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Anomaly Detection in Induction Machines

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***Abstract* - This article discusses statistics related to distribution of anomaly causes which affect the induction machines and particularly the ball bearing functioning. On one hand, we present a mathematical modeling of the "indentation" anomaly on the outer ring of the ball bearing. On the other hand, we don't make only a spectral analysis over the emitted signal, which is measured by a sensor disposed on the non rotating structure, but we also present experimental results carried out in the NDC (Non Destructive Control) Laboratory.**

***Key words:* Anomalies modeling, Induction machine, Spectral analysis.**

I. INTRODUCTION

The continuous monitoring and diagnosis of anomalies in industrial systems allow us to know the origins that may affect the system. Hence, electrical workouts, based on induction machine are widely used in industrial applications because of their low cost, their performance and their robustness [1]. However, degraded modes of functioning may occur during machine lifecycle. One of the main reasons for these failures remains the ball bearings anomalies [1] [2]. To ensure better system functioning, monitoring systems can be used in order to ensure preventive maintenance.

II. STATISTICAL STUDY OF THE ASYNCHRONOUS MACHINE ANOMALIES

Anomalies can be of various origins: electrical, mechanical, thermal, environmental or even magnetic. Their causes are multiple and can be classified into three groups [3] [4]:

a) Failure generators or anomaly initiators: engine overheating, electrical fault (short circuit), power boost, electrical insulation problem, wear of mechanical parts (ball bearings), fixations breaking, etc.
b) Faults amplifiers: frequent overloading, mechanical vibrations, wet environment, continuous heating, poor lubrication, aging, etc.
c) Manufacturing defects and human errors: manufacturing defects, defective parts, inadequate protections, bad sizing of the machine, etc [1].

The distribution of defects in the different parts of the engine is shown in Figure 1:

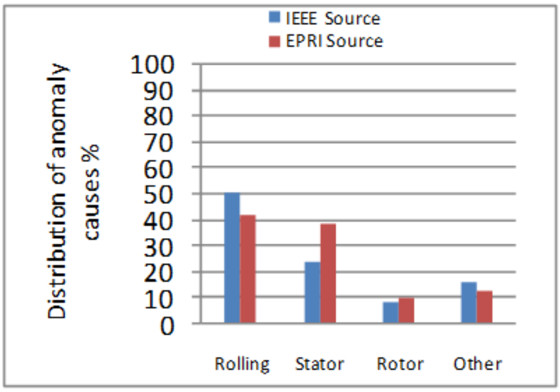


Figure1. Distribution of anomaly causes in asynchronous machines

The mechanical constraints are high, which explains the high rate of failure entailed by bearings [2]. These require an increased mechanical maintenance.

III. MECHANICAL DEFECTS

A. Bearings anomalies

The ball bearings act as an electromechanical interface between the stator and the rotor. In addition, they represent the holding element of the machine axis, allowing to ensure a proper rotation of the rotor. Most faults occur in bearings of induction motors as well as the reasons of their aging. This kind of fault is most common in medium and high power machines. It is usually related to bearing wear and specifically beads degradation, or tread. Their possible causes are [1][5][6]:

- Wear due to aging,
- High operating temperature,
- Loss of lubrication,
- Contaminated oil
- Mounting defaults
- Tree currents (Shaft Current)

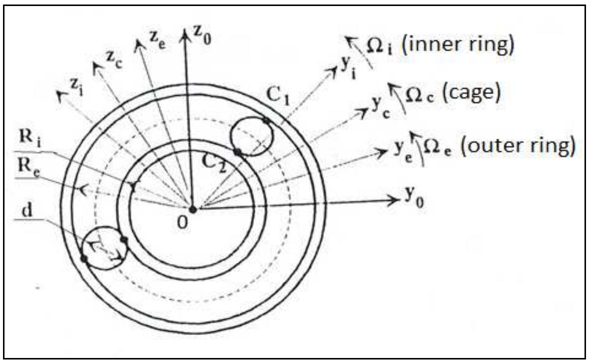
The direct consequences of this failure on the bearings are:

- Holes in the inner and outer raceway grooves.
- The ripple of their tread.
- Corrosion due to water.
- Lubrication fault problem due to the temperature.
- Separation, surface erosion caused by overload.

For the system, this type of defect results in oscillations of the load torque, additional losses and a clearance between the inner ring and the outer ring of the bearing causing vibrations coming from displacements of the rotor around the longitudinal machine axis. In the worst case, the presence of a defective bearing can lead to engine lock.

B. Modeling of bearing anomalies

Consider a bearing in a fixed reference (Oy_0z_0) [1] [6] [7].



d: ball diameter; Ω: angular velocity
Re: outer radius; Ri: inner radius

Figure 2: Repositories related to a rolling element

1) kinematic frequencies:

Defects, cracks, flaking etc..... may exist on the inner rings, outer, on the balls; they generate shock, so the periodic vibrations when the rotational speeds are constant.

