures interrupt a process, reduce production, and may damage other related machinery. In some factories, a very expensive scheduled maintenance is performed in order to prevent sudden motor failures. Therefore, there is a considerable demand to reduce maintenance costs and prevent unscheduled downtimes for electrical drive systems, especially AC induction machine.

The necessity to insure continuous and safety operation involves preventive maintenance methods.

Faults in AC induction machines produce one or more of the following symptoms:

- unbalanced voltages and line currents;
- increased torque pulsation;
- decreased average torque;
- increased losses and reduction in efficiency;
- excessive heating;
- disturbances in the current, voltage, flux waveforms.

Failure surveys have reported that the percentage of failure by components in induction machines is typically:

---

*Corresponding author. Tel./fax: +33 4 78 43 37 17.
E-mail address: olivier.ondel@ec-lyon.fr (O. Ondel).

[1] Member, IEEE.

0952-1976/$ - see front matter © 2007 Elsevier Ltd. All rights reserved.
doi:10.1016/j.engappai.2007.11.005

bearing related (40%), stator related (38%), rotor related (10%) and others (12%) (Motor Reliability Working Group, 1985; Popa et al., 2003).

In the past two decades, there has been research to provide new monitoring techniques for ac induction motors based:

- on analyzing vibration signals. Vas (1993) classifies machine according vibration levels, details the vibration troubles and the conditions to provide a good vibration monitoring. Gaydon (1979) detects the induction motor rotor faults by speed fluctuation measurements. Chang and Yacamini (1996) present the results of modal tests carried out on an induction motor stator, and the effects of irregularities on the vibration response of the machine. Tavner and Penman (1987) and Thompson (1999) realize a general survey of monitoring techniques,
- or analyzing signals other than currents such as temperature, voltage, and speed (Dister and Schiferl, 1998) or flux and torque (Lipo and Chang, 1986).

However, the vibration sensors are delicate and expensive.

Most of the recent research has been directed toward electrical monitoring of the motor in particular on inspecting the stator current. Current signals can easily be measured for condition monitoring and control.

At this time, the motor current signature analysis (MCSA) was the first attempt to detect electrical and mechanical faults with the so-called semi-invasive and low-cost sensors (Kliman and Koegl, 1988; Kliman et al., 1992; Benbouzid et al., 1997).

The drawback is that the characteristic spectral lines are not easily identifiable with inverter power supply because the current is affected by the multiple harmonics of the commutation frequency. Moreover, these spectral lines almost do not exist with very weak load level. Furthermore, the analysis of these current lines could be ineffective to detect the appearance of other defects such as those related to the stator. For these reasons, it is necessary to determine other features from various analyses (statistical analysis) (Casimir et al., 2005; Benbouzid, 2000).

Finally, a wide range of features are necessary in order to identify the maximum of defects (electrical and mechanical).

Despite various above-mentioned techniques, the monitoring and fault detection of electrical machines have moved from the traditional techniques to AI techniques in recent years (Filippetti et al., 2000; Borras et al., 2001; Tallam et al., 2001; Arkan et al., 2001; Casimir et al., 2003a, b; Ondel et al., 2005a, b). Research trends show that AI techniques will have a greater role in electrical motor diagnostic system with advanced practicability, sensitivity, reliability and automation.

Recent developments in hardware and software make it possible to produce a system for automatic condition monitoring of induction machines using signal processing and classification techniques for fault diagnosis. The most important point is that their design does not require a complete mathematical model of the induction motor.

In this context, this paper presents a diagnosis method (Fig. 1) based on current measurement and statistical pattern recognition (PR) analysis associated to an evolution tracking of various operating modes of the studied system. The pattern recognition can be used as a basis for the diagnosis system design. This evolution tracking will allow setting up a prediction algorithm in order to realize a preventive maintenance. In Section 2, a presentation of the various phases of pattern recognition approach for diagnosis is done (corresponding to step 1 and step 2 of Fig. 1). Firstly, this methodology consists to extract a signature from the signals. Then a decision rule is used in order to detect new functional states.

In Section 3, a new method, interpolating intermediate states and estimating the evolution of partially known states is described. Two approaches are used: a polynomial approach and a Kalman estimator and are associated with the step 3 of the global approach of diagnosis depicted in Fig. 1.

The use of polynomial approach allows obtaining all the intermediate states located between two classes (for instance depending on the level of load or the severity of the fault) of the same operating modes (for instance, for a given fault). This interpolator reduces the number of data constituting the knowledge base necessary for the use of pattern recognition approach, since in the diagnosis of electrical systems, it is difficult to gather a great amount of information.

Kalman estimator is used to predict the evolution of the classes out of the knowledge database (for instance for overload or the more severe fault) for a given operating mode.

In Section 4, predictions obtained with polynomial approach and Kalman filter approach are compared. The generality of the proposed methodology has been experimentally tested for a 5.5 kW squirrel-cage induction machine.

2. Diagnosis and pattern recognition

The aim of statistical PR is to classify objects (patterns) by comparison with reference patterns gathered into classes (clusters) (Fukunaga, 1990). Such a decision system based upon PR requires an a priori knowledge of the studied process in order to define objects and classes. In statistical PR, an object is a set of d features (x_1, x_2, …, x_p, …, x_d) represented as a point in the d-dimensional real space issued from these features. This space is named *feature space*. Thus a pattern i ($i = 1$–n, n being the total number of points composing the initial database), is characterized by a pattern vector (or a signature) $\underline{X}_i = [x_{i1}, x_{i2}, \ldots, x_{id}]$ belonging to $\Re^d$. The classes or clusters ($\Omega_1, \Omega_2, \ldots, \Omega_i, \ldots, \Omega_M$) are subspaces of $\Re^d$ including similar reference patterns. The principle of the recognition is to determine