# CORRELATION BETWEEN RADIAL VIBRATIONS AND EXTERNAL RADIAL MAGNETIC FIELD IN INDUCTION MACHINES. APPLICATION TO ELECTRICAL FAULT DIAGNOSIS

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***Abstract*** **– The aim of this paper is to draw a parallel between the vibrations and the external radial magnetic field on a faulty induction machine in order to improve the diagnosis. Actually, these two signals have both the airgap flux density as origin and, consequently, it seems interesting to compare the indications of each spectrum to make an accurate diagnosis. The study is based on the analytical airgap flux density. The presented faults are stator winding short-circuit and rotor broken bar.**

***Keywords***: *vibrations, external radial magnetic field, slotting effect, induction machine, short-circuit, spectra.*

## 1. INTRODUCTION

The vibrations have been widely used for the electrical machines diagnosis. Numerous studies, in this field, show that the vibratory analysis is very interesting to display faults, especially these which are of mechanical origin, as eccentricity, unbalance and rolling faults [1]. With regard to electrical faults detection, it seems that the preferential ways are the current [2] and the external magnetic field analyses [3].

Only one measurement is generally not sufficient to obtain a reliable diagnosis. Consequently, as the vibrations from magnetic origin, and the external radial magnetic field both result from the airgap flux density, it is interesting to correlate the spectra of each measure, to improve the analysis. In this way, the paper presents, firstly, the theoretical study for a cage induction machine, next the experimental device is presented. Finally, measured spectra are given for a healthy machine, for a machine which presents a stator short-circuit fault and a machine with a broken bar.

## 2. THEORETICAL STUDY

The theoretical study is based on the global analytical expression of an induction machine air-gap flux density given by (1).

$$b(\alpha^s,t) = \sum_k \sum_m \hat{B}_{k,m} \cos(k\omega t - m\alpha^s) \quad (1)$$

where $k$ and $m$ are respectively the frequency rank and the pole pair number of each flux density component. ω is the angular frequency of the fundamental supply current. The general expression of this airgap flux density, which depends on the time $t$ and on the angular position $\alpha^s$, locating a point in the airgap relatively to a stator spatial reference axis, is obtained multiplying the corresponding stator magnetomotive force by the permeance per surface unit [4]. The induction machine permeance is defined as following:

$$P_{MSA} = \sum_{ks=1}^{+\infty} \sum_{kr=1}^{+\infty} P_{kskr} \cos[(ksNts + krNtr)\alpha^s + krNtr\theta] \quad (2)$$

where $Nts$ and $Ntr$ are the number of stator slots and rotor bars, respectively. $P_{kskr}$ is a term which depends on the geometry of the machine, and $ks$ and $kr$ are two integers. θ is the angular distance between rotor and stator reference frames.

The external radial magnetic field is directly obtained from $b$; only the magnitude has to be multiplied by a coefficient of attenuation [5] which conveys the evolution of the components from the air-gap, through the stator.

The stator vibrations, from magnetic origin, are generated by the radial forces between the rotor and the stator frames. The force density $f$ can be calculated from the airgap flux density $b$:

$$f(\alpha^s,t) = \frac{b^2}{2\mu_0} \quad (3)$$

Relations (1) and (3) lead to the force density harmonic components, which can be expressed as following:

$$\begin{aligned} f(\alpha^s,t) = \frac{1}{2\mu_0} \sum_k \sum_{k'} \sum_m \sum_{m'} \hat{B}_{k,m} \hat{B}_{k',m'} \\ \cdot \cos\left[(k+k')\omega t - (m+m')\alpha^s\right] \\ + \cos\left[(k-k')\omega t - (m-m')\alpha^s\right] \end{aligned} \quad (4)$$

where $k'$ and $m'$ are the homologous of $k$ and $m$ in order to distinguish all the terms which result from the multiplication. Then, the determination of the stator mechanical deformations depends on two parameters:

- The mode m±m' of the deformation which has to be lower than 6.
- The mechanical resonance frequencies which depends on the mode but also on the geometrical characteristics of the machine [6].

