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3.1 Computer modeling of the system of technical diagnostics of electric motors with the use of Petri nets

Today, with the development of technical progress in Ukraine and around the world, in general, the issue of improving the reliability and efficiency of operation of electromechanical equipment (EME), first of all, electric motors of mining machines, is becoming increasingly relevant, since a significant proportion of this equipment requires replacement due to the exhaustion of the limited service life or overhaul, and this, in turn, leads to significant material and time costs due to downtime of technological equipment, product damage due to accidents, reduction of production efficiency, etc. High labour intensity of technical diagnostics of the current state of electromechanical equipment, and sometimes the complete absence of such diagnostics causes depreciation of fixed assets, increase in the cost of repairs and increase in the volume of repair work [71].

Also, enterprises use rather inefficient systems of planned preventive repairs and maintenance based on the number of hours of electromechanical equipment operation. Such approaches have significant disadvantages due to the fact that repairs are carried out according to the already formed schedules at the enterprise or after calculating the operating hours of EME due to the lack of objective indicators and tools for planning repair work, high labor intensity of calculations of labor costs, labor intensity of accounting of parameters, the complexity of prompt adjustment of planned repairs. The existing structure of the PPR system provides for an accident-free model of operation and repair of EME, however, in practice it is necessary to take into account unplanned repairs, the cause of which is often unsatisfactory technical condition or accidents due to poor maintenance [72-73].

In fig. 1 shows a simplified structure of the EME maintenance system according to the actual state, which reveals the essence of the algorithm for performing repairs of electromechanical equipment on the principle of continuous monitoring and diagnostics of technical condition. To implement this structure, it is necessary to develop a completely new model of the EME diagnostic system and apply modern technologies and devices, which will ensure a more normal organization of maintenance and reliable and efficient operation of the equipment [73].

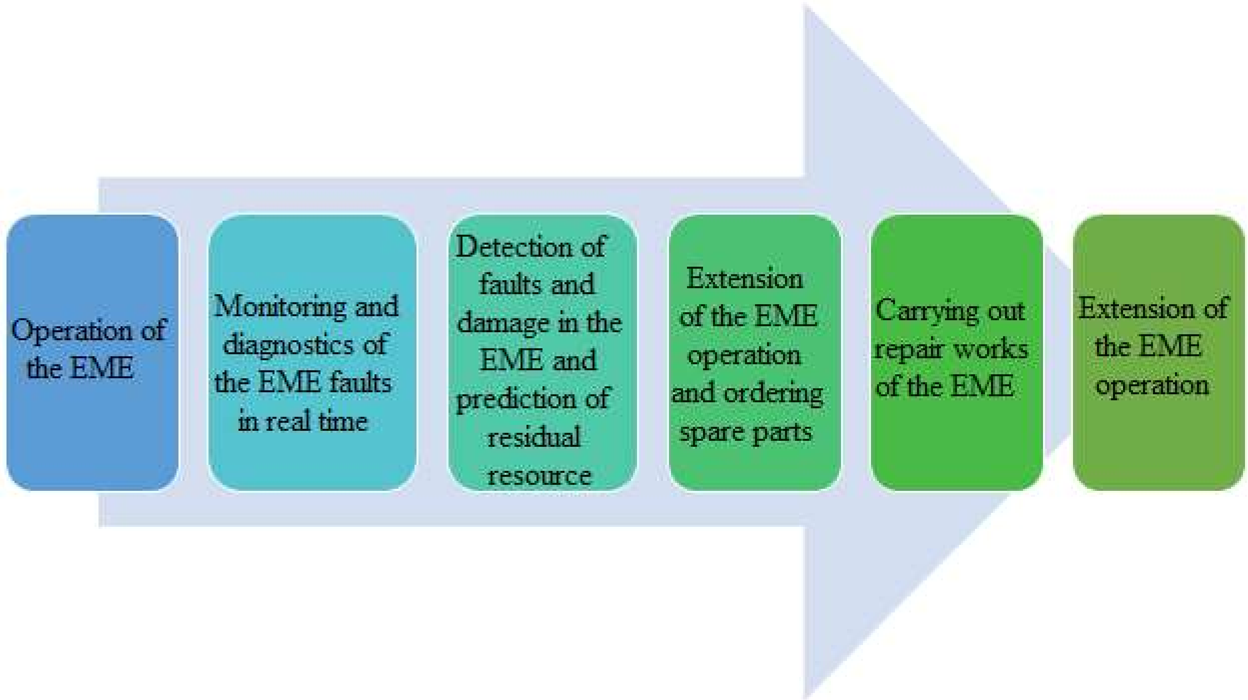

Figure 1. Simplified structure of the service system organization according to the actual state of electromechanical equipment

At the same time, the analysis of experience in the use of EME shows that a significant part of it still has a fairly large margin of reliability, and in the presence of reasonable recommendations, the service life of such equipment can be significantly increased. Such recommendations can be obtained by computer modeling of systems for diagnosing the technical condition of electric motors of mining machines.

The problem of reliability and technical diagnostics of electrical equipment has found numerous solutions in the works of Birger I., Haljasmaa A., Swee P., Kazak V.M., Dotsenko B.I., Kuzmin V.P., Kutsenko G.F. The problems of modeling complex systems based on Petri nets are devoted to the works of Peter J., Leskin A., Khanov A.A., Lomazov I.A.

Thus, the problem of developing and implementing computer models of systems for diagnosing the technical condition of mine electric motors using the most modern modeling methods based on the use of the Petri net approach remains relevant and requires new solutions, taking into account the requests for attracting modern developments in the field of information technology.

Currently, the assessment of the technical condition of electromechanical equipment is considered the main problem in its operation in production [74], the main task of which is to identify defects and damage to equipment.

Serviceable technical condition of the equipment is the state of EME that meets all the established parameters according to regulatory documents, otherwise it is defective. Defects in electromechanical equipment can occur at different points of the life cycle, namely, during manufacturing, installation, adjustment, operation, testing, repair, and have various consequences [75].

There are quite a lot of types of defects, which are usually divided into four main categories according to the degree of development of the defect: normal technical condition of the equipment; a defect at the initial stage of development that is subject to current repair, i.e. the presence of such a defect does not affect the operation of the EME; a highly developed defect for which major repairs must be carried out, the actual presence of such a defect limits the possibility of operation of electromechanical equipment and reduces the limited period of operation; a defect in the emergency stage of development, which leads the electrical equipment to its complete failure, that is, the presence of such defects makes the operation of EME impossible [71].

When identifying the current technical condition of electromechanical equipment and making decisions for its further operation, it is necessary to take into account the reliability and accuracy of the information obtained about its existing characteristic parameters that affect the condition of the equipment. Any method of control and diagnostics of technical condition can not provide complete reliability of the object of study. Measurements of diagnostic parameters may include errors, resulting in the possibility of obtaining a false diagnostic result. That is why for each method of diagnostics of technical condition there is its own regulatory documentation that regulates the purpose of each method, the procedure, means of control, analysis of results, possible types of defects of EME and recommendations for their elimination.

Modern experience in the operation of electric motors shows a significant number of failures, and their accident rate is 25% or more annually [76]. At many industrial enterprises, sudden failure of electric motors leads to such undesirable consequences as financial costs associated with disruption of the technological process and damage to products as a result of the accident; energy costs due to increased power consumption, and reduced fire safety, as well as possible short circuits that occur in the stator or rotor winding of a damaged electric motor, and abnormal modes of operation of electric motors that appear when they are overloaded with currents greater than nominal. Thus, there is a need to diagnose the current state of electric motors during their operation and determine their residual service life. To determine the scope of repair of electric motors, it becomes necessary to identify the nature of their faults and defects, which are shown in fig. 2 [72]. Analysis of the structure and the causes and consequences of electric motor failures shows that, firstly, the parameters to be monitored in the detection of defects are reduced to changes in current, temperature and time when gaining the appropriate speed during the load of the electric motor. Secondly, the given list of faults and their consequences does not contain information on changes in the phase shift of currents, no-load losses, distortion of current changes in time, as well as deviations from the sinusoidal form of this change.

