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Comparison of induction motor diagnostic methods based on spectra analysis of current and instantaneous power signals

Abstract. *The comparison of effectiveness of induction motors fault detection methods based on experimental results analysis is presented. Researches showed possible disadvantages of the current spectra analysis method and advantages of the method based on phase power and total three-phase instantaneous power spectra analysis.*

Streszczenie. *W pracy zaprezentowano porównanie skuteczności metod detekcji uszkodzeń silników indukcyjnych bazujące na analizie wyników eksperymentalnych. Badania pokazują możliwe słabe strony metody prądowej analizy spektralnej i wskazują na korzyści z używania metody opartej na analizie spektralnej całkowitej mocy chwilowej. (**Porównanie metod diagnostycznych silnika indukcyjnego opartych na analizie spektralnej prądu oraz na sygnałach mocy chwilowej**).*

Key words: induction motors, fault diagnosis, instantaneous power, frequency domain analysis, unsinusoidality, broken bars.
Słowa kluczowe: silniki indukcyjne, diagnostyka uszkodzeń, moc chwilowa, analiza dziedziny częstotliwości, niesinusidalność,

Introduction

It is well-known, that induction motors (IM) have very simple and reliable construction. However, there happen sudden failures of IM, and they may lead to significant pecuniary losses because of repair operations and idle time. Thus, timely diagnostics of incipient IM faults is a very important task. To achieve this effect different on-line IM diagnostic systems were developed.

Different reviews [1, 2] showed that most frequent IM defects are the following: the bearings defects (32-52%), stator windings defects (15-47%), rotor bars/rings (less than 5%), shaft or coupling defects (about 2%), defects caused by external devices (12-15%), other defects (10-15%). For detection of bearings faults there are well-developed and widely used methods of vibration diagnostics [3]. Most common rotor faults are the rotor-to-stator eccentricity and the rotor bar breaks. Most common stator defects are the short circuits in windings and also the windings asymmetry.

There is a range of methods for incipient fault detection. Widely used are monitoring of mechanical vibrations, currents, reverse sequence field and partial discharges.

Well-known IM incipient faults detection methods are successfully used for high- and average- power machines. However, there are some limitations to use these methods for low- and average- power machines because of economic reasons and sensors size [4].

In case of small and average-power induction motors, cheap and reliable fault detection methods could be developed basing on electrical signals analysis, such as voltage, current and instantaneous power signals [2–7]. Among such methods there are two efficient methods for on-line induction motors diagnostic – motor current spectra analysis (MCSA) [2, 7] and motor power spectra analysis (MPSA) [8].

For the analysis MCSA method needs only current signals of one or two phases. It is based on supervision of changing the motor current waveform [2, 7]. Fast Fourier Transform of motor current gives a current spectrum for fault detection procedure. Thus, presence in a motor current spectrum specific harmonics and their sidebands shows presence of electrical or mechanical damages. So this method is attractive due to its primary signals measuring simplicity, and nowadays there are a numerous diagnostic systems based on such analysis, for example [9]. It should be mentioned, that IM diagnostics based on current analysis depends on supply voltage quality, and in some cases can lead to wrong results [8].

Instantaneous power spectra analysis allows both detection of fault presence and estimation of damage degree by analysis of proper harmonic amplitude. As a result, the possibility to make the estimation of the energy of fault and the correlation of this energy to additional damage of IM parts under influence of vibrations caused by proper harmonic appears. Moreover, the MPSA allows analyzing of IM operation modes under significant nonlinearity when it is incorrect to use superposition principle for current harmonics. Also, MPSA gives additional harmonic components for analysis [8, 10]. This method needs the data of current and voltage measurement in two phases. Consequentlyt, it requires more sensors, but, hypothetically, gives more reliable results.

Thus, both considered methods allow one to detect most common damages of electrical machines and do not require expensive hardware for implementation. In order to choose best solution for implementation of IM diagnostic, it is necessary to compare methods MCSA and MPSA.

Problem statement

Comparative assessment of IM motor current spectra analysis and motor power spectra analysis methods for IM diagnostics.

