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MEASUREMENT UNCERTAINTY OF TEST STATION FOR MEASUREMENT OF ENERGY EFFICIENCY OF ELECTRICAL MACHINES

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ABSTRACT

The aim of this paper is to present the method for calculation of measurement uncertainty of test station for measurement of energy efficiency of electrical machines. Energy efficiency has been measured by direct method in accordance to international standard IEC 60034-2-1. Measurement uncertainties of all electrical and mechanical quantities of influence have been used for calculation of combined and extended measurement uncertainty. The paper contains the results of measurement of energy efficiency of the induction motor, model of energy efficiency, results of calculation of measurement uncertainty, as well as a discussion of all the results presented.

INTRODUCTION

Methods for measurement of energy efficiency of electrical machines has been subject of international standard IEC 60034-2-1 [1]. Besides the description of methods, this standard gives recommendation on required accuracy of instrumentation used for measurement of energy efficiency. Tolerance of the maximum allowed deviation between the test result and the declared value on the rating plate of energy efficiency is recommended by international standard IEC 60034-1 [2]. Thus, extended measurement uncertainty, calculated according to JCGM 100 [3], of energy efficiency should be lower than this tolerance.

Test station for determination of the energy efficiency of electrical motors has been developed at the Laboratory for Electrical machines, Electric drives and Automatics at the Faculty of Technical Sciences in Čačak [4]. It can be used for measurement of energy efficiency by direct method for electrical motors rated up to 7.5 kW. Measurement of all quantities of interest has been realised with data acquisition cards and PC with virtual instrument designed in LabVIEW program.

This paper presents the results of measurement of energy efficiency of the induction motor, gives a model of energy efficiency and results of calculations of measurement uncertainty.

A discussion of the obtained results is also given in the paper.

EQIPMENTS FOR MEASUREMENT OF ENERGY EFFICIENCY

Testing of electrical motor has been performed using the equipment presented in Fig. 1, numbered as follows: 1 - induction motor, 2 - load emulator, 3 - current transformers, 4 - torque and speed sensor, 5 - PC with LabVIEW software, 6 - data acquisition cards.

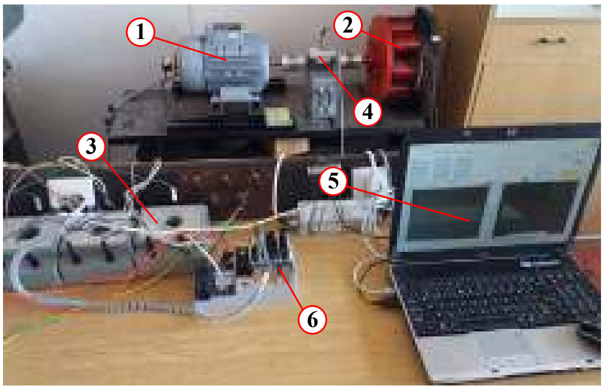

Fig. 1. Equipment for testing of electrical motor

Three-phase induction motor is powered over three-phase autotransformer connected directly to the electrical network and the load is generated using the load emulator [4]. The control of load emulator is performed by adjusting the current of the DC source. A commercial torque sensor HBM T20WN [5] has been used for torque and speed measurement. NI 9215 data acquisition card has been used for measurement of output voltages from the torque and speed sensor [6]. NI 9225 data acquisition card has been used for measurement of voltages supplied to the motor [7]. Current transformers are connected in series with the motor and they reduce electric currents below 5 A, which is suitable for measurement with NI 9227 data acquisition

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card [8]. LabVIEW application in a PC is used for presentation of all the results of interest, as well as for saving the data in its memory.

The block scheme of the whole system is given in Fig. 2.

