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IMPROVING THE SHIP'S POWER PLANT AUTOMATIC CONTROL SYSTEM BY USING A MODEL-ORIENTED DECISION SUPPORT SYSTEM IN ORDER TO REDUCE ACCIDENT RATE UNDER THE TRANSITIONAL AND DYNAMIC MODES OF OPERATION

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This paper proposes a method to improve the performance of a ship's power plant by reducing accidents within it under transitional operating modes. The method is based on decreasing the number of service personnel errors by using a model-oriented decision support system. In order to implement the proposed method, the structure of the system of automatic control of the ship's power plant has been improved. Such an improvement of the control system implied the integration of a modeling unit and a decision support unit into its structure. The modeling unit makes it possible to predict values of the controlled parameters under a transition mode of operation before they actually appear in the system as a result of the operator's actions. A mathematical model of the automatic control system under transitional operating modes has been built for this unit. In order to implement the decision support unit, a method has been devised to formalize the task of managing the power plant under transitional operating modes. The method essentially involves modeling a transitional operating regime, followed by an evaluation of the results based on regulatory requirements and an empirical criterion for assessing the quality of enabling the diesel generators to work in parallel. In addition, a method has been developed for the decision support unit to reduce the accident rate and improve performance with the help of a mathematical apparatus of fuzzy inference, fuzzy logic, and fuzzy sets. Transitional operating regimes resulting from actual erroneous operator actions during ship flights were investigated. As a result of using the proposed system, the power plant performance increases

Keywords: model-oriented system, method to improve accident rate and performance, accident rate, performance

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1. Introduction

Modern ship's power plants are multidimensional objects of control, whose complexity is constantly increasing. In addition, given additional functions and tasks, the composition and structure of the ship's power plants change. At the same time, a significant increase in the intensity of navigation, associated with the increase in the number of vessels in the world merchant fleet, their tonnage, and speed, significantly increased the accident rate of ships. Analysis of marine accident statistics confirms the prevailing human impact on the safety of navigation. Significant attention to this issue led to the adoption in 2003 by the International Maritime Organization (IMO) of a key document (resolution A.947/23) entitled "Human Element Vision, Principles and Goals".

Despite the actions being taken to improve safety, namely, improving the onshore maintenance and training of crews, equipping the vessels with the advanced integrated energy complexes and installations, the accident rate of vessels continues to increase [1]. The topic of this study corresponds to the priority area of research "Information and Communication Technologies", approved by the Law of Ukraine "On Priority Areas of Science and Technology", as well as the provision of the Maritime Doctrine of Ukraine to 2035.

The most severe cases are those related to failures and malfunctions. It should be taken into consideration that with the increase in the level of automation, the number of service personnel on ships is decreasing; the concept of a virtual mechanic on watch [2] is actively developing and is partially introduced. World leaders, such as Rolls Royce, are developing technologies to control a ship as a remote object with a gradual transition to full autonomy. It is assumed that the vessel would work as a remotely operated object with a gradual transition into full autonomy mode [3]. To this end, the leading developers of control systems plan to provide two sets of control algorithms: 1 – for fully self-functioning; 2 – to work under the control of the dispatcher [4]. This transition is also due to the desire of shipowners to increase the amount of cargo transported by the vessel.

If the ship's power plant and the vessel, in general, are managed onshore by a dispatcher, the task of control is complicated. The increase in complexity is due to the capabilities of the hardware, the constantly changing navigation conditions, the lack of personnel in the immediate vicinity of the controlled object.

Thus, it is a relevant task to reduce the number of emergency modes of power plant operation and improve performance by reducing the impact of errors of service personnel allowing for the prospect of switching to dispatcher's control.

A solution to this task is to design a model-oriented decision support system that would model and evaluate transitional processes to make estimation decisions using the heuristic rules laid down by experts. This system could be integrated with any automatic control system (ACS). This can be confirmed by the modern approaches of ACS equipment manufacturers to reduce the number of accidents in power plants: these include dispatcher's control with the help of a remote group of experts and the development of systems employing artificial intelligence elements [5–7]. Designing a model-oriented decision support system combines both modern approaches to reducing accidents.

Building such a system does not require any change in the hardware of modern ACSs but requires the integration of the new system with their structure. Such a system could also be used to upgrade the skills of the personnel who serve the power plant.

Thus, it is a relevant area of research to improve a power plant ACS by designing a model-oriented decision support system to be integrated with it.

2 Literature review and problem statement

Study [8] shows that models of modern power plants make it possible to calculate the parameters of the technological process with sufficient accuracy to assess the dynamics. However, in modern control systems, as demonstrated in [9], the use of models is allowed only at the design and setting up stage of systems. Approaches to improve accident-free and efficient performance at nuclear power plants [10] also use process parameters forecasting on models. All the models discussed above do not allow the structure to change. In the ship's power plant control systems, due to the small time constants, it is necessary to change the structure of the model in order to derive the precise parameters of the transitional regimes. Paper [11] shows the possibility of using a fuzzy logic apparatus to assess risks. That assessment cannot be performed at the time of the change in the dispatcher's operating mode.

An analysis of the causes of emergencies in [12] reveals that the main cause of accidents is the erroneous actions of service personnel [13]. This is especially true for the adequate actions of operators of complex systems under the transitional and dynamic modes of operation of power plants [14].

The result of analyzing the capabilities of modern control systems has confirmed that there are no elements that would take into account the influence of operator errors in modern systems. None of the existing systems contains elements and algorithms to reduce the influence of the human factor to decrease the number of accidents and improve performance.

Studies [15, 16] suggest a method of forecasting and managing a ship's power plant using a model of this plant with a permanent model structure. However, when the power plant's operational mode changes, the structure of the system changes as well, which affects the system model and modeling results.

Papers [17, 18] show that emergencies occur mainly when operating modes change, which often occur when the power plant's operational mode is changed. The emergence of new operating regimes is due to changes in the number of consumers or energy sources, which entails a change in the structure of the power plant.

In order to reduce the impact of the human factor on accidents, works [19, 20] propose methods for assessing the influence of the human factor using artificial intelligence algorithms, including the use of fuzzy inference algorithms.

The systematization of the results of the above studies allows us to believe that existing approaches to resolving the issue related to accidents caused by the influence of the human factor are based on prediction using a model of power plants and employing artificial intelligence algorithms. Such approaches are likely to find acceptable solutions only if the structure of the applied model of a power plant does not change. It follows that the considered approaches to reduce accidents would not make it possible to significantly decrease the accident rate. Most emergency modes occur under the transitional and dynamic modes of power plant operation that change the structure and composition of the model to be simulated.