Modern diagnostics of electrical equipment is conventionally divided into three main areas: parametric diagnostics, fault diagnostics and preventive diagnostics [77], the main purpose of which is to determine the cause of anomalies and take the necessary measures to prevent equipment failure by collecting data on the past and current technical condition. Effective monitoring of electromechanical equipment contains three stages: detection of signs, diagnosis of damage and prediction of the technical condition itself [78]. The detection of signs and diagnosis of failures usually involves the detection of an abnormal condition, as well as the determination of the location of defects and the prediction of the degree of failure [76].

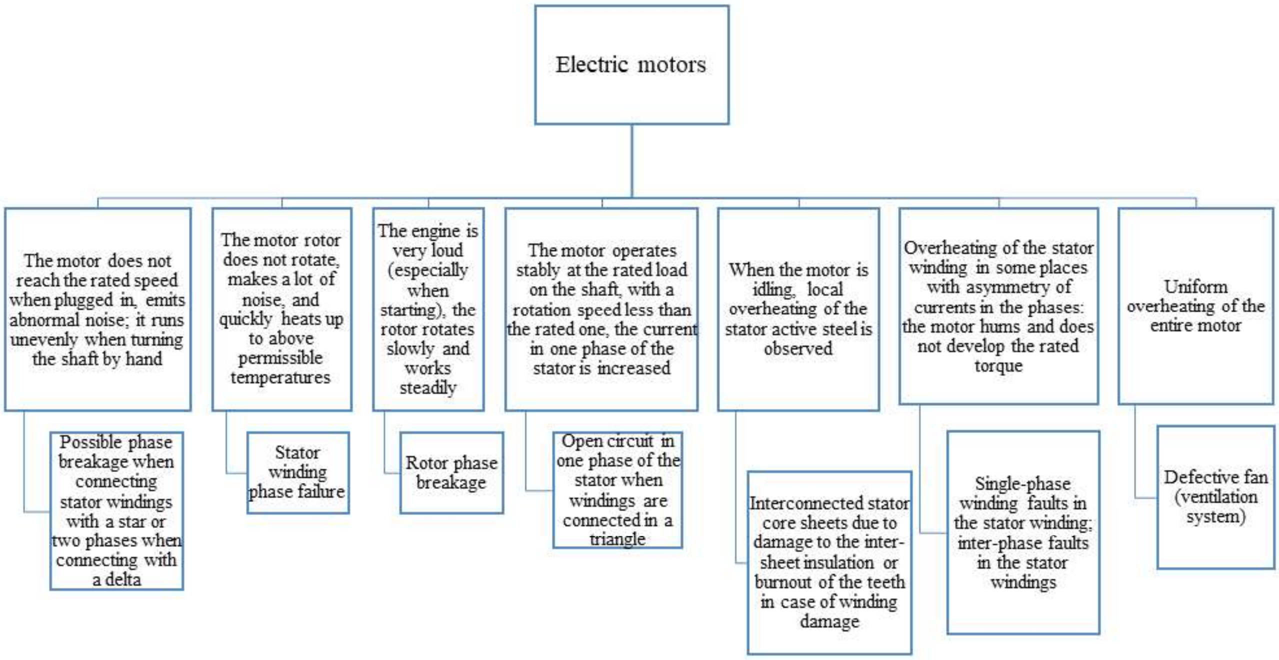

Figure 2. Possible defects of electric motors and causes of their occurrence

The use of a certain type of technical diagnosis is determined by the following conditions [77]:

- the purpose of the diagnostic object by the scope of use, operating conditions, etc;
- complexity of the object by design and the number of parameters for which control is performed;
- economic feasibility of diagnostics;
- degree of danger of emergency situation development and consequences of failures of the diagnostic object.

Currently, there are quite a few methods of monitoring and diagnostics of electromechanical equipment, but recently more relevant is the use of intelligent methods of diagnosing the technical condition of various systems, which involve the creation of mathematical models that contribute to understanding the behavior of a system, taking into account the detection of its damage and defects, while taking into account that mathematical modeling of complex processes of monitoring the state is a powerful tool in solving engineering problems in the diagnosis of technical conditions.

Therefore, due to the fact that the diagnostics of the state of any system is a complex bridging function due to the variety of controlled parameters, it is proposed to simplify the structure of the model and the efficiency of determining the states of electric motors by using modern information technologies with the use of Petri nets and advanced statistical methods. Now mathematical models using such algorithms are generally used in information systems [79-82] and in diagnostics in medicine [83-85] and complex mechanical systems [86]. In view of this, the construction of mathematical models of diagnostics is now becoming more widespread, but there are few available descriptions of models based on Petri nets, in particular in the field of technical diagnostics, although they show sufficiently high accuracy and reliability in modeling. Therefore, the use of this method for the construction of mathematical models of systems for diagnosing the technical condition and predicting the residual life of selected objects is quite relevant.

The main factor in the development of models of diagnostic systems for any electromechanical equipment is to determine the parameters that affect the technical condition, based on this, the choice of their set is justified. Thus, for the development of models, a system of classification of technical conditions was obtained (fig. 3), based on such energy-mechanical parameters as load - P, kW; voltage - U, kV; current - I, A; resistance - R, MOhm; temperature - t, ^{0}C; rotation speed - n, rev./min. The vector containing the set of selected parameters has the form:

$$C = \begin{bmatrix} P \\ U \\ I \\ R \\ t \\ n \end{bmatrix}. \qquad (1)$$

The power of the set of all elementary events (tuples) in this case is $N(\Omega) = 4^6$, while the power of the admissible set of events (tuples) $N(K) = 21$.

In accordance with (1), the designation of indicators of the operating modes of electric motors is performed as follows: "0" - normal parameter values; "+" - increase in parameter values; "-" - decrease in parameter values; "Δ" - no characteristic parameter values. In fig. 1 shows the failure tree of mine electric motors, according to which the classification of the obtained modes is performed with respect to four technical conditions, namely: normal operation, current repair, overhaul, complete failure of electrical equipment.

To perform the development of the model of the diagnostic system, first of all, the study of the influence of diagnostic indicators on the state of electric motors was carried out using the appropriate algorithm. Identification of factors influencing the appearance of these damages is provided by determining the correlation coefficient and checking its significance using Student's t-criterion. In this case, the null hypothesis H_0 is put forward that in the presence of the obtained sample set of values $x_i, i = 1,2,\dots,m$ of some indicator, and the set of observations $y_i, i = 1,2,\dots,m$ of some factor that can influence the studied indicator, the influence is not significant, while the alternative hypothesis H_1 states that the influence of the factor on the studied indicator is significant at the significance level α = 0.01:

$$H_0: r_{xy} = 0, \quad (2)$$

$$H_1: r_{xy} \neq 0, \quad (3)$$

r_{xy} – correlation coefficient, which is defined as

$$r_{xy} = \frac{K_{xy}}{\sigma_x \sigma_y}, \quad (4)$$

x i y – respectively, the studied indicator and the influence factor between which the correlation is searched;

K_{xy} – correlation moment,

σ_x i σ_y – mean square deviations of the indicator and factor respectively.

