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Estimation of the efficiency of vibration power application for induction motor diagnostics

***Abstract**. A method for calculation of an induction motor vibration power in frequency domain on the basis of harmonic composition of the signal of vibration acceleration or vibration velocity is offered. When this method is realized, there are no problems connected with integration of continuous signals in time domain. To estimate the efficiency of the proposed method the root-mean-square values of vibration power are calculated on the basis of harmonic composition of vibration velocity for most common induction motors fault types. It is shown that, when the root-mean-square values of vibration velocity are the same, the root-mean-square values of vibration power significantly differ, which may result in wrong diagnostics of induction motor faults.*

***Streszczenie.** W artykule zaproponowana została metoda obliczeń drgań mocy silników indukcyjnych w obszarze częstotliwościowym przy użyciu składowych harmonicznych sygnału akceleracji bądź szybkości drgań. Podczas używania tej metody nie u8jawniają się problemy związane całkowanie sygnałów ciągłych w obszarze czasu. Aby oszacować efektywność proponowanej metody wartości skuteczne mocy drgań zostały obliczone na podstawie składowych harmonicznych szybkości drgań dla większości typów defektów silników indukcyjnych. Zostało pokazane, że podczas gdy wartości skuteczne prędkości drgań są takie same, wartości skuteczne mocy drgań są znacząco różne. Stąd może wynikać błędna diagnostyka defektów silników indukcyjnych. (**Oszacowanie efektywności zastosowania drgań mocy do diagnostyki silników indukcyjnych**)*

Keywords: vibrating power, velocity, harmonic structure.
Słowa kluczowe: moc drgań, prędkość, struktura harmoniczna.

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Introduction

Energy conversion in induction motors (IM) is inevitably connected with occurrence of variable forces and moments giving rise to vibration. Spectral and phase characteristics of vibration shift, vibration velocity and vibration acceleration are widely used for vibration analysis. Still, if used separately, they do not give the idea of energy flows distribution in the analyzed object [1]. At present, when IM state is estimated according to vibration parameters, vibration velocity root-mean-square (RMS) value is used [2], which does not carry the information about the frequency, and consequently, about the motor oscillations energy. At the same time the researching of electromechanical system oscillation or vibration power allows one to consider oscillations frequency, which is necessary for the analysis of the distribution of oscillation energy flows in the space in the time or frequency domain. Reduction of torque variation in permanent magnet machines is often carried out by design without cogging torque [3-5]. However, in literature at present there is no information about vibration power variation depending on occurrence of different IM faults.

The purpose of the paper consists in the development of the method of calculating vibration power and its quantitative analysis when induction motors have certain fault and estimation of the expediency of the use of vibration power parameters for their diagnostics.

Material and results of the research

Instantaneous vibration power is found basing on the signals of stress, vibration velocity and vibration acceleration, measured along one of the axes [6]:

$$p_V(t) = v_V(t)\,f(t) = m v_V(t)\,a_V(t) = \\ = m v_V(t)\frac{dv_V(t)}{dt} = m a_V(t)\int a_V(t)dt, \quad (1)$$

where: $v_V(t)$ – vibration velocity instantaneous power, m/s; $f(t)$ – force instantaneous value, H; $a_V(t)$ – vibration acceleration instantaneous value, m/s^2 ; m – reduced mass, kg; t – time, s.

The advantage of the method of determining vibration power according to expression (1) consists in the absence of the necessity for force sensor; the use of vibration sensor is enough. In this case only one of the parameters – vibration velocity or vibration acceleration is measured directly. The other parameter is calculated indirectly on the basis of time integration or differentiation of the initial signal. Accelerometers are most commonly used for measuring vibrations. So, transformation of vibration acceleration into vibration velocity requires integration needing more complicated equipment and resulting in additional errors due to accumulation of integration errors.

Errors can be avoided during vibration velocity calculation if vibration acceleration signal harmonic composition is used instead of instantaneous values. In the calculation of harmonic components P_{Vn} of vibration power the integration operation is substituted by the calculation of vibration velocity harmonics V_{Vk} according to vibration acceleration harmonics $A_{Vk} = \frac{V_{Vk}}{\omega_k}$, and multiplication of vibration velocity signal instantaneous values – by convolution of vibration acceleration harmonics discrete series [7]:

$$P_{Vn} = m\left[V_{Vk} * V_{Vk}\omega_k + V_{Vk}\,g\right] = \frac{m}{\omega_k}\left[A_{Vk} * A_{Vk} + A_{Vk}\,g\right], \quad (2)$$

where: k – vibration velocity and vibration acceleration harmonic number; ω_k – frequency of k–th harmonic; n – vibration power harmonic number; g – gravitational acceleration, m/s^2; $*$ – discrete convolution operation.

