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Distortion of currents fault signature in induction motors with faulty cage under influence of mechanical torque oscillations

***Abstract**. The aim of the paper is to study the evolution of the additional frequency components in the stator phase currents of induction cage motors when they are simultaneously affected by electrical and mechanical faults. In particular effects of interaction of pulsating torque components caused by cage broken bars and low frequency mechanical torque oscillations are studied. It is shown by simulation that the overlapping of the frequencies of those torques may lead to an incorrect diagnosis of the motor cage damage by means of the Motor Current Signature Analysis what has been confirmed by experimental results*

Streszczenie.** Praca prezentuje analizę zmian widma prądów fazowych stojana silnika klatkowego w przypadkach jednoczesnego występowania uszkodzenia mechanicznego w układzie napędowym oraz uszkodzenia klatki. W szczególności badane są przypadki interakcji składowej pulsacyjnej w momencie elektromagnetycznym wywołanej uszkodzenia pręta klatki oraz w momencie obciążenia gdy ta częstotliwość jest bliska lub równa składowej generowanej przez silnik z uszkodzoną klatką. W pracy wykazano, że gdy te częstotliwości się pokrywają diagnoza stanu klatki na podstawie charakterystycznych dla uszkodzenia klatki składowych prądów stojana może być błędna. **Analizę zmian widma prądów fazowych stojana silnika klatkowego w przypadkach jednoczesnego występowania uszkodzenia mechanicznego oraz uszkodzenia klatki

Keywords: cage motor fault diagnosis, broken bar, load torque oscillations, Motor Current Signature Analysis.
Słowa kluczowe: silnik indukcyjny, diagnostyka uszkodzeń klatki, pęknięcie pręta klatki, pulsacje momentu obciążenia, analiza cech prądów stojana.

Introduction

Motor Current Signature Analysis (MCSA) has become a common tool for condition monitoring of industrial induction motors of medium-high voltage [1][2][3][4]. It is especially effective for on-line diagnosis of rotor cage faults. Numerous publications and case studies [5][6][7][8][9] show that sidebands around the main current component can be efficaciously used for such diagnosis. It is well-known that low frequency torque oscillations also generate sidebands in the same interval of frequency as broken bars components and MCSA is extensively used for diagnosis when the torque pulsations arise due to a fault in mechanical part of a drive [9][10][11].

In [12][13][14][15][16][17][18] it is reported that low frequency components of mechanical torque may lead to an incorrect diagnosis of rotor faults by triggering false alarms in the condition monitoring systems based on MCSA when additional components in the stator phase currents have the same frequencies. In this case it is not always possible to conclude the nature of the fault that is affecting the machine based on sidebands closed to the main current component.

The overlapping of both components may arise in high power induction machines driven centrifugal compressors when the operation point crosses the surge line (define on the compressor' map). 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. Consequently an alternating component in the compressor's torque arises [24]. 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. In big compressors, i.e. 7-8 MW power, the surge frequency is about 1-2 Hz.

The aim of the paper is to show changes in the stator phase current spectra of the induction motor when electrical and mechanical faults occur simultaneously. Influence of mean value of the load torque and magnitude and phase of its pulsating components is investigated for the case of one broken bar in the rotor cage. Special attention is focused on the case when frequencies of pulsating components of electromagnetic and mechanical torques are overlapped. The study is based on simulations using the four equation "*d-q*" model of induction motor considering only the main MMF harmonic effects. Faults in the cage are modelled by modifying the rotor resistance matrix. The results are also validated by measurements on a test bench.

Model of induction motor with faulty cage

The faults in the cage of induction motors can be modelled with different accuracy using various mathematical models. The most advanced are 3D or 2D field models taking into account also the rotor motion. At circuital approach the full model is constituted by 3+N+1 differential equations (N is the number of bars in a cage) considering full spectrum of MMFs, together with the equation of motion. However, very often circuital model is reduced to the four equation model for electric quantities, assuming mono-harmonic MMFs. These are especially attractive for engineering applications because allows finding the most important effects of cage asymmetry and required only the basic motor parameters. Commonly accepted the "d-q" model of induction motors at symmetrical cage has the form (1a,b)

