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Diagnosis of the Induction Machine Using Advanced Signal Processing Methods

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Abstract: This work is a part of the thematic of monitoring and fault diagnosis of the squirrel cage three-phase induction machine. The choice of this type of machine is justified by the growing success it has exhibited, mainly, in the electric drives with variable speed. Signal based detection methods are presented is validated in simulation. The proposed diagnosis approach requires only little experimental data, and more importantly it provides efficient simulation tools that allow characterizing faulty behavior.In this study, the proposed approach considers the value of rotor resistance as fixed for condition monitoring. This value in the diagnostic tools which one uses is not fixed contrary to the classical approaches of control of machine.

Keywords: Modeling, Induction Motor,Rotor Defect, Extended Kalman Filter.

1. INTRODUCTION

Large industrial systems are widely confronted to the challenges of reliability and availability of the production devices. Electric drives containing an induction machine are largely used in the industrial applications thanks to their low costs, high performances and robustness [1]. As known, a system can realize the assigned task, only under conditions ensuring the security. An early detection of anomalies in electrical motors may help avoiding downtimes [2].Our main contribution resides in the development of methods and technologies for monitoring and fault diagnosis in electrical machines such as the stator imbalance, rotor broken-bars and bearing faults.The failures of asynchronous machine are divided into various types of faults; broken rotor bars, shorted stator turns, shaft misalignments, loads vibrations, torque oscillations, gearbox, and bearing faults. Approximately (45%) of the failures are due to the bearing faults [3].Different techniques for condition monitoring using neural network can be found. A recent work based onin this context, we proposed two approaches of fault detection by monitoring the stator current: the signal approach and the system approach. The signal approach consists of implementing techniques and methods of signal processing and analysis [4] [5]. These different techniques are appropriate responses to various challenges and constraints encountered during diagnosis, such as load level and the disruption of the power supply. The approach system, on the contrary, allows complete automation of the fault diagnosis process from the acquisition and data processing to decision making.This paper proposes then a fault detection technique that takes into account some of the above discussed aspects. The proposed technique is based on stator current frequency spectral subtraction.

2. THE APPLICATION UNDER STUDY

The drive consists of an induction machine, pulse width inverter, rotor-steered flow control, a current measuring loop and a speed control loop. Fig.1 shows the overall scheme of the set.

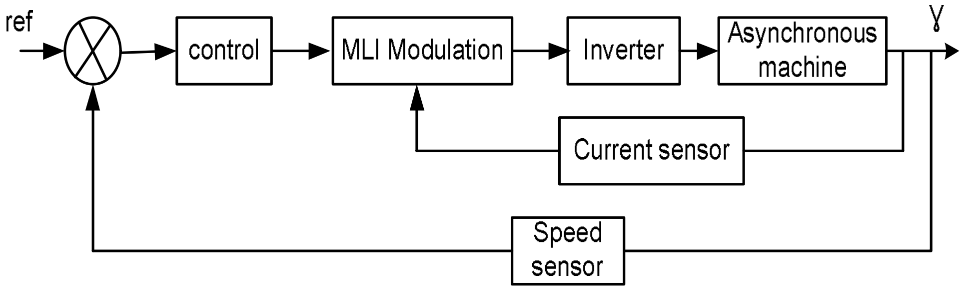


Fig. 1 Schematic diagram of the system under study

Using the equations, we can represent the matrix of the stator tensions [1]:

$$\begin{bmatrix} Vsa \\ Vsb \\ Vsc \end{bmatrix} = [R_s] \begin{bmatrix} isa \\ isb \\ isc \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} \varphi\, sa \\ \varphi\, sb \\ \varphi\, sc \end{bmatrix} \qquad (1)$$

Where the resistances matrix is written according to the supposition of symmetry:

$$[R_s] = \begin{bmatrix} r_s & 0 & 0 \\ 0 & r_s & 0 \\ 0 & 0 & r_s \end{bmatrix} \qquad (2)$$

On the level of the rotor, under - assumption-that - rotor-is comparable to a rotor with three-phase rollings up, the voltage are written:

$$\begin{bmatrix} Vra \\ Vrb \\ Vrc \end{bmatrix} = [R_R] \begin{bmatrix} ira \\ irb \\ irc \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} \varphi ra \\ \varphi rb \\ \varphi rc \end{bmatrix} \qquad (3)$$

Matrix RR has the same form that RS, flux vector are expressed according to the inductances matrix and stator and rotor currents.

