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Comparison of the results of simulation modeling of an asynchronous electric motor with the calculated electrodynamic and energy characteristics

***Abstract**. The paper presents the results of a comparison of the electrodynamic and energy characteristics and parameters of an asynchronous motor, obtained by simulation and calculated by the classical method. The mathematical model in the MATLab software environment is used for research. The research results are relevant when choosing and using the proposed simulation model of three-phase squirrel-cage asynchronous motors for further research, including the effect of various engine defects on its performance*

***Streszczenie.** W artykule przedstawiono wyniki porównania charakterystyk i parametrów elektrodynamicznych i energetycznych silnika asynchronicznego, uzyskanych metodą symulacji i obliczonych metodą klasyczną. Do badań wykorzystano model matematyczny wykonany w środowisku oprogramowania MATLab. Wyniki prac mają istotne znaczenie dla wyboru i wykorzystania zaproponowanego modelu symulacyjnego asynchronicznego silnika elektrycznego z wirnikiem klatkowym do dalszych badań, w tym wpływu różnego rodzaju uszkodzeń silnika na jego pracę. (**Porównanie wyników modelowania symulacyjnego asynchronicznego silnika elektrycznego z obliczonymi charakterystykami elektrodynamicznymi i energetycznymi**)*

Keywords: asynchronous motor, simulation modeling, charakterystyka elektrodynamiczna, mathematical model.
Słowa kluczowe: silnik asynchroniczny, modelowanie symulacyjne, electrodynamic characteristics, model matematyczny.

Introduction

Improving the operational reliability of electromechanical equipment is a modern priority task, the solution of which determines the result of the efficient operation of industrial and transport enterprises. Three-phase squirrel-cage asynchronous motors are among the most common electrical machines used to drive various mechanisms in all industries. Currently, almost 70% of the machines used in industry are three-phase asynchronous motors because they are simple, reliable and inexpensive [1]. The requirements for each technological process determine the need to set and maintain the operating parameters of the motors used with high accuracy at a given level. Many malfunctions and defects that occur in difficult operating conditions quickly progress and disable electric motors, even with a short service life, leading them to an emergency stop. Timely and reliable detection of damage not only increases the reliability of motors, but significantly reduces repair time and reduces unforeseen costs. Experience in the operation of asynchronous electric motors shows that the development and implementation of modern diagnostic tools based on a thorough study of the processes occurring when defects occur is one of the most important and effective factors in increasing the economic efficiency of using electromechanical equipment in industry [2, 3].

Determining the type and degree of damage, establishing their influence on the performance of electric motors, improving the accuracy of predicting the final resource and uptime is possible on the basis of studying electrodynamic processes that occur in the presence of defects of various kinds [4-6]. Mathematical modeling methods are widely used to conduct research in various fields [7-9]. Simulation models of asynchronous electric motors for the correct use of the results in improving diagnostic systems and studying processes occurring at different degrees of defects must be checked for compliance with the properties of the simulated object to real processes. The results of simulation modeling are of an estimated nature and require further verification, in particular, by conducting full-fledged experimental studies on real objects. Given that experimental studies are highly laborious, the paper proposes an approach to evaluating the results of simulation modeling by comparing them with a set of calculated energy and electrodynamic indicators of an asynchronous motor.

The aim of the article is to conduct a study on the evaluation of the selected mathematical model of an asynchronous motor by com-paring the results of simulation modeling and the electrodynamic characteristics and energy parameters calculated by the classical method. The use of a mathematical model with the established accuracy of the results of simulation modeling in further research will allow more correct consideration of the influence of defects in the operation of asynchronous motors to determine the method for their diagnosis and assessment of the degree of damage and study of the ongoing electrodynamic processes.

To achieve the aim, the following tasks were completed:

– the parameters and performance characteristics of the selected base motor were calculated according to the classical method;

– simulation modeling in the *MATLab* software environment of the operation of an asynchronous motor was carried out using the selected mathematical model;

– obtained as a result of mathematical modeling electrodynamic characteristics and energy parameters of an asynchronous electric motor;

– a comparison of the results of modeling and calculations using the electrodynamic characteristics of an asynchronous electric motor was carried out.