(1a) $$\frac{d}{dt}\begin{bmatrix}\psi_{sd}\\ \psi_{sq}\\ \psi'_{rd}\\ \psi'_{rq}\end{bmatrix}+\begin{bmatrix}-\omega_s\cdot\psi_{sq}\\ \omega_s\cdot\psi_{sd}\\ -\omega_r\cdot\psi'_{rq}\\ \omega_r\cdot\psi'_{rd}\end{bmatrix}+\begin{bmatrix}R_s\cdot i_{sd}\\ R_s\cdot i_{sq}\\ R'_r\cdot i'_{rd}\\ R'_r\cdot i'_{rq}\end{bmatrix}=\begin{bmatrix}u_{sd}\\ u_{sq}\\ 0\\ 0\end{bmatrix}$$

(1b) $$J\frac{d^2\varphi}{dt^2}+D\frac{d\varphi}{dt}=p\left(\psi_{sd}\cdot i_{sq}-\psi_{sq}\cdot i_{sd}\right)+T_m(t)$$

where

$$\begin{bmatrix}\psi_{sd}\\ \psi_{sq}\\ \psi'_{rd}\\ \psi'_{rq}\end{bmatrix}=\begin{bmatrix}L_{\sigma s}+L_m & 0 & L_m & 0\\ 0 & L_{\sigma s}+L_m & 0 & L_m\\ L_m & 0 & L'_{\sigma r}+L_m & 0\\ 0 & L_m & 0 & L'_{\sigma r}+L_m\end{bmatrix}\cdot\begin{bmatrix}i_{sd}\\ i_{sq}\\ i'_{rd}\\ i'_{rq}\end{bmatrix}$$

The equations (1a,b) constitute a class of models in rotating reference frames for stator and rotor quantities under the condition $\omega_s=\omega_r+p\omega$, where $d\varphi/dt=\omega$.

In [19][20] a four equation model of induction motor has been developed, which allows to take into account an arbitrary fault in a cage. It has been obtained for the full circuital model by limiting harmonic spectrum of MMFs to the main *p*-harmonic (“*p”* - the pole-pair number). That full model uses the 3-phase symmetrical components for stator and the *N*-phase symmetrical components for rotor quantities. Under assumptions that rotor cage leakage fluxes can be omitted it has been reduced to the four equation model. It describes the motor using symmetrical components “1” and “2” for the stator voltages and currents, and symmetrical components “*p*” and “*N-p*” of the cage mash currents. The cage asymmetry is represented in it by a modified rotor resistance matrix of the form

$$\begin{bmatrix} (1+k_s)R'^p_r & k_{as}R'^p_r e^{-j\varepsilon} \\ k_{as}R'^p_r e^{j\varepsilon} & (1+k_s)R'^p_r \end{bmatrix} \tag{2}$$

where R'^p_r is the resistance of the cage for “*p*” symmetrical component, recalculated to the stator. In fact, it is the rotor resistance in the “classical” equivalent scheme $R'_r = R'^p_r$. Coefficients k_s and k_{as} determine quantitatively the cage asymmetry. The coefficient k_s determines how much the rotor resistance for “*p*” symmetrical component grows due to cage fault, whereas the coefficient k_{as} determines the resistance coupling between the “*p*” and “*N-p*” symmetrical components of the rotor mash currents, i.e. determine the asymmetry of rotor mash currents. The coefficients k_s and k_{as} can be calculated exactly for any cage faults and also approximated for engineering praxis [19][20][21]. The matrix (2) is equivalent to the modification of the equations (1a) as follows

$$\begin{bmatrix} R_s \cdot i_{sd} \\ R_s \cdot i_{sq} \\ R'_r \cdot i'_{rd} \\ R'_r \cdot i'_{rq} \end{bmatrix} \Rightarrow \begin{bmatrix} R_s & 0 & 0 & 0 \\ 0 & R_s & 0 & 0 \\ 0 & 0 & R'_r \cdot \left(1+k_s+k_{as}\cdot cos(2\gamma_r)\right) & R'_r \cdot k_{as} \cdot sin(2\gamma_r) \\ 0 & 0 & R'_r \cdot k_{as} \cdot sin(2\gamma_r) & R'_r \cdot \left(1+k_s-k_{as}\cdot cos(2\gamma_r)\right) \end{bmatrix} \begin{bmatrix} i_{sd} \\ i_{sq} \\ i'_{rd} \\ i'_{rq} \end{bmatrix} \tag{3}$$

where $2\gamma_r = 2p\varphi - \varepsilon$. It has been proved in [22][23] that such model is valid for steady-states at small slips, up to the rated one, when the rotor cage leakage reactance can be neglected.

