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IDENTIFICATION OF THE THERMAL PROCESS IN AN INDUCTION MOTOR

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ІДЕНТИФІКАЦІЯ ТЕПЛОВОГО ПРОЦЕСУ В АСИНХРОННОМУ ДВИГУНІ

Purpose: synthesis of a mathematical model of an asynchronous motor, taking into account the impact of changes in the quality of electricity on the processes of heating and heat exchange for an economically justified choice of means of protection.

Methodology: Theoretical substantiation of the expediency of using a one-mass thermal model of an asynchronous motor, for the conditions of operation of the latter in conditions of low-quality electricity, in order to determine losses in it.

Results: Experimental studies of the operation of an asynchronous motor at nominal load were carried out. The obtained results of the measurements made it possible to determine the parameters of the single-mass thermal model, the heat transfer coefficient of the engine, and the coefficient of its heat capacity. A single-mass thermal model of an induction motor is a mathematical model used to describe the thermal processes occurring in an induction motor. This model is based on the assumption that all motor elements can be combined into one mass that heats up during engine operation. The model assumes that the thermal capacity of the motor is a constant, and the heat flow that is released during the operation of the motor is proportional to the square of the current passing through the motor windings. In addition, the model assumes the presence of thermal conductivity between the mass of the motor and the external environment, which affects the rate of heat dissipation.

Scientific novelty: A methodology for determining losses in an asynchronous motor using a synthesized mathematical model is proposed, taking into account the influence of changes in the quality of electricity on the processes of heating and heat exchange in it.

Practical significance: The obtained results indicate the adequacy of the proposed thermal model of an asynchronous motor operating in a network with low-quality electricity. Taking into account the fact that for many types of engines in the reference literature, there are no necessary data on the coefficients of heat transfer and heat capacity, and only the thermal time constants for certain types of engines are given, the value of the specified parameters of the model can be obtained on the basis of the methodology presented in the work. A single-mass thermal model can be useful for analyzing the thermal processes occurring in an induction motor and for improving the efficiency of the motor. In particular, it can help determine the optimal operating temperature of the motor, as well as calculate the necessary cooling system to ensure stable operation of the motor under conditions of variable load and temperature conditions.

Keywords: *asynchronous motor, single-mass thermal model, coefficients of heat transfer and heat capacity, low-quality electricity.*

Introduction. The presence of low-quality electricity in the shop networks of industrial enterprises leads to a decrease in the main indicators of the operation of asynchronous motors (AM), their accelerated physical aging, and, as a consequence, the occurrence of emergency situations. It is advisable to formulate this problem in the technical and economic plane, and its solution requires a detailed consideration of the system "electrical network - asynchronous motor" with the involvement of methods of mathematical modeling and implementation of computational experiments on a computer [1 – 3].

The economic assessment of various options for restoring electricity in shop networks to standard quality indicators is the basis proposed in [4 – 7] for a decision-making method for the operation of electrical equipment, including AM, operating in conditions of poor-quality supply voltage [8 – 10].

According to this methodology, according to the current indicators of the quality of electricity in the enterprise network [11 – 13] and on the basis of energy models [14 – 17] of the electromechanical converter, its energy indicators are calculated and the time interval of trouble-free operation.

In case of significant deviations of the indicators calculated in this way from the specified ones, various options for technical solutions for restoring the quality of the electric energy supplied to the engine are considered. For each of the options, a cost estimate is performed and a final decision is made on the conditions for its further work.

Wide experience in researching the effect of power quality on the operation of asynchronous motors with a has been accumulated by now [18 – 20].

Poor power quality in the workshops of industrial enterprises stipulates the increase in direct industrial costs due to the growing power consumption. Moreover, indirect costs related to the reduced operating life of electric machines are increasing as well.

As is known [13, 14], normative operating life of the all-purpose asynchronous motors is about ten years. However, that is true only for the cases when certain conditions are observed. The main condition here is the correspondence of the thermal mode of an electric machine to the insulation class.

Deterioration of the power quality results in the increase of heating losses and insulation temperature respectively. Combined with the overloads, that results in the considerable reduction of the operating life of the electric motors. Practice shows that in terms of 40% of all-purpose AM with nominal voltage of 0.4 kV, the operating life is 1.25…2 years [21].

The aim of the paper is to synthesize a mathematical model of an asynchronous motor, taking into account the influence of changes in the quality indicators of electricity on heating and heat transfer processes, for an economically justified choice of protective equipment.