$$\begin{bmatrix} \varphi sa \\ \varphi sb \\ \varphi sc \end{bmatrix} = [L_s] \begin{bmatrix} isa \\ isb \\ isc \end{bmatrix} + [M_{SR}] \begin{bmatrix} ira \\ irb \\ irc \end{bmatrix} \qquad (4)$$

$$\begin{bmatrix} \varphi ra \\ \varphi rb \\ \varphi rc \end{bmatrix} = [M_{RS}] \begin{bmatrix} isa \\ isb \\ isc \end{bmatrix} + [L_R] \begin{bmatrix} ira \\ irb \\ irc \end{bmatrix} \qquad (5)$$

In order to be able to give an account of the interactions between the phases, we expressed each resistance and inductance matrix according to the number of whorls of rollings up of the machine.

$$[R_S] = \begin{bmatrix} R_{sa} & 0 & 0 \\ 0 & R_{sb} & 0 \\ 0 & 0 & R_{sc} \end{bmatrix} = R_s \begin{bmatrix} n_{sa} & 0 & 0 \\ 0 & n_{sb} & 0 \\ 0 & 0 & n_{sc} \end{bmatrix}$$
$$[R_R] = \begin{bmatrix} R_{ra} & 0 & 0 \\ 0 & R_{rb} & 0 \\ 0 & 0 & R_{rc} \end{bmatrix} = R_r \begin{bmatrix} n_{ra} & 0 & 0 \\ 0 & n_{rb} & 0 \\ 0 & 0 & n_{rc} \end{bmatrix} \quad (6)$$

The expressions of the inductances are:

$$[L_S] = \begin{bmatrix} L_{sa} & M_{sab} & M_{sca} \\ M_{sab} & L_{sb} & M_{sbc} \\ M_{sca} & M_{sbc} & L_{sc} \end{bmatrix} = \begin{bmatrix} n_{sa}^2 l_s & n_{sa} n_{sb} m_s & n_{sa} n_{sc} m_s \\ n_{sa} n_{sb} m_s & n_{sb}^2 l_s & n_{sb} n_{sc} m_s \\ n_{sa} n_{sc} m_s & n_{sb} n_{sc} m_s & n_{sc}^2 l_s \end{bmatrix}$$
$$[L_R] = \begin{bmatrix} L_{ra} & M_{rab} & M_{rca} \\ M_{rab} & L_{rb} & M_{rbc} \\ M_{rca} & M_{rbc} & L_{rc} \end{bmatrix} = \begin{bmatrix} n_{ra}^2 l_r & n_{ra} n_{rb} m_r & n_{ra} n_{rc} m_r \\ n_{ra} n_{rb} m_r & n_{rb}^2 l_r & n_{rb} n_{rc} m_r \\ n_{ra} n_{rc} m_r & n_{rb} n_{rc} m_r & n_{rc}^2 l_r \end{bmatrix} \quad (7)$$

$$[M_{SR}(\theta)] = \begin{bmatrix} n_{sa}n_{ra}m_{sr}\cos(\theta)) & n_{sa}n_{rb}m_{sr}\cos(2\pi/3) & n_{sa}n_{rc}m_{sr}\cos(\theta-2\pi/3) \\ n_{sb}n_{ra}m_{sr}\cos(\theta-2\pi/3) & n_{sb}n_{rb}m_{sr}\cos(\theta) & n_{sb}n_{rc}m_{sr}\cos(\theta+2\pi/3) \\ n_{sc}n_{ra}m_{sr}\cos(\theta+2\pi/3 & n_{sc}n_{rb}m_{sr}\cos(\theta-2\pi/3) & n_{sc}n_{rc}m_{sr}\cos(\theta) \end{bmatrix} \quad (8)$$

$$[M_{SR}(\theta)] = [M_{RS}(\theta)]^T$$

Where m_{sr} is the maximum value of the stator-rotor mutual inductance.

A. DIAGNOSIS OF THE BEARING DEFECTS

The bearings consist mainly of the outer and inner raceway, the balls and the cage which assures equidistance between the balls. The number of balls is defined as Nb, their diameter as Db. The pitch diameter or diameter of the cage is designated Dc.The point of contact between a ball and the raceway is characterized by the contact angle β. The different faults occurring in a rolling-element bearing can be classified according to the affected element [6], [7]:

- Outer raceway defect
- Inner raceway defect
- Ball defect

Fig. 2 Bearing with cage fault.