For the estimation of the vibration power parameters depending on the type of IM fault and the degree of its progress the RMS values of vibration power were calculated according to its harmonic components (2).

The analysis was carried out for several most typical fault types: rotor imbalance, rotor eccentricity, stator windings asymmetry and rotor bars break. Presence of imbalance causes increase of vibration at the rotor rotational $f_{tr} = \frac{f_1}{p}(1-s)$ frequency, where f_1=50 Hz –

mains frequency; s – slipping; p – number of IM poles pairs [8-9]. Rotor eccentricity, ellipsoidal form of the stator inner bore in relation to the axis of rotor rotation usually occur as a defect of bearing pedestal assembly, fault of end shield state or when the stator is deformed. Vibration shows at frequency $f_0 = \frac{f_1}{p}$ of field rotation in the gap, at frequency $f_{em} = 2f_1$ of electromagnetic forces and is sometimes accompanied by occurrence of lateral harmonics [9]. Faults of IM stator electromagnetic system (slackening of core pressing, break of short circuit in stator winding) show up at electromagnetic forces action frequency $f_{em} = 2f_1$ [9, 10]. Special attention should be paid to the presence of fractional harmonics – 1/2, 3/2, 5/2, etc. of frequency f_{em}. Break or contact loss in the bars or rings of IM "squirrel cage" usually appear near the rotor shaft rotation frequency and are always accompanied by presence of additional harmonics shifted in relation to the rotor rotation frequency harmonic by an interval equal to double frequency of slipping $mf_{tr} \pm 2f_s$, where $f_s = f_0 - f_{tr}$ – slipping frequency; m – whole number [9, 10].

For preliminary vibration power estimation it is possible to assume that, when some of the described faults occur, one harmonic is most ponderous: at frequency f_{em} when there is a stator fault and at frequency f_{tr} – at rotor imbalance and faults. As an example, let us consider a case of parameter comparison for rotor imbalance and stator faults. Then vibration power RMS value dependence P_{Vrms} on vibration velocity RMS value V_{Vrms} is described by the expression:

$$P_{rms} = \sqrt{2} V_{Vrms} m 10^{-3} \sqrt{V_{Vrms}{}^2 (2\pi f)^2 10^{-6} + g^2} \;. \tag{3}$$

Analysis of expression (3) demonstrates that vibration power RMS value is significantly influenced by frequency f at which the fault shows up. Consequently, vibration power parameters indicate the amount of energy spent on vibrations of a mechanical system with asymmetry acquired due to damage. So, for low-power AIR80V4U2 IM (P_n=1.5 kW; p=2; m=50 kg), operating at s =0.05 the frequencies of faults occurrence differ by $f_{em} / f_{tr} = 3.8$ times, which, at the same vibration velocity RMS values, will result in different vibration power RMS values (Fig. 1).

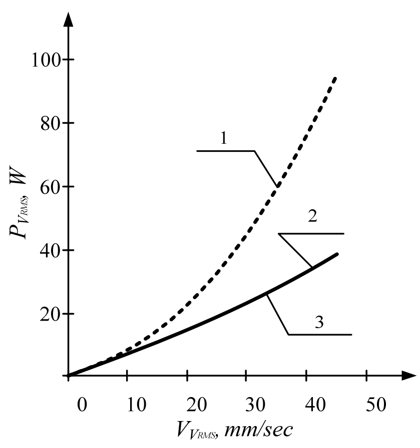

Fig. 1 Vibration power RMS value dependence on vibration velocity RMS value for the defects:
1 – stator damage, 2 – rotor broken bars, 3 – rotor imbalance

In real spectra of the vibration velocity with damaged IM besides the fundamental harmonic there are additional harmonics characterized by decrease of amplitude when frequency is increased (Fig. 2).

