Electric Power Systems Research 81 (2011) 158–169

Contents lists available at ScienceDirect

Electric Power Systems Research

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

An artificial immune system approach for fault detection in the stator and rotor circuits of induction machines

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ARTICLE INFO

Article history:
Received 7 May 2010
Received in revised form 7 August 2010
Accepted 9 August 2010
Available online 15 September 2010

Keywords:
Induction machine
Pattern recognition
Fault diagnosis
Artificial immune systems

ABSTRACT

In this paper, an artificial immune system approach to the detection and diagnosis of faults in the stator and rotor circuits of an induction machine is presented. The proposed technique requires the measurement of two stator currents to compute their $\alpha\beta$ representation before and after a fault condition. It is verified that for different faults, different patterns are generated by the vector $\alpha\beta$ representation, helping to construct a characteristic image of the operating condition of the induction machine.

A pattern recognition algorithm inspired by how the immune system operates throughout the body is proposed to identify and classify the fault condition. According to the proposed methodology, there is no need to know the details of machine operation in a certain regime and all phenomena and effects resulting from the machine operating in this regime are taken into account. Several experimental results obtained on 2.2 kW and 3.2 kW three-phase induction machines are presented and discussed to validate the methodology, verifying its good performance in preventive fault detection.

1. Introduction

Unpredictable faults in induction machines and its consequent economic and security implications justify the need for fault detection techniques adapted to preventive maintenance. Most of the faults in these machines occur at the stator and rotor level, being caused by a combination of mechanisms that are associated with the windings and rotor bars. These are subjected to the pernicious action of many stress mechanisms such as thermal, electrical, mechanical and environmental effects. As a result, various faults may occur, including winding inter-turn short-circuits, short-circuits between phases, broken rotor bars, etc. These stator and rotor unbalanced situations are responsible for the injection of negative sequence currents in the machine [1,2]. Thus, fault detection in induction machines can be carried out during qualification and quantification tests by looking for a negative current sequence superimposed on the stator currents.

Most research developed for fault detection in induction machines looks for solutions requiring the understanding of how the machine operates in certain fault regimes using detailed and/or simplified mathematical models [3–5]. However, it is important to emphasize the difficulty in obtaining models that can reproduce, with high enough precision, the phenomena occurring in machines, since some assumptions are usually made in the model. For example, iron losses are neglected, magnetic saturation effects in the machine are not taken into account, the air-gap is considered uniform, etc.

Other fault detection approaches use techniques based on pattern recognition methodologies that are, in general, a means of automating fault diagnosis without the presence of an operator. With these methodologies it is possible to relate the information processed in a certain instant with that stored *a posteriori*, allowing detection and fault diagnostics based on a trend analysis of certain machine parameters or by pattern recognition. Recently, in [6] and [7], very good examples are found on the application of fuzzy logic to pattern recognition systems used for fault detection in induction machines. The neural networks approach is another technique which, thanks to its learning capability, permits training for pattern recognition. The research described in [8–12] are new application examples of this technique for fault detection in induction machines. Regardless of fuzzy and neural network techniques, the use of digital signal processing techniques [1,13–18] also opens up new possibilities for fault detection in induction machines through interpretation of the electrical and even mechanical signals available from electric machines (currents, voltages, mechanical vibrations, etc.) when in a fault condition.

In this work, a new artificial immune system for detecting faults in induction machines by constructing a "characteristic image" of its operation is proposed. The strategy is based on comparing the machines dynamics when in a normal operating condition with its

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0378-7796/$ – see front matter
doi:10.1016/j.epsr.2010.08.003

Table 1
Electrical parameters of the nine windings induction machine for the stator essays.

P [kW]	U [V]	I [A]	N [rpm]	F [Hz]
2.2	220/380	4.98	1430	50

Table 2
Nameplate data of the DC machine used as load of the induction machine.

Armature			Field excitation	
P [kW]	U [V]	I [A]	N [rpm]	U [V]
3.0	220	16.0	1500	220

Table 3
Electrical parameters of the wound rotor induction machine for the rotor essays.

Stator				Rotor	
P [kW]	U [V]	I [A]	N [rpm]	I [A]	U [V]
3.2	220/380	14.0/8.1	1400	19.0	110

dynamics in an unbalanced state. According to the proposed strategy, there is no need to know the details of machine operation in a certain regime and all phenomena and effects which result from the machine operating in a given fault condition are taken into account. Using a stationary reference frame $\alpha\beta$ (Clarke transformation) to represent the currents, the $\alpha\beta$ currents exhibit different patterns, which allow creating a characteristic pattern of the operating regime of the induction machine. Besides, according to the proposed strategy, it is not necessary to know the operating details corresponding to a certain regime, and all phenomena and effects which result from the induction machine operating in this regime are taken into account.