Materials and research results. To study the effect of the operating modes of an electric motor on its thermal conditions, so-called thermal models are applied [22 – 25]. They are the equivalent circuits where electric losses act as the heat sources;

temperatures of structural components are within the nodes; and corresponding heat conductivities and capacities are located between them.

The considered models have different degree of detalization. A single-mass model, in which an electromechanical transducer is represented as a single homogeneous body with the overall temperature, is the simplest one. Although, the real temperature distribution is not uniform: temperature of the AM stator winding may exceed the case temperature by 15-20°C [26, 27].

More detailed models have minor prediction errors; however, that requires having additional data on heat conductivities and capacities of separate structural components of a motor. As a rule, such models are used only at the design stage. Besides, while applying those models, the transient-free thermal conditions are analyzed without consideration of their dynamics.

We consider that during the operation, it is the most expedient solution to use a single-mass thermal model; moreover, it is necessary to analyze the temperature of the AM component, being critical in terms of heating, - stator end winding – as the initial parameter of the model. It is well-known that this component is under the poorest cooling conditions since its thermal efficiency is effected mainly by means of the air.

A single-mass dynamic thermal model of the asynchronous motor is described by the following differential equation:

$$\Delta P = A \cdot \tau + \frac{\Delta \tau}{\Delta t} \cdot C. \tag{1}$$

here ΔP is the power of heating losses generated in the electric motor; τ is the exceedance of the motor temperature over the surrounding temperature; $\Delta\tau$ is the increment of the motor temperature per time Δt; A is the coefficient of thermal efficiency, J/(sec·C) (equal to the radiation heat loss per 1 sec in terms of the difference in the indicated temperatures $\tau = 1$ °C); C is the heat capacity of the motor, J/°C. The indicated heat capacity is equal to the amount of heat required for AM heating by 1°C in terms of the nonavailable radiation heat loss.

As is obvious, equation of thermal balance (1) has two unknown values – A and C, which may be defined with the help of experimental data by composing a system of equations relative to the unknowns. In this context, it is possible to improve the accuracy of determining a coefficient of thermal efficiency and heat capacity of a motor at the expense of the totals of parameters measured in several experiments:

$$\begin{cases} \dfrac{\sum \Delta P}{N} = A \cdot \sum \tau + \sum \dfrac{\Delta \tau}{\Delta t} \cdot C; \\ \dfrac{\sum \Delta P \cdot \tau}{N} = A \cdot \sum \tau^2 + \sum \dfrac{\Delta \tau}{\Delta t} \cdot \tau \cdot C. \end{cases} \tag{2}$$

Corresponding experiments have been carried out in terms of experimental workshop of Ukrspetsservis Ltd. Asynchronous motor of 4AX80A4У3 type has been analyzed (nominal parameters are as follows: U_n=220/380 V (Δ/Y), P_n=1.1 kW, n_n=1400 rot/min, I_n=4.8/2.8 A, η=75%, cos φ=0.81).

The motor is loaded on a direct-current generator of П31У4 type (nominal parameters are as follows: U_n=230 V, P_n=1.0 kW, n_n=1450 rot/min, I_n=4.3 A, η=75%). During the experiments, AM was heated under the nominal load; the cooling took place in terms of the non-rotating rotor.

A hole was made in the motor cover to determine the temperature of winding faces with the help of laser pyrometer of Fluke 568 type. The hole was open only for a short period for measuring (5 sec); when the electric motor was operating, the hole was closed to prevent the heat exchange between the internal and external air. Currents and voltages were recorded with the help of a mobile measuring and diagnostic complex based on the current sensors of LA 25A type, voltage sensors LV100P (made by LEM, Switzerland), and AD converter E-440 (L-CARD, Russia). Table 1 shows the characteristics of the measuring channels.

Table 1

Characteristics of the measuring channels of a mobile measuring and diagnostic complex

Component	**Characteristics**
AD converter	
TYPE	E-440
Number of channels	16 differential ones
Digit capacity	12 bits
Conversion time	1.7 mcs
Input range	±5.12V;±2.56V;±1.024V;
Maximum conversion frequency	200 kHz
Zero shift	±0.5LOD; max 1LOD.
Voltage sensor	
TYPE	LV-400
Input range	0 – 500 V
Output range	0 – 10 V
Maximum static error	0.015%
Maximum dynamic error	0.03%
Current sensor	
TYPE	LA-100 C
Input range	0 – 250 A
Output range	0 – 10 V
Maximum static error	0.03%
Maximum dynamic error	0.08%

To eliminate the experiment error stipulated by the increased heating during the starting, the tested electric motor is accelerated with the help of a loading machine operating under the motoring conditions. Only when the facility reaches the idling speed, source voltage is supplied to the asynchronous motor, and a loading machine is placed in the dynamic braking mode (Fig.1).

