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EVALUATION OF EXPANDED UNCERTAINTY OF INSTANTANEOUS POWER MEASUREMENT IN A BEARING DIAGNOSTIC SYSTEM

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Abstract: The paper presents the issues concerning the estimation of the expanded uncertainty in the system for the diagnosis of rolling bearings, consisting of transducers: voltage and current-voltage, which is used for diagnostic bearing motors method based on the measurement and analysis of the instantaneous power signal consumed by the induction motor. It presents the methodology for assessing the measurement uncertainty and presents examples of the results of analyses. On this basis, conclusions were drawn regarding the accuracy of the measurement system designed to diagnose bearings of induction motors by analysis of instantaneous power.

Key words: measurement uncertainty, instantaneous power, bearings diagnostic, measurement system.

1. INTRODUCTION

Components such as bearings, shaft, stator winding and rotor may be damaged in the induction motors. Statistical data shows that the most common failures of induction machines are caused by damage to the bearing [1, 2]. The subject of the evaluation of the technical condition of the bearings is very important, both technically and economically and is the main component of the machines supervision.

Bearing diagnostics can be carried out based on the method, which relies on the measurement and analysis of the variability of the signal instantaneous power, defined as the product of instantaneous current and voltage power supplied to the engines.

The essence of this method lies in the fact that when the damaged portion of the bearing comes in contact with another bearing element it causes a temporary increase in the resistance torque and therefore power consumed by the machine, which results in the appearance of additional harmonics in the spectrum of the signal product of the instantaneous voltage and current [1]. These components can be used as a diagnostic symptom, on the basis of which it was possible to evaluate the technical condition of the bearings in induction machines.

2. MEASUREMENT METHOD

The method of performing diagnostic tests of bearing failures is based on the use of the product of the instantaneous current and voltage, spectral analysis of the resulting signal and determining the frequency characteristic of the damage and identify them in the spectrum of instantaneous power. In the described method, the measurement is carried out by taking the signal, which is a measure of the current and voltage supplied to the machine.

The process of conditioning the current signal is performed using the current-voltage transducer LEM CT-5T, and conditioning of the voltage signal is done by a voltage transducer LEM CV3-500. Current-voltage transducer enables the measurement of DC, AC and pulse currents: with high accuracy, providing galvanic isolation between the primary and secondary circuit. The frequency processing range is 0 Hz - 500 kHz and transmission is 5A/5V. The CT-5T sensor error does not exceed ± 0.1% of the current rated efficiency and the value of the offset voltage is ± 0.6 mV. In turn, the voltage transducer is designed to measure direct and alternating voltages with voltage efficiency of 350 V. It provides galvanic isolation between the test and measured circuit. The CV3-500 transducer transmission is 500V/10V, the maximum error does not exceed ± 0.6% of the effective value of the rated voltage and voltage offset equals 13 mV. Then, both signals are fed to the measuring system, whose main component is the NI PXI 4462 [3] data acquisition card installed in the NI PXI 1031 cassette measuring. Signals from the measurement cassette are transferred to a PC, where they are analysed using software developed in LabVIEW called "Bearings-Power" [1]. Diagram of the measurement system shown in Figure 1.

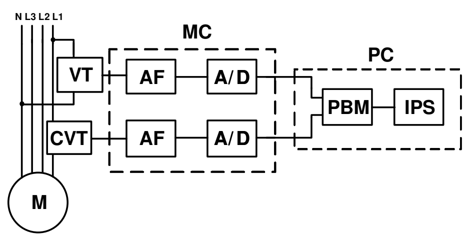

Fig. 1. The block diagram of the measurement system with the NI PXI 1031: VT – voltage transducer, CVT – current/voltage transducer, AF – anti-aliasing filter, A/D – analogue-to-digital converter, MC –NI PXI 1033 measurement cassette with PXI 4462 data acquisition card, PC – computer with the software, PBM – program block multiplying current and voltage, IPS – instantaneous power spectrum analysis application [1]

Machines STG80X-4C type were studied of the following parameters: P_n = 1.1 kW, U_n = 400/230 V, I_n = 2.9/5.0 A. The measurements were performed for both undamaged engines and machines with different types of bearing failures.

3. ESITMATING MEASUREMENT UNCERTAINTY

Modern metrology is required to specify which measurement uncertainty can be expected in the testing under certain conditions.

Metrological analysis of the system for diagnostics of bearings, which use an instantaneous power signal, was conducted to clarify which measurement uncertainty is to be expected, when making measurements with the use of the presented method.