In the following section, the patterns shown by the stator currents due to the fault condition are analyzed under the $\alpha\beta$ stationary reference frame through experimental results. The proposed fault detection algorithm inspired by the operating principles of the immune system is presented in Section 3. The proposed fault detection strategy is tested under different fault operating conditions and is presented and analyzed in Section 4, while conclusions are drawn in Section 5.

2. The test set-up

In the present work, the experimental study has been performed on two induction machines. For the stator essays, a squirrel-cage induction machine with nine windings available has been used. This machine has been star-connected with three windings per phase. The electrical parameters of this induction machine are listed in Table 1. An independent DC generator machine was used as load. Table 2 lists the nameplate data of the DC machine.

The rotor essays have used a wound rotor induction machine. The electrical parameters of this induction machine are listed in Table 3. An independent excitation DC generator was used as load. Table 4 lists the nameplate data of the DC machine.

The supply voltage to both induction machines has been effectuated by a three-phase balanced supply through a 3-phase variable auto-transformer. The machines were run at nominal voltages under no-load as well load conditions. The stator currents were measured using a sensor current with a resolution of 100 mV/A and recorded by a digital oscilloscope (Tecktronics DSA1200). The current signals were changed using the Clark transformation using an algorithm written in MATLAB.

Table 4
Nameplate data of the DC machine used as load of the wound rotor induction machine.

Armature			Field excitation	
P [kW]	U [V]	I [A]	N [rpm]	U [V]
3.0	220	13.6	1500	220

3. Stator current patterns due to unbalanced conditions: brief analysis

Fault situations in an induction machine, either at stator or rotor level, represent an unbalanced operating condition which is reflected in the machine. Before introducing the proposed fault detection strategy, this section briefly analyzes how the unbalanced condition of a stator or rotor in an induction machine affects the shape of its stator currents. The vector representation of the stator currents in $\alpha\beta$ coordinates is also presented and their pattern analyzed according to each type of fault.

3.1. Unbalanced stator condition

A 2.2 kW, 380 V, 50 Hz squirrel-cage induction machine having three independent windings per phase was used in the unbalanced stator experimental tests. The induction machine was star-connected using three windings in series per phase. The unbalanced condition of the stator was reproduced in laboratory by placing a variable resistance in parallel with one of the stator windings. The unbalanced stator tests were run under no-load and rated load conditions.

When representing the stator currents by their $\alpha\beta$ components, Fig. 1(a) above shows their waveform when the machine operates in its normal condition. Note that some inherent machine asymmetries appear in the $\alpha\beta$ components, which are characterized by different amplitudes although maintaining the $\pi/2$ phase angle. The results shown in Fig. 1(a) below illustrate the fact that, when making a vector representation of the $\alpha\beta$ components of the stator currents with the induction machine operating in normal condition, the pattern that emerges is a deformed circle, which was derived from the already existing residual asymmetries in the machine. On the other hand, it is noticeable that, in an ideal operating situation, the pattern would be a perfect circle.

Fig. 1(b) above presents the $\alpha\beta$ components under the unbalanced stator condition. Compared with the results in Fig. 1(a) above, the amplitude of the α-component increases, while a 3rd harmonic frequency becomes more prominent in the β-component and verified by the distortion present in its waveform. Fig. 1(b) shows the effect that the unbalanced condition of the stator has on the resulting pattern made by the $\alpha\beta$ components. It can be observed that the circular pattern has disappeared and is replaced by an elliptical one instead. A set of experimental tests was also conducted with the induction machine operating under unbalanced stator and rated load conditions. The results obtained were similar to those shown above, but with larger amplitude.

3.2. Unbalanced rotor condition

The results described above show that a stator fault can be detected by classifying the pattern taken by the $\alpha\beta$ components: circular being no fault and elliptical indicating a stator fault. In the following, it is studied how a rotor asymmetry in an induction machine affects the shape of its stator currents.

A 3.2 kW, 380 V, 50 Hz wound rotor induction machine was used. The rotor asymmetry was produced by inserting a variable resistance in one of the rotor phases. The tests were run for rated load conditions.

When representing the stator currents by their $\alpha\beta$ components, Fig. 1(c) and (d) above shows their time evolution for the nor-