INFLUENCE OF INDIVIDUAL STANDARD UNCERTAINTIES ON TOTAL UNCERTAINTY OF ENERGY EFFICIENCY OF A THREE-PHASE INDUCTION MOTOR

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Abstract

The aim of this paper is to present an analysis of the influence of individual standard measurement uncertainties on the total measurement uncertainty of energy efficiency of electrical machines. Energy efficiency has been measured by direct method in accordance to international standard IEC 60034-2-1 and its model has been determined. Measurement uncertainties of all electrical and mechanical quantities have been varied within practical limits and used for calculation of combined and extended measurement uncertainty according to the model. A variation of total uncertainty with each individual uncertainty has been presented and analysed. The paper contains the results of calculation of measurement uncertainty, as well as a discussion of all the results presented.

Keywords: measurement uncertainty, energy efficiency, electrical machines.

INTRODUCTION

Laboratory setup for direct method of measurement of energy efficiency of induction motor, as well as appropriate mathematical model of the efficiency was presented in [1]. Measurements were made in accordance with IEC standards [2, 3]. Based on the measurements and mathematical model expanded uncertainty budget was formed according to JCGM [4]. It was found that, at rated power, relative uncertainty of energy efficiency of the tested motor was much lower than the one proposed by standard [2].

Based on the standard IEC 60034-2-1 [5], recommended accuracy parameters for each device used in efficiency measurement are: the accuracy class of measuring instruments for electrical quantities should be 0.2, the errors of the instrument transformers are not greater than ±0.5% or ±0.3% (depending on the used measuring method), the torque measurements should have accuracy of ±0.2% of full scale and the speed measurement should be accurate within 0,1% or 1 revolution per minute whichever gives the least error. However, the accuracy class of the available instrumentation can often vary from these values. This can have significant influence on reported energy efficiency.

This paper presents the results for expanded uncertainty of energy efficiency of induction motor under variable standard uncertainty of used measurement equipment. Also, analysis and appropriate discussion of the results obtained are given in the paper.

MATHEMATICAL MODEL OF ENERGY EFFICIENCY AND ITS UNCERTAINTY

As presented in [1], mathematical model of energy efficiency of the motor can be presented as:

$$\eta = \frac{2\pi k_T U_T\, p}{K_{CT} k_n\, \Delta t \left(U_1 I_1 + U_2 I_2 + U_3 I_3\right)\cos\varphi} 100\ [\%]\,. \quad (1)$$

Mathematical expression for combined standard uncertainty is:

$$u_c = \sqrt{\sum_i \left(c_i u\left(x_i\right)\right)^2}\,, \quad (2)$$

where $c_i=\partial\eta/\partial x_i$, x_i are input (influential) quantities in the mathematical model (1) and $u(x_i)$ are their standard uncertainties.

Standard uncertainties and ranges of used measurement equipment are given by the manufacturers under the assumption of rectangular distribution of the results, so that:

$$u(U_i)=\left(\frac{\delta_{U_{iR}}}{100}U_i+\frac{\delta_{U_{iM}}}{100}U_{\max}\right)\Big/\sqrt{3}\ [\mathrm{V}],\ i=1,2,3,$$

$$U_{\max}=425\,[\mathrm{V}],$$

$$u(I_i)=\left(\frac{\delta_{I_{iR}}}{100}I_i+\frac{\delta_{I_{iM}}}{100}I_{\max}\right)\Big/\sqrt{3}\,[\mathrm{A}],\ i=1,2,3,$$

$$I_{\max}=7.07\,[\mathrm{A}],$$

$$u(U_T)=\left(\frac{\delta_{U_{TR}}}{100}U_T+\frac{\delta_{U_{TM}}}{100}U_{T\max}\right)\Big/\sqrt{3}\ [\mathrm{V}],$$