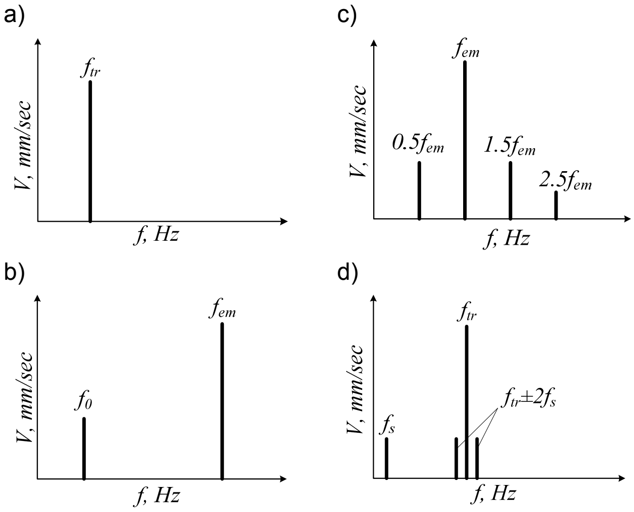

Fig. 2 Typical form of IM vibration velocity spectra for most common fault types: imbalance (a), rotor eccentricity (b), stator faults (c), rotor broken bars (d)

Frequency with the highest amplitude value was taken as the basic frequency of the spectrum for the analytical description of vibration power RMS value depending on vibration velocity RMS value for various fault types when spectral composition of vibration velocity signal was complex. At other frequencies the amplitude values of vibration frequency harmonics were expressed by coefficients k_i, reflecting relation of amplitude values of current i-th harmonics to the amplitude value of the basic frequency harmonic.

So, for the case of stator faults (Fig 2. c) the expression describing vibration power RMS value P_{Vrms} dependence on RMS value $V_{V(f_{em})}$ vibration velocity of basic frequency f_{em} harmonic is of the form:

$$\begin{aligned} &P_{rms}\left(V_{V(f_{em})}\right) = m V_{V(f_{em})} 10^{-3} \times \\ &\times \sqrt{a_1 V_{V(f_{em})}^2 10^{-6} \left(2\pi f_{em}\right)^2 + b_1 V_{V(f_{em})} 10^{-3} \left(2\pi f_{em}\right) g + c_1 g^2} \,, \end{aligned} \tag{4}$$

where: $\tilde{n}_1 = 2\left(k_1^2 + k_2^2 + k_3^2 + 1\right)$; $k_1 = V_{V(0.5 f_{em})} / V_{V(f_{em})}$;

$k_2 = V_{V(1.5 f_{em})} / V_{V(f_{em})}$;

$k_3 = V_{V(2.5 f_{em})} / V_{V(f_{em})}$;

$$a_1 = 0.5 \begin{pmatrix} k_1^4 + 4k_1^3 k_2 + 19 k_1^2 k_2^2 + 32 k_1^2 k_2 k_3 + 41 k_1^2 k_3^2 + 11 k_1^2 \\ +50 k_1 k_2^2 k_3 + 23 k_1 k_2 + 33 k_1 k_3 + 9 k_2^4 + 79 k_2^2 k_3^2 + \\ +31 k_2^2 + 25 k_3^4 + 59 k_3^2 + 4 \end{pmatrix};$$

$b_1 = \left(5.7 k_1 + 17 k_1 k_2 + 28 k_2 k_3\right)$.

Expression for determination of the dependence of vibration velocity RMS value V_{Vrms} on RMS value $V_{V(f_{em})}$ vibration velocity of basic frequency harmonic:

$$V_{Vrms}\left(V_{V(f_{em})}\right) = \sqrt{2} V_{V(f_{em})} \sqrt{k_1^2 + k_2^2 + k_3^2 + 1} \,. \tag{5}$$

When a family of characteristics $P_{Vrms} = f\left(V_{Vrms}\right)$ was created for the case of stator winding faults at different amplitude values of fractional harmonics, the coefficients were assumed equal $k_1 = k_2 = k_3 = k$ for the values range $k = 0,\ 0.1,\ 0.2,\ 0.4$ (Fig. 3). The specified range of values of k for each fault type was chosen based on harmonics amplitudes distribution typical of these faults [8-11].