Confirmation of the null hypothesis is provided by fulfilling the following condition:

$$|z^*| < t_{1-\frac{\alpha}{2}}(n), \quad (5)$$

n – number of degrees of freedom, $n = m - 2$;

m – the size of the sample population;

$t_{1-\frac{\alpha}{2}}$ – quantile of the Student's distribution at the significance level α;

z^* – sample criterion statistics on the corresponding empirical data:

$$z^* = \frac{r_{xy} \cdot \sqrt{n}}{\sqrt{1 - r_{xy}^2}}. \quad (6)$$

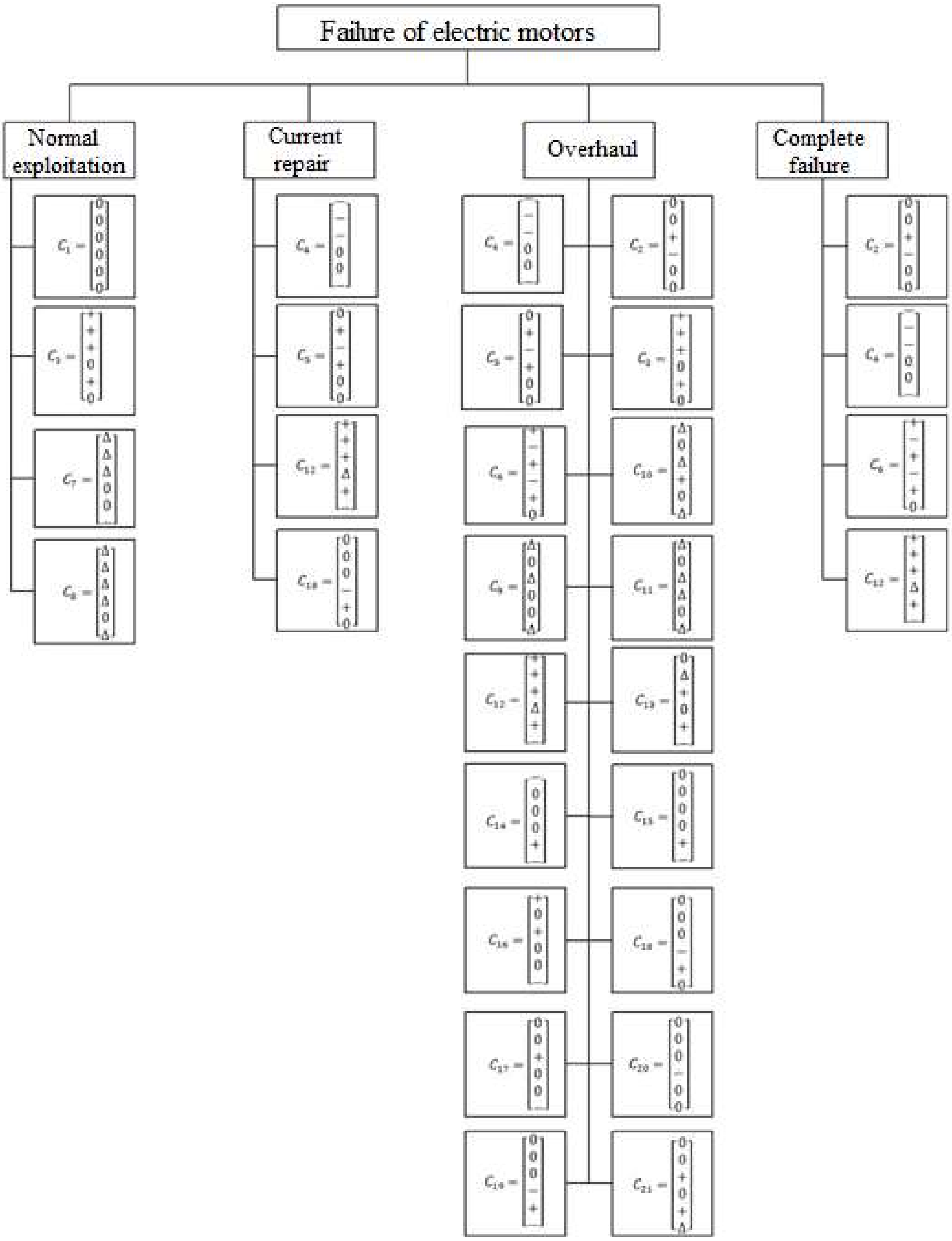

Figure 3. Failure tree of electric motors of mining machines

Thus, the dependences between the leakage current through the interphase insulation and the phase currents, between the phase shift of current and voltage and the leakage insulation were determined. The first study was conducted using a computer model in Matlab - Simulink, which is shown in fig. 4. As a result of the research, it was found that the dependence of phase currents on load is more significant than the dependence on insulation resistance. As a result, it was assumed that the dependence on the load can be eliminated by determining the dependence of the leakage current on the difference between the phase currents. The results of the dynamics of changes in the difference of currents between the phases depending on the leakage current through the insulation are shown in fig. 5.

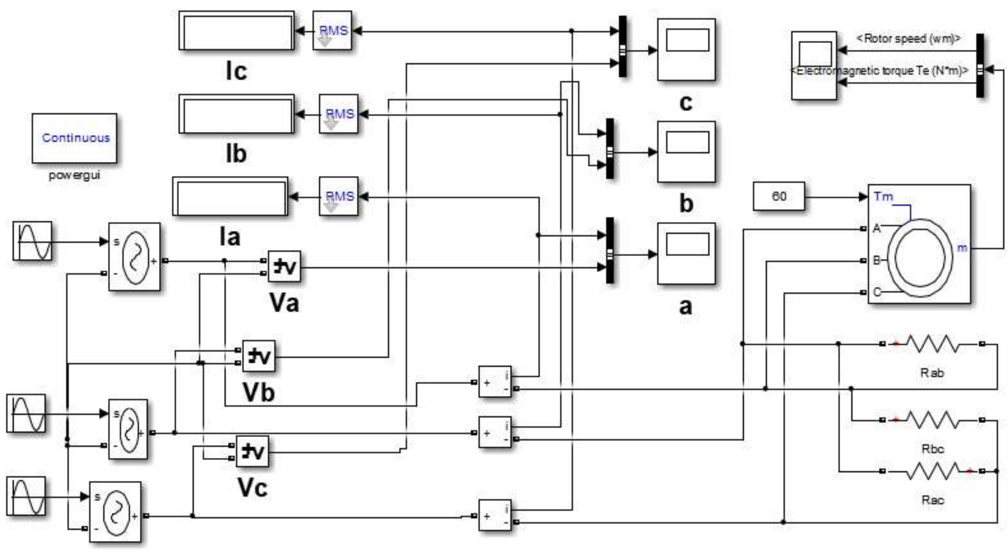

Figure 4. Computer model for measuring phase currents depending on leakage current through insulation

In Table 1, the definition of the critical values of the correlation coefficients is presented, which show that the hypothesis H_0 regarding the absence of the influence of the identified factors on the interphase insulation in electric motors is not confirmed, since the condition $|z^*| < t_{0,995}(20)$ is not fulfilled due to the fact that the sample value of the statistics significantly exceeds the quantile of the distribution of the Student's t-test at the significance level α = 0.01. This circumstance indicates that the leakage current through the insulation between the phases of the motor correlates with the differences in the currents of phases AB and AC and allows us to confirm the occurrence of a violation of the interphase insulation in electric motors under the influence of the identified factors.