As shown above, the impact on the accident rate and errors of the operating personnel are not taken into account in modern control systems.

This part of the problem can be resolved by using models with a variable structure that account for the features of transient and dynamic modes in power plants.

3. The aim and objectives of the study

The aim of this study is to improve the power plant automatic control system by devising models and methods for a model-oriented decision support system to reduce the number of accidents due to faulty operator actions.

To accomplish the aim, the following tasks have been set:

– to build a mathematical model of the power plant ACS under the transitional and dynamic modes of operation;

– to develop a new ACS structure and formalize a task of control under the transitional and dynamic modes;

– to devise decision-making methods to assess the impact of possible disturbances on accident rate and performance.

4. The study materials and methods

We studied transitional and dynamic modes employing a mathematical apparatus of differential equations.

The numerical integration Runge-Kutta method of the 4th order was used to solve the system of equations. This method makes it possible to obtain the results of the solution with the accuracy necessary for analysis.

All the methods and models constructed were implemented in the SGE software. The software was developed in the C++ algorithmic programming language.

To implement the methods based on a fuzzy inference algorithm, the algorithms for implementing fuzzy inference and fuzzy-sets operations were included in the software.

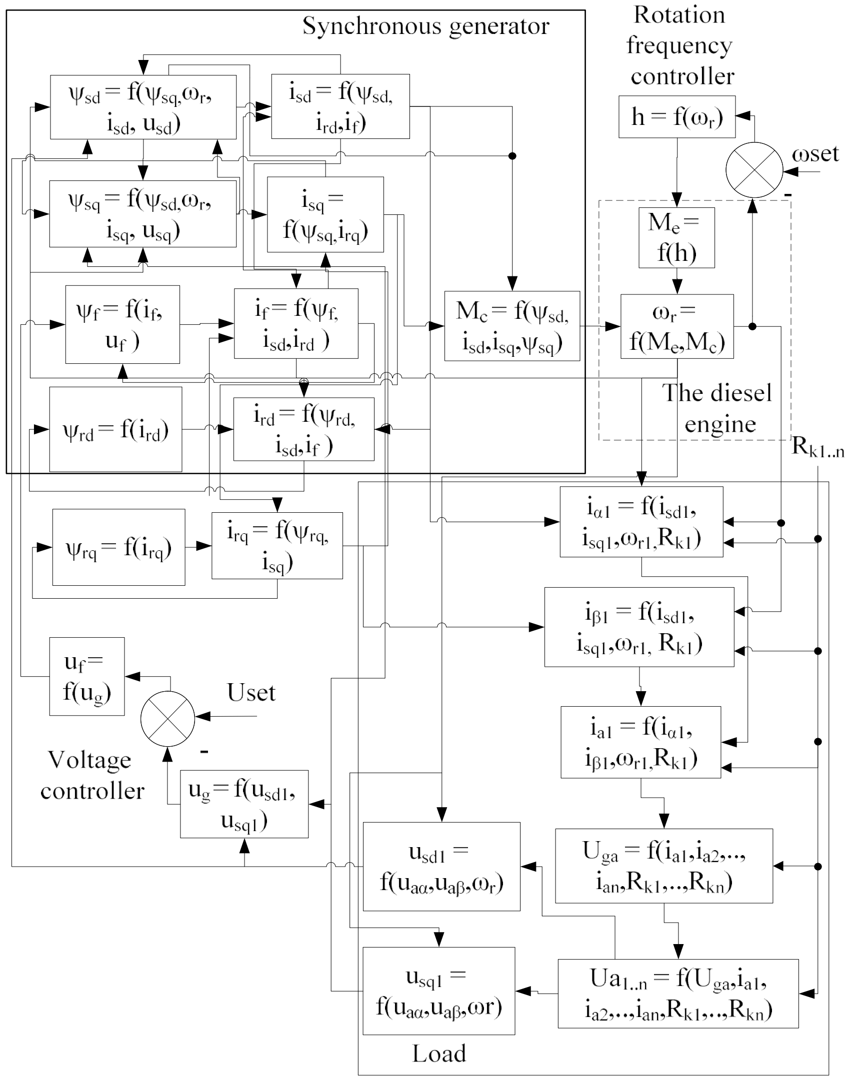

Fig. 1. Functional scheme of an automatic control system

5. Results of studying the new structure of an automatic control system, the model and methods to improve the accident rate

5. 1. A mathematical model of the power plant automatic control system under the transitional and dynamic modes of operation

To construct a mathematical model, a functional scheme of the automatic control system was built: Fig. 1.

The power plant ACS mathematical model includes equations for the following assemblies: a synchronous generator; the diesel drive; a drive engine shaft rotation frequency controller; a generator voltage regulator. In addition, to study the transitional and dynamic modes, the model contains equations of the active and reactive components of a load of generators; switching and load-sharing devices.

The model of a synchronous generator can be recorded in the following Cauchy form:

$$\frac{d\psi_{sd}}{d\tau} = \psi_{sq}\omega_r - r_s i_{sd} - u_{sd};$$

$$\frac{d\psi_{sq}}{d\tau} = \psi_{sd}\omega_r - r_s i_{sq} - u_{sq};$$

$$\frac{d\psi_{rd}}{d\tau} = -r_r i_{rd}; \frac{d\psi_{rq}}{d\tau} = -r_r i_{rq}; \quad \frac{d\psi_f}{d\tau} = u_f - r_f i_f, \quad (1)$$

where ψ_{sd}, ψ_{sq}, ψ_{rd}, ψ_{rq} are the projections of flux linkages on the *d, q* axes d, q, rel. units; u_{sd}, u_{sq} are the projections of voltages, rel. units; r_s, r_r, r_f are the resistances of the stator, rotor, and an excitation winding, rel. units; i_{sd}, i_{sq}, i_{rd}, i_{rq} are the projections of current, rel. units; ψ_f, i_f, u_f are the flux linkage, current, and the voltage of an excitation winding, rel. units; τ – time, s.

$$\psi_{sd} = (L_d + L_{sd}) i_{sd} + L_d i_{rd} + L_d i_f;$$

$$\psi_{rd} = (L_d + L_{rd}) i_{rd} + L_d i_{sd} + L_d i_f;$$

$$\psi_f = L_d i_{sd} + L_d i_{rd} + L_f i_f; \quad (2)$$

$$\psi_{sq} = \left(L_q + L_{sq}\right) i_{sq} + L_q i_{rq};$$

$$\psi_{rq} = \left(L_q + L_{rq}\right) i_{rq} + L_q i_{sq},$$

where: L_{sd}, L_{sq}, L_{rd}, L_{rq}, L_d, L_q are the inductivities of scattering and contour of magnetization of the stator and rotor windings, rel. units; L_f is the inductivity of an excitation winding, rel. units.