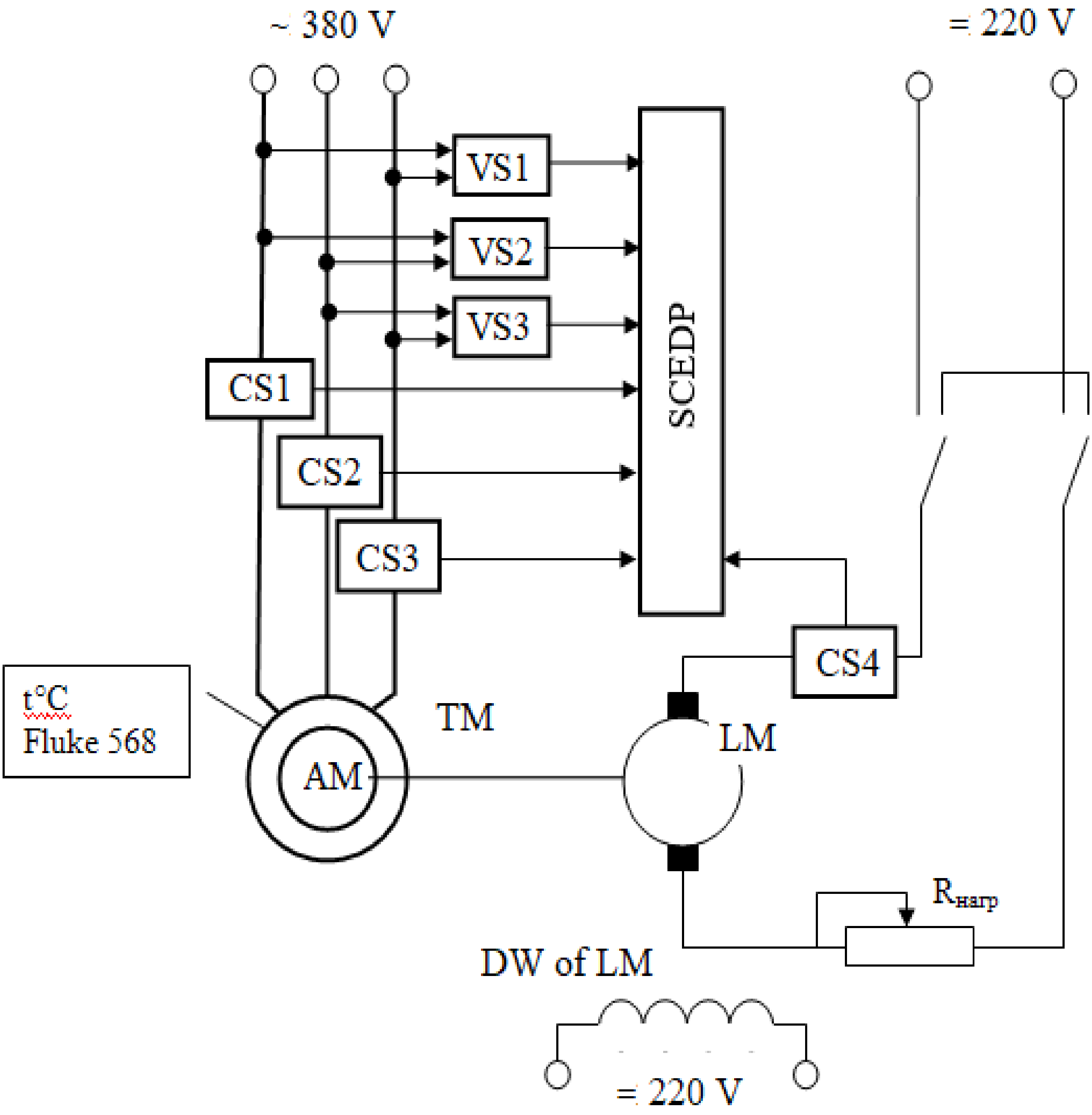

Fig. 1. Schematic of the experience to test adequacy of a thermal model of an asynchronous motor:
TM, LM – test machine and loading machine; SCEDP– system to control electric drive parameters (measuring complex); VS – voltage sensor; CS – current sensor; DW of LM – drive winding of loading machine

Table 2 represents the results of the experiment of test motor heating in terms of ideal supply voltage.