It is well-known that cage faults produce at steady-states an oscillating component of the electromagnetic torque with frequency $2 \cdot s \cdot f_0$, which is relatively low at normal operations of induction motors. Then, low frequency load torque oscillations can interact to oscillating component produced by cage faults. Such load oscillations can happen due to rotor position dependent load or when loaded torque is varied periodically in time due to any reasons. In [12][14][16] there are reported interactions of both torques for piston compressor drives or defects in the coupling and load. In [18] there are described such interactions in drives where rotational speed of the load is slow, in which the low torque oscillations are produced by unbalance or misalignment in the load. In [17] is reported that low frequency torque oscillations can appear in rotary compressors due to surge phenomena, i.e. when the compressor cannot add enough energy to the pumped liquid/gas in order to overcome the output pressure causing a rapid mass flow reversal and speed oscillations. For big compressor the surge frequency could be (1-2) Hz.

In order to model the low load torque oscillations appearing simultaneously to the cage fault, the alternating component has been added to the loaded torque.

$$T_m(t) = T_0 + T_{os} \cdot sin\left(2 \cdot \pi \cdot f_m \cdot t + \alpha\right) \tag{4}$$

It has been assumed that it is mono-harmonic and it has the frequency independent of the rotation speed of the motor, but rather small to interact to the pulsation component of the electromagnetic torque generated by the motor with faults in the cage.

The equations (1a,b), substituting relations (3) and (4), are the basis for simulations of interactions due to low frequency oscillating components of electromechanical and mechanical at simultaneously appearing the faults in the cage and the mechanical part of a drive.

Simulation Results

The aim of simulations was to study the influence of the load torque oscillation parameters (faulty frequency f_m and phase α) on the main sidebands of the stator phase currents for a motor with faulty cage. It was assumed that one bar is broken. For the sake of simplicity, only three cases are reported in this paper as similar behaviour was observed:

i. mechanical faulty frequency f_m gets close to the value of broken bar sidebands
ii. overlap of both faulty frequencies
iii. influence of mechanical phase angle α

The influence of the load torque oscillation on the stator current spectra is studied. The magnitude of oscillating load torque component has been chosen to obtain the sidebands due to torque oscillations comparable to those due to the cage fault. Therefore, the magnitude of the load torque oscillating component has been fixed as $T_{os} = 0{,}1 \cdot T_0$. Simulations have been done based on parameters of a motor with rated data: $P_N = 4kW$, $U_N = 660V(Y)$, and $n_N = 1445rpm$ with *N* = 28 rotor bars. In order to keep the linearity of the magnetic motor core, for simulation and experimental results the line voltage has been limited to $400V(Y)$, hence, the load torque was $T_0 = 12{,}9Nm$ and the motor reached the slip $s = 0.0455$.The moment of inertia for the systems selected was 8 times the inertia of the motor ($J = 0.0197kg/m^2$). Under these conditions the sidebands caused by the cage fault arise at frequencies: $f_{1-2s} = 45{,}45Hz$ and $f_{1+2s} = 54{,}55Hz$`. The oscillating component frequency of the electromagnetic torque is 4.45Hz. In successive simulations the frequency f_m of the load oscillating component has been changed to: 4Hz, 5Hz and 4.55Hz, i.e.: lower and greater than the torque frequency due to the cage fault and the frequency overlapping case. Results of these three simulations are shown in Figs. 1 – 3.

Fig. 1 shows the spectrum of stator currents for the load torque oscillation frequency $f_m = 4Hz$. In the spectrum the sidebands caused by the cage fault appear: $f_{1-2s} = 45,45Hz$ and $f_{1+2s} = 54,55Hz$ but also the components produced by the load torque oscillations at $f_0 - f_m = 46Hz$ and $f_0 + f_m = 54Hz$, with comparable magnitudes. As it can be observed, even if the frequencies of both oscillating torques are very close, the magnitude of frequencies do not interact with each other. The amplitude of the broken bar fault when the motor was tested considering only the electrical faults were respectively: 68.37 dB and 51,49 Hz.