Fig. 3 Bearing with outer race fault

B. CHARACTERISTIC FAULT FREQUENCIES

The frequencies at which these pulses and vibration occur are predictable and depend on which surface of the bearing contains the fault. The frequencies also depend on the geometrical dimensions of the bearings and the rotational speed of the rotor. Therefore, there is one predictable characteristic fault frequency for each of the four parts of a given bearing, running at a certain rotor speed in Hertz, fr. These fault frequencies are given by [8], [9], [10].

$$f_c = \frac{1}{2} f_r \left(1 - \frac{D_b cos\theta}{D_c}\right) \tag{9}$$

Outer raceway fault:

$$f_0 = \frac{N_b}{2} f_r \left(1 - \frac{D_b}{D_c} cos\beta\right) \tag{10}$$

Inner raceway fault:

$$f_i = \frac{N_b}{2} f_r \left(1 + \frac{D_b}{D_c} cos\beta\right) \tag{11}$$

Ball fault:

$$f_b = \frac{D_c}{D_b} f_r \left(1 - \frac{D_b^2}{D_c^2} cos^2\beta\right) \tag{12}$$

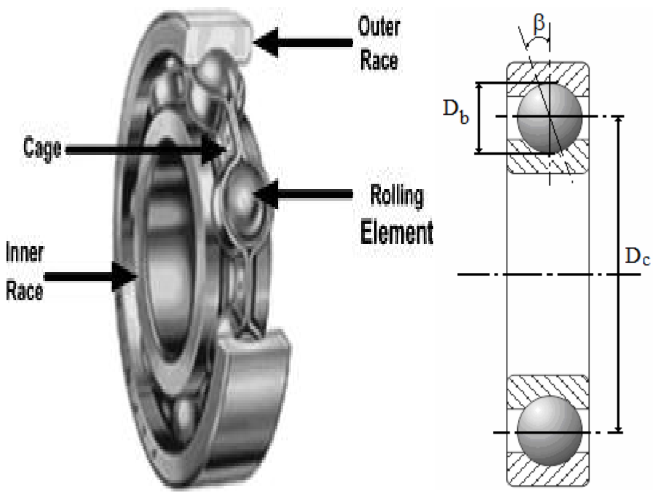


Fig. 4 Geomtry of a rolling

C. BEARING FAILURES IMPACT ON INDUCTION MACHINE STATOR CURRENT

In [12], it has been presented a model studying the influence of bearing damage on the induction machine stator current. The authors consider the generation of rotating eccentricities at bearing fault characteristic frequencies fc. These eccentricities lead to periodical changes in the mechanical inductances which produce additional frequencies fbf in the stator current. The characteristic fault frequencies are essentially modulated by the electrical supply frequency, and the resulting fault frequency components in the stator current are predicted by the following equation (5).

$$f_{bf} = |f_s \pm k f_c| \tag{13}$$

Where fs is the stator current frequency, and ƙ = 1, 2, 3....

This model has been applied in several works dealing withbearing faults detection. The above model components areanalyzed using spectral analysis in [13].In [14] time frequency and time-scale methods are used to identify bearing faults by analyzing stator current based on the same model. Therefore, the [9] approach has been adopted to model bearing failure effects on induction machine stator current.

3. SIMULATION RESULTS AND DISCUSSION

The test conditions are the following:

- From t=0 to t=0.3s, flux application
- From 0.3 to 1.8s, liner increase of the speed reference
- From 1.8s constant speed
- At t=3s, fault in the machine

The observers are enabled from beginning

A. HEALTHYSTATE

Our approach in this part of simulation is to see the behavior of the induction machine in healthy mode and with electric defect (rotor, stator, inverter) in the mode transitory and permanent, after from there will introduce an observer on the outlet side of the machine (extended Kalman filter) is to see its reaction. The results result from rotor resistance, the stator current FFT.

The following figure takes the form of the current in a phase of the induction machine. One can distinguish there the various phases related to the order from the system: phase of fluxing, phase of application of the instruction of couple related to the slope of speed, then stabilization the speed and instruction of couple. Up to 0.3 second, the purpose of the applied voltages is to position the vector flow in the machine, as from this moment, an instruction of couple is applied to the order and speed believes.