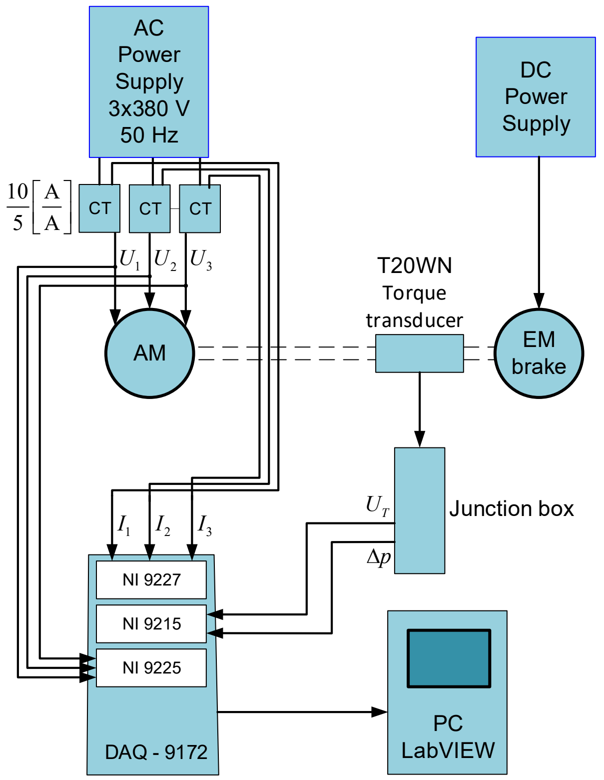

Fig. 2. Block scheme of test station.

MATHEMATICAL MODEL OF ENERGY EFFICIENCY AND ITS UNCERTAINTY

According to the direct method [1], the efficiency has been calculated as a ratio of input electrical power P_{el} and output mechanical power P_{mech} multiplied by 100 to be expressed in percent:

$$\eta = \frac{P_{mech}}{P_{el}} 100 \; [\%], \tag{1}$$

Electrical power has been calculated using measured effective values of voltages U_1, U_2, U_3 and currents I_1, I_2, I_3, taking into account ratio of current transformers K_{CT} (10/5 A/A) and power factor cosφ:

$$P_{el} = K_{CT}\left(U_1 I_1 + U_2 I_2 + U_3 I_3\right)\cos\varphi \; [\mathrm{W}]. \tag{2}$$

Mechanical power has been calculated using measured torque T and motor speed n:

$$P_{mech} = 2\pi T n \; [\mathrm{W}]. \tag{3}$$

Torque has been obtained from measured output voltage U_T of torque sensor as $T=k_T U_T$, where k_T is the sensitivity of torque sensor. Motor speed has been obtained from the measurement of the number of impulses p at the output of encoder during a predefined period Δt, taking into account encoder sensitivity k_n, as:

$$n = \frac{p}{k_n \Delta t} \left[\frac{1}{s}\right]. \tag{4}$$

Accordingly, mathematical model of energy efficiency of the motor has been expressed as:

$$\eta = \frac{2\pi k_T U_T p}{K_{CT} k_n \Delta t\left(U_1 I_1 + U_2 I_2 + U_3 I_3\right)\cos\varphi} 100 \; [\%]. \tag{5}$$

Combined standard uncertainty of energy efficiency has been calculated as:

$$u_c = \sqrt{\sum_i \left(c_i u\left(x_i\right)\right)^2}, \tag{6}$$

where $c_i=\partial\eta/\partial x_i$, x_i are input (influential) quantities in the mathematical model (5) and $u(x_i)$ are their standard uncertainties. According to (5), input quantities are voltages U_1, U_2, U_3 and currents I_1, I_2, I_3, ratio K_{CT}, voltage U_T, sensitivity k_T and number of impulses p. Their standard uncertainties have been defined by the manufacturer (under the assumption of rectangular distribution of the results), as follows:

$$u\left(U_i\right) = \left(\frac{0.05}{100}U_i + \frac{0.008}{100}U_{\max}\right)\Big/\sqrt{3} \; [\mathrm{V}], \; i=1,2,3,$$

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

$$u\left(I_i\right) = \left(\frac{0.05}{100}I_i + \frac{0.008}{100}I_{\max}\right)\Big/\sqrt{3} \; [\mathrm{A}], \; i=1,2,3,$$

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

$$u\left(U_T\right) = \left(\frac{0.02}{100}U_T + \frac{0.014}{100}U_{T\max}\right)\Big/\sqrt{3} \; [\mathrm{V}], \tag{7}$$

$$U_{T\max} = 10.4\,[\mathrm{V}],$$

$$u\left(K_{CT}\right) = \left(\frac{0.2}{100}K_{CT}\right)\Big/\sqrt{3} \; [\mathrm{A/A}],$$

$$u\left(k_T\right) = \left(\frac{0.2}{100}k_T\right)\Big/\sqrt{3} \; [\mathrm{Nm/V}],$$

$$u\left(p\right) = \frac{1}{\sqrt{3}} \; [\mathrm{imp}].$$

MEASUREMENT RESULTS AND DISCUSSION

Rated data for the tested motor are given in Table 1. Its efficiency has been measured at rated load.