Choice of a model for the study of electrodynamic processes and the basic type of motor

The statistics of operating experience of asynchronous motors shows that the largest share of operability failures is due to failures in the stator and, according to various data, taking into account the operating area, 77-85%, the rotor accounts for 6-8% and the bearing assembly - up to 8-14% [1, 3, 10]. The main part of the defects in the motor leads to the occurrence of an asymmetric rotating stator field. Therefore, to conduct a study on the manifestation of a larger range of damage, it is necessary to use a reliable mathematical model of an asynchronous motor with the possibility of research, including under asymmetric modes that occur during operation with various types of stator defects [11-13].

To conduct research on electromagnetic processes, there are a large number of approaches to simulation modeling of asynchronous motors. Their differences are mainly related to the choice of the coordinate system in which differential equations are composed that describe the operation of an asynchronous motor. In works [6, 11], a model is considered in which the equations de-scribing the operation of an asynchronous motor are written in d-q coordinates, i.e. in a single-phase coordinate system. When using such a model, it becomes difficult to determine some parameters, for example, the imbalance of phase currents, which is necessary for diagnosing a number of defects.

When modeling asynchronous motors with asymmetric windings, it is advisable to use a system of differential equations in hindered coordinates, as noted in [14]. To solve the problem, the use of other coordinate systems is incorrect. This is evidenced by studies in [15, 16].

To implement the simulation modeling of the operation mode of an asynchronous motor with asymmetrical windings, which occurs in the event of damage to one or more stator windings, one should set a change in the leakage inductance and active resistance of the corresponding winding (windings). That is, it is necessary to establish how much the actual values of the specified parameters differ from the nominal values. After that, take into account how the mutual inductance of the windings will change. To determine the change in the mutual inductance of the windings, it is necessary to establish what effect the change in the complex resistance of one winding (several windings) has on the inductance of the magnetic circuit. The papers [17, 18] show the established relationship between the winding inductances and the geometric dimensions of the windings, which must be taken into account when simulation modeling.

Thus, in order to conduct further research with a wider range of possible defects that affect the operating modes of motors, it is necessary to use a mathematical model of an asynchronous motor with the possibility of creating an asymmetric rotating field, made in “braking coordinates”, taking into account losses in steel and mechanical losses. In addition, for the implementation of this modeling principle, one should take into account the mutual inductance of the windings when the complex resistance of one or more phases of the stator winding, simulating its damage, changes. When determining the change in the mutual inductances of the windings, it is necessary to determine what effect the change in the complex resistance of one winding (two windings) has on the inductance of the magnetic circuit and establish the relationship between the inductances of the windings and the geometric dimensions of the windings, as well as the effect on the leakage inductance of each phase and mutual phase inductances.

The simulation model of an asynchronous motor proposed and used in the work, for which the reliability of real processes is established, is made in "braked coordinates". The general view of the model and its implementation in the *MATLab* software environment are presented and discussed in detail in [19]. The implementation of the mathematical model [19] based on the configuration of mutual inductance with a change in the complex resistance of one or more phases of the motor is considered in [20]. This model can be adapted to study the operation of an asynchronous motor when such a defect occurs in it as an interturn short circuit of the stator windings, which entails an asymmetric rotation field, as well as to determine the starting and operating characteristics of the motor, calculate energy indicators when the asynchronous motor is operating with the specified defect. Thus, simulation modeling of an asynchronous electric motor was carried out using a mathematical model given and discussed in detail in [20].

The simulation model of an asynchronous motor, made in the *MATLab* software environment, is shown in fig. 1. The following parameters are displayed: stator phase voltages, stator phase currents, rotor phase currents, motor shaft speed and useful motor shaft torque. For this purpose, an oscilloscope implemented on the Scope element was used. This oscilloscope has four sections: *Us, Is, Ir, n, M*. The first section displays the voltages of the stator phases, the second – the phase currents of the stator, the third – the phase currents of the rotor, the fourth – the frequency of rotation of the motor shaft and the torque on the motor shaft. The signals corresponding to the torque on the motor shaft and the frequency of rotation of the motor shaft are displayed on the display of the *Display* measuring unit. This is necessary to determine the exact value of the indicated values. If it is necessary to measure the amplitudes and phase angles of the stator voltages, rotor currents, the *Complex to Magnitude-Angle* unit is used, at the input of which a response signal is applied, at the output there are the signals corresponding to the amplitude and phase of this signal. After that, the received signals are displayed on an indication organized using Display units.