The measuring function, used for the measurement of instantaneous power $p(t)$, is shown by the formula:

$$p(t) = u(t) \cdot i(t) \,. \tag{1}$$

Due to the fact that it is an indirect measurement and according to the law of uncertainty propagation [4], the uncertainty $u(p)$ is represented by the relationship:

$$u(p) = \sqrt{\left(\frac{\partial p}{\partial u}\right)^2 u^2(u) + \left(\frac{\partial p}{\partial i}\right)^2 u^2(i) + \\ + 2\frac{\partial p}{\partial u}\frac{\partial p}{\partial i} u(u)u(i)r(u,i)} \,, \tag{2}$$

where : $u(u)$ – uncertainty of voltage measurement, $u(i)$ – uncertainty of current measurement, $r(u, i)$ – correlation coefficient equal to:

$$r(u,i) = \frac{u(u,i)}{u(u)u(i)} \,. \tag{3}$$

Apparent from the foregoing is that, in order to determine the measurement uncertainty of instantaneous power at $u(p)$ one should determine three parameters: the variance measurement voltage $u^2(u)$, the variance of the current measurement $u^2(i)$ and the correlation coefficient between current and voltage $r(u, i)$.

In order to estimate the uncertainty of voltage measurement one should determine the variance resulting from the random error of voltage measurement and variance associated with the voltage transducer error and the variance estimation of voltage measurement data acquisition card. However, to estimate the uncertainty of current measurement one should determine the variance resulting from the random error of measurement of current as well as the variance associated with the current/voltage transducer error and variance estimation of voltage measurement acquisition card.

3.1. Voltage measurement uncertainty

Uncertainty of voltage measurement by Type A method was determined as the deviation of measurement results from the approximating polynomial [5, 6]. In the first stage, the least squares method fit the functions to the measured points. The approximating polynomial coefficients were calculated using the Jacobian matrix. The best results were obtained for ninth grade polynomials (correlation coefficient $R^2 \approx 1$). Other values were determined as the uncertainty of Type B on the basis of data provided by the manufacturer in the specifications of the used transducers and data acquisition cards.

Measurement uncertainty arising from the sampling error $u_A(u)$ is [5, 6]:

$$u_A(u) = \sqrt{\frac{\sum_{i=1}^{n}\left(y_i - \sum_{l=0}^{m} a_l x_i^l\right)^2}{n-m-1}} \,, \tag{4}$$

where: y_i –the measurement results, a – coefficients of the approximating polynomial, n – number of approximated points, m – degree of approximating polynomial, l - degree of the polynomial.

Figure 2 shows an example of measurement results of voltage $u(t)$ for a motor with a damaged bearings at a load of 70% I_n with a designated approximating polynomial $u_a(t)$.

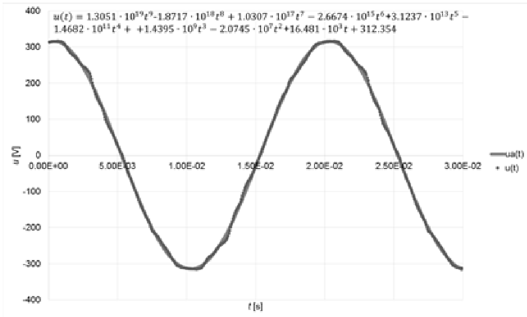

Fig. 2. Results of the measurement voltage $u(t)$ for a motor with a damaged bearing at a load of 70% I_n

Then, uncertainty was estimated with Type A method as a deviation of measurement results from the approximating polynomial calculated according to the equation (4). As a result of calculations, the obtained value of this uncertainty $u_A(u)$ is equal to 5.54 V.

Similarly, the procedure for the designation of uncertainty was done method Type A for all the results obtained from voltage measurements.

The next stage involved an evaluation of the uncertainties of Type B method of measuring the voltage, according to the relationship:

$$u_B^2(u) = \left(\frac{\partial u}{\partial u_u}\right)^2 u^2(u_u) + \left(\frac{\partial u}{\partial u_{DAQ}}\right)^2 u^2(u_{DAQ}) \,, \tag{5}$$

where: $u^2{}_B(u)$ – variation of voltage measurement, $u^2(u_{DAQ})$ – variance of the voltage measurement data acquisition card, $u^2(u_u)$ – variance caused by the limiting error of the voltage transducer.

The estimate of the voltage measurement variance $u^2(u_{DAQ})$, assuming a rectangular probability distribution, has been determined on the basis of the following formula [4]:

$$u^2(u_{DAQ}) = \left(\frac{\Delta E_{DAQ}}{\sqrt{3}}\right)^2 \,, \tag{6}$$

where: ΔE_{DAQ} – the total error of the voltage measurement data acquisition card.

The value of the total error of voltage measurement data acquisition card describes the following relationship [7]:

$$\Delta E_{DAQ} = \pm\left[\left(U_{in} \cdot \delta E_{\%Gain}\right) + \left(U_{in} \cdot \delta E_{\%Flatness}\right) + \Delta E_{offset}\right], \quad (7)$$

where: U_{in} – input signal level, $\delta E_{\%Gain}$ – analogue input gain error, ΔE_{offset} – offset error, $\delta E_{\%Flatness}$ – flatness error.