The fundamental frequencies of these vibrations are related to the so-called basic kinematic frequencies:

fc: the cage rotation frequency compared to a fixed reference.

$$f_c = \frac{\Omega_c}{2\pi} \tag{1}$$

fb: rotational frequency of an element with respect to an axis passing through its center:

$$f_b = \frac{\Omega_b}{2\pi} \tag{2}$$

The speeds of relative displacements null at C1 and C2 contact points. Using the frequencies f_i of rotation of the inner ring, f_e of the outer ring and the contact angle α, the cage frequency is expressed as:

$$f_c = \frac{1}{2}\left(1 - \frac{d\cos\alpha}{Dm}\right) f_i + \frac{1}{2}\left(1 + \frac{d\cos\alpha}{Dm}\right) f_e \tag{3}$$

By introducing the frequency and angle α contact, the ball frequency f_b is expressed as :

$$f_b = \frac{1}{2}\frac{Dm}{d}\left| f_e - f_i \right|\left(1 - \frac{d\cos\alpha}{Dm}\right)\left(1 + \frac{d\cos\alpha}{Dm}\right) \tag{4}$$

Forms 3 and 4 define the basic kinematic frequencies (cage and ball) from the rotation frequencies of the f_i inner and f_e outer rings.

At frequencies f_c and f_b base associated defects:

-Frequency of rotation of the cage, cage defects:

$$f_{cage\,defects} = f_c = \frac{1}{2}\left(1 - \frac{d\cos\alpha}{Dm}\right) f_i + \frac{1}{2}\left(1 + \frac{d\cos\alpha}{Dm}\right) f_e \tag{5}$$

- Rotation frequency of a rolling element; Z number of rolling elements:

$$f_{element} = f_b = \frac{1}{2}\frac{Dm}{d}\left| f_e - f_i \right|\left(1 - \left(\frac{d}{Dm}\right)^2 \cos^2\alpha\right) \tag{6}$$

-Frequency due to a defect on the inner ring:

$$f_{inner\ ring} = \mathrm{f}_{\mathrm{b,int}} = \frac{Z}{2}\left| f_i - f_e \right|\left(1 + \frac{d}{Dm}\cos\alpha\right) \tag{7}$$

-Frequency due to a defect on the outer ring:

$$f_{outer\ ring} = \mathrm{f}_{\mathrm{b,ext}} = \frac{Z}{2}\left| f_e - f_i \right|\left(1 - \frac{d}{Dm}\cos\alpha\right) \tag{8}$$

2) Modeling anomaly on the outer ring:

Suppose chipping (indentation) of small size; the passage of a ball on this peeling causes a force in a radial plane perpendicular to the rotation line with a contact angle α Figure3 [1][7][9]:

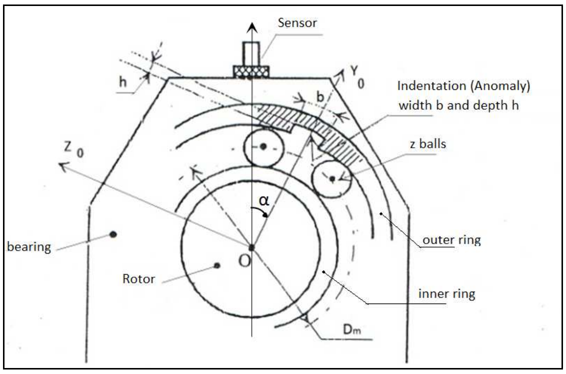


Figure 3: Fault on the fixed bearing outer ring

The set of rolling elements causes a series of pulses described in a fixed reference frame (Ox_oy_o) by a line series; the pulse frequency is equal to f_{bext}:

$$\mathrm{SHA}_{1/\mathrm{fbext}} = \sum_{k=-\infty}^{\infty} \delta\left(1 - \frac{k}{f_{bext}}\right) \qquad (9)$$

With SHA : Dirac distribution

These assumptions allow relatively simple mathematical developments to.

A rotating force to the speed (2πfr) of the rotor due to an imbalance, an arrow, to a defect of coaxiality. The turning force causes a variation in the force between the rolling element and the fault, this force models pulse amplitude of the series.

The radial force, applied in the stead of the anomaly, is written:

$$f(t) = A(1 + \gamma \cos 2\pi f_r).\mathrm{SHA}_{1/f_{bext}}(t) \qquad (10)$$

with $\boldsymbol{\gamma}$ is the rate modulation.

The signal h (t) output from the sensor disposed on the structure of Figure 3 in a radially pulse applied to the right defect the pulse comb signal is:

$$\mathrm{S}(t) = \mathrm{h(t)} * \mathrm{f(t)} \quad \Leftrightarrow \quad S(\nu) = H(\nu).F(\nu) \qquad (11)$$

ν frequency : $-\infty < \nu < \infty$

H(ν) : transfer function of sensor structure

$$F(\nu) = A\left(\delta(\nu) + \frac{\gamma}{2}[\delta(\nu - f_r) + \delta(\nu + f_r)]\right) * \left(f_{bext}.SHA_{fbext}(\nu)\right) \qquad (12)$$

$$\mathrm{SHA}_{\mathrm{fbext}}(\nu) = \sum_{m=-\infty}^{\infty} \delta\left(\nu - mf_{bext}\right) \qquad (13)$$