### 2.1. Case of healthy machine

A $p$ pole pair healthy induction machine fed by a three phase balanced sine current system is considered. If only the effects generated by the stator are taken into account, then the rank $k$ of one air-gap flux density component is given by:

$$k = [1 + krNtr\frac{(1-s)}{p}] \qquad (5)$$

where $s$ is the slip of the machine. This expression highlights the rotor slotting spectral lines which are defined by $kr = \pm1, \pm2, \pm3\ldots$

### 2.2. Case of faulty machine: short-circuit fault

A short-circuit of $\zeta^s$ turns on an elementary section of $n^{s}$' turns in phase q is considered. The modeling of the fault keeps the original winding and considers, separately, the $\zeta^s$ turns, as shows in figure 1.

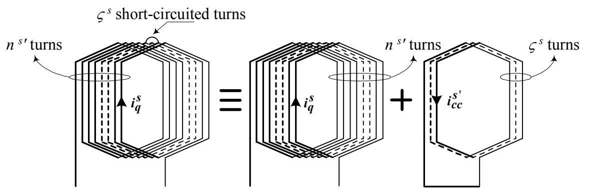



Figure 1: Modeling of a stator short-circuit fault.

The virtual current $i_{cc}^{s'}$ which flows in the $\zeta^s$ turns is defined by equation (6) where $i_{cc}^{s}$ corresponds to the induced short circuit current. It is moreover supposed that the supply current $i^s_q$ do not change with the fault. In that conditions, the flux density components due to the fault are only tied to the current in the $\zeta^s$ independent turns effects.

$$i_{cc}^{s'} = i_{cc}^{s} + i_q^s \qquad (6)$$

It can be shown that some particular components are very sensitive to the fault [7]. Their frequency ranks $k^s_{cc}$ are the same than these defined, for the healthy machine, by the relation (5) and they correspond to the rotor slotting spectral lines. The pole pair number of these sensitive components is m=±1. Concerning the vibratory spectrum, these sensitive airgap flux density components generate, according to (4), spectral lines at $f_1$ and $f_2$ frequencies:

$$f_1 = \left[2 + (kr + kr')Ntr\frac{(1-s)}{p}\right]f \qquad (7)$$

$$f_2 = \left[(kr - kr')Ntr\frac{(1-s)}{p}\right]f \qquad (8)$$

The first rotor slotting spectral lines can be found in the vibratory spectrum by taken [kr=±1, kr'=0] and [kr=0, kr'=±1].

### 2.3. Case of faulty machine: broken bar fault

To study the broken bar fault, the rotor is modeled through the circuit given in figure 2.

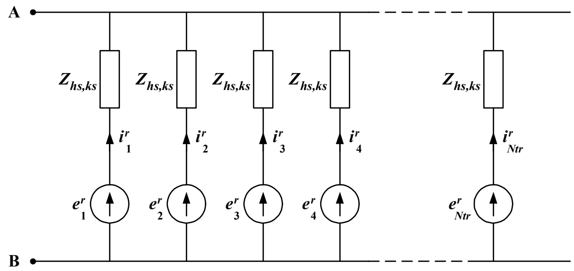



Figure 2: Modeling of a squirrel-cage rotor.

The generators correspond to the electromotive force harmonics induced in each bar. The $Z_{hs,ks}$ impedances are the ones which limit the harmonic currents in each bar.
In the case of a healthy machine, the voltage $u_{AB}$ between the two end-rings is null. On the other hand, when a bar is broken, this voltage is not zero, what creates a dissymmetry in the magneto-motive force distribution. So the faulty rotor generates new flux density components at other frequency ranks $k^r_{bc}$ defined as following:

$$k_{bc}^r = [1 - (hs - \frac{hr}{p} + ksNs - kr^*Nr](1-s) \qquad (9)$$

The $hr'/p$ term displays new spectral lines which will appear at plus or minus the rotating frequency around the spectral lines existing for the healthy machine, in the radial field spectrum but also in the vibratory one.

## 3. EXPERIMENTAL DEVICE

### 3.1. Principle of measurement

Measurements are realized on experimental machines which are designed in order to generate, or not, a fault. A flux sensor and an accelerometer are placed, as shown on figure 3. The position of the flux sensor is chosen to measure the external radial magnetic field which is defined such as the line fields are in a perpendicular plan to the machine axis.
The e.m.f. delivered by the flux sensor and the signal from the accelerometer are sent to a 16-bit analyzer, which is useful to observe small spectral lines (up to -100dB with regard to the full range value).