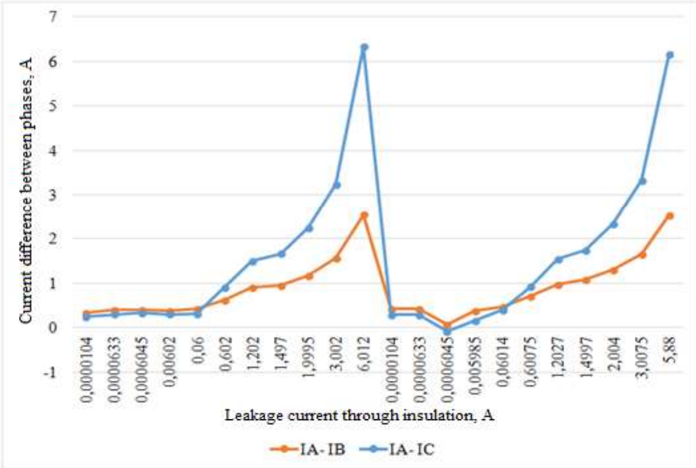

Figure 5. Dynamics of changes in the current difference between phases depending on the leakage current through the insulation

Table 1.

Determination of critical values of correlation coefficients

Parameter	Symbolic designation	$r_{A\text{-}B}$	$r_{A\text{-}C}$
correlation coefficient	*r*	0,989	0,9987
sample value of statistics	z*	29,9	87,62
is the quantile of the distribution of the Student's t-test (α=0.01)	*t*	2,85	2,85
acceptance of the hypothesis H_0: r=0	yes/no	no	no

Obtaining indicators of the dependence between the phase shift of current and voltage and the coil insulation was performed using the model shown in fig. 6. The dependences of phase currents and phase shifts on inductance were revealed, on the basis of which the parameters with which the coil fault can correlate were determined. The results of the research are presented in fig. 7.

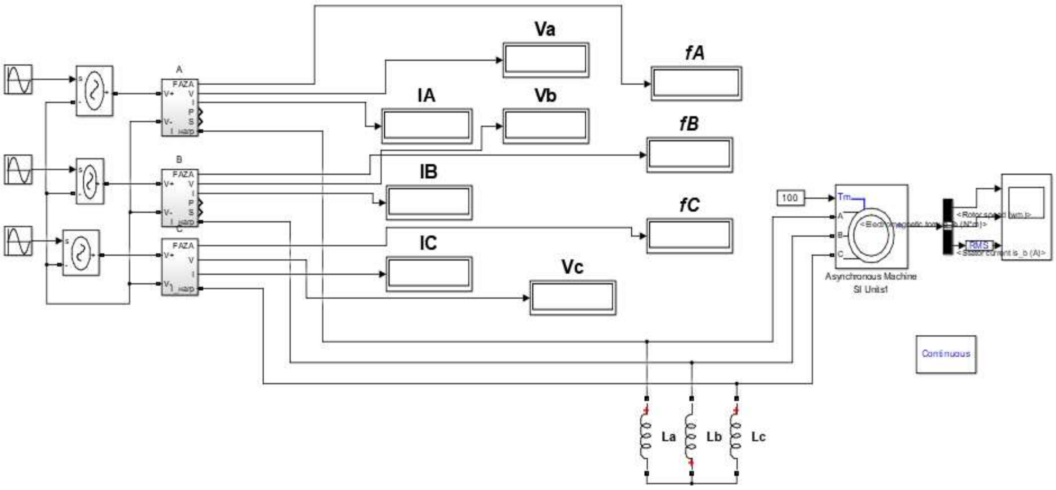

Figure 6. Computer model for determining the parameters with which the loop fault correlates

In Table 2, the results of the study of the critical values of the correlation coefficients are shown, which show that the hypothesis H0 regarding the absence of the influence of the identified factors on the appearance of the coil insulation defect in motors is not confirmed due to the failure to meet the specified condition $|z^*| < t_{0,995}(14)$, since the sample value of the obtained statistical values significantly exceeds the quantile of the distribution of Student's t criterion at the significance level α = 0.01. They also indicate that the fault is strongly related to the phase shift between voltage and current and significantly correlates with the difference of currents in the phases opposite to the one where the fault occurred.

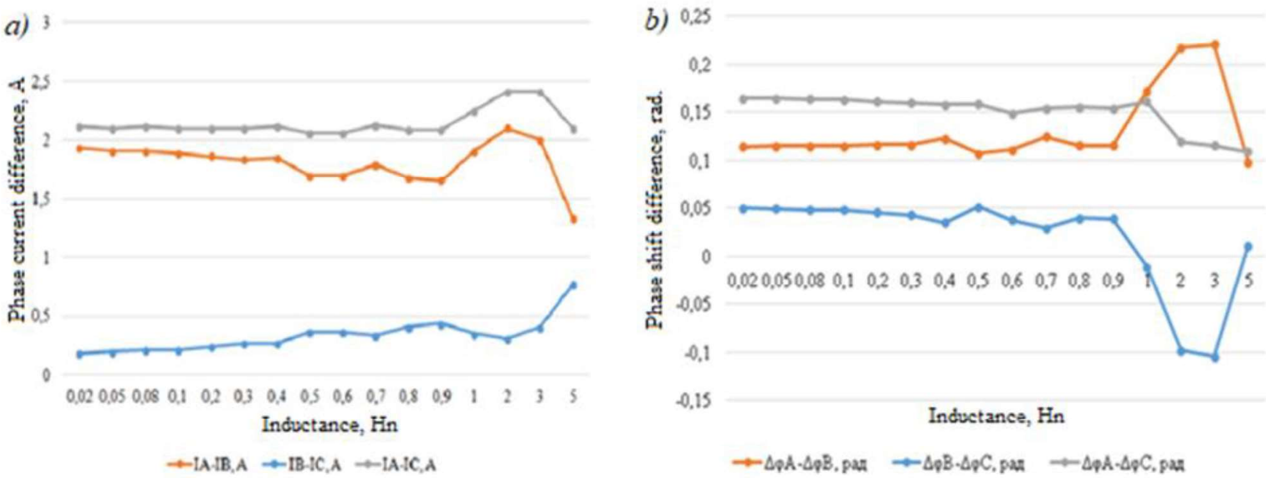

Figure 7. Dynamics of changes: a) difference of phase currents from inductance; b) difference of phase shift from inductance

Table 2.

Results of the study of critical values of correlation coefficients

Parameters		I_A-I_B, A	I_B-I_C, A	I_A-I_C, A	$\Delta\varphi_A$-$\Delta\varphi_B$, rad.	$\Delta\varphi_B$-$\Delta\varphi_C$, rad.	$\Delta\varphi_A$-$\Delta\varphi_C$, rad.
correlation coefficient	*r*	-0,44	0,87	0,42	0,33	-0,59	-0,93
sample value of statistics	z*	-1,833	6,602	1,732	1,308	-2,734	-9,467
is the quantile of the distribution of the Student's t-test (α=0.01)	*t*	2,977	2,977	2,977	2,977	2,977	2,977
acceptance of the hypothesis H_0: r=0	yes/no	yes	no	yes	yes	yes	no

Thus, the obtained high correlation coefficients indicate the existence of a significant relationship between the leakage current through the phase-to-phase insulation and the phase currents, as well as between the phase shift of the current and voltage and the coil insulation of electric motors. These circumstances were taken into account when developing the model of current monitoring of energy-mechanical parameters and diagnostics of technical condition, which are associated with violations of coil and phase insulation.

Modeling of the diagnostic process using Petri nets is carried out using the event level and involves the use of graph theory. In this case, the transitions will reflect the events, and the positions, respectively, show the state that is assumed in the system, and the state that is accepted by the system after performing the appropriate actions. Analysis of the simulation results will allow to determine the technical condition of electric motors at any control algorithms and procedures performed.

