Influence on Rotor Broken Bar Fault Diagnosis of Mechanical Torque Pulsations by Means of FFT

A.J. Fernandez Gomez, T.J. Sobczyk and K. Weinreb

***Abstract* — Induction machines are connected to a wide variety of mechanical elements. A failure in drive or load will affect the performance of the whole system. Therefore, it will cause malfunction of the "healthy element" and it may lead to itshe destruction with time. Nowadays it is possible to monitor the state of drive and load by analysing the electrical machine signatures applying MCSA such as FFT and statistical indicators like neural networks fuzzy logic algorithms. In order to be effective it has to be defined with features of the signals which are going to be studied, as well as the magnitudes which imply a fault. This paper attempts to point out the effects over the typical signatures used for fault diagnosis of rotor cage and mechanical faults when the fault frequency of both load and drive coincides by means of FFT applied to the stator phase currents, supported with simulation and experimental results.**

Index Terms* — *FFT, Induction Motor, Mechanical Fault, Rotor Cage

I. INTRODUCTION

FAULT diagnosis of electrical motors is a topic frequently discussed in relation to industrial solutions, above all in those cases where high power machines run the productive process. The scientific community together with industry have dealt with this challenge for many years now, but still there is no global solution available due to the evolution of the industry. For instance, the development of new drives for electrical motors brought new difficulties in the condition monitoring and fault diagnosis.

In many publications and studies, sidebands $(1 \pm 2s) \cdot f_0$ around the main component at 50 Hz are typically used for diagnosis of electrical and mechanical faults in induction machines [1] [7] [9] [11]. However, it is not always possible to conclude which type of fault is affecting the machine as the analysis of those components has been considered insufficient. Some authors have suggested alternative methods in which other frequencies of the stator phase currents, electromagnetic toque or rotor speed, are studied. In [8] authors suggest the use of the component at frequency $(5-4s) \cdot f_0$ in order to detect rotor fault due to the fact that this component increases with the number of broken bars while it remains almost unchanged for the inertia of the motor-load unit as well as for supply voltage distortion or unbalance. The effects of higher harmonics due to cage asymmetry have been studied on [10]. In [5] the influence of the broken bar on the motor's electromagnetic characteristics has been studied in frequencies close to 300 Hz applying Finite Element method (FEM) models. Additionally, in [12] it is shown that the diagnosis of broken bar improves by taking several spectral components instead of classical components located around main frequencies. In [13] the components around the principal slot harmonic PHS have been considered in order to detect the mechanical unbalance.

Nevertheless, those studies have not considered the possible effects over the frequency magnitudes that may have happened when two of these faults occur simultaneously due to the interactions existing between electrical and mechanical components of the electrical machine.

In large scale motors, at nominal conditions, the slip is rather small and has its frequency sidebands in a range of few Herz. However, low frequency components are also a typical effect when a fault occurs in turbo-machinery. For instance, Surge in centrifugal compressors.

Surge is a phenomenon in which the compressor cannot add enough energy to the liquid/gas pumped in order to overcome the output pressure causing a rapid mass flow reversal and speed oscillations. As a consequence, the compressor demands an increase of the torque deliver by the compressor's driver. Ergo, an alternating component in the compressor's torque arises [4]. This phenomenon appears when the operation point of the compressor crosses the stability limit in the compressor's map and may cause severe damage to the machine. Surge may arise due to many factors such as ingestion of foreign objects which results in damage or due to the accumulation of impurities. In big

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compressors, i.e. 7-8 MW power, the surge frequency is about 1-2 Hz [3].

The aim of the paper is to show the changes produced in the stator phase current spectra of the induction motors when electrical and mechanical faults occur simultaneously due to the fact that characteristic frequencies of both faults may be equal. The study is supported by simulation and experimental results. Influence of load and magnitude and phase of the mechanical fault have been considered for the case of one broken bar.

Simulation and experimental results have shown differences in magnitudes of the sidebands as a function of the mechanical load conditions.

Simulink has been selected as a platform to develop faulty dynamic models of induction motor IM based on effect of main magneto-motive forces.