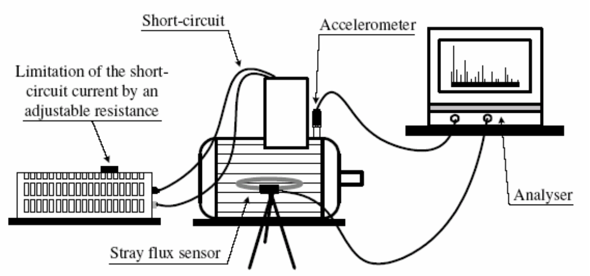



Figure 3: Principle of measurement.

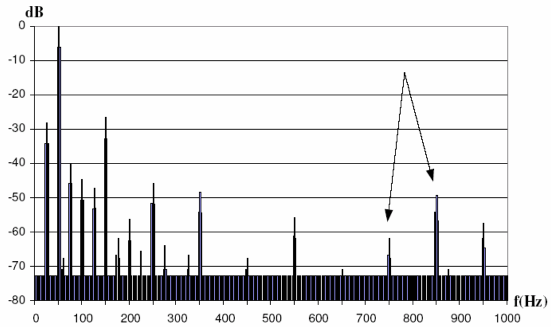
### 3.2. Presentation of the faulty machines

The machine used for the study of a stator short-circuit fault is a 11kW, 400/660V induction machine with $p$=2, $Nts$=48 and $Ntr$=32. On this machine, all the elementary sections are extracted and can be connected to each other. One elementary section short-circuited is equivalent to 12,5% of one stator winding phase. In order to cause no damage, the short-circuit current is limited by an adjustable resistance.
The tests related to the broken bar fault are realized on a 4kW/50Hz, 220/380V induction machine with $p$=2, $Nts$=48 and $Ntr$=28. This machine has two rotors: a first which is healthy and a second where one bar is bored.
All the experiments are done for the machines operating at no load ($s \approx 0$).

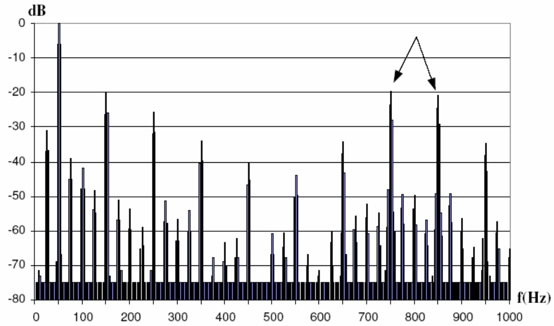
## 4. RESULTS OF THE EXTERNAL RADIAL MAGNETIC FIELD AND VIBRATIONS MEASUREMENTS

### 4.1. Stator short-circuit fault

The first rotor slotting spectral lines in the external magnetic field spectra are directly given by equation (5). They are at 750 and 850Hz (cf. figure 4(a)). In the spectra of radial vibrations, we can find the corresponding spectral lines at 700, 800 and 850Hz, from the relations (7) and (8), even if these one are drowned among the others (cf. figure 5(a)).
During the tests with fault, the supply current is equal to 3,6A and the short-circuit current is limited to 30A. The figures 4(b) and 5(b) highlight that the rotor slotting spectral lines are really sensitive to the fault. Moreover, it is shown that a good correlation exists between the two kinds of measurements. The sensitivity of the rotor spectral lines in the vibratory spectrum is amplified because the supplementary flux density components generated by the fault have 2 poles (m=±1). Consequently, these components generate force components of mode 0 or 2, which are able to produce important vibrations.