Fundamentals of induction motors diagnostic methods based on electric signals analysis

The idea of IM fault detection methods based on the electric signals analysis consists in correspondence of IM defects to certain harmonics in electric signal spectra. Each damage type causes modulation of motor currents with unique frequencies.

In papers [2, 7, 11–13] the equations for determining fault frequencies in current signal caused by rotor bar breaks, rotor eccentricity, stator windings short-turns and bearings damages are described. All these equations are presented in tab.1, column "*Current frequencies caused by damage*". All these frequencies lead to current modulations. In tab. 1, column "*Current modulations, caused by damage*" there is an equation for calculation of current modulations caused by each considered damage type.

In paper [10] the expressions for calculation of instantaneous power of motor, operating with damage, were described. These expressions are in tab. 1, column "*Instantaneous powers of motor operating with damage*".

Table 1. Correspondence of IM faults to current and instantaneous power harmonics and modulation frequencies

Broken rotor bars	$f_{bb} = f_s[1 \pm 2s]$, where f_s is the supply fundamental frequency, s is the motor slip.	$i_{bb}(t) = i(t)[1 + I_m \cos(2\pi f_{bb} t)] =$ $= i(t) + \frac{\sqrt{2}}{2} I_1 I_m \begin{bmatrix} \cos(2\pi(f_s - f_{bb})t - \varphi) + \\ + \cos(2\pi(f_s + f_{bb})t - \varphi) \end{bmatrix}$, where I_m is the relative current modulation amplitude; f_{bb} is the modulating frequency.	$p_{bb}(t) = i_{bb}(t)u(t) =$ $= P_0 + U_1 I_1 \cos(\varphi)\cos(2\omega t) +$ $+ U_1 I_1 \sin(\varphi)\sin(2\omega t) +$ $+ \begin{pmatrix} I_1 I_m U_1 \cos[2\pi(f_s - f_{bb})t - \varphi] + \\ + I_1 I_m U_1 \cos[2\pi(f_s + f_{bb})t - \varphi] \end{pmatrix} \cos(2\omega t)$.
Air gap eccentricity	$f_{ec\_f} = f_s \pm k f_r$, where $f_r = (1 - s)/p$, where s is the motor slip, p is the number of pole pairs; $f_{ec\_p} = [(kR \pm n_d)((1 - s)/p) + \eta] f_s$, where R is the number of rotor slots; k is the positive integer number; n_d is an integer due to dynamic eccentricity; η is the time harmonics present in the motor supply.	