II. Electical and Mechanical Fault Models

A. Broken Bar Model

As a consequence of the broken bar, the rotor cage symmetry is lost. In terms of modelling, the equivalent resistance of the cage changes. This approach is only valid for slip values close to the nominal, otherwise the inductance matrix must also be changed. Usually, the new resistance value of the element broken inside the cage (bar or ring segment) is estimated as 20 times the "healthy" value [2]. The induction motor model of broken bar can be reduced to a set of four electrical and two mechanical equations. An equivalent rotor cage resistance can be calculated by applying the symmetry k_s and the asymmetry k_{as} coefficients [10]. Therefore, these factors represent the severity of the fault. In the frequency spectra of the simulated current sidebands $(1 \pm 2s) \cdot f_0$ arises.

B. Mechanical Fault Model

Gearboxes, bearings, compressors are also subject to faults. If they are not detected on time, they may cause severe damage in the electrical motors, especially in those with big power as they are suffering big mechanical efforts.

Speaking about modelling, for instance, an unbalanced rotation shaft due to a fault in a gearbox or a broken ball in a bearing creates an additional torque and in some cases an asymmetry in the air-gap. The reaction of the induction motor due to this type of faults can be studied through the set of the two mechanical equations included in the classical model of the induction machine. In this paper a generic mechanical fault that causes pulsations in the load torque is studied.

The pulsating torque added is modelled by the following equation:

$$T_l = T_{cons} + T_A \cdot sin(2 \cdot \pi \cdot f_f \cdot t + \alpha) \tag{1}$$

where T_{cons} is the constant component of the torque, T_A is the amplitude of the torque oscillation, f_f is the faulty frequency and α is the phase of the sinusoidal component.

For more details about modelling above faults, lectors may find [2] interesting.

III. Simulation Results

Two cases have been simulated: a) the objective of the first case is to study changes in the sideband's magnitude according to the faulty frequency for different load conditions:

$$f_f = 2 \cdot s \cdot f_0 \tag{2}$$

b) The second type of simulation have consisted in testing the influence of the phase α .

A 2MW induction motor, with 36 rotor bars and inertia J = 34 kgm2, has been chosen for simulation purposes.

It is worth mentioning that ripple caused in stator currents due to the torque pulsations is equivalent to the ripple caused by the broken bar.

In both cases, magnitudes of sidebands have been referred to the value of 50 Hz established as 100 dB.

A. Influence of " f_f " over sideband's magnitude

Following simulations have been carried out under following assumptions:

- Machine loaded with nominal Torque.
- Inertia of the system considered as twice the motor's inertia.