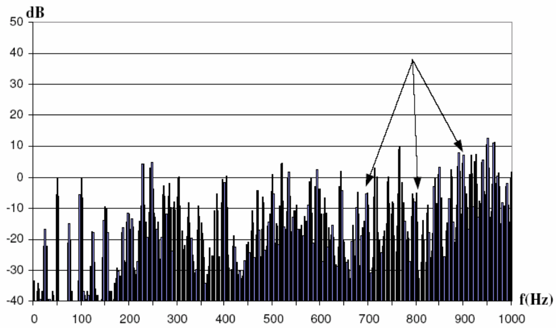



(a) Without fault

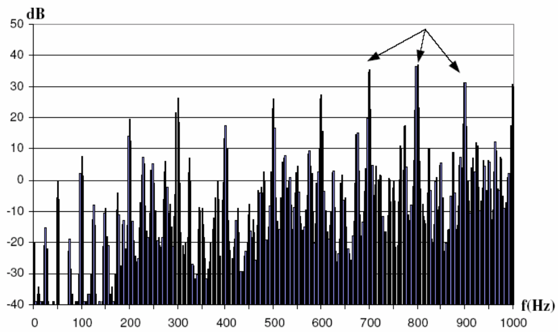



(b) With short-circuit fault – $I_{cc}$=30A

Figure 4: External radial magnetic field spectra.




(a) Without fault

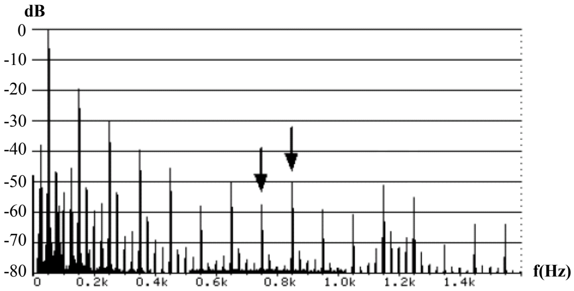



(b) With short-circuit fault – Icc=30A

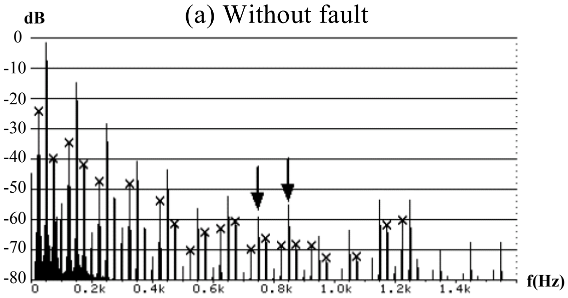
Figure 5: Spectra of radial vibrations.

### 4.2. Broken bar fault

The external magnetic field spectra, related to a healthy machine and a machine with one broken rotor bar, are given by the figure 6 where the rotor slotting spectral lines are arrowed.



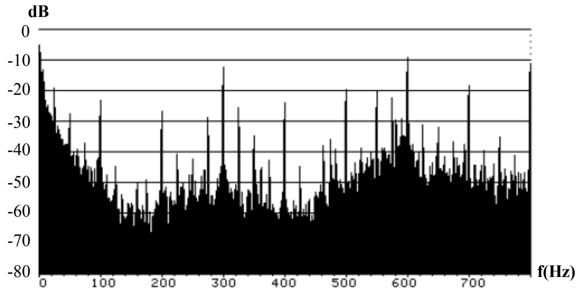

(a) Without fault



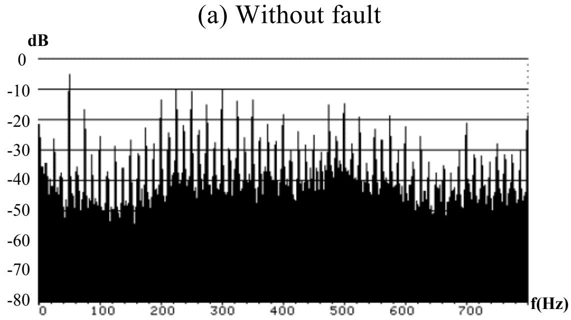

(b) With one broken bar

Figure 6: External radial magnetic field spectra.

It can be noticed that new spectral lines appear with the fault. These same phenomena can be observed on the spectra of radial vibrations (figure 7) and are more perceptible in this second kind of measurement.




(a) Without fault




(b) With one broken bar

Figure 7: Spectra of radial vibrations.

## 5. CONCLUSION

The correlation between the external radial magnetic field and the vibrations is conspicuous in this paper. Only the study of the slotting spectral lines is presented, but the analyses can also be applied on the other spectral lines.
Moreover, the study shows that a defect reveals some sensitive spectral lines in the both spectra which are a good indicator for the diagnosis. Consequently, it can be interesting to use the observations performed on the external radial magnetic field to improve the vibratory analysis, and inversely.

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