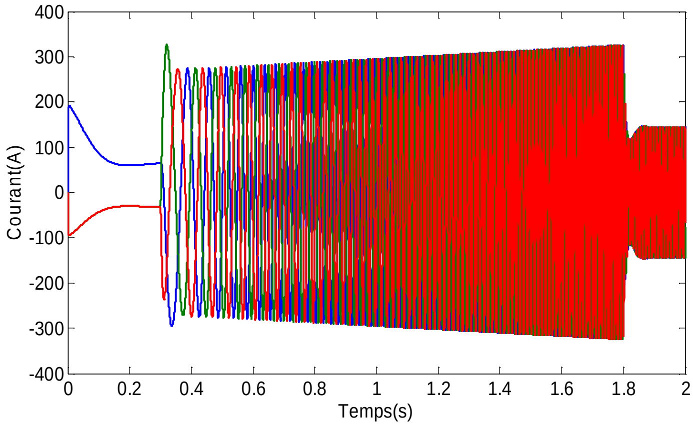


Fig. 5 Stator current

B. Defect In the rotor

Rotor faults Figure 6 takes the form of the stator current for an unbalanced defect (40% of whorls removed in the phase at fault), note the appearance of the lines in the spectrum of the current. The defect with the rotor is characterized by the appearance of two frequencies (1±2g) or g represents the slip (92,2Hz et107Hz) around the electric frequency f electric (100Hz). If the FFT of this signal is made, this defect will be very difficult to detect in the spectrum of the current because the amplitude of the line at the fundamental frequency is very important compared to that of the required line and these lines are at a frequency frame the line with fundamental with a difference related to the slip (in general very weak).

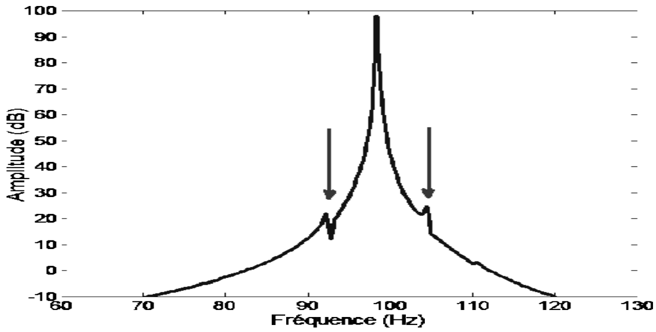


Fig. 6 Stator current under rotor fault

C. DEFECT in STATOR

Figure 7 takes the form of the stator current for a defect unbalanced to the stator (40% of whorls removed at fault on a phase). Let us note the appearance of the frequency, which characterizes the defect, which is 3felectric (300Hz). The appearance of the lines in the spectrum of the current is due to the application of the defect to the moment t= 3s, it is easy to detect the frequency, which characterizes the defect in low frequency. (See figure below after the stator phase current FFT).

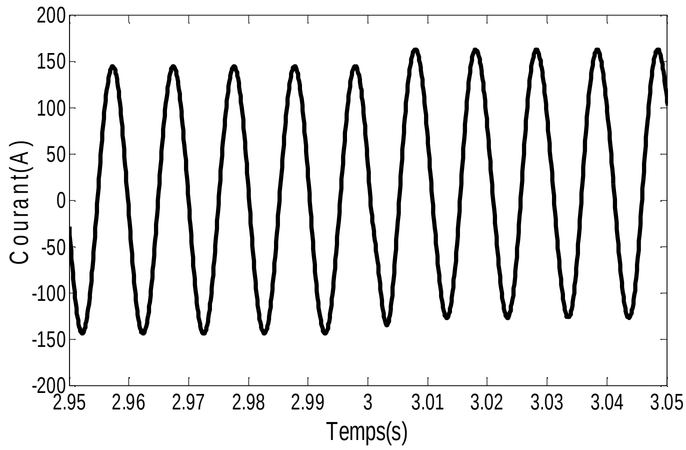
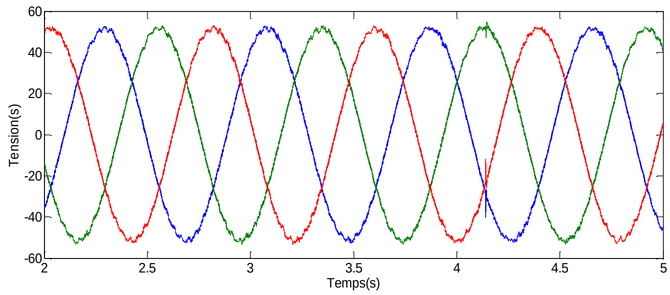


Fig. 7 Stator current of the machine at fault to the stator

D. INVERTER FAULT

We chose to take into account the effects of an open component. For this, we have included a block to block the control orders arriving at the switch considered to be faulty.