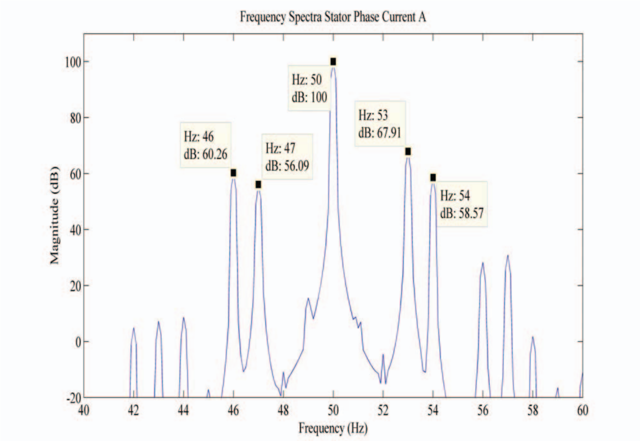

Fig. 1 Frequency spectra BB and Mechanical Fault 1

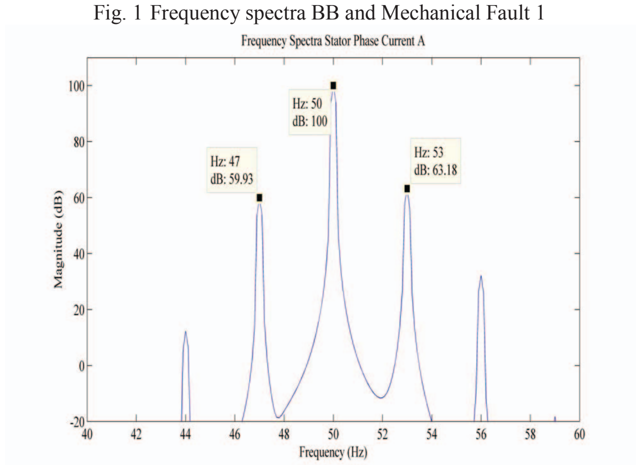

Fig. 2 Frequency spectra BB and Mechanical Fault 2

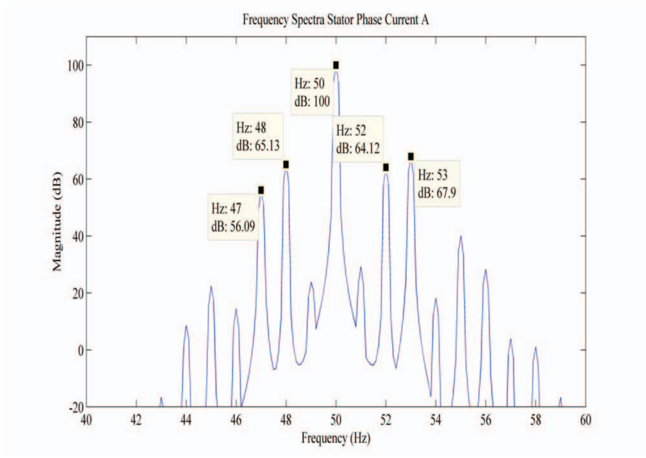

Fig. 3 Frequency spectra BB and Mechanical Fault 3

Above figures show how the magnitude of the $(1 \pm 2s) \cdot f_0$ frequency components changes if the frequency of the mechanical fault is close to $2 \cdot s \cdot f_0$. Fig. 1, Fig. 2 and Fig. 3 represent the machine loaded with nominal torque. Only one case is exposed due to the fact that same trends have been seen, considering different levels of load.

Frequencies 47Hz and 53 Hz correspond to the broken bar sidebands whose values are 56.09 dB and 67.91 dB respectively. The two extra components marked in Fig.1, and Fig. 3 correspond to the mechanical fault with $f_f = 4$ and $f_f = 2$.

Two phenomena can be distinguished. Firstly, if both frequencies coincide ($f_f = 3$) there is a change of the sideband magnitudes $(1 \pm 2s) \cdot f_0$ from 56.09 dB to 59.93 dB and from 67.91 to 63.18. Secondly, the magnitude of the frequency components related to the mechanical fault increases if f_f decreases independent of the oscillations amplitude (it was kept constant).

B. Influence of "α" over sideband's magnitude

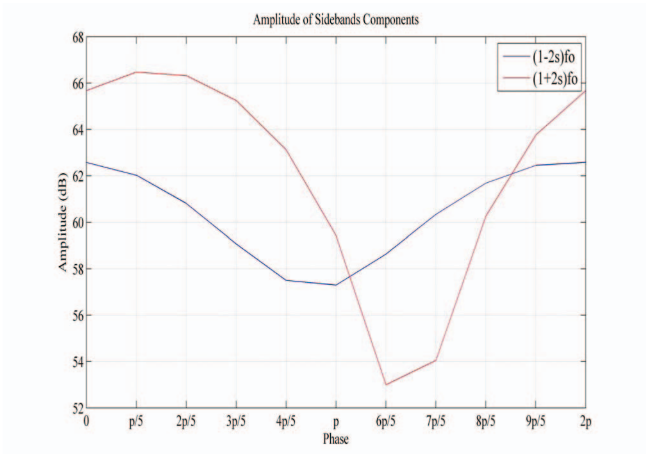

Fig. 4 Sideband's Magnitudes Evolution for Different Phases

The simulation parameters have been set up in a way that the frequency of both faults is 3 Hz and the inertia of the system equals twice the motor inertia. The phase of the alternating component of the mechanical load α has been increased from 0 to 2π in ten steps.

Fig. 4 shows that phase α determines which of the sidebands increase or decrease.

According to the simulation results, the frequency of the mechanical faults and also the phase influence the sideband magnitudes $(1 \pm 2s) \cdot f_0$.