The development of a model of the system for diagnosing the technical condition of mine electric motors is carried out using fuzzy Petri nets, which can be represented as a tuple [87]:

$$PN = < P, T, I, Q, M, Z, S >, \tag{7}$$

$P -$ a finite set of events, $P = \{p_0, p_1, p_2, \dots, p_n\}$;

$T -$ a finite set of transitions, $T = \{t_1, t_2, t_3, \dots, t_v\}$;

$I -$ input function $I(t) = p$, which determines the multiplicity of input arcs of transitions;

$Q -$ output function that determines the multiplicity of output arcs of transitions $Q(t) = p$;

$M -$ markings, $M = \{m_1, m_2, m_3, \dots, m_w\}$, $m_i = m(p_i)$, $i = \overline{1 \dots w}$;

$Z -$ parameters of time delay of markers in the network positions, $Z = \{z_1, z_2, z_3, \dots, z_w\}$;

$S -$ parameters of the time delay of markers in the network positions, $S = \{s_1, s_2, s_3, \dots, s_w\}$.

In fig. 8 shows the Petri net of the process of controlling a set of energy-mechanical parameters and diagnosing the technical condition of electric motors of mining machines.

Modeling using Petri nets should meet the following requirements [88]:

$$|I(p_i)| = \left|\left[t_j \middle| p_i \in Q(t_j)\right]\right| = 1, \tag{8}$$

$$|Q(p_i)| = \left|\left[t_j \middle| p_i \in I(t_j)\right]\right| = 1. \tag{9}$$

Moreover, the transition $t_j \in T$ performed under the following condition [89-91]:

$$t_j: m(p_i) \geq \#\big(p_i, I(t_j)\big). \tag{10}$$

Then the new marking will be defined as follows:

$$m'(p_i) = m(p_i) - \#\big(p_i, I(t_j)\big) + \#\big(p_i, Q(t_j)\big), \tag{11}$$

and if condition (10) is not satisfied, then the marking will be as follows:

$$m"(p_i) = m(p_i) - \#\big(p_i, I(t_{j+1})\big) + \#\Big(p_i, Q\big(t_{j-1}\big)\Big), \tag{12}$$

where the following restriction arises:

$$t_{j+1}: m(p_i) \geq \#\big(p_i, I(t_{j+1})\big). \tag{13}$$

According to fig. 8, the formal description of the model of the electric motor diagnostic system is as follows:

- finite set of events $P = \{p_0, p_1, p_2, \dots \dots, p_{46}\}$
- finite set of transitions $T = \{t_1, t_2, t_3, \dots \dots, t_{47}\}$
- set of input functions $I = \{I(t_1), I(t_2), I(t_3), \dots \dots, I(t_{47})\}$
- set of output functions $Q = \{Q(t_1), Q(t_2), Q(t_3), \dots \dots, Q(t_{47})\}$

Let us describe the main components of the above model (fig. 8), which show the algorithm for performing the process of diagnosing the electric motors of mining machines:

- start of diagnostics p_0;

- signal is applied to the motors t_1;

- formation of technical characteristics of electric motors of 7 types $p_1, p_2, p_3, p_4, p_5, p_6, p_7$;

- measurement of six parameters for each electric motor $t_2, t_3, t_4, t_5, t_6, t_7, t_8$;

- evaluation of energy-mechanical parameters, namely load P, kW; voltage U, V; current I, A; insulation resistance R, Ohm; temperature t, ^{0}C; rotor speed n, rev./min.:

$$p_8(P,\ kW)=[P_k],\ p_9(U,\ V)=[U_k],\ p_{10}(I,A)=[I_k],\ p_{11}(R,\ Ohm)=[R_k],\ p_{12}(t,{}^0C)=[t_k],$$
$$p_{13}(n,\ rev./min.)=[n_k],$$

k=1,2,3,4,5,6,7 – respectively, the type of electric motors that are diagnosed.

- the measured parameters are compared $t_9, t_{10}, t_{11}, t_{12}, t_{13}, t_{14}$;

- the formation of possible operating modes of electric motors $p_{14}, p_{15}, p_{16}, p_{17}, p_{18}, p_{19}, p_{20}, p_{21}, p_{22}, p_{23}, p_{25}, p_{25}, p_{26}, p_{27}, p_{28}, p_{29}, p_{30}, p_{31}, p_{32}, p_{33}, p_{34},$ is carried out, and each mode corresponds to the following set of parameters:

$$C_{k_l} = \begin{bmatrix} P_k, kW \\ U_k, V \\ I_k, \mathrm{A} \\ R_k, \mathrm{O}hm \\ t_k, {}^\circ\mathrm{C} \\ n_k, rev./min. \end{bmatrix}, \qquad (14)$$

$l = \overline{1,2,\dots,f} -$ number of the corresponding mode of operation of electric motors.

- the received parameters of the corresponding operating state of the electric motors are transmitted $t_{15}, t_{16}, t_{17}, t_{18}, t_{19}, t_{20}, t_{21}, t_{22}, t_{23}, t_{25}, t_{25}, t_{26}, t_{27}, t_{28}, t_{29}, t_{30}, t_{31}, t_{32}, t_{33}, t_{34}, t_{35}$;

- a decision is made on the technical condition in accordance with the results of the comparison of the measured energy-mechanical parameters: p_{35} – normal exploitation; p_{36} – current repair of the electric motor; p_{37} – overhaul of the electric motor; p_{38} – complete replacement of damaged parts at the electrical plant;