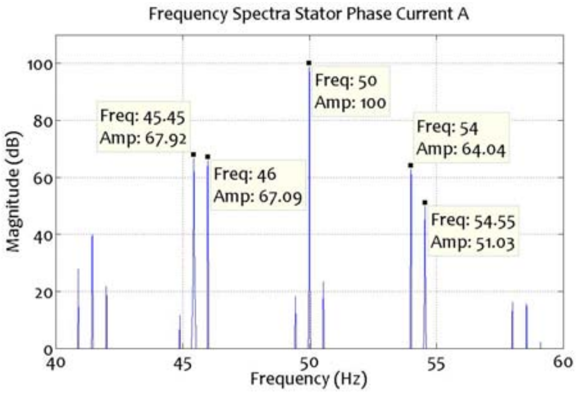

Fig.1. The spectrum of the phase stator current at $f_m = 4Hz$

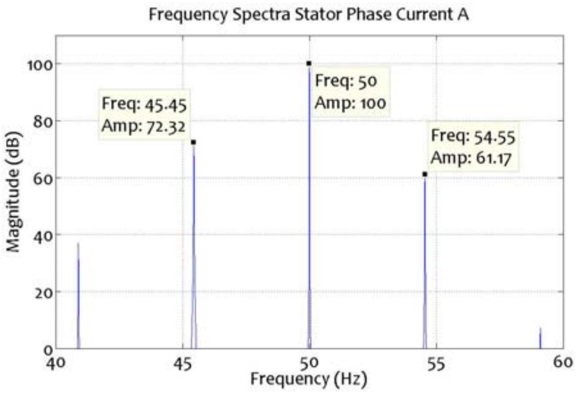

Fig.2. The spectrum of the phase stator current at $2sf_0 = f_m = 4.55Hz$

Fig. 2 shows the current spectrum when the frequency of the oscillation component of the load torque overlapped the pulsating component of the electromagnetic torque of the motor with faulty cage. In this case only two sidebands appear, but their magnitudes have been changed. Both sideband's magnitude has increased approximately 4.4 dB the left component and 10 dB the right component.

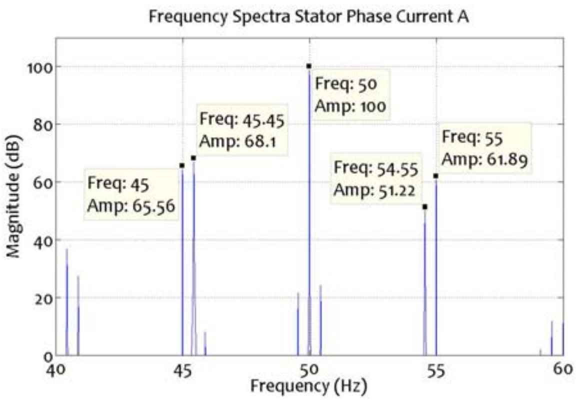

Fig.3. The spectrum of the phase stator current at $f_m = 5Hz$

Fig.3 shows the current spectrum for the load torque pulsating component frequency equals $f_m = 5Hz$. Now, again sideband bars are separated and new bars at frequencies $f_0 - f_m = 45Hz$ and $f_0 + f_m = 55Hz$ arise. The sidebands produced by the cage fault have the same magnitudes as at $f_m = 4.55Hz$. Magnitudes of sidebands follow from load torque pulsation are roughly 2 dB lower that for $f_m = 4Hz$.

From the results shown in these three figures it can be concluded that overlapping frequencies of pulsations due to cage and mechanical faults may lead to an incorrect diagnosis based on MCSA. In that case changes of sideband's magnitudes of stator current spectra depend on the magnitudes and frequency of oscillation components of electromagnetic and loaded torques. However, it is still not clear if those changes are also influenced by the phase angle. The magnitude and phase of the torque produced by the cage fault depend on the type of the fault and for one broken bar in the cage those values are fixed.

The third simulations reported in this paper concern on the influence of the phase angle of the load torque oscillating component over the main sideband's of stator currents, keeping the magnitude of the mechanical oscillation constant, i.e. $T_{os} = 0,1 \cdot T_0$ as it happened in the previous simulations. The cage fault is limited to one broken bar as well.

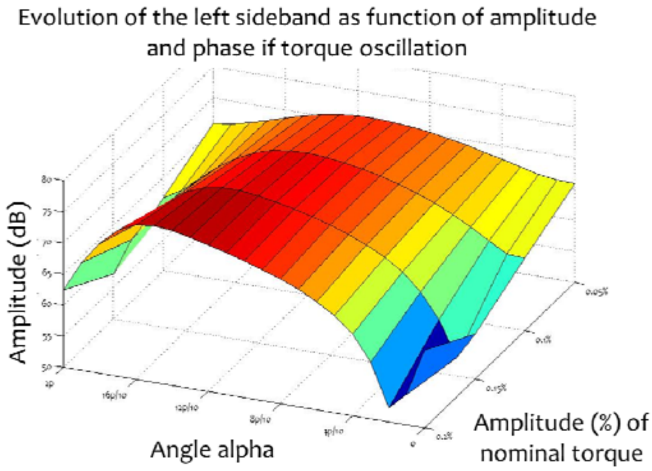

Fig.4. Map of the left sideband's amplitude as function of the torque oscillation phase and amplitude.