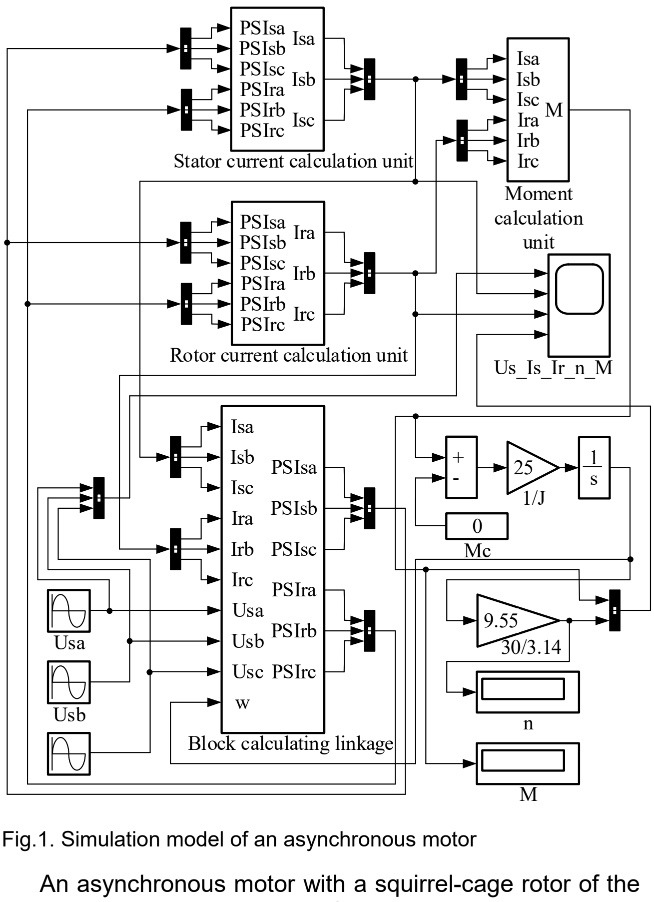

Fig.1. Simulation model of an asynchronous motor

An asynchronous motor with a squirrel-cage rotor of the AIR132M4 type with a power of 11kW with a supply voltage of 220/380 V was chosen as the base motor for research. The rating data of the motor are given in Table 1.

For the nominal mode of the motor (see Table 1) according to the method given in [21], the following parameters were calculated:

– moment on the motor shaft; frequency of rotation of the motor shaft; useful power;

Table 1. The parameters of the sensor

Parameter	Designation	Unit	Value
Rated shaft power	P_n	*kW*	11,0
Rated phase voltage	U_S	*V*	220
Supply voltage frequency	f_S	*Hz*	50
Synchronous speed of the stator field	$n_{n.idle}$	*rpm*	1500
Mechanical idle losses	ΔP_{idle}	*W*	59,7
Idle loading moment	T_{idle}	*N·m*	0,38
Real idle current	$I_{S.idle}$	*A*	9,44
Idle current amplitude	$I_{S.iAdle}$	*A*	13,35
Stator active resistance	r_1	*Ω*	0,5
Stator reactance	x_1	*Ω*	0,56
Number of stator phase turns	w	-	96
Stator winding length	l_a	*m*	0,163
Rated motor speed	n_n	*rpm*	1450
Rated torque on the motor shaft	T_n	*N·m*	72,671
Motor moment of inertia	J	$kg{\cdot}m^2$	0,04
Efficiency	η	*%*	88,4
Power factor	$cos\varphi$	*p.u.*	0,84

– active, reactive and apparent power consumed from the network; losses in steel and copper of the stator and losses in the rotor; mechanical losses;

– phase current of the stator winding; Efficiency and power factor $cos\varphi_1$. The supports are also calculated: the active resistance of the stator winding and the active resistance of the rotor winding, reduced to the stator winding; reactive supports of the stator winding and the resistance of the rotor winding, reduced to the stator winding and in the magnetizing circuit. Some calculated parameters of the prototype motor according to the classical method differ from the passport data. So, the error in calculating the useful power was 0,045%, the error in calculating the efficiency – 0,114%, the error in calculating $cos\varphi_1$ – 0,237%. The given deviations have the maximum differences among other calculated parameters, which is explained by the error of the calculation method used.