IV. Experimental Results

In order to prove that the trends shown in simulation agree with experimental data, the same experiments were applied to the motor model T-DF112M-4 connected in Y.

1) Inlfuence of Torque Pulsations over Broken Bar Sideband's Magnitude

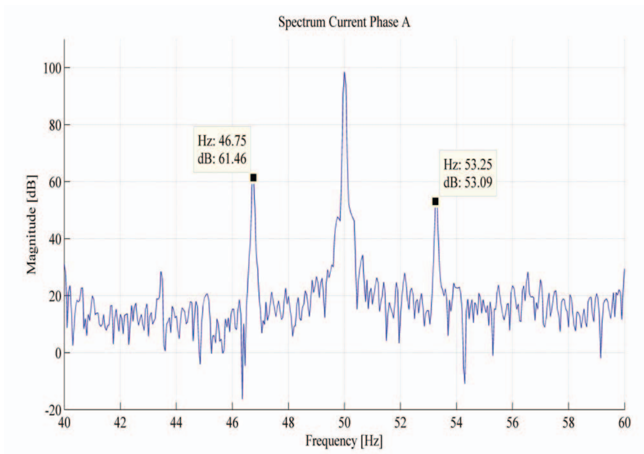

Fig. 5 Frequency Spectra of One BB with 90% of Load

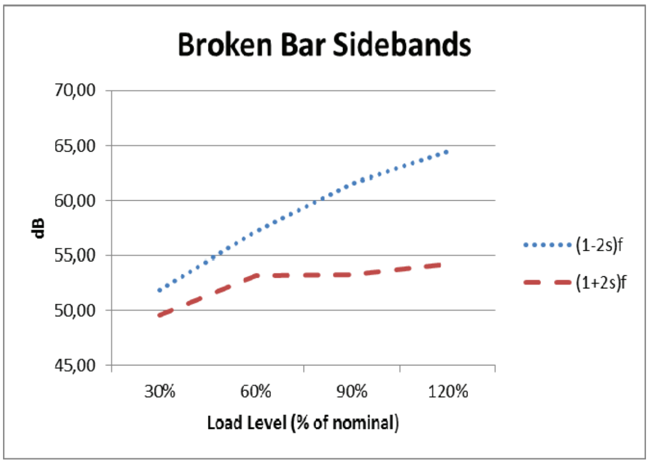

Fig. 6 Evolution of sidebands around main harmonic according the load

TABLE I
Sideband Magnitudes for One Broken Bar

Average	30% Load	60% Load	90% Load	120% Load
(1-2s)f	51,85	57,16	61,51	64,45
(1+2)f	49,52	53,18	53,30	54,25

Fig. 5 shows the sidebands $(1 \pm 2s) \cdot f_0$ inherit to the broken bar when the motor is loaded with 90% of the nominal torque. However, the same effect can also be observed in dynamic eccentricity faults [14]. The evolution of sideband magnitude according to the load (Fig. 2) confirms that actually the rotor has one of the bars broken.

A DC motor acting as a generator has been used to control the resistive torque of the induction machine by changing the field winding of the rotor through computer using a rectifier. By setting a load torque profile defined by (1), it is possible to control the amplitude and frequency of the torque pulsations.

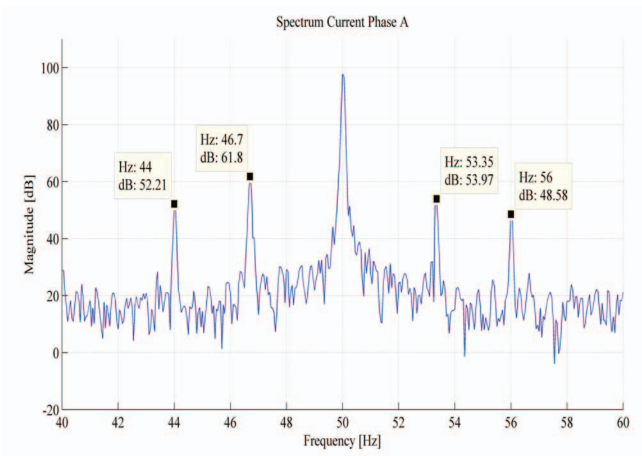

Fig. 7 Frequency Spectra of One BB + Pulsating Torque with Frequency 6 Hz loaded at 90%