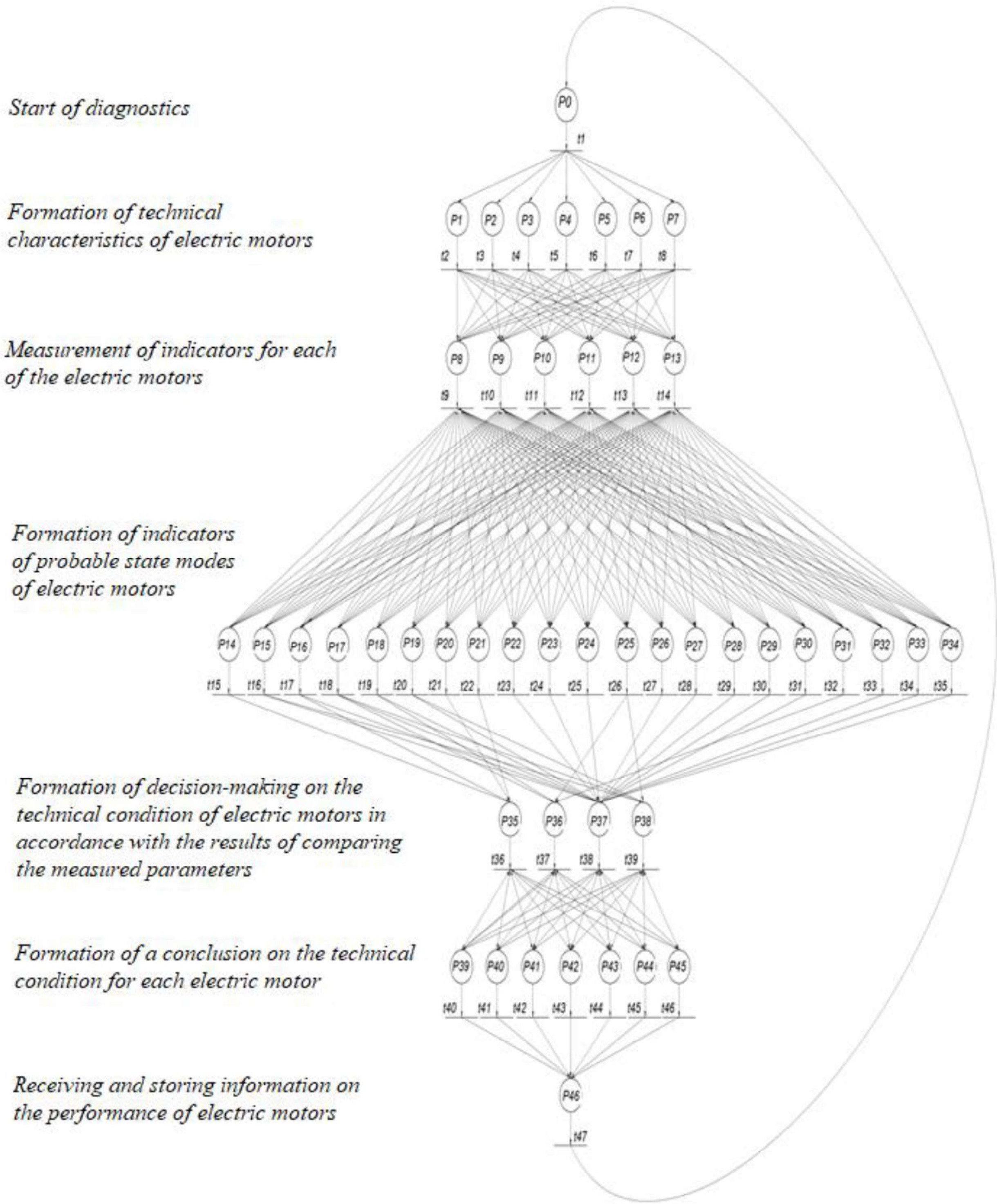

Figure 8. Model of the process of control of a set of energy-mechanical parameters and diagnostics of the technical condition of mine electric motors using Petri nets

- transfer of the obtained diagnosis of the current state for each of the engines t_{36}, t_{37}, t_{38}, t_{39};

- the formation of a conclusion on the technical condition for each of the diagnosed electric motors p_{39}, p_{40}, p_{41}, p_{42}, p_{43}, p_{44}, p_{45} is provided;

- information about the current state is transmitted to the information network t_{40}, t_{41}, t_{42}, t_{43}, t_{44}, t_{45}, t_{46};

- information on the performance of electric motors is received and stored in the system p_{46};

- if necessary, the process of collecting information on monitoring of electric motors is repeated t_{47}.

According to these conditions, we form a dynamic model for the given scheme, which is defined by the system of equations:

$$\begin{cases} m'(p_0)=m(p_0)-1(\#(p_0,I(t_1))=1)-1(\#(p_{46},I(t_{47}))=1)+1(\#(p_0,Q(t_{47}))=1), \\ m'(p_1)=m(p_1)-1(\#(p_1,I(t_1))=1)+1(\#(p_1,Q(t_2))=1), \\ \ldots \\ m'(p_{14})=m(p_{14})-1(\#(p_{14},I(t_9))=1)-1(\#(p_{14},I(t_{10}))=1)-1(\#(p_{14},I(t_{11}))=1)- \\ -1(\#(p_{14},I(t_{12}))=1)-1(\#(p_{14},I(t_{13}))=1)-1(\#(p_{14},I(t_{14}))=1)+1(\#(p_{14},Q(t_{15}))=1), \\ m''(p_{14})=m(p_{14})-1(\#(p_{14},I(t_{15}))=1)+1(\#(p_{14},Q(t_9))=1)+1(\#(p_{14},Q(t_{10}))=1)+ \\ +1(\#(p_{14},Q(t_{11}))=1)+1(\#(p_{14},Q(t_{12}))=1)+1(\#(p_{14},Q(t_{13}))=1)+1(\#(p_{14},Q(t_{14}))=1), \\ \ldots \\ m'(p_{45})=m(p_{45})-1(\#(p_{45},I(t_{36}))=1)-1(\#(p_{45},I(t_{37}))=1)-1(\#(p_{45},I(t_{38}))=1)- \\ -1(\#(p_{45},I(t_{39}))=1)+1(\#(p_{45},Q(t_{46}))=1), \\ m''(p_{45})=m(p_{45})-1(\#(p_{45},I(t_{46}))=1)+1(\#(p_{45},Q(t_{36}))=1)+1(\#(p_{45},Q(t_{37}))=1)+ \\ +1(\#(p_{45},Q(t_{38}))=1)+1(\#(p_{45},Q(t_{39}))=1), \\ m'(p_{46})=m(p_{46})-1(\#(p_{46},I(t_{40}))=1)-1(\#(p_{46},I(t_{41}))=1)- \\ -1(\#(p_{46},I(t_{42}))=1)-1(\#(p_{46},I(t_{43}))=1)-1(\#(p_{46},I(t_{44}))=1)- \\ -1(\#(p_{46},I(t_{45}))=1)-1(\#(p_{46},I(t_{46}))=1)+1(\#(p_{46},Q(t_{47}))=1), \end{cases} \quad (15)$$

The developed mathematical model allows classifying diagnostic objects into four classes, provided that the residual life of electric motors is obtained: normal operation, current repair, overhaul and complete failure.

The study of the given dynamic model of the system for diagnosing the technical condition of mine electric motors using Petri nets is carried out according to the algorithm shown in fig. 9.

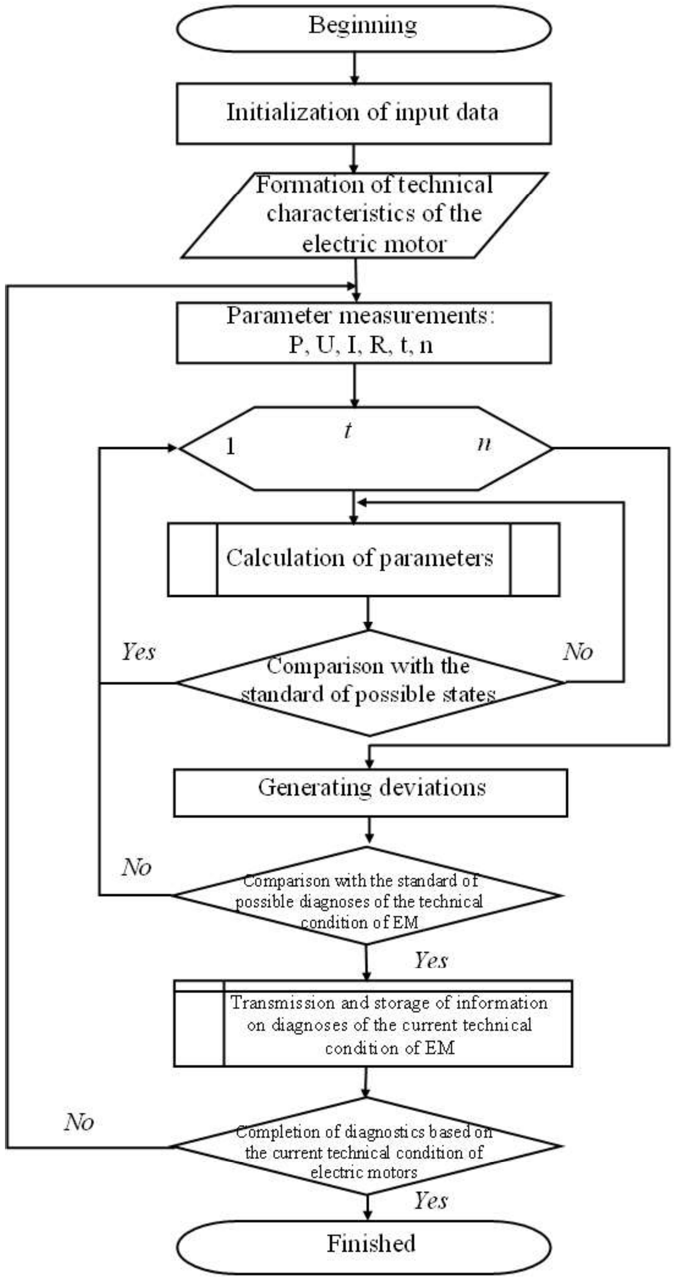

Figure 9. Modeling algorithm in terms of Petri nets in the form of a block diagram

The study was carried out in accordance with the collected sample of 200 observations on electric motors of 7 types of electric motors (EKV4-140 - 35 pcs., EKV4-160-2 - 23 pcs., EDKOFV-51/4 - 38 pcs., EDKOFV-315M4 - 26 pcs., VAO62-4-U5 - 28 pcs., VAO2-280S4 - 31 pcs., 2BP250S4 - 19 pcs.), which, in turn, were classified into four classes: normal operation, current repair, overhaul and complete failure (fig. 10). The results of the study of the obtained model of the system for monitoring energy-mechanical parameters and diagnosing the technical condition of mine electric motors using Petri nets are shown in fig. 11.