To evaluate the results of simulation modeling on the selected mathematical model of an asynchronous electric motor, according to the specified classical technique [21], the performance characteristics are calculated, shown in Table 2. The table highlights the values of the parameters corresponding to the nominal mode.

Results of simulation modeling of electrodynamic actions of an asynchronous electric motor

When setting symmetrical phase voltages of the stator on the model, the timing diagrams of which are shown in fig. 2, the values of the stator phase currents (fig. 3), the rotor phase currents (fig. 4) are obtained. The values of the stator phase voltage and the stator and rotor phase currents are given by the instantaneous values of these parameters.

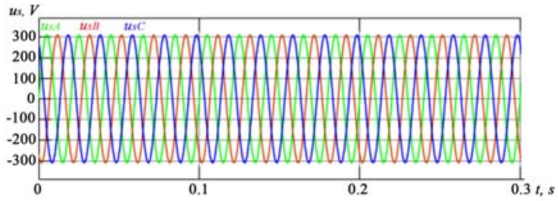

Fig.2. Timing diagrams of stator phase voltages for nominal mode

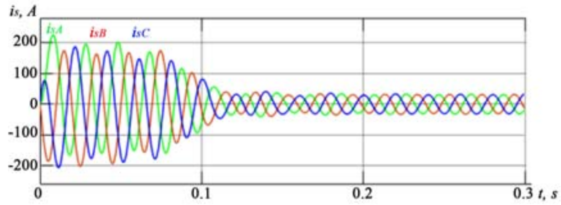

Fig.3. Timing diagrams of stator phase currents for nominal mode

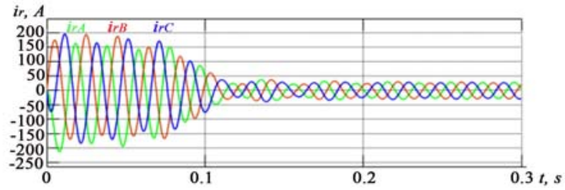

Fig.4. Timing diagrams of rotor phase currents for nominal mode

Table 2. Calculation of the performance characteristics of an asynchronous motor

Calculation formula	Unit	Rotor slip (s)										
		0,01	0,015	0,02	0,025	0,03	**0,03364**	0,035	0,04	0,045	0,05	0,055
$Z=\sqrt{R^2+X^2}$	Ohm	38,38	25,78	19,49	15,72	13,22	**11,86**	11,43	10,09	9,06	8,23	7,55
$I''=U_1/Z$	A	5,732	8,534	11,288	13,995	16,641	**18,55**	19,248	21,804	24,283	26,731	29,139
$\cos\varphi_2'=R/Z$	–	0,999	0,998	0,997	0,995	0,993	**0,992**	0,99	0,988	0,985	0,982	0,979
$\sin\varphi_2'=X/Z$	–	0,041	0,061	0,080	0,099	0,118	**0,132**	0,136	0,155	0,172	0,19	0,207
$I_{1a}=I_{0a}+I_2''\cos\varphi_2'$	A	6,254	9,045	11,782	14,453	17,053	**18,930**	19,584	22,070	24,447	26,778	29,055
$I_{1r}=I_{0r}+I_2''\sin\varphi_2'$	A	9,655	9,940	10,323	10,805	11,383	**11,868**	12,037	12,799	13,596	14,498	15,451
$I_1=\sqrt{I_{1a}^2+I_{1r}^2}$	A	11,503	13,439	15,664	18,045	20,503	**22,343**	22,987	25,513	27,793	30,451	32,908
$I_2'=c_1I_2''$	A	5,875	8,747	11,57	14,345	17,057	**19,013**	19,792	22,349	24,89	27,399	29,867
$P_1=3U_1I_{1a}\cdot10^{-3}$	kW	4,127	5,969	7,776	9,539	11,255	**12,494**	12,925	14,566	16,135	17,673	19,176
$P_{e1}=3I_1^2r_1\cdot10^{-3}$	kW	0,198	0,271	0,368	0,488	0,631	**0,749**	0,793	0,976	1,174	1,391	1,624