For the case of rotor eccentricity (Fig 2. b) the expression describing vibration power RMS value P_{Vrms} dependence on the RMS value $V_{V(f_{em})}$ vibration velocity of basic frequency f_{em} harmonic is of the form:

(6) $$P_{rms}\left(V_{V(f_{em})}\right) = mV_{V(f_{em})}10^{-3}\sqrt{V_{V(f_{em})}^2 a_2 10^{-6} + g^2 b_2},$$

where:

$$a_2 = 2k_1^2\left(k_1^2\left(2\pi f_0\right)^2 + 3\left(2\pi f_0\right)\left(2\pi f_{em}\right) + \left(2\pi f_{em}\right)^2 + \left(2\pi f_0\right)^2\right) +$$
$$+2\pi f_{em};\ b_2 = 2\left(k_1^2 + 1\right);\ k_1 = V_{V(f_0)} / V_{V(f_{em})}.$$

Expression for determination of the dependence of vibration velocity RMS value V_{Vrms} on the RMS value $V_{V(f_{em})}$ vibration velocity of basic frequency harmonic for the case of rotor eccentricity:

(7) $$V_{rms}\left(V_{V(f_{em})}\right) = \sqrt{2}V_{V(f_{em})}\sqrt{k_1^2 + 1}.$$

When a family of characteristics $P_{Vrms} = f\left(V_{Vrms}\right)$ was created for the case of rotor eccentricity, coefficient k_1 was assumed equal to $k_1 = 0.1,\ 0.25,\ 0.5$ (Fig. 4).

When rotor broken bars (Fig 2. d), the expression describing vibration power RMS value P_{Vrms} dependence on the RMS value $V_{V(f_{tr})}$ vibration velocity of basic frequency f_{tr} harmonic is of the form:

(8) $$P_{rms}\left(V_{V(f_{tr})}\right) = mV_{V(f_{tr})}10^{-3}\sqrt{V_{V(f_{tr})}^2 a_3 10^{-6} + g^2 b_3},$$

where:

$$a_2 = 4\left(2\pi f_s\right)^2\left(8k_1^4 - 3k_1^3 + 5k_1^2\right) - 8\left(2\pi f_s\right)\left(2\pi f_{tr}\right)\times$$
$$\times\left(5k_1^4 - k_1^3 + 6k_1^2\right) + 2\left(2\pi f_{tr}\right)^2\left(8k_1^4 + 2k_1^3 + 20k_1^2 + 5\right);$$
$$b_3 = 3k_1^2 + 1;$$
$$k_1 = V_{V(f_{tr}-2f_s)} / V_{V(f_{tr})} = V_{V(f_{tr}+2f_s)} / V_{V(f_{tr})}.$$

Expression for determination of the dependence of vibration velocity RMS value V_{rms} on the RMS value $V_{V(f_{tr})}$ vibration velocity of basic frequency harmonic:

(9) $$V_{rms}\left(V_{V(f_{tr})}\right) = \sqrt{2}V_{V(f_{tr})}\sqrt{3k_1^2 + 1}.$$

When creating a family of characteristics $P_{Vrms} = f\left(V_{Vrms}\right)$ for the case of rotor broken bars, coefficient k_1 was assumed equal to $k_1 = 0,\ 0.05\ 0.1,\ 0.15,\ 0.2$ (Fig. 5).

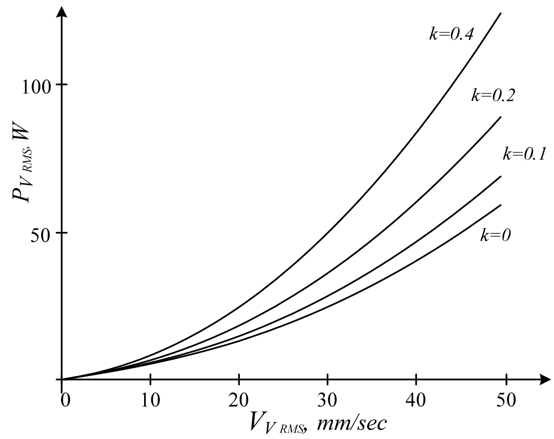

Fig. 3 Dependence of vibration power RMS value on vibration velocity RMS value under stator windings faults

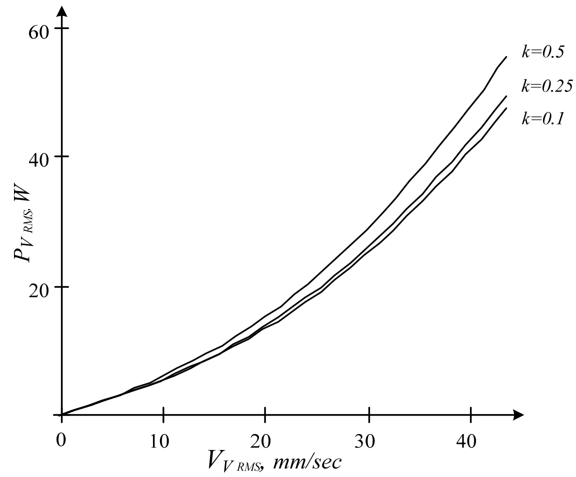

Fig. 4 Dependence of vibration power RMS value on vibration velocity RMS value in the presence of rotor eccentricity