The equations of inductivity and synchronous generator currents can be recorded as follows:

$$l_{rd} = \frac{L_d}{L_d + L_{rd}};\quad l_{rq} = \frac{L_q}{L_q + L_{rq}};\quad l_{sd} = \frac{L_d + L_{sd}}{L_d};$$

$$l_{sq} = \frac{L_q + L_{sq}}{L_q};\quad l_f = \frac{L_d}{L_f};\quad k_c = \frac{L_q}{L_d};$$

$$i_{sd} = \frac{1}{\Delta_d}\left[\psi_{sd}\left(1 - l_f l_{rd}\right) + \psi_{rd} l_{rd}\left(l_f - 1\right) + \psi_f l_f \left(l_{rd} - 1\right)\right];$$

$$i_{rd} = \frac{l_{rd}}{\Delta_d}\left[\psi_{sd}\left(l_f - 1\right) + \psi_{rd}\left(l_{sd} - l_f\right) + \psi_f l_f \left(1 - l_{sd}\right)\right];$$

$$i_f = \frac{l_f}{\Delta_d}\left[\psi_{sd}\left(l_{rd} - 1\right) + \psi_{rd}\left(1 - l_{sd}\right) + \psi_f\left(l_{sd} - l_{rd}\right)\right];$$

$$i_{sq} = \frac{1}{\Delta_q}\left(\psi_{sq} - \psi_{rq} l_{rq}\right);\quad i_{rq} = \frac{l_{rq}}{\Delta_q}\left(-\psi_{sq} + \psi_{rq} l_{sq}\right);$$

$$\Delta_d = L_d\left[l_{sd}\left(1 - l_{rd} l_f\right) + 2 l_{rd} l_f - l_{rd} - l_f\right];$$

$$\Delta_q = k_c L_d\left[l_{sq} - l_{rq}\right). \qquad (3)$$

By selecting the values of relative inductivity and the inertia factor k_c, one can set the type of a generator rotor. For example, for the synchronous, apparently polar generator without a damper winding:

$$l_{rd} = l_{rq} = 0,\quad r_r = \infty,\quad k_c \neq 1.$$

The generator's electrical load:

$$\frac{du_\alpha}{d\tau} = \frac{1}{C}\left(i_\alpha - i_{L\alpha} - g u_\alpha\right);\quad \frac{du_\beta}{d\tau} = \frac{1}{C}\left(i_\beta - i_{L\beta} - g u_\beta\right);$$

$$\frac{di_{L\alpha}}{d\tau} = \frac{u_\alpha}{L};\quad \frac{di_{L\beta}}{d\tau} = \frac{u_\beta}{L}, \qquad (4)$$

where g, L, C is the conductivity, inductivity, and load capacity, rel. units.

The excitation system and the proportional voltage regulator of the synchronous generator can be described by the first-order differential equation:

$$\frac{dU_f}{dt} = \left[-U_f + K_f\left(U_{set} - U_{gen}\right)\right] / T_f, \qquad (5)$$

where K_f is the transfer factor of the proportional voltage regulator; $U_{gen} = \sqrt{u_{sd}^2 + u_{sq}^2}$ is the voltage vector module; U_{set} is the predefined voltage value.

Without taking into consideration the thermal processes in the cylinders of the diesel drive, its equations can be described by the differential equation of the first order [21]:

$$J\frac{d\omega_r}{d\tau} = M_d - M_c;$$

$$M_c = \mathrm{Re}\left(\bar{\Psi}_s\right)\cdot \mathrm{Im}\left(\bar{I}_s\right) - \mathrm{Im}\left(\bar{\Psi}_s\right)\cdot \mathrm{Re}\left(\bar{I}_s\right), \qquad (6)$$

where ω_r is the frequency of rotation of the rotor of the generator, rel. units; J is the moment of inertia of the engine shaft, the rotor of the generator, and the attached masses, rel. units; $M_d = f(\omega_r, p_1, ..., p_n, \tau)$ is the mechanical moment of the drive engine, rel. units; p_i is the engine parameters, rel. units; M_c is the electromagnetic moment of the generator, rel. units.

For a rotation frequency controller of the indirect action, the equations in the Cauchy form are as follows:

$$\frac{dh}{d\tau} = \frac{1}{T_c}(\eta - h);$$

$$\frac{dl}{d\tau} = -\frac{T_l}{T_r^2} l - \frac{\delta}{T_r^2}\eta - \frac{\delta_i}{T_r^2}(h - \xi) - \frac{1}{T_r^2}\Delta\omega;$$

$$\frac{d\eta}{d\tau} = l;\quad \frac{d\xi}{d\tau} = \frac{1}{T_i}(h - \xi), \qquad (7)$$

where h is the fuel pump rack index; η is the position of a measuring body; ξ is the cataract movement; T_r is the time constant of a meter; T_l is the time constant of viscous friction; T_i is the time constant of a cataract; δ is the statism of the regulator; δ_i is the cataract statism; $\Delta\omega$ is the deviation of rotational frequency; T_c is the time constant of the servomotor; l, η are the coordinates of a measuring body.

Transitional and dynamic modes occur mainly when consumers or power sources are connected or disconnected from the ship's network. To take into consideration these features, it is necessary to build a structural scheme (Fig. 2, *a*) and an estimation scheme (Fig. 2, *b*) of a ship's power plant.

Using an estimation scheme, algebraic and differential equations can be derived to study transitional and dynamic modes.