Table 2

Results of experiment #1, ideal supply voltage

Time, sec	Effective temperature value, °C	Temperature value predicted in terms of the model, °C	Absolute error, °C
0	0.0	0	0
120	5.4	6	1
240	10.4	12	1
360	12.0	17	5
480	14.7	21	6
600	26.1	25	-1
720	28.7	28	0
840	34.7	31	-3
960	37.6	34	-3
1080	40.1	37	-3
1200	43.4	39	-5
1320	45.0	41	-4
1440	46,7	42	-4
1560	47.7	44	-4
1680	48.7	45	-3
1800	50.0	47	-3
1920	50.0	48	-2
Final value	75.7	73	-2

Fig. 2 shows the experimentally obtained curve of test motor heating in terms of ideal supply voltage.

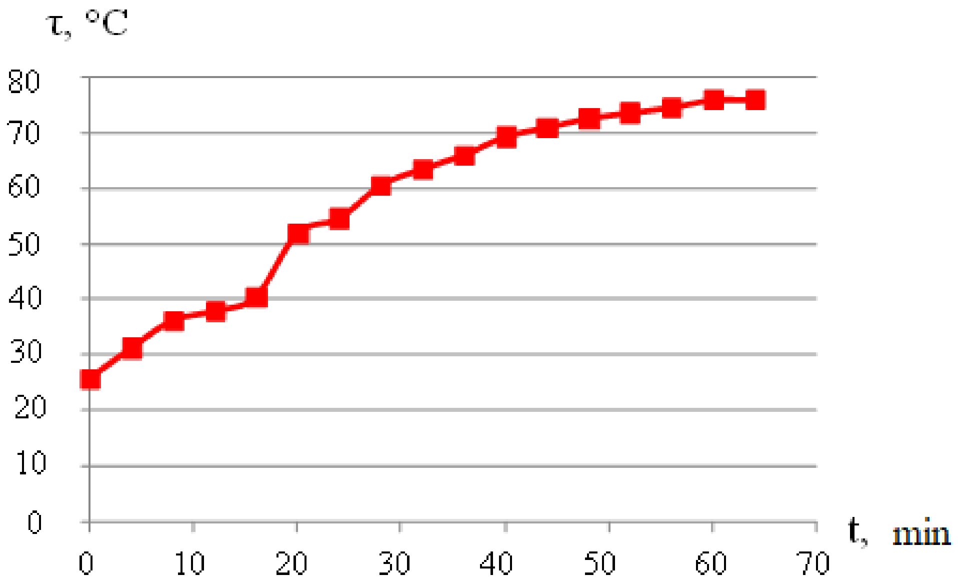

Fig. 2. Curve of motor heating while operating in terms of nominal load and ideal supply voltage

Within the period of 62 minutes, the motor temperature has reached the final value of 76.3°C. The experiment results have made it possible to compose a system of equations (2) and to calculate the parameters of a single-mass thermal model. The parameters are as follows: coefficient of the motor's thermal efficiency while rotating is A=11.2 J/(sec×°C), heat capacity of the electric motor is C – 12.1 kJ/°C.

Taking into account the fact that the reference literature contains rather scarce data on thermal parameters of the electric machines (as a rule, there is only the information concerning thermal time constants for motors of certain classes and power ranges), the considered method of their determination while identifying a specific AM model is rather topical.

Further, the heating experiments were carried out in terms of different degrees of distortion of the electric motor supply voltage. The experimental results are represented in Tables 3 and 4.

Table 3

Results of experiment #2, distorted supply voltage

Time, sec	Effective temperature value, °C	Temperature value predicted in terms of the model, °C	Absolute error, °C
0	0.0	0	0.0
120	12.0	12	0.1
240	23.1	21	1.7
360	30.8	29	1.6
480	33.9	36	-1.7
600	38.7	41	-2.0
720	44.0	45	-0.8
840	44.3	48	-3.9
960	52.0	51	1.0
1080	54.1	53	0.9
1200	54.4	55	-0.6
1320	56.4	56	0.0
1440	56.2	58	-1.4
1560	58.1	59	-0.5
1680	62.0	59	2.6
1800	58.9	60	-1.1
1920	61.2	61	0.6
Final value	86.0	86	0.0

Table 4

Results of experiment #3, distorted supply voltage

Time, sec	Effective temperature value, °C	Temperature value predicted in terms of the model, °C	Absolute error, °C
0	0.0	0	0.0
120	13.8	13	0.6
240	21.9	24	-2.1
360	34.1	33	1.5
480	37.8	40	-1.9
600	46.9	45	1.5
720	47.9	50	-2.1
840	55.5	54	1.7
960	55.3	57	-1.6
1080	60.3	59	0.9
1200	61.1	61	-0.2
1320	64.3	63	1.4
1440	65.5	64	1.2
1560	62.8	65	-2.6
1680	62.8	66	-3.4
1800	69.7	67	2.8
1920	68.1	68	0.6
Final value	93.0	93	0.0

Further experiments #2-4 were carried out in terms of different degrees of distortion of electric motor power supply. The quality indices of the latter (coefficient of distortion of the sinusoidal voltage curve k_U, coefficient of voltage unsymmetry on the reverse sequence ε_2) are given in Table 5.