$i_{ecc}(t) = i(t) + \frac{\sqrt{2}}{2} I_1 \sum_{k=1}^{K} \begin{bmatrix} I_{e1k} \cos(2\pi(f_s - kf_r)t - \\ - \alpha_{e1k} - \varphi) + \\ + I_{e2k} \cos(2\pi(f_s + kf_r)t - \\ - \alpha_{e2k} - \varphi) \end{bmatrix}$, where I_{e1k}, α_{e1k} are the relative current amplitude and the initial phase angle for frequencies $(f_s - kf_r)$; I_{e2k}, α_{e2k} are the relative current amplitude and the initial phase angle for frequencies $(f_s + kf_r)$.	$p_{ecc}(t) = i_{ecc}(t)u(t) =$ $= P_0 + U_1 I_1 \cos(\varphi)\cos(2\omega t) + U_1 I_1 \sin(\varphi)\sin(2\omega t) +$ $+ \sqrt{2} U_1 \cos(2\omega t) \sum_{k=1}^{K} \begin{bmatrix} I_{e1k} \cos\begin{bmatrix} 2\pi(f_s - kf_r)t - \\ - \alpha_{e1k} - \varphi \end{bmatrix} + \\ + I_{e2k} \cos\begin{bmatrix} 2\pi(f_s + kf_r)t - \\ - \alpha_{e2k} - \varphi \end{bmatrix} \end{bmatrix}$.
Stator windings short-turns	$f_{st} = f_s [n((1 - s)/p) \pm k]$, where f_s is the supply main frequency; n is a positive integer number (1, 2, 3…); k can be equal to 1, 3, 5 or 7.	$i_m(t) = i(t)[1 + I_m \cos(2\pi f_{st} t - \varphi)] =$ $= i(t) + \sqrt{2}/2\, I_1 I_m [\cos(2\pi f_{st} t - \varphi)]$, where f_{st} is the modulating frequency.	$p_m(t) = i_m(t)u(t) =$ $= P_0 + U_1 I_1 \cos(\varphi)\cos(2\omega t) +$ $+ U_1 I_1 \sin(\varphi)\sin(2\omega t) +$ $+ 1/(2 I_1 I_m U_1 \cos[2\pi f_{st} t - \varphi] \cos(2\omega t))$.
Bearing damage	$f_{brg} = [f_s \pm m f_{i,o}]$, where $m = 1, 2, 3\ldots$, and $f_{i,o}$ is one of the characteristic vibration frequencies, which are based upon the bearing dimensions: $f_{i,o} = \frac{n}{2} f_v \left[1 \pm \frac{b_d}{p_d} \cos\beta\right]$, where n is the number of bearing balls; f_v is the rotation frequency; b_d is the ball diameter; p_d is the bearing pitch diameter; β is the contact angle of the balls on the races.	$i_{brg}(t) = i(t) + \frac{\sqrt{2}}{2} I_1 \sum_{k=1}^{K} \begin{bmatrix} I_{b1k} \cos(2\pi(f_s - kf_{brg})t - \\ - \alpha_{b1k} - \varphi) + \\ + I_{b2k} \cos(2\pi(f_s + kf_{brg})t - \\ - \alpha_{b2k} - \varphi) \end{bmatrix}$ where I_{b1k}, α_{b1k} are the relative current amplitude and the initial phase angle for frequencies $(f_s - kf_{brg})$, I_{b2k}, α_{b2k} are the relative current amplitude and the initial phase angle for frequencies $(f_s + kf_{brg})$.	$p_{brg}(t) = i_{brg}(t)u(t) =$ $= P_0 + U_1 I_1 \cos(\varphi)\cos(2\omega t) +$ $+ U_1 I_1 \sin(\varphi)\sin(2\omega t) +$ $+ I_1 U_1 \cos(2\omega t) \sum_{k=1}^{K} \begin{bmatrix} I_{b1k} \cos(2\pi(f_s - kf_{brg})t - \\ - \alpha_{b1k} - \varphi) + \\ + I_{b2k} \cos(2\pi(f_s + kf_{brg})t - \\ - \alpha_{b2k} - \varphi) \end{bmatrix}$.