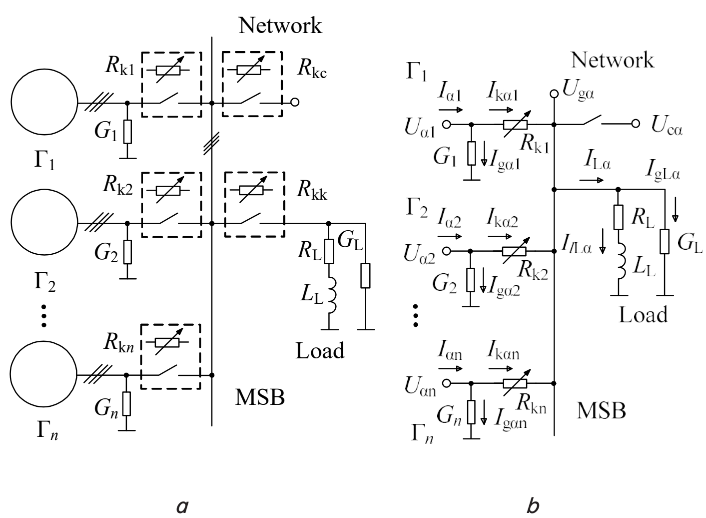

Fig. 2. Ship's power plant schemes: *a* – structural; *b* – estimation

The equations of the stator chains of generators, network, and load are recorded according to Fig. 2 in the stationary coordinate system α, β relative to the following voltages:

$$U_{g\alpha}=\begin{pmatrix} I_{\alpha1}+I_{\alpha2}+...+I_{\alpha i}-U_{\alpha1}G_1- \\ -U_{\alpha2}G_2-......-U_{\alpha n}G_n-I_{lL\alpha} \end{pmatrix}/G_L;$$

$$U_{\alpha1}=\frac{I_{\alpha1}R_{k1}+U_{g1}}{1+R_{k1}G_1};\quad U_{\alpha2}=\frac{I_{\alpha2}R_{k2}+U_{g2}}{1+R_{k2}G_2};$$

$$U_{\alpha n}=\frac{I_{\alpha n}R_{kn}+U_{gn}}{1+R_{kn}G_n}; \qquad (8)$$

$$\frac{dI_{lL\alpha}}{dt}=\left(U_{g\alpha}-I_{lL\alpha}R_L\right)/L_L,$$

where G_i is the conductivity of measuring circuits and generator insulation leaks; G_L, R_L, L_L are the load parameters; R_{ki} is the resistance of keys.

Equations (1) to (7), which describe the processes of enabling generators to work in parallel, are solved in conjunction with the equations of load connection devices (8), which makes it possible to connect generators to each other and to the network.

The resulting equations make it possible to obtain a model of the variable structure due to the ability to simulate the transition and dynamic modes of connection to a non-limited number of generator units.

5. 2. Formalizing the task of control under the transitional and dynamic modes for an improved ACS structure

Since modern ACSs do not make it possible to predict possible emergency modes and to investigate the quality of transitional and dynamic modes before they occur, it is necessary to improve the ACS structure (Fig. 3). Fig. 3 shows that the improvement is to integrate a model-oriented decision support system with the ACS.

An improved ACS requires a method to formalize tasks of control, which consists of the following steps.

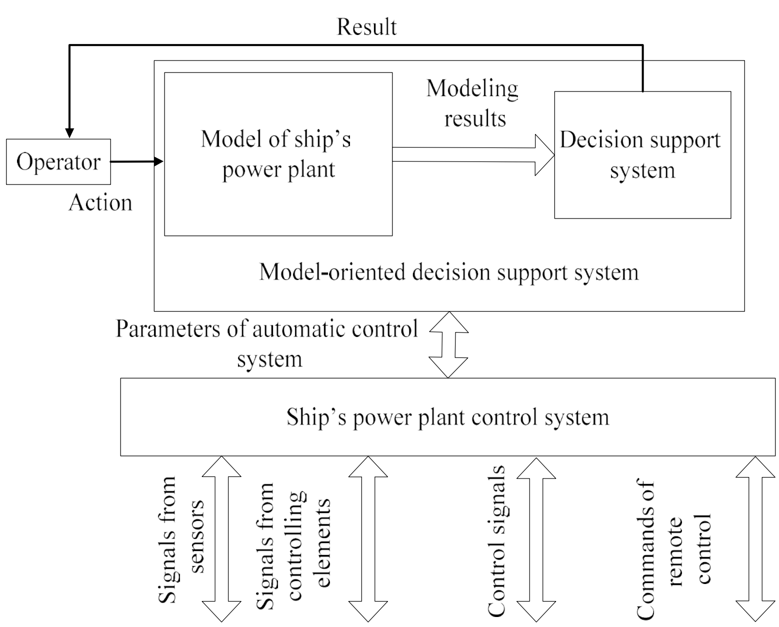

Fig. 3. Functional scheme of the advanced power plant automatic control system

Step 1. Model the transitional and dynamic modes in ACS at the time of the change in the mode of operation of the power plant.

Step 2. Determine the quality indicators for voltage adjustment, the frequency of rotation; calculate the criterion to assess enabling to work in parallel.

$$\delta U^{+}_{dyn}=\frac{\Delta U_{dyn,\max}-\Delta U_r}{U_r}\cdot 100,$$

$$\delta U^{-}_{dyn}=\frac{\Delta U_{dyn,\min}-\Delta U_r}{U_r}\cdot 100,$$

where δU^{+}_{dyn} is the transitional deviation of the voltage during unloading; δU^{-}_{dyn} is the transitional deviation of the voltage during the load reset, U_r is the established value of voltage, ΔU is the value of the insensitivity zone.

Step 3. If the current or voltage values are consistent with the settings of the protection system, the result of the assessment is the triggering of the protection system.

Step 4. If the current or voltage values coincide with the alarm system's settings, the result of the assessment is the triggering of an emergency warning alarm.

Step 5. Assess the criterion value to evaluate enabling to work in parallel.

$$I=\sum_{i=1}^{n}\left|\Delta y_i\right|, \qquad (9)$$

where Δy_i is the rotational frequency deviation module at the i-th step after being enabled to work in parallel, I is the integral of the rotational frequency deviation module.

Step 6. Assess the values of active and reactive capacity.

Step 7. The result of the operator's assessment of the possible consequences of the regime change is being transferred.

$$P_{quality}=f\left(i,u,w,S,Q\right);$$

$$P_{alarm}=f\left(i_{alarm},u_{alarm},w_{alarm}\right);$$

$$P_{prot}=f\left(i_{protection},u_{protection},w_{protection}\right),$$

where $P_{quality}$ is the comprehensive measure of the quality of the new power plant operating mode, *i, u, w, S, Q* are the values for current, voltage, rotational frequency, the criterion for assessing the quality of being enabled to work in parallel, and the reactive power of the new mode.

5. 3. Decision-making methods to assess the impact of possible disturbances on accident rate and performance

The method for improving performance and reducing accident rate by using a fuzzy logic apparatus involves the following:

Step 1. Model the transitional and dynamic modes in the power plant ACS at the time of change in the mode of operation.

Step 2. Calculate the criterion to assess enabling to work in parallel and the time of the transition process from formula (9).

Step 3. Fuzzify and form a tuple of the input linguistic variables: "Current", "Voltage", "Area", "Control Time."

Step 4. Run a fuzzy inference algorithm.

Step 5. Derive a value for the output linguistic variable “Result.”