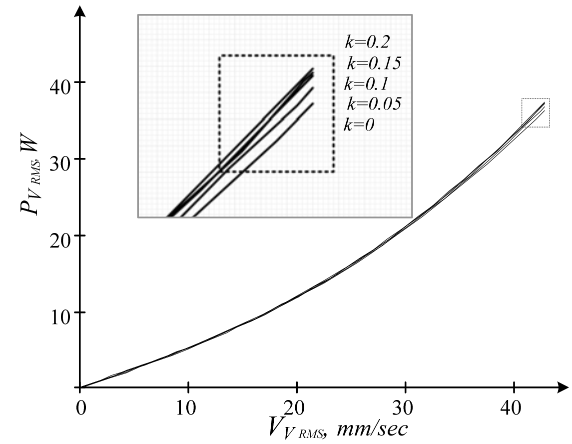

Fig. 5 Dependence of vibration power RMS value on vibration velocity RMS value in the presence of rotor broken bars

Analysis of dependences $P_{Vrms} = f\left(V_{Vrms}\right)$ for stator and rotor windings faults, rotor eccentricity, when harmonic composition is complex, confirms the difference of vibration power RMS value for different IM fault types when vibration velocity RMS value are the same.

To confirm the calculation of vibration power parameters of damaged IM experimental research was carried out with the use of a designed computer-aided measuring complex [11]. It contained a personal computer, an analog-digital converter (16 channels, 12 bits, 350 kHz) with a USB interface, sensors of current, voltage and was supplemented with sensors of vibration acceleration (Wilcoxon 784A).

Experimental research was carried out for a healthy IM, an IM with damages of one, two and three rotor bars and for an IM with damaged stator windings (0.3, 2.5, 14%).

IM stator winding damages were imitated by tapping the winding, and rotor winding damages – by breaking the contact between the bar and the cage ring [11].

Vibration velocity spectral composition was calculated on the basis of spectral composition of vibration acceleration, and spectral composition of vibration power was found according to (2).

Characteristics $P_{Vrms} = f\left(V_{Vrms}\right)$ (Fig. 6) are built for the cases of stator and rotor faults according to the results of experimental data processing. Analysis of the created characteristics $P_{Vrms} = f\left(V_{Vrms}\right)$ also shows difference of vibration power RMS value for different IM fault types when vibration velocity RMS value are the same.

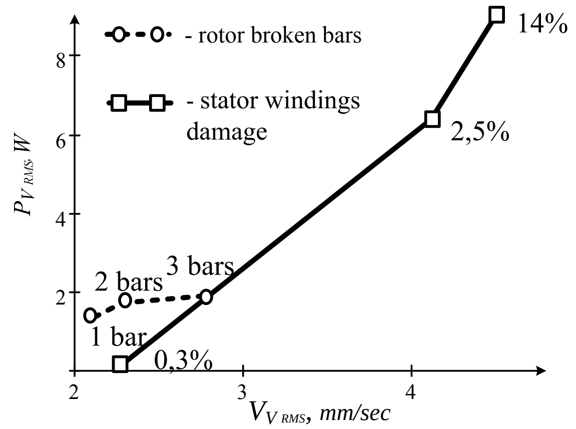

Fig. 6 Dependence of vibration power RMS value on vibration velocity RMS value when stator are damaged and rotor broken bars

Conclusions

A method for determination of vibration power on the basis of vibration velocity harmonic composition has been proposed. When this method is realized, there are no problems connected with continuous signals integration. It enables carrying out the analysis in both analytical and numerical form.

Comparative analysis of calculation and experimental data for different types of induction motor faults demonstrated that, at equal vibration velocity values, the values of vibration power differ significantly, which may result in incorrect diagnostics of induction motors state when vibration velocity parameters are used.

The direction of further research is determined by the necessity for substantiation and quantitative determination of the limits of the areas of levels of technical state of induction motors of different power, depending on root-mean-square values of vibration power.

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