УДК 004.891 https://doi.org/10.33082/td.2017.1-1.05

МЕТОД ПРОТИАВАРІЙНОГО КЕРУВАННЯ СКЛАДНИМИ ТЕХНІЧНИМИ СИСТЕМАМИ

МЕТОД ПРОТИВОАВАРИЙНОГО УПРАВЛЕНИЯ СЛОЖНЫМИ ТЕХНИЧЕСКИМИ СИСТЕМАМИ

METHOD FOR ANTIFAULT CONTROL OF COMPLEX TECHNICAL SYSTEMS

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Запропоновано метод протиаварійного керування складними технічними системами (СТС) на основі гібридних експертних систем (ГЕС), що включають нейронні мережі (НМ) і нечітку логіку з використанням бази даних (БД) і автоматизованої бази знань (БЗ).

Розроблена протиаварійна система управління СТС на основі ГЕС використовує переваги відомих методів ГЕС і протиаварійного керування, компенсуючи недоліки один одного.

Ключові слова: *складна технічна система, протиаварійне управління, діагностика, прогнозування, гібридна експертна система, нейронні мережі, нечітка логіка, база даних, база знань.*

Предложен метод противоаварийного управления сложными техническими системами (СТС) на основе гибридных экспертных систем (ГЭС), включающих нейронные сети (НС) и нечёткую логику с использованием базы данных (БД) и автоматизированной базы знаний (БЗ).

Разработанная противоаварийная система управления СТС на основе ГЭС использует достоинства известных методов ГЭС и противоаварийного управления, компенсируя недостатки друг друга.

Ключевые слова: *сложная техническая система, противоаварийное управление, диагностика, прогнозирование, гибридная экспертная система, нейронные сети, нечёткая логика, база данных, база знаний.*

A method for antifault control of complex technical systems (CTS) is proposed using hybrid expert systems (HES), which are built on the basis of neural networks (NN) and fuzzy logic that uses databases (DB) and automated knowledge bases (KB). This method uses monitoring, diagnostics and forecasting of the CTS data, calculating its operability.

Then the reliability of the system under consideration is determined from the obtained data. Also, the system is capable of self-learning. Proceeding from this, with the help of a multi-agent control system, the system is influenced to avoid emergencies.

As a result, the CTS emergency control system was developed that combines the advantages of the previously known HES and antifault control methods, which complement each other's advantages and compensate each other's shortcomings.

Keywords: *hybrid expert system, neural networks, fuzzy logic, database, knowledge base, antifault control, diagnostics, forecasting, complex technical system.*

Introduction. The modern vessel contains numerous CTS [1; 2], affecting the efficiency of ship operation.

The safety of navigation is largely related to ensuring the operability, and hence the reliability of operation of their CTS.

Variable modes and operating conditions of the CTS often lead to a decrease in the operability of systems, an increase in the probability of failure of systems and their elements [3; 4; 5; 6].

Increasingly, for antifault control of the CTS are using HES, taking into account their multifunctionality [2; 7; 8].

From this it follows that the development of a HES, capable of avoiding such difficulties at the stage of creation and at the same time, qualitatively processing information, is today quite relevant.

Analysis of major achievements and literature. Different methods of decision making are combined in the HES: genetic algorithms, NN, etc.

NN is successfully applied in a wide variety of fields. They have entered into practice wherever it is necessary to solve the tasks of forecasting, classification or management [9].

The main drawback of systems with fuzzy logic is the impossibility of adaptation and training.

However, this is replaced by the merit of methods with NN – fast learning and adaptation [10], as well as: broad possibilities and ease of use [9].

Their main drawback is the need to attract a training sample, the size and reliability of its elements affect the quality of the forecast [11].

The knowledge accumulated by the HC is distributed among all its elements, which makes them practically inaccessible to the observer.

At the same time, such a defect has no control systems with fuzzy logic [10].

From the analysis of literature sources, the relevance of developing a method for antifault control of CTS on the basis of HES, including neural networks and fuzzy logic using a database and an automated knowledge base, follows.

Purpose of the study, statement of the task. Development of a method for antifault control of CTS on the basis of HES, including NN and fuzzy logic with the use of a DB and an automated KB.

Research materials. In accordance with the developed method, HES interacts with a multi-agent antifault control (AFC) system (fig. 1).