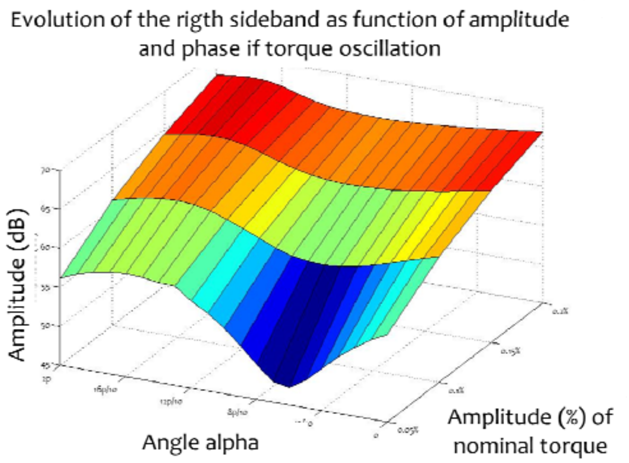

Fig.5. Map of the right sideband's amplitude as function of the torque oscillation phase and amplitude.

Fig. 4 and Fig. 5 shows the changes of sideband's magnitudes in dB versus the phase angle α and the amplitude of the torque oscillations. The left sideband fluctuates around the magnitude produced by the cage fault by 11 dB, but right sideband change essentially even by 12 dB and always is at least 8dB greater (Cage asymmetry sidebands reference values: i) Left: 67.92 dB \ ii) Right: 51.03 dB). It is evident that in such cases mechanical faults can be triggering false alarms on the rotor fault condition monitoring systems based on MCSA.

Experimental Results

In order to prove that the trends shown in simulations agree with experimental data, the measurement results presented in this paper show the motor stator phase current spectra working under the same conditions. The motor was loaded at $T_0 = 12{,}9 Nm$ and supplied with 400 V in Y connection. A DC motor acting as a generator has been used to control the loaded torque of the induction machine by changing the rotor field current using a rectifier. The software used to control the rectifier varies the voltage supplied the field rotor winding according to the torque desired, which has been setup following (4).

The experimental tests conducted at the laboratory consisted in studying the behaviour of the sidebands according to the frequency, amplitude and phase angle of the load torque pulsating component. Different loads and amplitudes of its pulsating component have been tested showing the similar trend observed in simulations. As the aim of the paper is to show that such overlapping can miss diagnosis of the cage faults, in this paper there are reported only results of three cases where both faulty frequencies overlapped at different phase angle of the load pulsating component.