Step 6. De-fuzzify the output variable “Result”.

Step 7. Infer and send a message to the operator about the possible results of the regime change.

To assess the impact of perturbations on accident rate and performance, the power plant ACS’s functional scheme has been improved taking into consideration the proposed methods and model (Fig. 4).

Decision-making response surfaces were built on the basis of methods proposed earlier using a fuzzy inference algorithm [22] for a model-oriented decision support system (Fig. 5, 6).

Part of the surface marked in Fig. 5 by 1, which corresponds to the voltage of 85–100 % of the rated voltage and a transition time from 0 to 1.5 s, corresponds to the non-emergency mode of generators. Part of the surface, marked by 2, to the emergency mode for voltage (the voltage protection would work); by 3, to the emergency mode for two parameters at once.

Part of the surface marked in Fig. 6 by 1, which corresponds to the voltage of 85–100 % of the rated voltage and a current of up to 80 % of the rated current, corresponds to the failure-free mode of power plant operation. Part of the surface, marked by 3, to the emergency mode for voltage and current (the protection for voltage and current is enabled); by 2, to the emergency mode for both parameters at once.

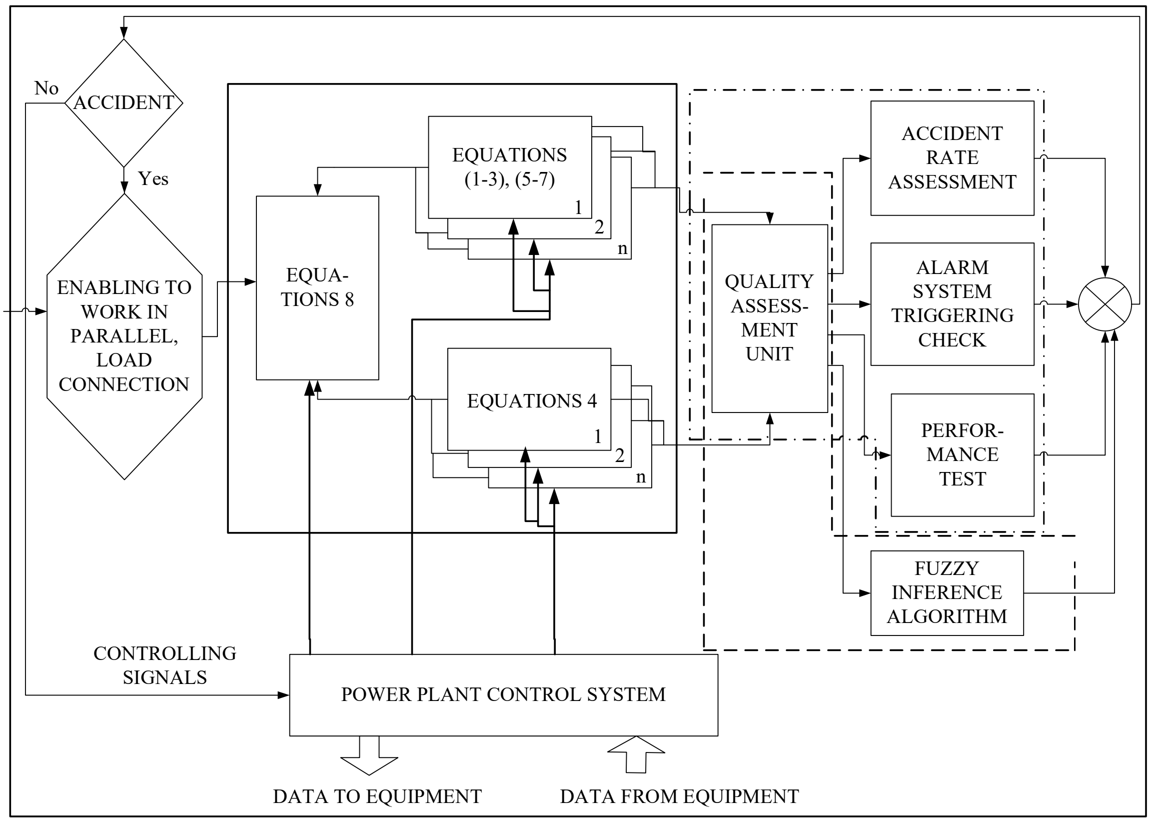

Fig. 4. Functional scheme of the improved power plant automatic control system taking into consideration the developed models and methods

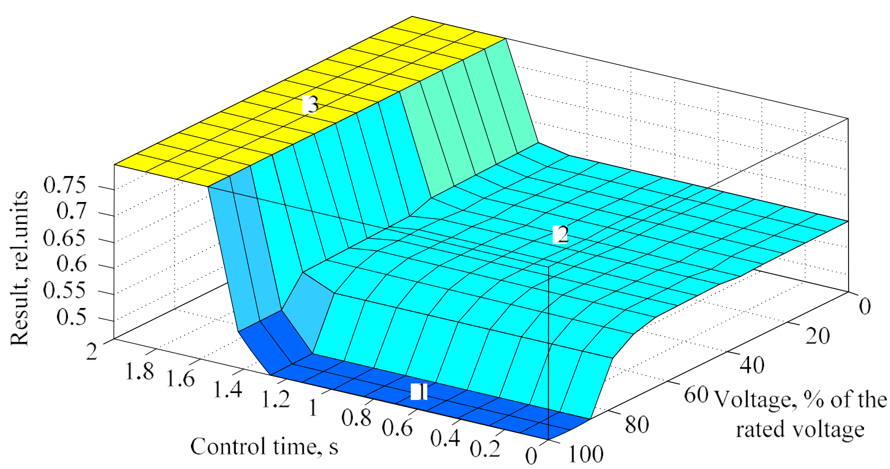

Fig. 5. The response surface of decision-making for the transition process time and the voltage of the generator

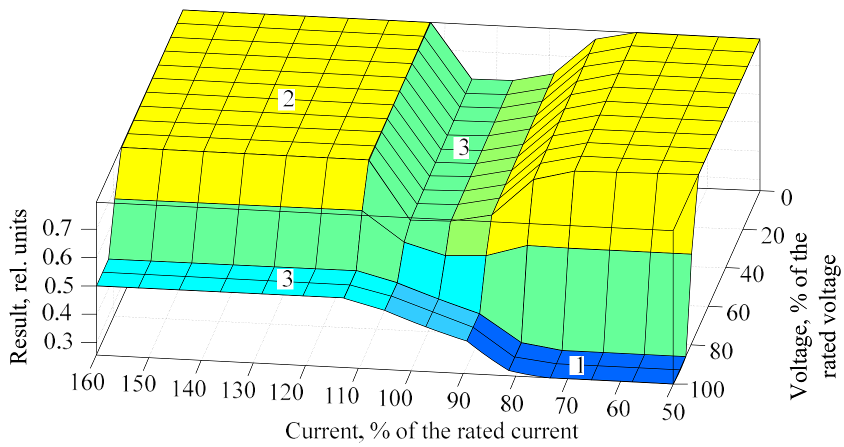

Fig. 6. The response surface of decision-making for the power and voltage of the generator

The diesel generator was disturbed by a current change of 23 % of the rated current in the range from 0.42. to 0.65 rel. units. Experiments were conducted to determine the dynamic characteristics of the diesel generator for voltage (Fig. 3, curve 1) and current (Fig. 7, curve 4). The experiments were carried out at an operating vessel.