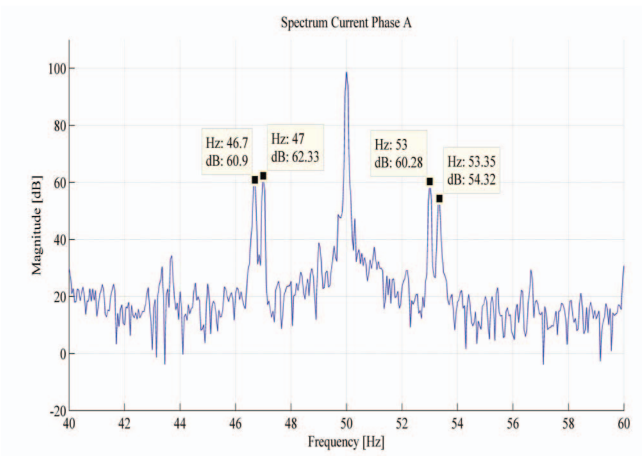

Fig. 8 Frequency Spectra of One BB + Pulsating Torque with Frequency 3 Hz loaded at 90%

Fig. 7 and Fig. 8 show the frequency spectra of the stator phase currents when the mechanical fault is simulated (frequency components at 46.7 Hz and 53.35 Hz correspond to the broken bar). It can be observed how the amplitude of the frequency components caused by the mechanical fault increased if f_f decreases. Left sideband has increased from 52 dB to 62.33 dB and right sideband from 48.6 dB to 60.3 dB. The same result could be seen in simulation.

The first case study consisted in studying the behaviour of the sidebands regarding the frequency of the mechanical fault. Different loads and amplitudes of the pulsating torque have been tested showing similar results. With the aim of clarity, only a few cases in which both faulty frequencies coincides are presented in the paper.

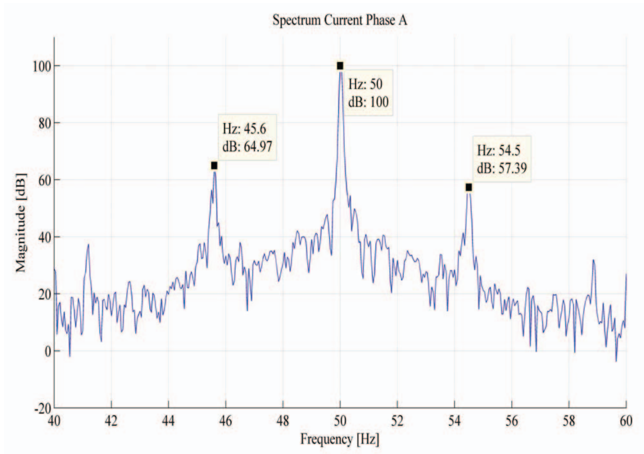

Fig. 9 Frequency Spectra of One BB + Mechanical Fault with same frequency loaded at 120% and pulsation's amplitude 30%

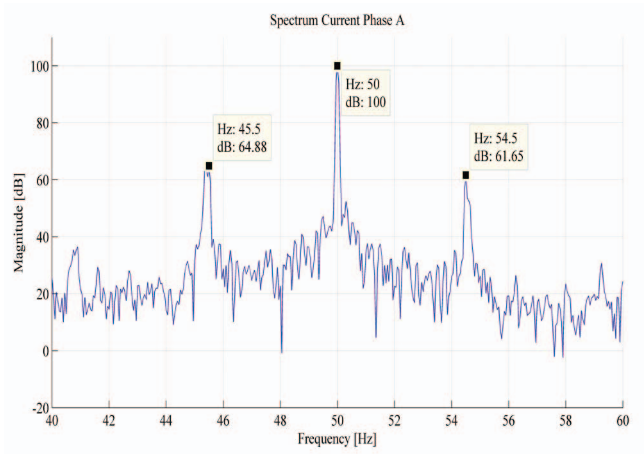

Fig. 10 Frequency Spectra of One BB + Mechanical Fault with same frequency loaded at 120% and pulsation's amplitude 40%

For instance, Fig. 9 shows the frequency spectra when the motor is loaded at 120% of the nominal torque and the oscillation's amplitude was set to 30% of this value. In comparison to one broken bar fault, the magnitude of both components has changed. Left sideband from 61.8 dB to 64.97 dB and right sideband from 53.97 to 57.39 dB. Fig. 10 shows the motor loaded at 120% of nominal torque but a pulsation torque with amplitude 40%. Again, magnitude of both components has changed. Left sidebands has increased up to 64.88 dB and right sideband up to 61.65 dB.