Based on data provided by the manufacturer of the data acquisition card [3], the voltage measurement variance $u^2(u_{DAQ})$ has been estimated, which is: $11.05 \cdot 10^{-3}$ V^2.

The variance resulting from the limiting error of the voltage transducer (ΔE_u) is estimated, assuming a rectangular probability distribution, using the formula [4]:

$$u^2(u_u) = \left(\frac{\Delta E_u}{\sqrt{3}}\right)^2. \quad (8)$$

The value of the voltage measurement error using a CV3-500 transducer can be written as [8]:

$$\Delta E_u = \pm\left[\left(E_{in} \cdot \delta E_{\%R}\right) + \Delta E_{offset}\right], \quad (9)$$

where: $\delta E_{\%R}$ – relative error of the current measured value.

Based on the above dependency and on data provided by the manufacturer in specifications of the used transducer, the value of individual components has been estimated. The variance $u^2(u_u)$ is $54.95 \cdot 10^{-3}$ V^2.

The combined standard uncertainty of the voltage measurement $u_c(u)$ was calculated according to the formula [4, 6]:

$$u_c(u) = \sqrt{u_A^2(u) + u_B^2(u)}. \quad (10)$$

Then, for a coverage factor $k = 2$, which corresponds approximately to the coverage probability of 95%, the expanded uncertainty U_u of voltage measurement was estimated, using the formula [4]:

$$U_u = k \cdot u_c(u). \quad (11)$$

On the basis of calculations budgets of uncertainty of voltage measurement were prepared. An example of uncertainty budget estimate of 230 V motor with a defective bearing is presented in Table 1.

Table 1. Uncertainty budget of voltage estimate for the value 230 V

Quantity X_n	Estimate of x_n quantity	Standard variance $u^2(x_n)$	Probability distribution	Sensitivity coefficient c_n	Share in the combined uncertainty $u_n(y)$
u	230.00 V	30.69 V^2	normal	1.00 V/V	5.540 V
u_{DAQ}	4.60 V	11.05E-3 V^2	rectangular	50.0 V/V	0.525 V
u_u	4.60 V	54.95E-3 V^2	rectangular	50.0 V/V	1.172 V
			Standard uncertainty $u_c(u)$		5.687 V
			Expanded uncertainty U_u		11.37 V

On the basis of the calculation, result of the voltage measurement at a given coverage factor can be written as: $U = (230.00 \pm 11.37)$ V.

3.2. Uncertainty of current measurement

To estimate the uncertainty of current measurement, the methodology used is similar to the procedure for determining the uncertainty of voltage measurement.

Figure 3 shows results of current measurement $i(t)$ for a motor with a damaged bearing at a load of 70% I_n with a designated approximating polynomial $i_a(t)$.

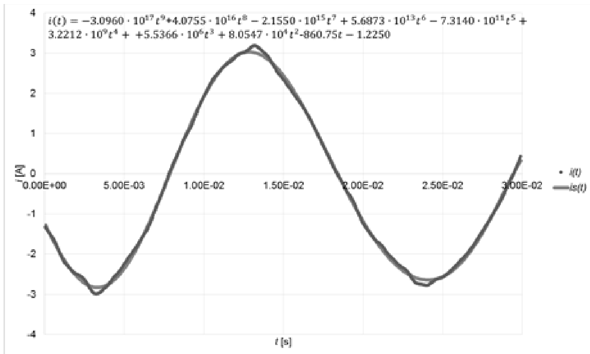

Fig. 3. The results of measuring the current $i(t)$ for a motor with a damaged bearing at a load of 70% I_n

Then, according to equation (4), using the uncertainty Type A method, the current was estimated which is $u_A(i) = 63.72 \cdot 10^{-3}$ A in the discussed case.

The procedure for the designation of uncertainty for all measurements of current supply for the tested machines was similar.

Then an estimation of uncertainty using Type B measuring current method was done using the relationship:

$$u_B^2(i) = \left(\frac{\partial i}{\partial u_i}\right)^2 u^2(u_i) + \left(\frac{\partial i}{\partial u_{DAQ}}\right)^2 u^2(u_{DAQ}), \quad (12)$$

where: $u_B^2(i)$ – variance designated with the use of Type B current measurement method, $u^2(u_{DAQ})$ – variance of the voltage measurement data acquisition card, $u^2(u_i)$ – variance caused by the limiting error of the current-voltage transducer.

Assuming a rectangular probability distribution, variance $u^2(u_i)$ was determined as [4]:

$$u^2(u_i) = \left(\frac{\Delta E_i}{\sqrt{3}}\right)^2, \quad (13)$$

where: ΔE_i – current-voltage transducer limiting error.