Similar experiments were carried out on the generator model (Fig. 3, curve 2 – generator voltage, curve 3 – generator current). The extent of divergence between the curves obtained from simulation and those found experimentally was estimated by calculating the relative error of the simulation. The highest of the maximum relative modeling errors is 0.92 %.

The method of decision-making to assess the impact of possible disturbances on accident rate and performance, taking into consideration the developed system, involves the following steps.

Step 1. Determine the current and voltage deviation.

Step 2. Calculate the transition process time based on the formula: $t_{tp}=t_{dz}-t_{sl}$, where t_{dz} is the time point at which the adjustable parameter value is within the insensitivity zone and no longer comes out of it, s; t_{sl} is the moment of disturbance, s.

Step 3. Determine a region of the surface hosting the values from Steps 1 and 2.

Step 4. Depending on the surface region, conclude on the accident rate and regime performance.

Analyzing the surfaces of all possible modes in Fig. 5, 6, one can draw the following conclusions: surfaces that correspond to failure-free modes occupy 20 % of the entire surface, and the remaining 80 % are not allowed when using this method.

Experiments involving the HFC7 636-84K diesel generator with a capacity of 2,000 kVA, made in the Republic of Korea (Fig. 7), were used to assess the modeling error.

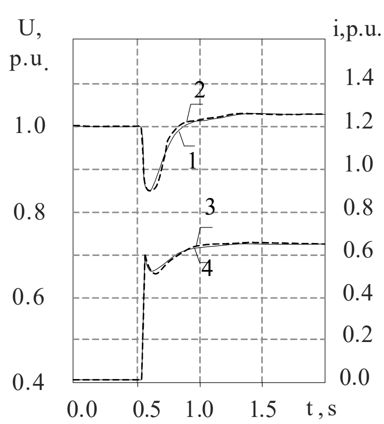

Fig. 7. Experimental (curves 1, 3) and model (curves 2, 4) tests of the diesel generator for voltage and current: 1 – voltage change as a result of the experiment involving the generator; 2 – voltage change as a result of the experiment involving the model; 3 – change of current as a result of the experiment involving the generator; 4 – change of current as a result of the experiment involving the model

To assess the performance of the improved power plant ACS, we shall simulate the connection of the load with a capacity of 30 % of the power of the generator.

The charts of the dynamic processes for the generator current phase (Fig. 8, *a*), the excitation voltage (Fig. 8, *b*), the frequency of rotation (Fig. 8, *c*), and the voltage of the generator phase (Fig. 8, *d*) are shown in Fig. 8. The load is connected to the generator under a star-star scheme with an isolated zero wire. The load is symmetrical. The output linguistic variable values after de-fuzzification equal 0, which indicates an accident-free mode of operation [23].

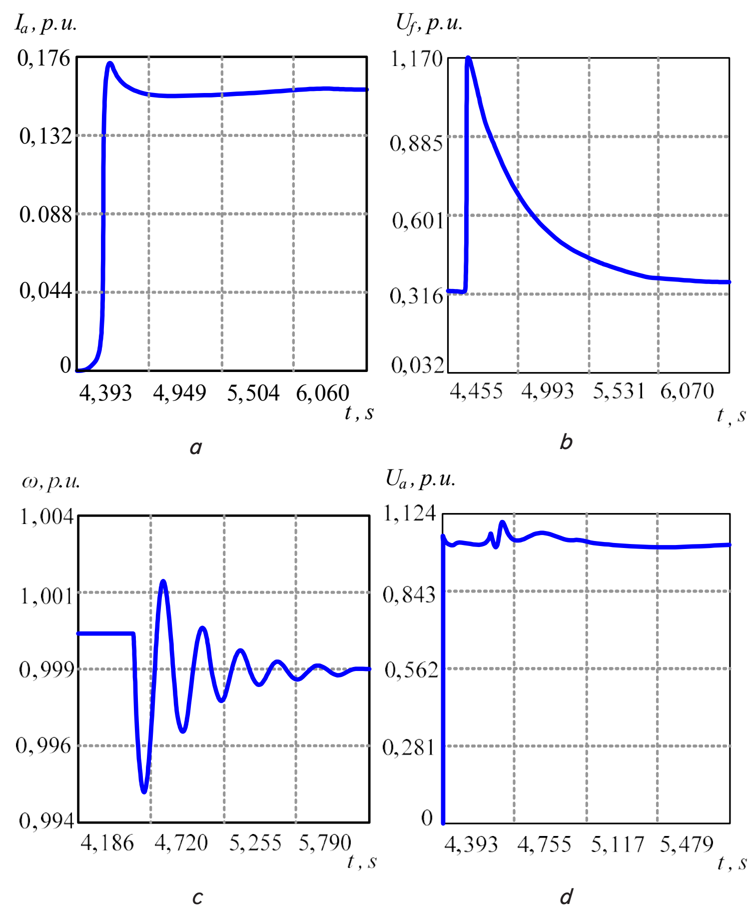

Fig. 8. Connecting a load at a power of 30 % of the generator's power

At the time of enabling the diesel generators to work in parallel with increased insensitivity of one of the controllers of the frequency of rotation, as can be seen from Fig. 9, the values of phase current (*a*) and voltage (*b*) are drastically altered. However, deviation values do not correspond to the values of the protection settings. The transitional process time was not determined for the frequency of rotation, Fig. 9, the values of the transition process evaluation results are unsatisfactory. The output linguistic variable values after de-fuzzification equal 0.85, which characterizes the emergency mode [24, 25].

In the event of this malfunction during the parallel operation of the diesel generator assemblies, de-energization and severe consequences for the diesel engines are possible.