Experience #4 corresponds to the motor operation with the temperature exceeding the admissible one for that insulation class F(105°C); AM may be in such a state only for a short period of time due to the possibility of thermal breakdown of its windings.

Table 5

Power quality indices in the experiments and final temperature values of the AM winding

Experience No.	Coefficient of distortion of the sinusoidal voltage curve $k_{U,}$ %	Coefficient of voltage unsymmetry on the reverse sequence ε_2, %	Final absolute temperature, τ°C
1	0	0	76.3
2	0	4	85.1
3	8	0	92.5
4	13.0	0	117.8

The considered experiments have been used to test the adequacy of the proposed AM dynamic thermal model. Figures 3-5 show the comparison of the graphs of temperature exceedance of the motor over the surrounding temperature in those heating experiments with the calculated curves obtained with the help of electrochemical [8, 17] and thermal model of an asynchronous motor [28-30].

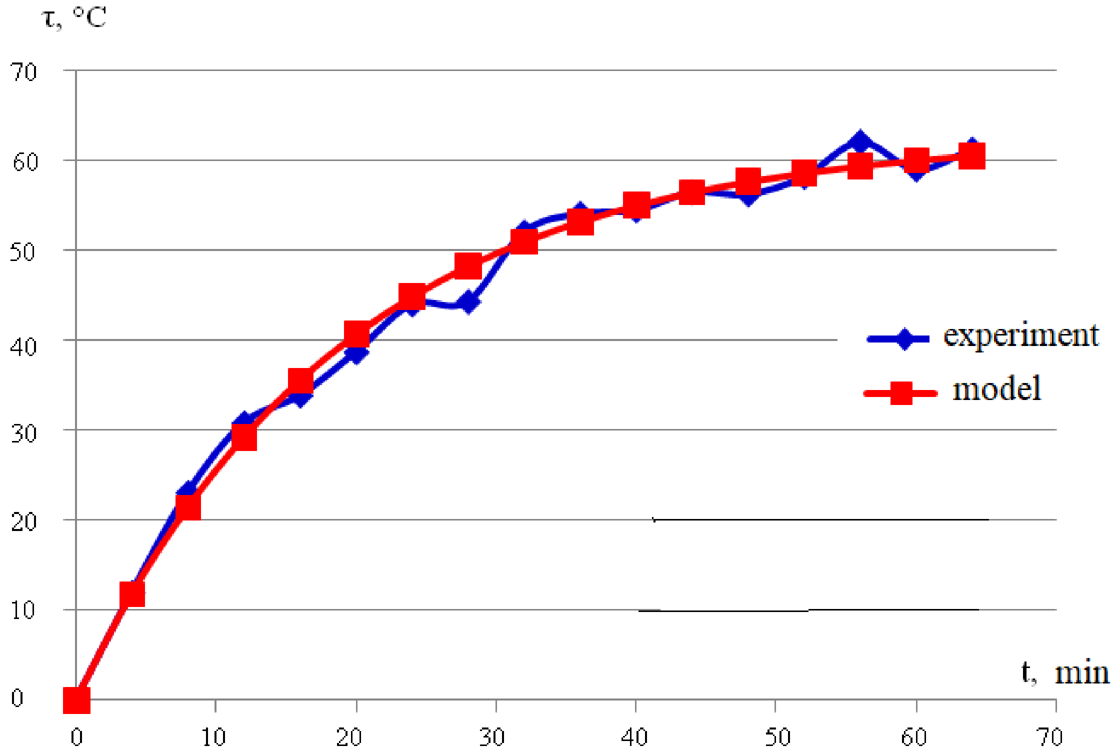

Fig. 3. Curves of motor heating in experiment # 2

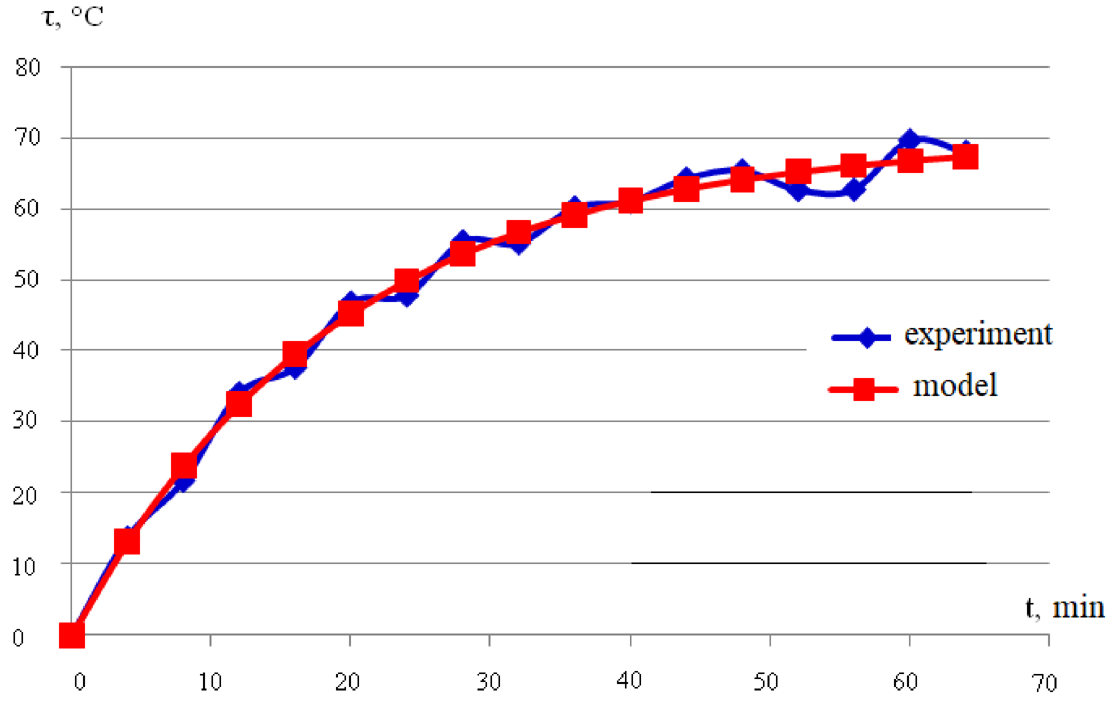

Fig. 4. Curves of motor heating in experiment # 3

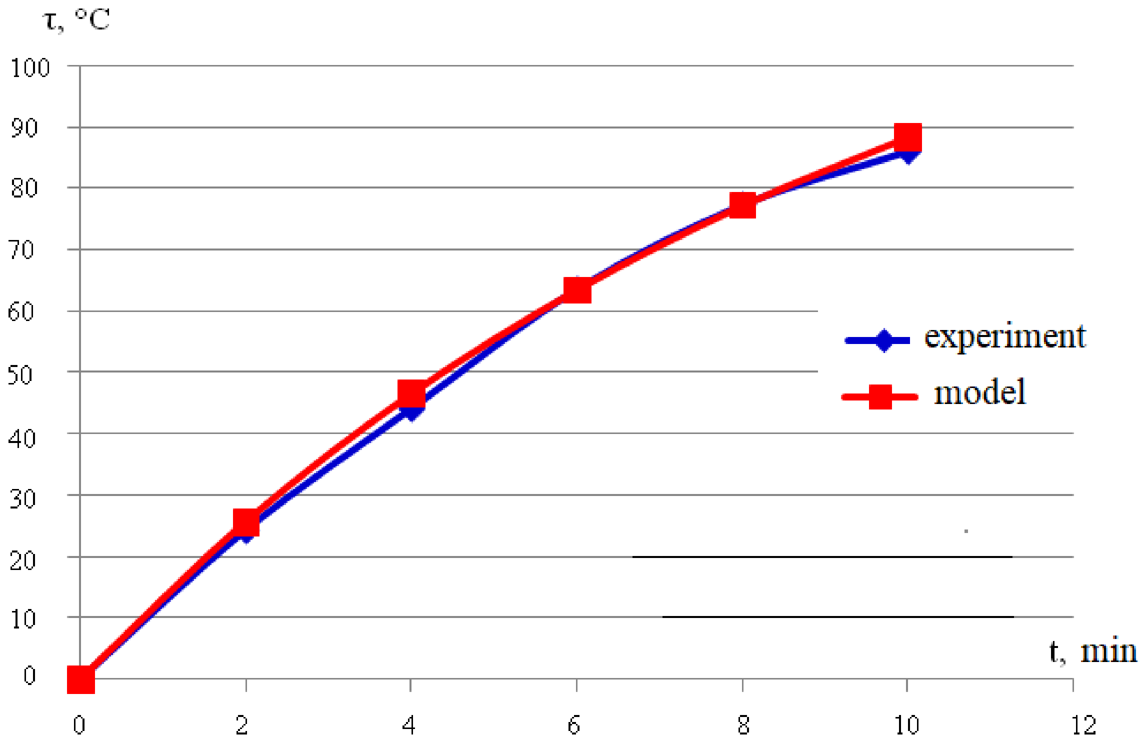

Fig. 5. Curves of motor heating in experiment # 4

Next, error of the predicted temperature value in the heating dynamics was calculated. Fig. 6 demonstrates the experimental and calculated (predicted) temperature values for all the performed experiments which are used to test the model adequacy according to the method represented in [31-35]. In this context, different format of markers belongs to the corresponding experiments.