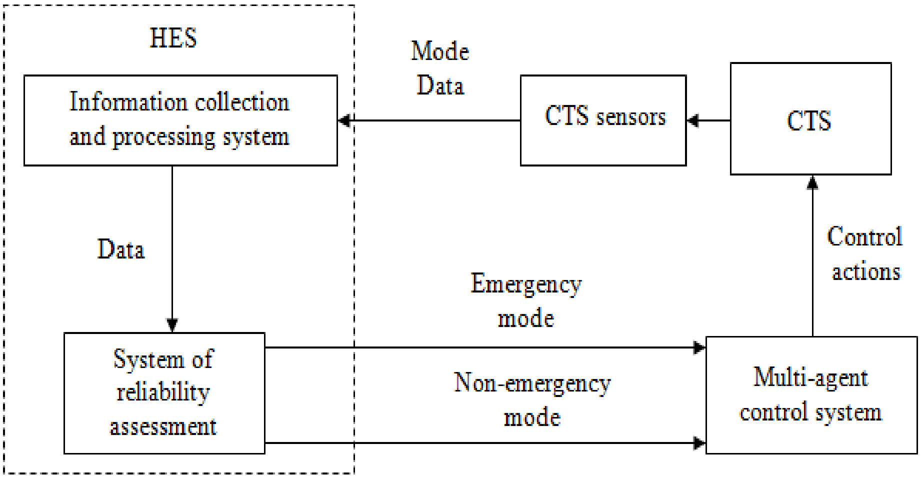


Fig. 1. Structure of the AFC circuit on the basis of HES

The solution of the task of assessing the reliability of the CTS within the framework of the HES is a consistent solution of such tasks:

– tuning HES;
– construction of hierarchy of CTS structures;
– the choice of the solution method for each structure;
– formation of the KB for all methods used;
– calculation of assessments;
– interpretation and explanation of the assessments obtained.

An example of the structure of such a system (fig. 2).

The assessments of the technical state of the CTS is determined by the dependence [12]

$$P = F^P(p_1, p_2, ..., p_m), \tag{1}$$

where P – CTS operability;

$F(\ )$ – function of formalized dependence;

$p_1, p_2, ..., p_m$ – calculation assessments of the operability of technical nodes of the CTS;

m – number of calculated assessments.