With $\boldsymbol{\delta}$: Dirac distribution

$$S(\nu) = A.f_{bext}.H(\nu).\begin{bmatrix} SHA_{fbext}(\nu) + \frac{\gamma}{2} SHA_{fbext}[\nu - (kf_{bext} - f_r)] \\ + \frac{\gamma}{2} SHA_{fbext}[\nu - (mf_{bext} + f_r)] \end{bmatrix} \qquad (14)$$

The $SHA_{fbext}(\nu)$ comb repeats the frequency f_{bext} the Dirac distribution δ (ν) for ν = 0 (convolution). The comb $SHA_{fbext}[\nu - (kf_{bext} - f_r)]$ result of the convolution by $\delta(\nu + f_r)$ by $SHA_{fbext}(\nu)$, and for $SHA_{fbext}[\nu - (mf_{bext} + f_r)]$.

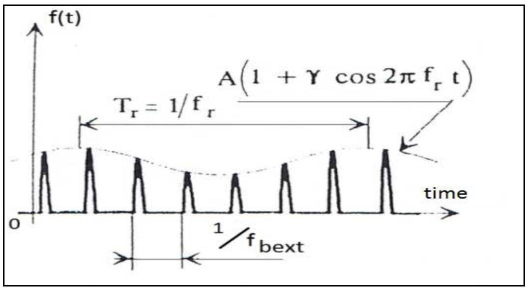


Figure4: Radial force applied to the right defect.

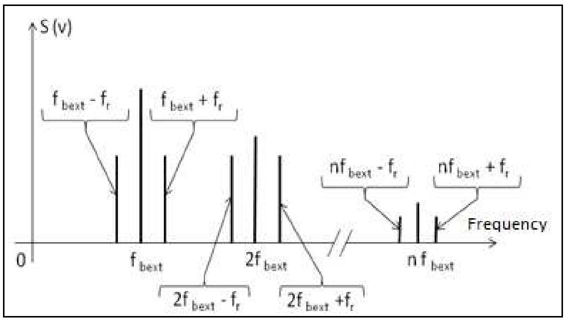


Figure5: Spectrum S(ν)

In fact, the spectrum S (ν) contains components whose frequencies are defined by figure 5 .We note that the impulsive of excitement introduced nf_{bext} components to higher frequencies ; nf_{bext} ; $nf_{bext} \pm f_r$, when the pulses are not Dirac distributed pulses, the components of the pulses become negligible as n increases. $nf_{bext} \pm f_r$; in deed, the faults are represented by periodic pulses of finite length, which does not substantially alter the components $nf_{bext} \pm f_r$.

IV. Experimental Results

The Induction machine on which the experimental tests were carried out presents an anomaly "indentation" of small dimension on the outer ring of the bearing SKF6016 reference.

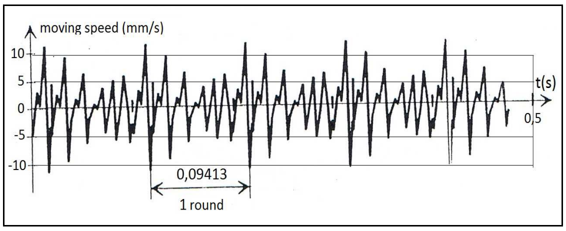


Figure6: Speed of force movement

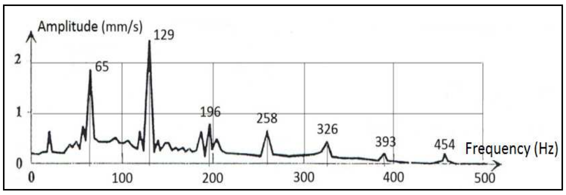


Figure7: Spectre of vibration amplitude

A. Interpretation:

The obtained signals given by figures 6 and 7 show the vibration of a ball rolling bearing, the outer ring is fixed; the rotational speed of the inner ring is equal 630 rev / min

$$f_{bint} = f_r \rightarrow 10{,}60\text{Hz} \rightarrow 94{,}13\text{ms} .$$

The spectrum contains lines of: $\approx k\ 65$Hz; $k = 1, 2, 3, \ldots\ n$; Theoretical kinematic frequency 65,38Hz differs kinematic measured frequency.

Around the first 3 harmonics, lines at ± 8 Hz are observed. This set of lines expresses a defect on the outer ring and a theoretical frequency of modulation amplitude 65,38Hz.

V. CONCLUSION

The measured kinematic frequencies may differ from theoretical ones, especially when the degradation of raceways is important. This difference may also result from insufficient or excessive load or accidental rotation of the fixed ring. Anomalies on the outer ring, the inner ring, the rolling elements, and the cage cause forces or movements, which generate vibrations measured by a sensor generally disposed on the non-rotating structure (Figure 3). The analysis of the signals delivered by the sensor provides elements in the temporal and frequency domains. These elements allow us to generate frequency components which are useful for the monitoring systems that facilitate diagnosis.

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