To assess the performance of the developed improved ACS, its performance was calculated as follows:

$$P=\left(1-\frac{P_{LOOSES}}{P_{FULL}}\right)\cdot 100\,\%,$$

where P_{LOOSES} is the amount of electricity spent to restore power after de-energization, kW; P_{FULL} is the total amount of electricity spent, kW.

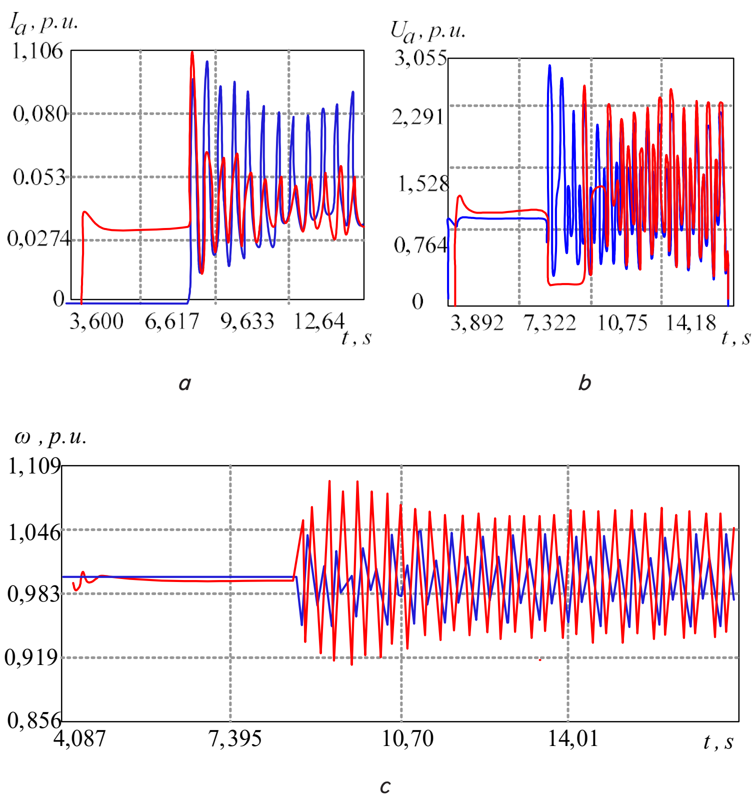

Fig. 9. Enabling the diesel generators to work in parallel with increased insensitivity of the rotational frequency regulator

The dependences of performance on the time the ship moves when it is de-energized are shown in Fig. 10. With a model-oriented decision support system, the number of de-energized cases is reduced while the performance increases depending on the number of de-energizations that have been prevented.

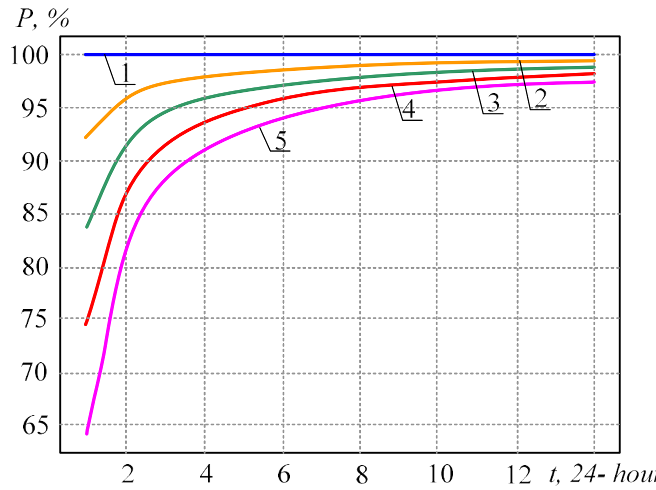

Fig. 10. Dependence of performance on the time the ship moves when it is de-energized

Curve 1 (Fig. 10) corresponds to constant performance when there is no de-energization. In curve 2, the number of de-energization events is reduced to one case using a model-oriented decision support system. Curves 3–5 (Fig. 3) show a change in performance at two, three, and four de-energizations over 24 hours.

6. Discussion of results of the development of a new structure of automatic control system, the model and methods to improve the failure-free operation

Our results of numerical modeling show (Fig. 7, 8) that the built model with a variable structure makes it possible to study the transitional and dynamic modes in a power plant. Using a variable model structure improves accuracy in modeling transitional and dynamic modes. Changing the structure is made possible by using equations (8).

The devised method to formalize a control task makes it possible to determine the quality of transitional and dynamic modes in a power plant with the possibility to determine the triggering of the protection system and emergency warning alarm. This approach allows the prediction of possible emergencies by modeling transitional and dynamic modes.

The constructed method of improving failure-free operation involving a mathematical apparatus of fuzzy logic makes it possible to identify possible emergencies using the product knowledge base updated by experts. This approach allows an experienced expert to model the decision-making process on possible emergencies.

Both proposed approaches, as seen from Fig. 10, make it possible to reduce the number of emergencies.

The improved ASU structure, which includes our developed model and methods, could be integrated with any control system based on programmable controllers.

Restrictions on the application of the new ACS structure are related to the possibility of the hardware implementation of an object-oriented decision support system. When a ship is retrofitted or equipment is replaced, a model must be changed to use the improved ACS. In addition, when applying an improved ACS, the operator may accept the conclusion of a possible accident or disagree as it is s/he who makes the decision and is responsible for the results of his/her activities.

7. Conclusions

1. The proposed model of the power plant ACS makes it possible to change its structure in the process of modeling, which enables the calculation of power plant parameters under the transitional and dynamic modes. Features of the model include the possibility to investigate transition processes when connecting an unlimited number of generator units.

2. The improved structure of the power plant ACS makes it possible to prevent the consequences of erroneous actions of the operator owing to the model-oriented decision support system integrated with it. We have also shown that such a structure makes it possible to take into consideration the possibility of unacceptable operating regimes related to equipment malfunctions. The developed method to formalize a control task and the method to improve accident-free operation allow determining the possibility of triggering protection systems and emergency alarms before they are actually triggered in the power plant.

3. The decision-making method to assess the impact of possible disturbances on accident rate and performance using a fuzzy inference algorithm makes it possible to simulate the decision-making process about the possibility of an emergency mode or unacceptable regime by an experienced expert. This becomes possible by using heuristic rules created by experts. The knowledge base employed in the fuzzy inference algorithm could be updated to reflect changes in operating requirements and equipment condition.