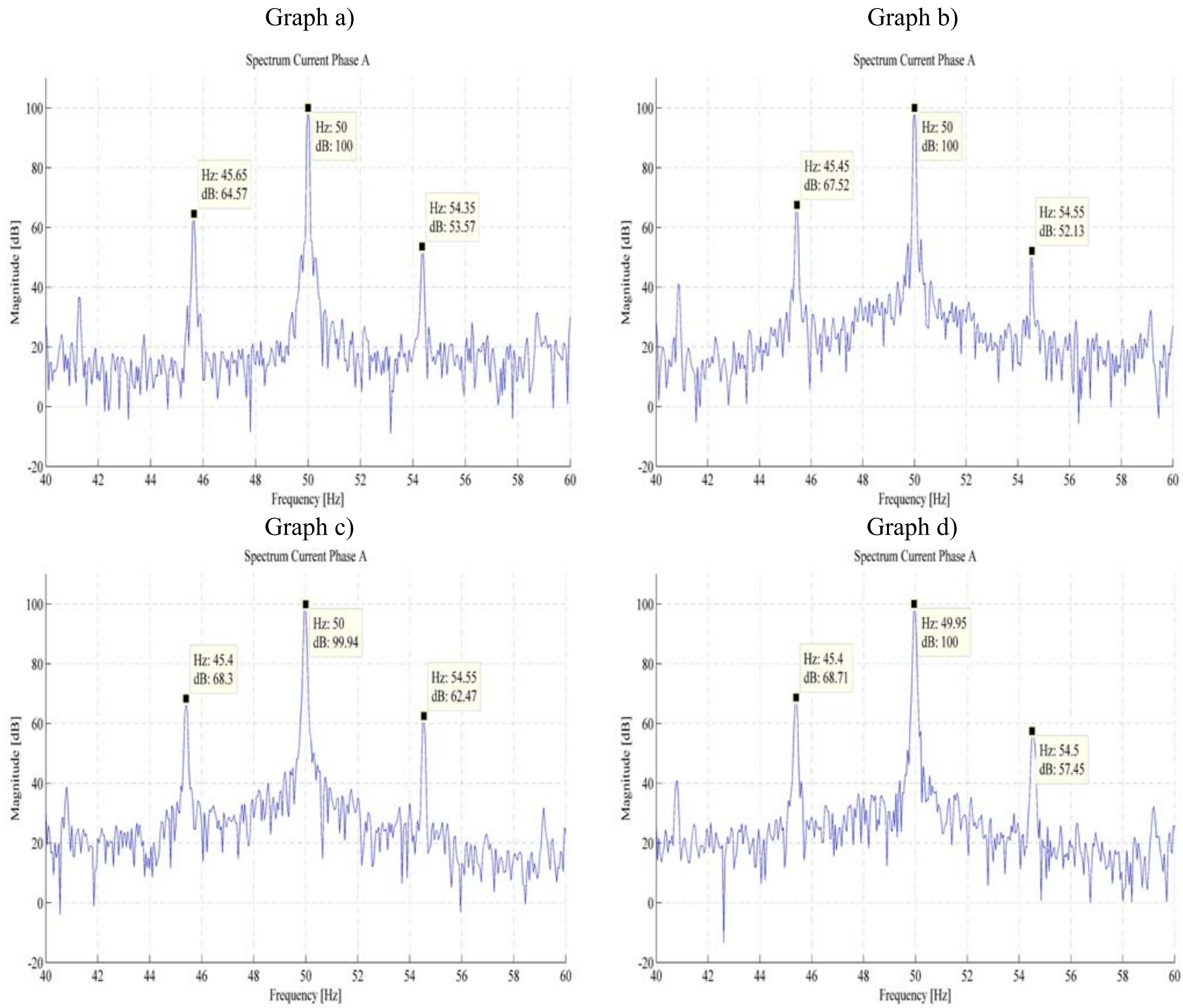

Fig.6. Sidebands evolution considering faulty frequency overlapping for different the load pulsating component phase; graph a) one broken bar only, graphs with simultaneous faults: graph b) $\alpha = 0$; graph c) $\alpha = \pi/4$; graph d) $\alpha = \pi/2$

Fig.6 shows the current spectra when overlapped frequency equals 4,55Hz and the amplitude of the torque pulsating component is $T_{os} = 0{,}1 \cdot T_0$. The graph a) shows a reference spectrum when only the fault in a cage appear. The graphs b), c) and d) present the spectra for three values of the phase angle: $\alpha = 0$, $\alpha = \pi/4$ and $\alpha = \pi/2$. It is evident the amplitudes of sidebands are changed, the left by (3-4)dB and the right one even by 10dB. Such results are rather close to the trend shown in Fig. 4 and Fig. 5., i.e., the amplitude of the left sideband is changed less than the amplitude of the right one. Even if there are some differences, comparison to the simulation seems to be satisfactory.

Conclusions

A comparative study of the induction motor frequency spectra of the stator currents when the motor is affected by two faults in rotor cage and mechanical part of a drive have been presented in the paper based on simulations results and laboratory experiments. A special attention has been paid to the cases when the torque pulsations produced by a motor with faulty cage and generated in the load torque have the same low frequencies. According to the results, the magnitudes of the sideband components in the stator current spectra, characteristic for cage faults, suffer meaningful changes as a function of the phase of the load torque pulsating component. It leads to possible misinterpretation of cage condition based on those sidebands. However, the stator current spectra is rather sensitive with respect to the frequencies of torque pulsation components produced by a motor with faulty cage or/and the load. Even a small variation of the load torque mean value changes the motor speed, consequently, the sidebands produced by both faults do not overlap as the frequencies vary.

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 part of a drive, due to the fact that nowadays industry demands solutions customized for individual systems.

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