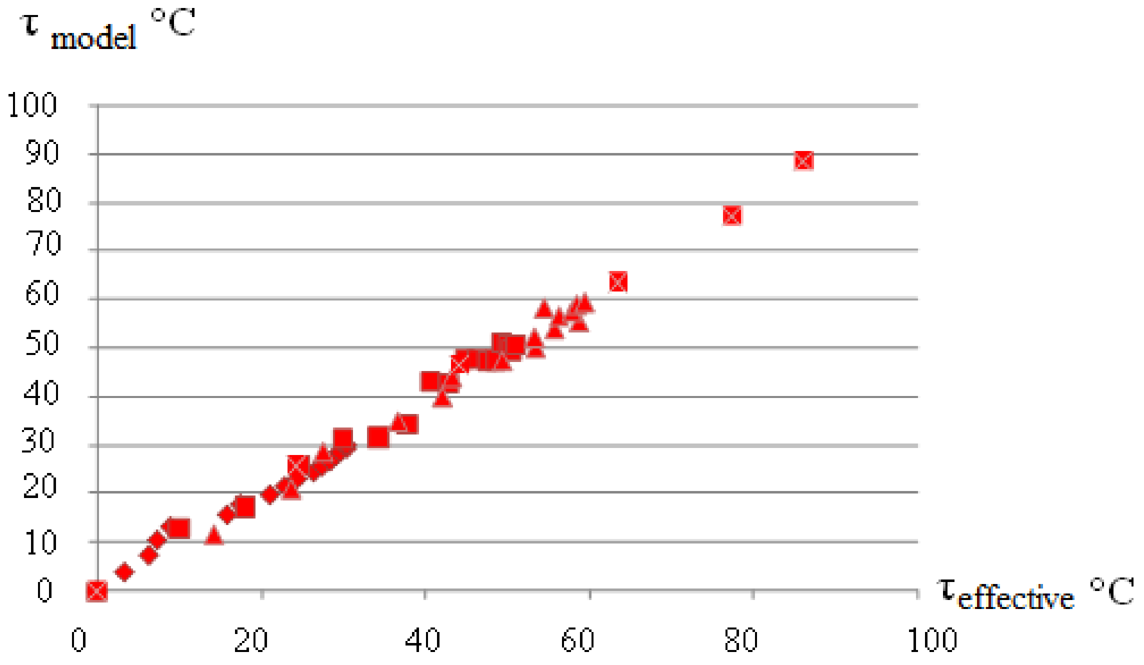

Fig. 6. Relations of the predicted τ_m and experimental τ_{ef} values of the temperature exceedance of AM winding

The carried out test for the adequacy supposes obtaining of the following equation of linear regression:

$$Y_n^* = a_0 + a_1 Y_{ef}, \tag{3}$$

where

$$a_0 = \overline{Y_n} - r_{Y_{ef}Y_n}\,\sigma_{Y_n}\big/\sigma_{Y_{ef}}\,\overline{Y_{ef}}; \qquad a_1 = r_{Y_{ef}Y_n}\,\sigma_{Y_n}\big/\sigma_{Y_{ef}}\;. \tag{4}$$

Here, $\overline{Y_n}, \overline{Y_{ef}}$ are the average values of the predicted and effective values; $r_{Y_{ef}Y_n}$ is the coefficient of correlation between them; $\sigma_{Y_n}, \sigma_{Y_{ef}}$ are the mean square deviations.