$$U_{T\max}=10.4\ [\mathrm{V}], \qquad (3)$$

$$u(K_{CT})=\left(\frac{\delta_{K_{CT}}}{100}K_{CT}\right)\Big/\sqrt{3}\ [\mathrm{A/A}],$$

$$u(k_T)=\left(\frac{\delta_{k_T}}{100}k_T\right)\Big/\sqrt{3}\ [\mathrm{Nm/V}],$$

$$u(p)=\frac{\Delta p}{\sqrt{3}}\ [\mathrm{imp}].$$

Parameters $\delta_{U_{iR}}$, $\delta_{U_{iM}}$, $\delta_{I_{iR}}$, $\delta_{I_{iM}}$, $\delta_{U_{TR}}$ and $\delta_{U_{TM}}$, in (3) represent Gain Error and Offset Error of acquisition systems, while $\delta_{K_{CT}}$ and δ_{k_T} represent accuracy classes of current transformers and torque sensor sensitivity, respectively. Parameter Δp, corresponds to the resolution of the encoder.

These parameters are known for the used equipment. For the purpose of the analysis presented in this paper the parameters are taken to be variable in order to investigate their influence on expanded uncertainty.

The influence of individual accuracy parameter on expanded uncertainty with the coverage factor of k=2 is analysed in the following section.

CALCULATION RESULTS AND DISCUSSION

Table 1 presents rated data for the tested induction motor. It was chosen for testing because the efficiency class was unknown.

Table 1
Rated data of tested motor

U_n [V]	I_n [A]	f_n [Hz]	n_n [rpm]	P_n [kW]	n_s [rpm]	cosφ
220	6	50	920	1.1	1000	0.7

Table 2 presents data for rated ratio of current transformers K_{CT}, rated sensitivities of the torque and speed sensors (k_T and k_n), as well as time interval between measurements Δt.

Table 2
Data for current transformers, sensors and acquisition interval

K_{CT} [A/A]	k_T [Nm/V]	k_n [imp/rot]	Δt [s]
2	2	360	1

Table 3 presents measured values of all quantities obtained during the determination of energy efficiency.

Table 3
Measurement results

Input quantity	x_i	*Input quantity*	x_i
U_1 [V]	220.28	I_2 [A]	3.42
U_2 [V]	216.33	I_3 [A]	3.41
U_3 [V]	217.41	U_T [V]	5.63
I_1 [A]	3.49	p [imp]	5598

Tables 4 to 7 show results of calculation of expanded uncertainty of energy efficiency obtained for variable accuracy parameters $\delta_{U_{iR}}$, $\delta_{U_{iM}}$, $\delta_{I_{iR}}$, $\delta_{I_{iM}}$, $\delta_{U_{TR}}$, $\delta_{U_{TM}}$, $\delta_{K_{CT}}$, δ_{k_T} and Δp. Calculations have been performed so that only one parameter has been varied while other parameters were constant having actual values given by manufacturers (bold numbers).

Results of variation of the expanded measurement uncertainty of energy efficiency with the accuracy parameters of voltage, current and torque acquisition system are presented in Tables 4, 5 and 6, respectively.

Table 4

Variation of expanded measurement uncertainty with accuracy parameters of voltage acquisition

$\delta_{U_{iM}}$	$\delta_{U_{iR}}$	ku_c [%]	$\delta_{U_{iR}}$	$\delta_{U_{iM}}$	ku_c [%]
0.008	0.005	0.2730	**0.05**	0.001	0.2739
	0.01	0.2731		0.002	0.2740
	0.02	0.2734		0.005	0.2743
	0.05	0.2746		**0.008**	0.2746
	0.1	0.2782		0.02	0.2760
	0.2	0.2909		0.05	0.2815
	0.5	0.3641		0.1	0.2961
	1	0.5477		0.2	0.3421
	2.5	1.2075		0.5	0.5529
	5	2.3611		1	0.9773

Table 5

Variation of expanded measurement uncertainty with accuracy parameters of current acquisition