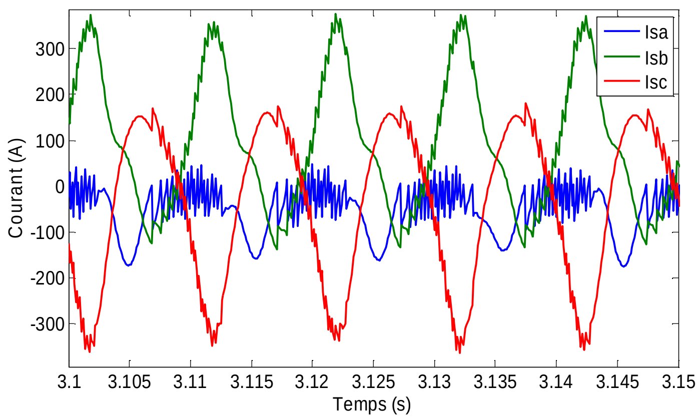


Fig 8.The speed of the stator currents and the spectrum of the machine with inverter fault

E.DIAGNOSIS OF THE BEARING DEFECTS

The following figures show the spectra of the torque reference (output of the speed corrector) for the different bearing defects considered.

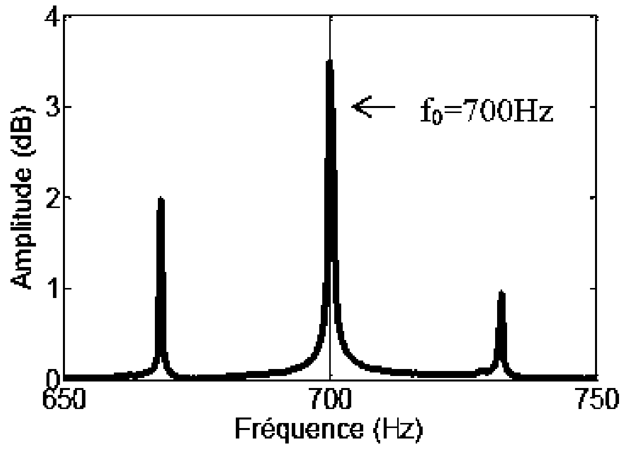


Fig 9.Spectrum of Outer race defective bearing

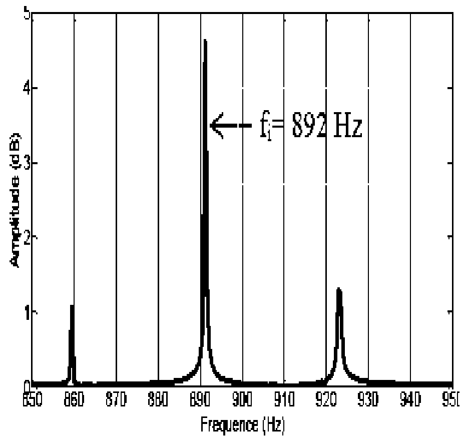


Fig 10.Spectrum of inter race defective bearing

4. CONCLUSION

This work focused on the diagnosis and detection of defects of the asynchronous machine. Three types of faults were processed, namely stator fault, rotor fault and rolling fault. We have drawn up a non-exhaustive list of numerous failures through the description of the state of the rotating machine for diagnostic purposes.
We then presented the different approaches to modeling, the techniques and other diagnostic tools being very numerous, we classified them in two approaches: a signal approach based on signal processing of measurable quantities, namely current and voltage. A system approach, in this case classification by time-frequency representations.
The vectorial control of the induction machine requires observers (possibly extended). We first of all showed that the use of an extended observer for diagnosis purpose made it possible to detect the principal defects in the electrical machine. The parameter used for the diagnosis is the estimated rotor resistance. We showed that by coupling a spectral analysis of the estimated parameter that the technique could appear useful. The Kalman filter uses dynamics of the rotor resistance, which defines the evolution its value in time domain to obtain reliable data in the case of healthy machine (convergence of the estimate). We are aware of having studied only certain aspects of a very vast subject of study, which requires the comprehension of the system and the use of suitable tools.

APPENDIX

Rs = 0.0142Ω; Ls = 0.001314 H; Rr = 0.0126Ω; Lr = 0.001286H; Lm = 0.00123H; p = 3; σ = 0.1047; Q = 0, 1; R= 0, 01.

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