The indicated parameters were calculated according to the formulas:

$$r_{Y_{ef}Y_n} = \frac{\sum_1^L \left(Y_{ef} - \overline{Y_{ef}}\right)\left(Y_n - \overline{Y_n}\right)}{L\sigma_{Y_{ef}}\sigma_{Y_n}}, \tag{5}$$

$$\sigma_{Y_{ef}} = \sqrt{\sum_1^L \left(Y_{ef} - \overline{Y_{ef}}\right)^2 / \left(L-1\right)}, \tag{6}$$

$$\sigma_{Y_n} = \sqrt{\sum_1^L \left(Y_n - \overline{Y_n}\right)^2 / \left(L-1\right)}, \tag{7}$$

where $L = 57$ is the volume of statistic sampling (number of the temperature measurements in all the experiments).

The mean square absolute error of measurements was determined as:

$$\Delta Y_n = t_p \sigma_{Y_n}^*, \tag{8}$$

where t_p is the Student's coefficient for the given reliability and number of freedom degrees $k = L - 1$. In the case under consideration, reliability was taken as $p = 0.05$. Here, $\sigma_{Y_n}^*$ is the residual mean square deviation calculated according to the formula:

$$\sigma_{Y_n}^* = \sqrt{\sum_1^L \left(Y_n - Y_n^*\right)^2 / \left(L-1\right)}. \tag{9}$$

The mean square relative error of prediction was determined as follows:

$$\delta_{Y_n} = \left|\Delta Y_n\right| / Y_{n\max} 100\%, \tag{10}$$

Where $Y_{n\,max}$ is the highest value of the predicted one.

Finally, the obtained values are as follows:

$\sigma_{\text{Yef}} = 21.2$ ºC, $\sigma_{\text{Yп}} = 20.9$ ºC, $r_{\text{YefYп}} = 0.99$,
$\sigma^*_{\text{Yn}} = 2.34$ ºC, $\Delta \text{Y}_{\text{n}} = 0.28$ ºC, $\delta_{\text{Yn}} = 3.2\%$.

Conclusion. The obtained results show the adequacy of the proposed thermal model of an asynchronous motor operating in the mains with poor quality power. Taking into consideration the fact that in terms of many motor types, reference literature does not contain the required data on the coefficients of thermal efficiency and thermal capacity, and only thermal constants of time are given for certain motor types, values of the specified parameters of the model may be obtained basing on the methodology represented in the paper.

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АНОТАЦІЯ

Мета. Синтез математичної моделі асинхронного двигуна з урахуванням впливу зміни якісних показників електроенергії на процеси нагріву та теплообміну для економічно обґрунтованого вибору засобів захисту.

Методика: Теоретичне обгрунтування доцільності використання одномасової теплової моделі асинхронного двигуна, для умов роботи останнього в умовах неякісної електроенергії, задля визначення втрат в ньому.

Результати: Було проведено експериментальні дослідження роботи асинхронного двигуна при номінальному навантаженні. Отримані результати вимірювань дозволили визначити параметри одномасової теплової моделі коефіцієнт тепловіддачі двигуна, та коефіцієнт його теплоємності. Одномасова теплова модель асинхронного двигуна - це математична модель, яка використовується для опису теплових процесів, що відбуваються в асинхронному двигуні. Ця модель базується на припущенні, що всі елементи двигуна можна об'єднати в одну масу, яка нагрівається при роботі двигуна. Модель передбачає, що теплова ємність мотора є константою, а тепловий потік, який виділяється в процесі роботи двигуна, пропорційний квадрату струму, що проходить через обмотки двигуна. Крім того, модель передбачає наявність теплової провідності між масою двигуна і зовнішнім середовищем, яка впливає на швидкість розсіювання тепла.

Наукова новизна: Запропоновано методологію визначення втрат в асинхронному двигуні за допомогою синтезованої математичної моделі з урахуванням впливу зміни якісних показників електроенергії на процеси нагріву та теплообміну в ньому.

Практичне значення: Отримані результати свідчать про адекватність запропонованої теплової моделі асинхронного двигуна, що працює в мережі з неякісною електроенергією. Враховуючи те, що для багатьох типів двигунів у довідковій літературі відсутні необхідні дані щодо коефіцієнтів тепловіддачі і теплоємності, а наводяться лише теплові сталі часу для окремих типів двигунів, значення вказаних параметрів моделі може бути отримана на основі методології, представленої в роботі. Одномасова теплова модель може бути корисною для аналізу теплових процесів, що відбуваються в асинхронному двигуні, та для покращення ефективності роботи двигуна. Зокрема, вона може допомогти визначити оптимальну температуру роботи двигуна, а також розрахувати необхідну систему охолодження для забезпечення стабільної роботи двигуна в умовах змінної навантаженості та температурного режиму.

Ключові слова: *асинхронний двигун, одномасова теплова модель, коефіцієнти тепловіддачі і теплоємності, неякісна електроенергія.*