$P_{e2}=3I_2'^2r_2'\cdot10^{-3}$	kW	0,037	0,083	0,144	0,0222	0,314	**0,39**	0,42	0,539	0,669	0,811	0,963
$P_{add}=0,005\cdot P_1$	kW	0,0206	0,0298	0,0389	0,0477	0,0563	**0,0625**	0,0646	0,0728	0,0807	0,0884	0,0959
$\sum P=P_{st}+P_{mech}+P_{e1}+P_{e2}+P_{add}$	kW	0,543	0,671	0,838	1,045	1,288	**1,488**	1,565	1,875	2,210	2,577	2,971
$P_2=P_1-\sum P$	kW	3,585	5,299	6,938	8,494	9,967	**11,00**	11,361	12,691	13,925	15,096	16,206
$\eta=1-\sum P/P_1$	p.u.	0,868	0,888	0,892	0,89	0,886	**0,881**	0,879	0,871	0,863	0,854	0,845
$\cos\varphi=I_{1a}/I_1$	p.u.	0,544	0,673	0,752	0,801	0,832	**0,847**	0,852	0,865	0,874	0,879	0,883
$n_2=n_1\cdot(1-S)$	rpm	1485	1477,5	1470	1462,5	1455	**1450**	1447,5	1440	1432,5	1425	1417,5
$T_n=9550\,P_2/n_2$	N·m	23,05	34,25	45,07	55,46	65,42	**72,47**	74,95	84,16	92,83	101,16	109,18

To evaluate the results of the selected mathematical model, simulation modeling of the electrodynamic processes of the operation of an asynchronous electric motor was carried out with the passport data given in Table 1. The results of modeling the dependence of active power *(P_1)*, useful power *(P_2)* consumed from the network, average stator current (I_{1mid}), efficiency *(η)*, power factor *(cosφ)* and torque on the motor shaft *(T)* on the rotor speed *(n_2)* are given in Table 3. The simulation modeling was carried out with a fixed speed of the motor shaft.

Table 3. Results of simulation modeling of an asynchronous electric motor operation

n_2, rpm	P_2, kW	P_1, kW	I_{1mid}, A	η, p.u.	cosφ, p.u.	T, N·m
1425,7	15,059	17,309	30,71	0,87	0,854	100,865
1440,8	12,54	14,153	25,082	0,886	0,855	83,132
1450,0	**11,0**	**12,332**	**21,879**	**0,892**	**0,854**	**72,443**
1470,8	6,611	7,313	14,853	0,904	0,746	42,923
1485,8	3,201	3,553	10,744	0,901	0,501	20,573
1488,3	2,607	2,916	10,275	0,894	0,43	16,727
1490,8	2,002	2,265	9,989	0,884	0,347	12,824
1493,3	1,375	1,631	9,768	0,843	0,253	8,793
1494,8	1,012	1,273	9,596	0,795	0,201	6,458
1496,4	0,605	0,861	9,518	0,703	0,137	3,8596
1497,9	0,231	0,547	9,429	0,419	0,078	1,473
1498	0	0,156	9,403	0	0,025	0

Useful power in table 3 is determined by:

(1) $$P_2 = T \cdot \omega$$

where T - the moment on the motor shaft, *N·m*, ω - the rotation speed of the motor shaft.

The rotation speed of the motor shaft for pairs of field-owls p=2 is determined by:

(2) $$\omega = \frac{n}{9{,}55}$$

where *n* - the actual speed of the motor shaft, rpm.