Experimental research

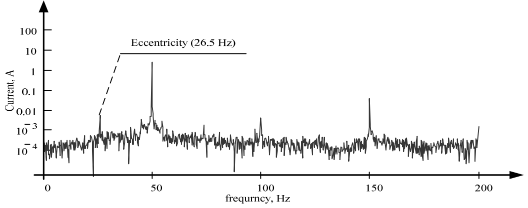
To compare both considered diagnostic methods, a series of experiments were done. Three identical induction motors of type AIR80V4U2, (1.5 kW, 1500 min^{-1}) were used for testing. These motors were artificially damaged with three most frequently caused damage types: stator winding short-circuits, rotor bar breaks and air gap eccentricity. Currents andvoltages of phases were measured both under idle mode and full load mode, and then they were analyzed. As all motors are identical, there is possibility to change all damaged stators and rotors. This allows one to investigate motors operating with different damage level and operating with some damages existing simultaneously.

The following damage types were chosen for investigation of their progress: rotor bar breaks and stator windings unsymmetry. Correspondence of motor damages to test sequence number is presented in Table 2. All tests were done for IM operating with rated load.

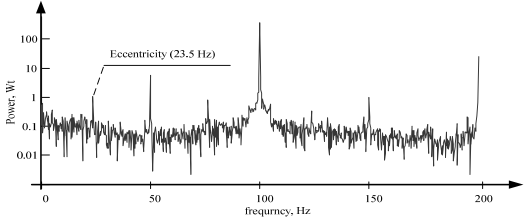
Table 2. Tests with artificially damaged IM

Test number	Damage type	Phase "C" unsymmetry, %	Number of rotor broken bars
1	Healthy motor	-	-
2	Stator windings unsymmetry	0.3	-
3		2.52	-
4		14	-
5	Rotor bar breaks	-	1
6		-	2
7		-	3
8	Stator windings unsymmetry and rotor bar breaks	2.52	1
9		2.52	2
10		2.52	3

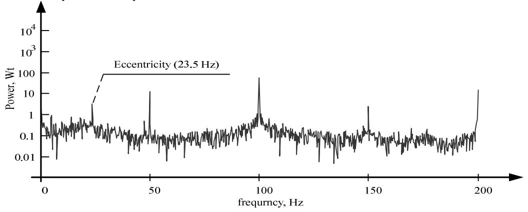
The application of MCSA and MPSA (test #1) shows, that there is eccentricity of tested motor. It can be seen because of current harmonic presence on the frequencies corresponding to rotor rotational frequency (Fig. 1, a) and its combination with power supply main frequency in power spectra (Fig. 1, b, c). This eccentricity can be explained by displacement of stator and rotor centroidal axis caused by assembling and disassembling of tested motor.



a) Phase A current spectrum



b) Phase A power spectrum

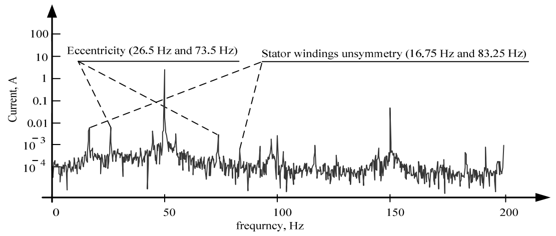


c) Total three-phase power spectrum

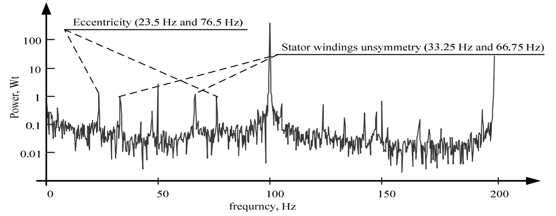
Fig. 1. Electric signals spectra for test #1

The analysis of most typical damage cases, such as phase "C" unsymmetry of 2.52 %, two rotor broken bars, and both these damages existing simultaneously (Table 2, tests #3, #6, #8) was done.

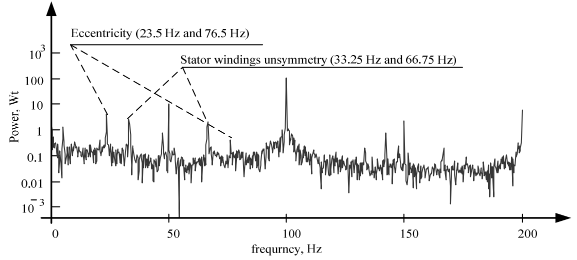
If there is stator windings unsymmety, phase current spectra, besides harmonics related to rotational speed and connected to eccentricity, contains harmonics with frequencies f_{st} (Table 1, Fig. 2, a). Phase power spectrum and total three-phase instantaneous power spectrum contain harmonics $p_m(t)$ (Table 1, Fig. 2, b, c). It should be mentioned, that power harmonics amplitudes are greater than current harmonics. If there are rotor bar breaks, phase current spectra, in addition to fundamental component, contain two sideband components with frequencies f_{bb} (Table 2, Fig. 3, a). In power spectra, besides sideband components, there is a low-frequency component with modulation frequency (for this test it is 5.5 Hz), which is an additional diagnostic feature (Fig. 3, b, c). These harmonics confirm equation for calculation $p_{bb}(t)$ (Table 1).