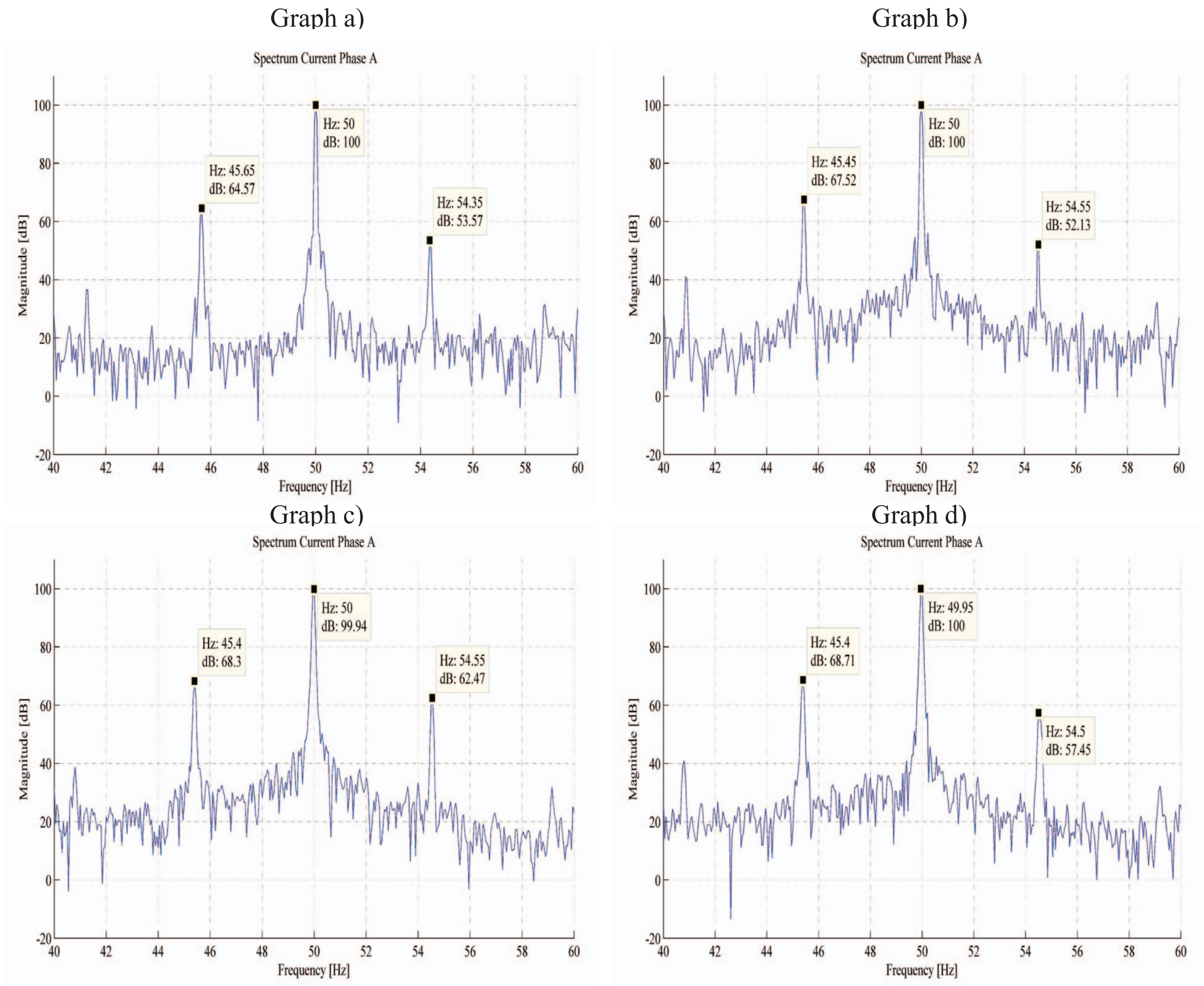

Fig. 11 Evolution of the Sideband's Magnitude according changes on Torque Pulsation Phase: a) One Broken Bar; b) Broken Bar and Mechanical fault with $\alpha = 0$; c) Broken Bar and Mechanical fault with $\alpha = \pi/4$; c) Broken Bar and Mechanical fault with $\alpha = \pi/2$