The instantaneous reactive power is determined by:

(3) $$Q_1 = -\frac{1}{\sqrt{3}}\left(u_{s\alpha}\left(i_{s\beta} - i_{s\gamma}\right) + u_{s\beta}\left(i_{s\gamma} - i_{s\alpha}\right) + u_{s\gamma}\left(i_{s\alpha} - i_{s\beta}\right)\right)$$

Instantaneous apparent power consumed from the network:

(4) $$S_1 = u_{s\alpha} \cdot i_{s\alpha} + u_{s\beta} \cdot i_{s\beta} + u_{s\gamma} \cdot i_{s\gamma}$$

Then the value of the instantaneous active power consumed from the network can be determined as:

(5) $$P_1 = \sqrt{\left(S_1\right)^2 - \left(Q_1\right)^2}$$

The efficiency is determined by:

(6) $$\eta = \frac{P_2}{P_1}$$

The power factor can be determined using the expression:

(7) $$\cos\varphi = \frac{P_1}{S_1}$$

According to the results of simulation modeling (*mod*) given in Table 3 and calculated data (*calc*) from Table 2, the mechanical characteristics *n_2=f(T)* and the dependence of the rotor speed on the useful load on the shaft *n_2=f(P_2)* are constructed in fig. 5 and fig. 6, respectively.

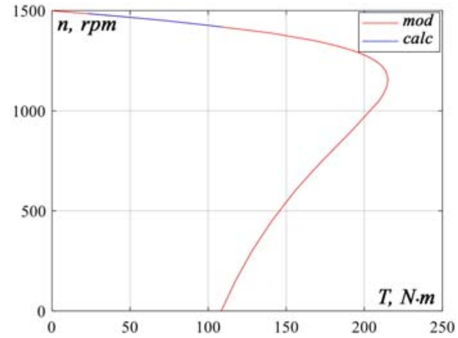

Fig.5. Motor mechanical characteristics

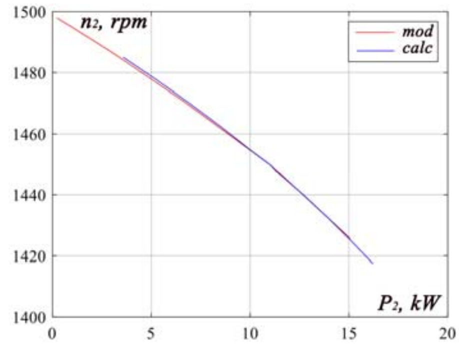

Fig.6. Dependence of the rotor speed on the useful load on the shaft

Based on the results of tables 3 and 2, the dependences are plotted for the relative value of the active power consumed from the network on the relative value of the useful power *P_1*=f(P_2*)* *(P_1/P_{1H}=f(P_2/P_{2H}))* (Fig. 7) and the dependence of the average relative value phase current of the stator on the relative value of useful power *(I_{1mid}*)=f(P_2*)* *(I_1/I_{1H})=f(P_2/P_{2H})* (Fig. 8).

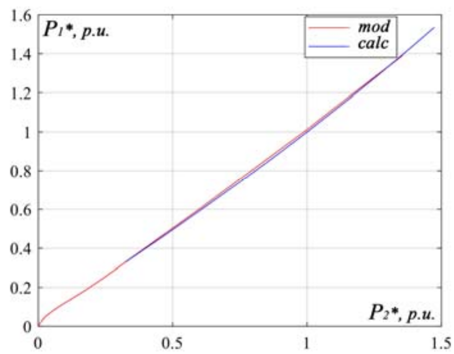

Fig.7. Dependence of the relative value of active power consumed from the network *(P_1*)* *(P_1*=P_1/P_{1rat})* on the relative value of useful power *(P_2*)* *(P_2*=P_2/P_{2rat})*

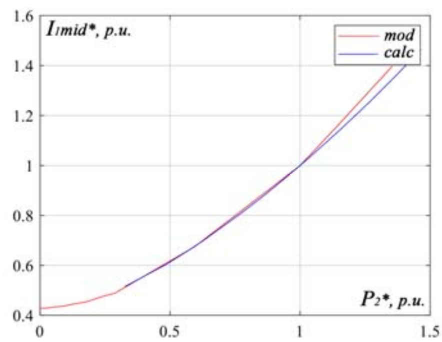

Fig.8. Dependence of the average relative value of the stator phase current *(I_{1mid}*)* *(I_{1mid}*=I_{1mid}/$I_{1mid.rat}$)* on the relative value of the useful power *(P_2*)* *(P_2*=P_2/P_{2rat})*

Based on the results of tables 3 and 2, the dependences of the energy indicators of the motor are plotted: efficiency $\eta = f(P_2/P_{2H})$ (Fig. 9) and power factor $\cos\varphi = f(P_2/P_{2H})$, (Fig. 10) on the relative value of the useful power.