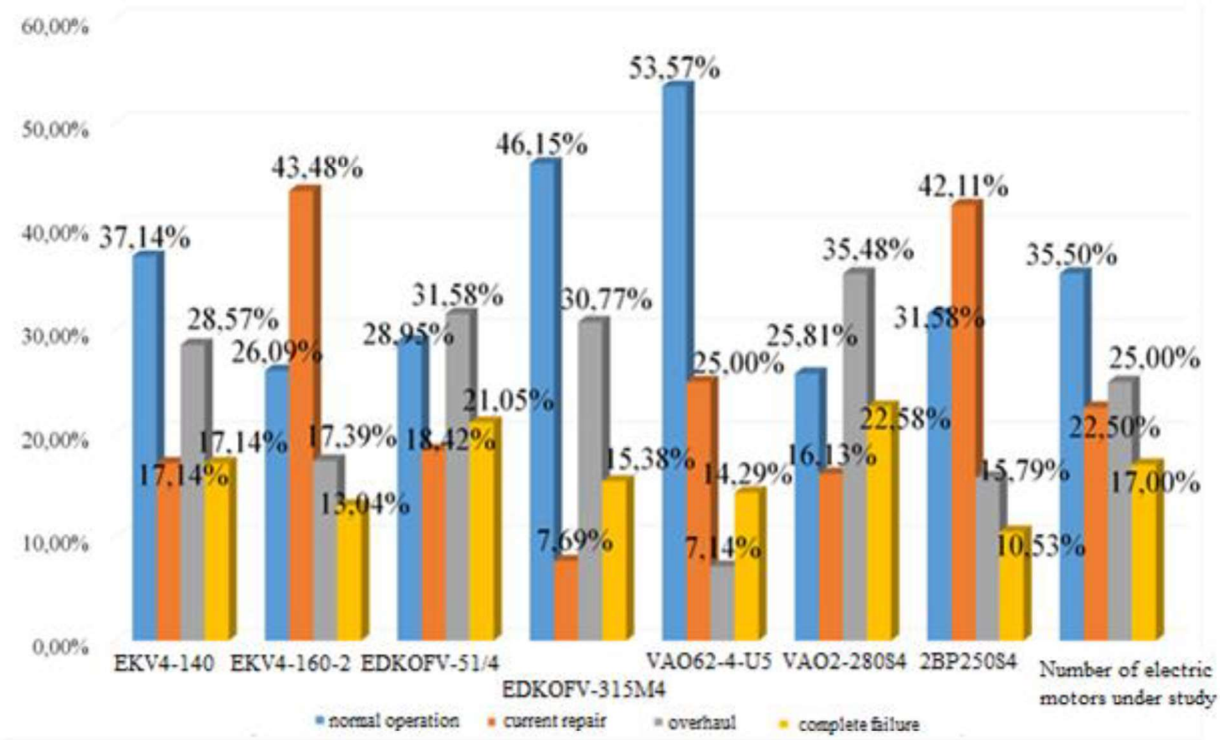

Figure 10. Empirical indicators of the state of the objects under study

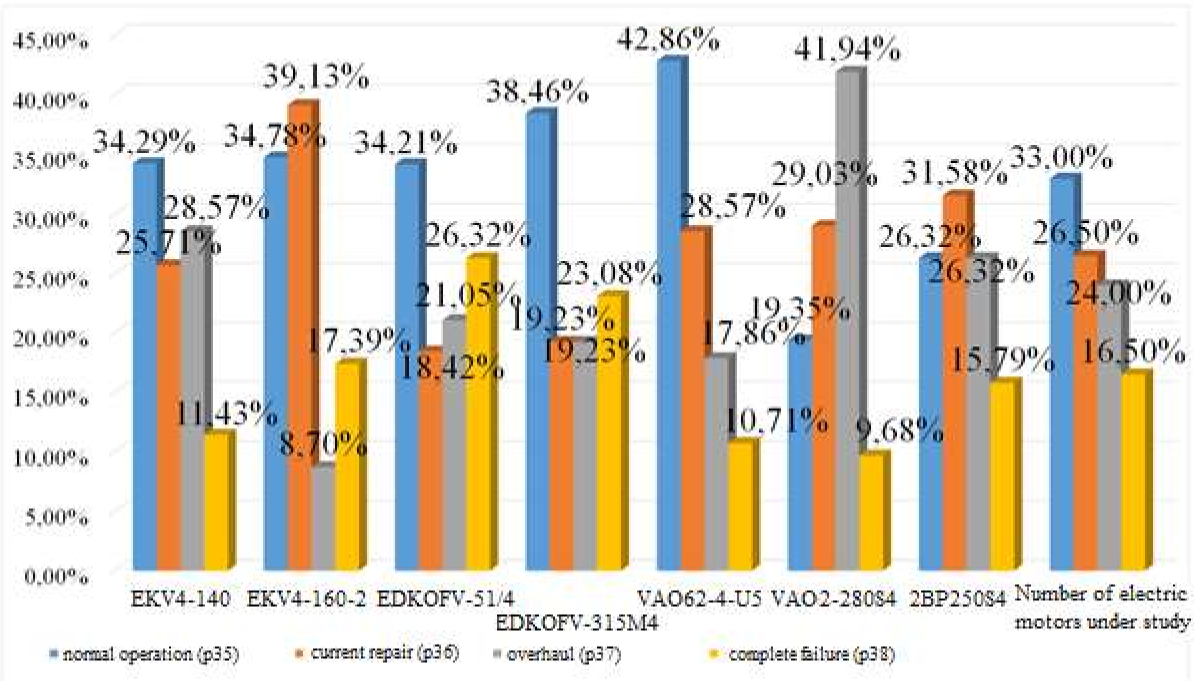

Figure 11. Results of implementation of the model of the diagnostic system for electric motors based on Petri nets

Fig. 12 and Table 3 show the differences in the results of the study of the technical condition of electric motors from the reference values. A comparison of the known empirical data of the EMs to be diagnosed with the obtained results of their diagnostics according to the developed model was performed.

Table 3.

Results of engine diagnostics by the obtained model in comparison with empirical data

Type of electric motors	Deviations from empirical indicators (model based on Petri nets)			
	normal exploitation, %	current repair, %	overhaul, %	complete replacement, %
EKV4-140	-2,86	+8,57	0,00	-5,71
EKV4-160-2	+8,70	-4,35	-8,70	+4,35
EDKOFV-51/4	-5,26	0,00	-10,53	+5,26
EDKOFV-315M4	-7,69	+11,54	-11,54	+7,69
VAO62-4-U5	-10,71	+3,57	+10,71	-3,57
VAO2-280S4	-6,45	+12,90	+6,45	-12,90
2BP250S4	-5,26	-10,53	+10,53	+5,26
Absolute average deviation from empirical values	**6,7**	**7,35**	**8,35**	**6,39**

Thus, according to the data obtained, it can be seen that the maximum deviation of the modeling results using Petri nets from the empirical values is about 11%, and the absolute average deviation is in the range of 6-8.5%. However, in the case of the types EDKOFV-315M4 and VAO2-280S4, the obtained deviation indicators are slightly overestimated and amount to ±11.54% and ±12.9%, respectively.