a) Phase A current spectrum

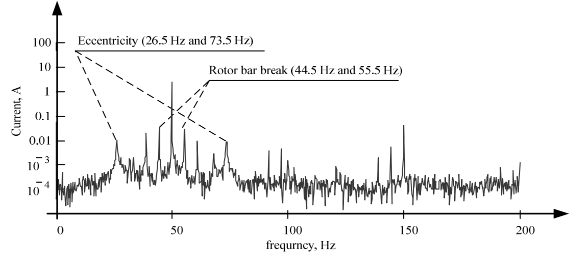


b) Phase A power spectrum

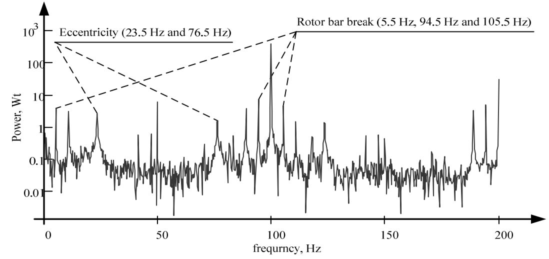


c) Total three-phase power spectrum

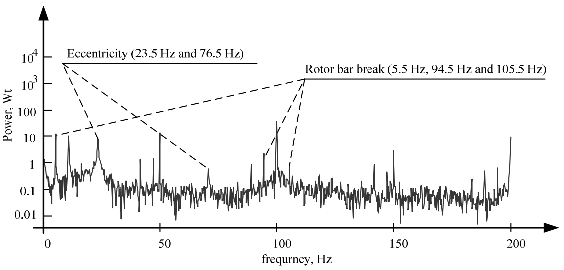
Fig. 2. Electric signals spectra for test #3



a) Phase A current spectrum



b) Phase A power spectrum

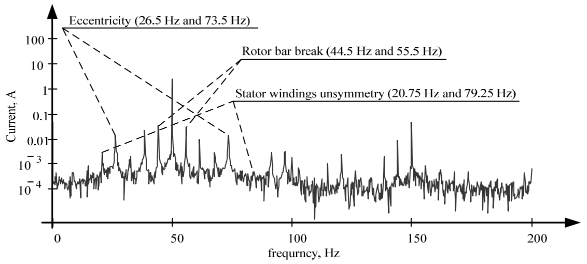


c) Total three-phase power spectra

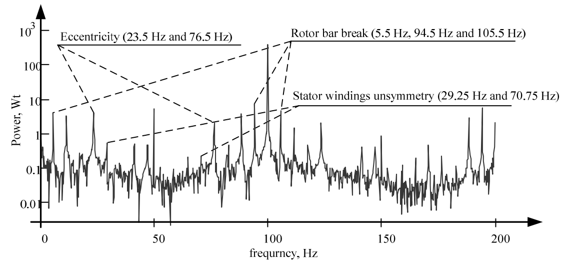
Fig. 3. Electric signals spectra for test #6

If both considered damages exist simultaneously, the amplitudes of phase current spectrum harmonics, related to stator unsymmetry, are too low and can be wrongly detected as noise harmonics (Fig. 4, a). Unlike current spectrum, power spectra harmonics are clearly visible and can be easily detected (Fig. 4, b, c).

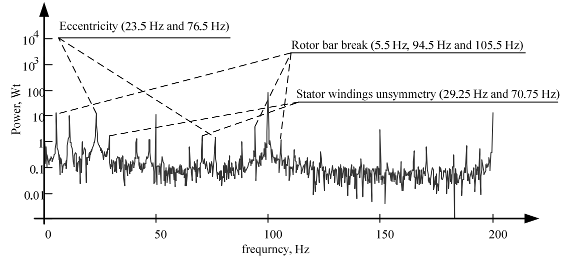
Thus, experimental tests analysis showed possibility of utilization of both considered IM diagnostic methods for IM fault detection. But diagnostics based on MPSA is more reliable, because powers spectra contain more diagnostic information, power harmonics related to damages have higher amplitudes, and this method showed better results for detection of simultaneously existed faults.



a) Phase A current spectrum



b) Phase A power spectrum



c) Total three-phase power spectrum

Fig. 4. Electric signals spectra for test #8

Conclusions

A comparison of IM fault detection methods based on MCSA and MPSA showed that both methods can be used for detection of the most common motor damages. But MCSA in some cases may lead to wrong diagnosis, because of small amplitude values of harmonics, related to damage. MPSA allows avoiding such mistakes, and it can be considered as more suitable and reliable method for IM fault detection.

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