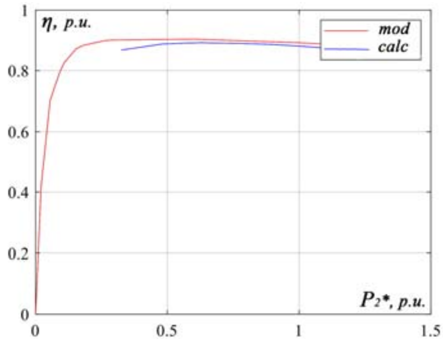

Fig.9. Dependence of the efficiency factor (η) on the relative value of the useful power (P_2^*) $(P_2^*=P_2/P_{2rat})$

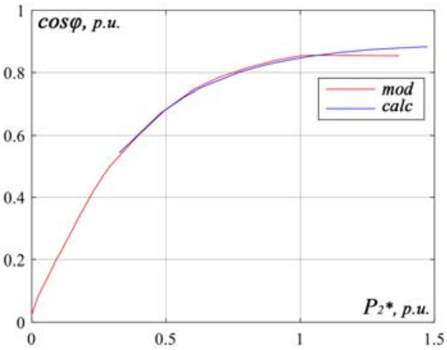

Fig.10. Dependence of the power factor ($\cos\varphi$) on the relative value of the useful power (P_2^*) $(P_2^*=P_2/P_{2rat})$

Analysis of the results of simulation modeling in comparison with the calculated electrodynamic and energy characteristics and motor parameters shown in figures 5-10 indicates a high degree of compliance of the results obtained with the calculated ones and a sufficiently high dynamic stability of the model in the working range *(T=23,0-110,0 N·m)* (see fig. 5, 6). The greatest deviations are the discrepancies in the energy indicators of the motor, which are 1,2% for the efficiency factor and 0,8% for the power factor $\cos\varphi$, which is explained by the errors of the calculation method.

Conclusion

Defects or damage to squirrel-cage asynchronous motors require timely diagnosis and study of their effect on the parameters and characteristics of operating electrical equipment. An effective means of assessing the influence of defects on the energy and electrodynamic processes occurring in an asynchronous motor is simulation modeling. Verification and evaluation of results of simulation modeling obtained on specific mathematical models for compliance with real ongoing processes is a necessary issue that helps to increase the level of correctness of the results when they are used in further studies of asynchronous electric motors. The most reliable results on establishing the level of model adequacy can be obtained by conducting experimental studies on real objects. Taking into account the significant laboriousness of conducting experimental studies in the work, an approach is proposed for evaluating the results of simulation modeling by comparing them with a set of calculated energy and electrodynamic indicators of an asynchronous motor, which is the novelty of this work.

Based on the results of the studies, it is found that the greatest discrepancies between the calculated data and the data obtained during modeling take place for a set of energy indicators and are: for efficiency factor – 1,2%, for power factor $\cos\varphi$ – 0,8%, which is explained by errors calculation method. Comparison of the electrodynamic characteristics and parameters shows a fairly high accuracy of the results obtained in the simulation modeling. Thus, the discrepancies in the torque values at the nominal rotor speed n_2 =1450 rpm are: the calculated value T=72,47 Nm, the value obtained by modeling T=72,443 Nm. The discrepancies in the values of the calculated and obtained by modeling torques over the entire operating range of the electric motor, with the rotation of the rotor shaft n_2=1417-1485 rpm, which corresponds to T=23,0–110,0 Nm, also have an insignificant level that can be neglected.

The research results have shown the possibility of using the proposed simulation model for further research, in particular, the impact on the manifestation of various types of electrical defects in an asynchronous motor on its performance, with a fairly high correspondence of the results to the calculated values.

Subsequent work will be aimed at studying the effect of interturn short circuit in the phases of the stator winding of an asynchronous electric motor on its performance using the proposed mathematical model while improving the system for diagnosing asynchronous motors.

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