Taking into account the error of the current-voltage transducer, which is calculated the same way as limiting error voltage transducers, based on data from the manufacturer's specifications, the value of this component of variance was estimated, which is $u^2(u_i) = 2.202 \cdot 10^{-6}$ V^2.

In the next step, the current measurement combined uncertainty was determined according to the formula [4, 6]:

$$u_c(i) = \sqrt{u_A^2(i) + u_{cB}^2(i)}. \quad (14)$$

To determine the combined uncertainty, calculations of the variance of the voltage measurement data acquisition card $u^2(u_{DAQ})$ were used.

Then, for a coverage factor $k = 2$, which corresponds approximately to the coverage probability of approximately 95%, the expanded uncertainty U_i of current measurement was estimated, using the formula [4]:

$$U_i = k \cdot u_c(i) \,. \tag{15}$$

Examples of the calculation results of the combined uncertainty estimate of the current value of 1.97 A for a motor with a damaged bearing are shown in Table 2.

Table 2. Uncertainty budget of current estimate for the value 1.97 A

Quantity X_n	Estimate of x_n quantity	Standard variance $u^2(x_n)$	Probability distribution	Sensitivity coefficient c_n	Share in the combined uncertainty $u_n(y)$
i	1.97 A	4.060E-3 A^2	normal	1.00 A/A	63.72E-3 A
u_{DAQ}	1.97 V	2.239E-5 V^2	rectangular	1.00 A/V	4.732E-3 A
u_i	1.97 V	2.202E-6 V^2	rectangular	1.00 A/V	1.484E-3 A
			Standard uncertainty $u_c(i)$		63.91E-3 A
			Expanded uncertainty U_i		0.13 A

On the basis of the calculation result of current measurement, the assumed expansion factor can be written as: $I = (1.97 \pm 0.13)$ A.

3.3. The uncertainty of instantaneous power measurement

Uncertainties $u(p)$ of the instantaneous power measurement in the system of voltage and current-voltage transmitters was calculated according to the formula (2). After taking into account the correlation coefficient which, for the discussed case is $r(u, i) = -0.55$ the uncertainty of instantaneous power was calculated as $u(p) = 12.67$ VA.

Then, for a coverage factor $k = 2$, which corresponds approximately to the coverage probability of 95% [4], the estimated expanded uncertainty of measurement of instantaneous power, which is $U_p = 25.33$ VA was estimated.

4. SUMMARY

This paper describes the GUM methodology for estimate the uncertainty of the measurement system, built from the voltage and current-voltage transducers, which has been used for diagnostic testing of bearings in induction machines.

The metrological analysis can specify which measurement uncertainty can be expected, making the diagnostic of rolling bearing in induction motors under certain conditions, using a test method for the measurement and analysis of instantaneous power. The result of measurement of instantaneous power for the engine with a damaged bearing at a voltage of 230 V and the current values of 1.97 A can be shown as: $p = (453.10 \pm 25.33)$ VA.

On the basis of calculations it can be concluded that there is a dominant component of random, concerning the uncertainty as determined by Type A method. Although, the uncertainty of measurement of the instantaneous power is of only a few percent of the measured value, according to the author, the estimated measurement uncertainty does not preclude the use of this system for the diagnosis of bearings.

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SZACOWANIE NIEPEWNOŚCI ROZSZERZONEJ POMIARU MOCY CHWILOWEJ W SYSTEMIE DIAGNOSTYKI ŁOŻYSK

W artykule przedstawiono zagadnienie dotyczące szacowania niepewności rozszerzonej układu do diagnostyki łożysk tocznych przy wykorzystaniu metody badawczej, opartej na pomiarze i analizie sygnału mocy chwilowej pobieranej przez silnik indukcyjny. Zastosowano metodologię GUM do oceny niepewności pomiaru i przedstawiono przykładowe wyniki wykonanych analiz. Przeprowadzona analiza metrologiczna pozwala sprecyzować, jakiej niepewności pomiaru można się spodziewać, dokonując badań diagnostycznych łożysk tocznych silników indukcyjnych w określonych warunkach, na stanowisku badawczym metodą pomiaru i analizy mocy chwilowej. Dla wartości napięcia 230 V i wartości natężenia prądu 1,97 A wynik pomiaru mocy chwilowej można przedstawić jako: $p = (453{,}10 \pm 25{,}33)$ VA. Na podstawie przeprowadzonych obliczeń można stwierdzić, iż dominujący jest tu składnik losowy typu A. Ze względu na fakt, iż wartość niepewności wynosi kilka procent wartości mierzonej prowadzone są dalsze prace, których celem będzie obniżenie wartości niepewności poprzez modyfikację układu pomiarowego.

Słowa kluczowe: niepewność pomiaru, moc chwilowa, diagnostyka łożysk, układ pomiarowy.