References

1. Burmeister, H.-C., Bruhn, W., Rødseth, Ø. J., Porathe, T. (2014). Autonomous Unmanned Merchant Vessel and its Contribution towards the e-Navigation Implementation: The MUNIN Perspective. International Journal of e-Navigation and Maritime Economy, 1, 1–13. doi: https://doi.org/10.1016/j.enavi.2014.12.002
2. Zubowicz, T., Armiński, K., Witkowska, A., Śmierzchalski, R. (2019). Marine autonomous surface ship - control system configuration. IFAC-PapersOnLine, 52 (8), 409–415. doi: https://doi.org/10.1016/j.ifacol.2019.08.100
3. Utne, I. B., Schjølberg, I., Roe, E. (2019). High reliability management and control operator risks in autonomous marine systems and operations. Ocean Engineering, 171, 399–416. doi: https://doi.org/10.1016/j.oceaneng.2018.11.034
4. Hughes, G., Kornowa-Weichel, M. (2004). Whose fault is it anyway?: A practical illustration of human factors in process safety. Journal of Hazardous Materials, 115 (1-3), 127–132. doi: https://doi.org/10.1016/j.jhazmat.2004.06.005
5. Papalambrou, G., Samokhin, S., Topaloglou, S., Planakis, N., Kyrtatos, N., Zenger, K. (2017). Model predictive control for hybrid diesel-electric marine propulsion. IFAC-PapersOnLine, 50 (1), 11064–11069. doi: https://doi.org/10.1016/j.ifacol.2017.08.2488
6. Valdez Banda, O. A., Kannos, S., Goerlandt, F., van Gelder, P. H. A. J. M., Bergström, M., Kujala, P. (2019). A systemic hazard analysis and management process for the concept design phase of an autonomous vessel. Reliability Engineering & System Safety, 191, 106584. doi: https://doi.org/10.1016/j.ress.2019.106584
7. Fan, S., Zhang, J., Blanco-Davis, E., Yang, Z., Yan, X. (2020). Maritime accident prevention strategy formulation from a human factor perspective using Bayesian Networks and TOPSIS. Ocean Engineering, 210, 107544. doi: https://doi.org/10.1016/j.oceaneng.2020.107544
8. Sujesh, G., Ramesh, S. (2018). Modeling and control of diesel engines: A systematic review. Alexandria Engineering Journal, 57 (4), 4033–4048. doi: https://doi.org/10.1016/j.aej.2018.02.011
9. Boldea, I., Tutelea, L. (2018). Reluctance Electric Machines: Design and Control. CRC Press, 430. doi: https://doi.org/10.1201/9780429458316
10. Pelykh, S. N., Maksimov, M. V., Baskakov, V. E. (2008). Model of cladding failure estimation under multiple cyclic reactor power changes. Paper presented at the 2nd International Conference on Current Problems in Nuclear Physics and Atomic Energy, NPAE 2008 - Proceedings, 638–641.
11. Jeong, B., Oguz, E., Wang, H., Zhou, P. (2018). Multi-criteria decision-making for marine propulsion: Hybrid, diesel electric and diesel mechanical systems from cost-environment-risk perspectives. Applied Energy, 230, 1065–1081. doi: https://doi.org/10.1016/j.apenergy.2018.09.074
12. Coraddu, A., Oneto, L., Navas de Maya, B., Kurt, R. (2020). Determining the most influential human factors in maritime accidents: A data-driven approach. Ocean Engineering, 211, 107588. doi: https://doi.org/10.1016/j.oceaneng.2020.107588
13. Qiao, W., Liu, Y., Ma, X., Liu, Y. (2020). A methodology to evaluate human factors contributed to maritime accident by mapping fuzzy FT into ANN based on HFACS. Ocean Engineering, 197, 106892. doi: https://doi.org/10.1016/j.oceaneng.2019.106892
14. Endrina, N., Konovessis, D., Sourina, O., Krishnan, G. (2019). Influence of ship design and operational factors on human performance and evaluation of effects and sensitivity using risk models. Ocean Engineering, 184, 143–158. doi: https://doi.org/10.1016/j.oceaneng.2019.05.001
15. Baykov, A., Dar'enkov, A., Kurkin, A., Sosnina, E. (2019). Mathematical modelling of a tidal power station with diesel and wind units. Journal of King Saud University - Science, 31 (4), 1491–1498. doi: https://doi.org/10.1016/j.jksus.2019.01.009
16. Kundur, P. (1993). Power system stability and control. McGraw-Hill Inc., 1200.

17. Boldea, I. (2020). Induction Machines Handbook: Steady State Modeling and Performance. CRC Press, 443. doi: https://doi.org/10.1201/9781003033417
18. Brunetkin, A. I., Maksimov, M. V. (2015). The method for determination of a combustible gase composition during its combustion. Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu, 5, 83–90.
19. Dahl, A. R., Thorat, L., Skjetne, R. (2018). Model Predictive Control of Marine Vessel Power System by Use of Structure Preserving Model. IFAC-PapersOnLine, 51 (29), 335–340. doi: https://doi.org/10.1016/j.ifacol.2018.09.501
20. Skjong, S., Pedersen, E. (2017). A real-time simulator framework for marine power plants with weak power grids. Mechatronics, 47, 24–36. doi: https://doi.org/10.1016/j.mechatronics.2017.09.001
21. Thorat, L., Skjetne, R. (2017). Load-dependent start-stop of gensets modeled as a hybrid dynamical system. IFAC-PapersOnLine, 50 (1), 9321–9328. doi: https://doi.org/10.1016/j.ifacol.2017.08.1180
22. Li, W., Li, H., Gu, S., Chen, T. (2020). Process fault diagnosis with model- and knowledge-based approaches: Advances and opportunities. Control Engineering Practice, 105, 104637. doi: https://doi.org/10.1016/j.conengprac.2020.104637
23. Pelykh, S. N., Maksimov, M. V., Nikolsky, M. V. (2014). A method for minimization of cladding failure parameter accumulation probability in VVER fuel elements. Problems of Atomic Science and Technology, 4 (92), 108–116.
24. Vishnevskiy, L., Voytetskiy, I., Voytetskaya, T. (2019). Using model-oriented decision-making support system for the improvement of safe operation of a ship electric power installation. Computational Problems of Electrical Engineering, 9 (1), 37–43. Available at: http://science.lpnu.ua/jcpee/all-volumes-and-issues/volume-9-number-1-2019/using-model-oriented-decision-making-support
25. Vishnevsky, L., Voytetsky, I., Voytetskaya, T. (2019). Marine Electrical Power Plant Dynamic Modes Evaluation Using a Fuzzy Inference System. 2019 IEEE 20th International Conference on Computational Problems of Electrical Engineering (CPEE). doi: https://doi.org/10.1109/cpee47179.2019.8949175