$\delta_{I_{iM}}$	$\delta_{I_{iR}}$	ku_c [%]	$\delta_{I_{iR}}$	$\delta_{I_{iM}}$	ku_c [%]
0.05	0.01	0.2552	**0.1**	0.005	0.2412
	0.02	0.2571		0.01	0.2436
	0.05	0.2632		0.02	0.2495
	0.1	0.2746		**0.05**	0.2746
	0.2	0.3016		0.1	0.3348
	0.5	0.4047		0.2	0.4907
	1	0.6105		0.5	1.0345
	2.5	1.2866		1	1.9822
	5	2.4453		2.5	4.8563

Table 6

Variation of expanded measurement uncertainty with accuracy parameters of torque acquisition

$\delta_{U_{TM}}$	$\delta_{U_{TR}}$	ku_c [%]	$\delta_{U_{TR}}$	$\delta_{U_{TM}}$	ku_c [%]
0.014	0.002	0.2730	**0.02**	0.002	0.2727
	0.005	0.2732		0.005	0.2731
	0.01	0.2736		0.01	0.2738
	0.02	0.2746		**0.014**	0.2746
	0.05	0.2789		0.02	0.2759
	0.1	0.2905		0.05	0.2869
	0.2	0.3278		0.1	0.3186
	0.5	0.5053		0.2	0.4165
	1	0.8742		0.5	0.8111
	2.5	2.0635		1	1.5363

Results of variation of the expanded measurement uncertainty of energy efficiency with the accuracy parameters of current transformers, torque sensor and speed sensor are presented in Table 7.

Table 7

Variation of expanded measurement uncertainty with accuracy parameters of current transformers, torque sensor and speed sensor

$\delta_{K_{CT}}$	ku_c [%]	δ_{k_T}	ku_c [%]	Δp	ku_c [%]
0.05	0.2254	0.05	0.2254	0.05	0.2742
0.1	0.2361	0.1	0.2361	0.1	0.2742
0.2	0.2746	**0.2**	0.2746	0.2	0.2742
0.5	0.4616	0.5	0.4616	0.5	0.2743
1	0.8396	1	0.8396	**1**	0.2746
2	1.6348	2	1.6348	2	0.2757
2.5	2.0367	2.5	2.0367	2.5	0.2766
5	4.0552	5	4.0552	5	0.2836

According to the results presented in Tables 4 to 7, decreasing of the accuracy parameters bellow actual values for used equipment has a slight influence on the value of expanded uncertainty of energy efficiency of the induction motor. Also, their increase up to five times slightly influences the expanded uncertainty. However, their increase more than five times can have significant influence and can rise the expanded uncertainty more than five times, as can be expected.

Further increase of the measurement uncertainty can be obtained if two or more accuracy parameters increase simultaneously.

According to standard IEC 60034-1 [2], relative uncertainty of the measured efficiency should not be higher than 4.5% of its value, meaning, for estimated efficiency of 70.13% [1], highest acceptable value of uncertainty is 70.13·4.5/100=3.16%. This condition has been met in almost all analysed cases which are related to variation of individual accuracy parameters. However, usage of two or more measuring instruments with lower accuracy than recommended by the standard IEC 60034-2-1 can lead to significant increase of the measurement uncertainty above acceptable value. Therefore, an attention should be paid to the selection of measuring equipment.

CONCLUSION

This paper presents the analysis of influence of individual standard measurement uncertainties on the expanded measurement uncertainty of energy efficiency of induction motor.

Expanded measurement uncertainty has been calculated according to the mathematical model of energy efficiency. Variation of standard uncertainties was performed by variation of accuracy parameters of each measuring device separately, over the range of realistic and standardised values.

It has been found that the decrease or slight increase of the accuracy parameters bellow values recommended by IEC standard has no significant influence on the expanded uncertainty. However, increase of accuracy parameters more than five times have significant influence on the calculated uncertainty. The worst case would be simultaneous increase of two or more accuracy parameters.

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