2) *Effect over Sideband's Magnitudes Caused by Phase Change*

Despite the above results, it is still not clear if the differences in sideband's magnitude are only caused by the increase of the oscillation's amplitude or if there is another factor involved. The influence over the sideband magnitude of torque pulsations also depends on the phase as simulation results have pointed out. Fig. 11 shows the evolution of the sidebands as a function of the phase. The experiment consisted in loading the motor up to the 120% of the nominal load. After a few seconds, torque pulsation with amplitude 30% and frequency $2sf_0$ arises with successive changes of phase.

Graph a) shows the spectra of the machine loaded without mechanical fault. In graph b) it can be seen as the magnitudes varies due to the torque pulsations for $\alpha = 0$. Graph c) shows the frequency spectra with $\alpha = \pi/4$ and graph d) with $\alpha = \pi/2$. It is clear that changes in the sideband magnitude also depends on the mechanical fault phase.

V. Conclusions

A comparative studies of the induction motor frequency spectra of the stator currents when it is affected by two faults with same characteristic frequency components have been presented in the paper supported by simulations and experimental data by means of FFT.

The characteristics of the torque pulsations depend on the mechanical side and it may happen that the frequency of the pulsations interferes with the sidebands $(1 \pm 2s)\cdot f_0$ extensively used for diagnosis of broken bar and mechanical faults.

According to the simulation and experimental results, the magnitude of the $(1 \pm 2s)\cdot f_0$ components suffer meaningful changes as a function of the amplitude and phase of the mechanical fault, leading to possible misinterpretation of the results derived from IM diagnosis due to changes in the sidebands amplitudes.

One of the techniques applied to detect the presence of broken bar or incipient broken bar in electrical motors consisted in studying the differences between the magnitudes of the two sidebands establishing global fault indicators [1] [10]. The presence of a mechanical fault produces variations in magnitudes that may alter the value of the indicator leading to incorrect diagnosis.

It is noteworthy that high difference between sideband components can be attributed to cases where more than one bar was damaged. Future research may be focused on studying systems which include not only a model of the electrical machine plus a generic mechanical fault, but also the mechanical load driven, due to the fact that nowadays industry demands solutions customized for individual systems. The inclusion of electrical machines models in the studies carried out to evaluate failures in turbo-machinery could point out that damage could be increased due to electrical faults and vice versa.

VI. Annexes

TABLE II
Nominal Parameters Motor T-DF112M-4

Parameter	Value	Parameter	Value
Power	4 Kw	Speed	1445 rpm
Voltage	660 V (Y)	Pole Pair	2
Current	4.6 A (Y)	Rotor Bars	28
Frequency	50 Hz	Stator Slots	24
cos (φ)	0.86 (Y)	Inertia	0.0197 kgm^2

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Konrad Weinreb was born in 1950 and educated in Poland. He received MSc, PhD degrees in electrical engineering from the Faculty of Electrical Engineering, Automatics and Electronics at the University of Mining and Metallurgy, Cracow and DSc degree in electrical engineering from the R&D Center of Federal Grid Company, Moscow, Russia, in 1973, 1983 and 2013, respectively. He worked at the University of Mining and Metallurgy in Cracow (1973-1992) and next at the Cracow University of Technology at the Faculty of Electrical & Computer Engineering. Presently he is the Vice-manager of the Institute on Electromechanical Energy Conversion. His main research fields are: mathematical modelling and fault diagnosis of Electrical Machines and Drives, on-line condition monitoring for induction and synchronous motors. He has published more than 80 scientific papers in Polish and international journals and proceedings of conferences.