Table 1. *Rated data of tested motor*

Manufacturer	ATB SEVER Subotica, Serbia
Type	1.ZK 90 L-6
$U_{\Delta n}/U_{Yn}$ [V]	220/380
$I_{\Delta n}/I_{Yn}$ [A]	6/3.5
f_n [Hz]	50
n_n [rpm]	920
P_n [kW]	1.1
n_s [rpm]	1000
cosφ	0.7

Data for the rated ratio of current transformers, rated sensitivities of sensors and time interval for speed measurement are given in Table 2.

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

At the beginning, measurement of energy efficiency has been performed at rated output power of the motor. The results obtained, as well as calculated combined measurement uncertainty, are given in Table 3.

Table 3. *Budget of measurement uncertainty*

Input quantity	x_i	$u(x_i)$	c_i	$\lvert c_i \rvert u(x_i)$ [%]
U_1	220.28 [V]	0.0825 [V]	-0.109 [%/V]	0.0090
U_2	216.33 [V]	0.0821 [V]	-0.107 [%/V]	0.0088
U_3	217.41 [V]	0.0824 [V]	-0.107 [%/V]	0.0088
I_1	3.49 [A]	0.0021 [A]	-13.62 [%/A]	0.0292
I_2	3.42 [A]	0.0021 [A]	-13.54 [%/A]	0.0290
I_3	3.41 [A]	0.0021 [A]	-13.60 [%/A]	0.0291
U_T	5,63 [V]	0.0015 [V]	12.45 [%/V]	0.0291
p	5598 [imp]	0.5774 [imp]	0.0125 [%/imp]	0.0072
K_{CT}	2 [A/A]	0.0023 [A/A]	-35.066 [%A/A]	0.0810
k_T	2 [Nm/V]	0.0023 [Nm/V]	35.066 [%V/Nm]	0.0810
η	70.13 [%]		u_c	0.13

According to the results from Table 3, measured energy efficiency of the motor is 70.13 % and combined uncertainty is 0.13 %. By multiplying the combined uncertainty u_c by a coverage factor k=2, the expanded uncertainty amounts 0.26 %. Therefore, the reported result of energy efficiency is:

$$\eta = (70.13 \pm 0.26)\ [\%]. \tag{8}$$

Relative uncertainty of the measured efficiency is 100·0.26/70.13=0.37 %. This is much lower than the declared tolerance on efficiency recommended by international standard IEC 60034-1 [2], which can be calculated as 15(1−η) [%]. For the tested motor this tolerance amounts about 4.5 %, much higher than calculated expanded uncertainty.

Highest contributions to the budget of the uncertainty are contributions of current transformers and torque sensor and lowest contributions are contributions of voltages and encoder.

In order to check the uncertainty at other conditions, measurements have been repeated for output powers of 926 W and 336 W. Calculated expanded uncertainties amount 0.25 % and 0.13 %, respectively.

All results presented indicate that measurement uncertainty of test station for energy efficiency measurement is very low in the whole range of operation of the motor (up to 1.1 kW).

CONCLUSION

This paper presents the method for calculation of measurement uncertainty of test station for measurement of energy efficiency of electrical machines. Measurement of energy efficiency has been performed by the direct method, in accordance to international standard IEC 60034-2-1. A mathematical model of energy efficiency has been developed according to the input electrical power and the output mechanical power. Combined and extended measurement uncertainty has been calculated according to the mathematical model of energy efficiency and standard uncertainties of all influencing quantities.

The results of measurement of energy efficiency of the induction motor and results of calculations of measurement uncertainty have been presented in the paper. Calculated uncertainties are much lower than tolerances declared in IEC 60034-1 standard.

A discussion of the obtained results is also given in the paper.

ACKNOWLEDGEMENTS

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