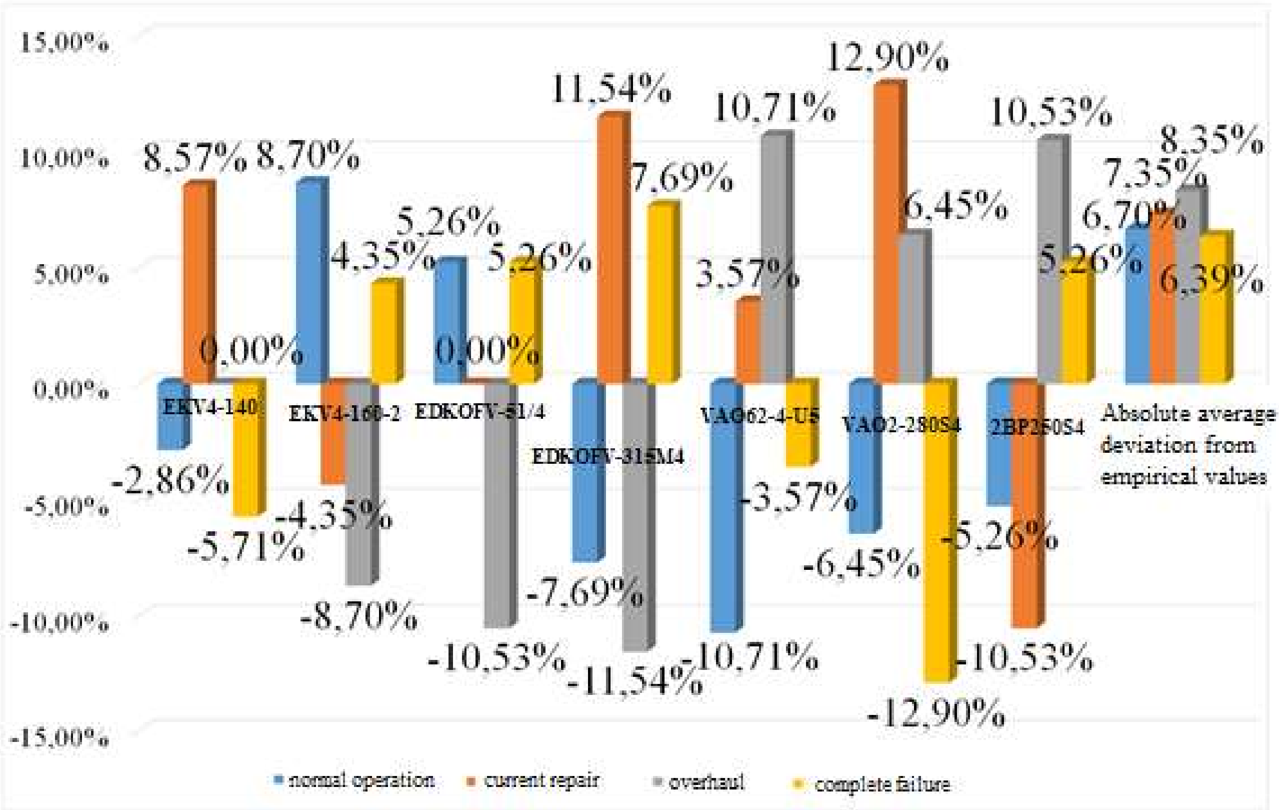

Figure 12. Deviation of simulation results from empirical values (model based on Petri nets)

The developed model of the system of diagnostics of the technical condition of electric motors of mining machines with the use of Petri nets has shown quite high reliability of diagnostics. When comparing the results of all models with each other for each of the seven types of electric motors, it was found that the closer the result to the empirical values, the higher the reliability of determining their technical condition.

The quality of the developed model of the diagnostic system was also determined by testing, which was based on the control of two indicators of the developed algorithm, namely the time of diagnostics due to the control of energy-mechanical parameters (0.024 sec.) and the coincidence of diagnostic results with empirical indicators (92.8 %). In view of this, the advantages of the obtained model with the use of Petri nets can be noted: quite good indicators of coincidence of diagnostic results and insignificant time costs of implementation, which leads to its recommendation for use in diagnosing the technical condition of electric motors of mining machines.

58. "Rainwater Harvesting for Livestock". www.ntotank.com. Retrieved 2018-11-21.

59. Zhu, Qiang; et al. (2015). Rainwater Harvesting for Agriculture and Water Supply. Beijing: Springer. p. 20. ISBN 978-981-287-964-6.

60. Development of methods for estimating the environmental risk of degradation of the surface water state / Rybalova, O. Eastern-European Journal Of Enterprise Technologies. 2018. № 2(10 (92)). P.p. 4-17.

61. Nanbakhsh H., Kazemi-Yazdi S., Scholz M.Design comparison of experimental storm water detention systemstreating concentrated road runoff .Science of the Total Environment. 2001. Vol. 380. P.p. 220–228.

62. Kinkade-Levario, Heather (2007). Design for Water : Rainwater Harvesting, Stormwater Catchment, and Alternate Water Reuse. Gabriola Island, B.C.: New Society Publishers. p. 27. ISBN 978-0-86571-580-6.

63. Brannvall E. Improvement of storm water runoff treatment system with natural mineral sorbent. Geologija. Vilnius. 2007. Vol. 59. P.p. 72–76.

64. Impact assessment of highway drainage on surface water quality / M. Bruen, [etal.]. Wexford, Environmental Protection Agency. 2006. 272 p.

65. Rural Water Supply Network. "Rural Water Supply Network Self-supply site". www.rural-water-supply.net/en/self-supply. Retrieved 2017-03-19.

66. Гелетуха Г.Г., Т.А. Желєзна Т.А. Стан та перспективи розвитку біоенергетики в Україні . Промышленная теплотехника. 2017. Т. 39, № 2, С. 60-64.

67. Бєгун С.В. Розвиток біоенергетики в Україні: застосування досвіду ЄС. Енергетична та техногенна безпека. Серія «Національна безпека». 2020. № 28. С. 1-19.

68. Kaletnik G., Pryshliak N. Bioenergy potential development of the agrarian sector as a component of sustainable development of Ukraine. Management mechanisms and development strategies of economic entities in conditions of institutional transformations of the global environment: collective monograph. Edited by M. Bezpartochnyi, in 2 volumes. 2019. P. 96-104.

69. Kaletnik H., Pryshliak V., Pryshliak N. Public Policy and Biofuels: Energy, Environment and Food Trilemma. Journal of Environmental Management and Tourism. 2019. Volume X, 3 (35). P. 479-487..

70. Лутковська С. М., Зеленчук Н. В. Розвиток біоенергетики в Україні – енергетична та економічна безпека в умовах сталого розвитку. Ефективна економіка. 2021. № 12, С. 46-53.

71. Казак В. М. Надійність та діагностика електрообладнання: навч. посіб. / В. М. Казак, Б. І. Доценко, В. П. Кузьмін. – Київ: НАУ,2013. – 280 с.

72. Куценко Г. Ф. Монтаж, эксплуатация и ремонт электроустановок: практическое пособие / Г. Ф. Куценко. – Мн.: Дизайн ПРО, 2006. – 472 с.