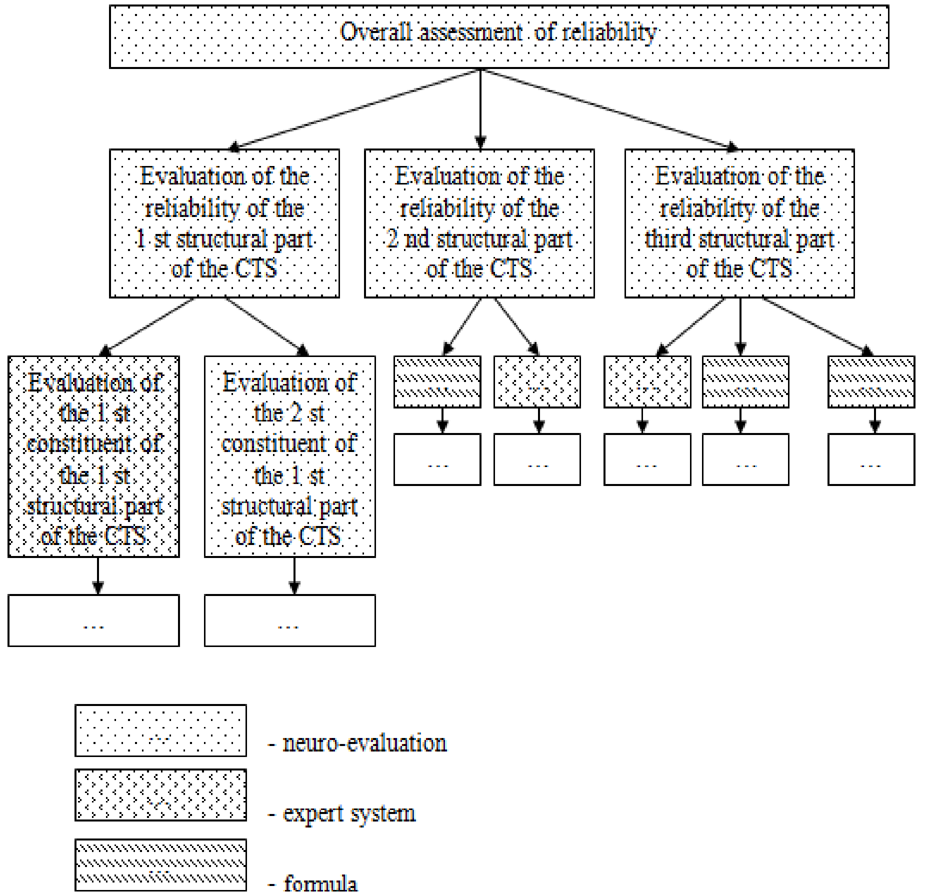


Fig. 2. Structure of the CTS reliability assessment model

The calculation assessment of the operability of each technical node of the CTS is based on the parameters of these nodes, as well as their type (linguistic, non-linguistic). Depending on this, each assessment of the operability is based on an automated expert KB, where the calculations for the variables are analyzed, and then the final result of the assessment performance evaluation is derived based on the received calculations using a NN.

Mathematically, this is expressed by the following formula:

$$p_m = N\left(F_{m1}\left(x_{m11},\dots,x_{m1n}\right),\dots,F_{mh}\left(x_{mh},\dots,x_{mhk}\right),y_{m11},y_{m12}\right), \qquad (2)$$

where $N(\ )$ – NN function;
x, y – variable parameters of the technical node CTS;
h – number of functions for a given node;
n, k – number of variables for each function.

HES processes incoming information into it at equal intervals, in the form of variables from CTS sensors (linguistic and non-linguistic) and variables of external factors that affect the value of the error in the operation of the system.

Also, on the basis of the critical values of these variables, abnormal (emergency) situations occurring in the operation of the CTS can occur.

$$P(t_i) = \langle X(t), Y(t), F(t) \rangle, \tag{3}$$

where $X(t) = \{x_1(t_i), x_2(t_i), ..., x_n(t_i), i \in [1;T]\}$ – set of non-linguistic variables at time t_i;

n – number of non-linguistic variables;

T – number of moment of time;

$Y(t) = \{y_1(t_i), y_2(t_i), ..., y_m(t_i), i \in [1;T]\}$ – set of lin-guistic variables at time t_i;

m – number of linguistic variables;

$F(t) = \{f_1(t_i), f_2(t_i), ..., f_h(t_i), i \in [1;T]\}$ – set of external factors affecting the operation of the system at time t_i (error);

h – number of factors;

$P(t_i), i \in [1;T]$ – the value of operability at time t_i.

Emergency and abnormal situations arising during the operation of the CTS are formed at critical values of one or several sensor variables from the structural parts of the CTS, or environmental variables that affect the operation of the system. Dependence of abnormal situations on the variables of the CTS and external variables is described by the formulas given below.

$$S(t) = [X(t), Y(t), F(t)], \tag{4}$$

where $S(t) = \{s_1(t_i), s_2(t_i), ..., s_k(t_i), i \in [1;T]\}$ – set of possible situations that can arise during the operation of the system at time t_i;

k – number of situations

It follows from the formulas obtained that the variables, both external and internal (linguistic and non-linguistic), form the value of operability, and at the same time can create local emergency or abnormal situations in one or several parts of the CTS structure, which as a whole forms the reliability of the CTS (emergency or non-emergency modes).

The influence of variables on the value of operability and the formation of various situations occurring in the system is described by formulas

$$(F(t)\cap X(t)\cap Y(t))\rightarrow\begin{cases} S(t) \\ P(t_i), i\in[1;T] \end{cases} \tag{5}$$

Wherein:

$$X(t)\rightarrow[p_1(t_i), p_2(t_i),..., p_m(t_i)] \tag{6}$$

$$Y(t)\rightarrow Y(t_i) \tag{7}$$

$$F(t)\rightarrow\Delta(t_i), \Delta(t_i)\in[0;1] \tag{8}$$

where $p_1(t_i), p_2(t_i),..., p_m(t_i)$ – calculation assessments of the operability of the technical nodes of the CTS at time t_i;

$Y(t_i)$ – general linguistic variable at time t_i;

$\Delta(t_i)$ – error in the calculation of the value of operability at time t_i.

The reliability of the work of CTS is affected by the value of its operability, consisting of calculated assessments of the operability, the general linguistic variable and the error of operability. Based on this, it is possible to compile a hierarchy of factors that affect the reliability of the system (fig. 3).

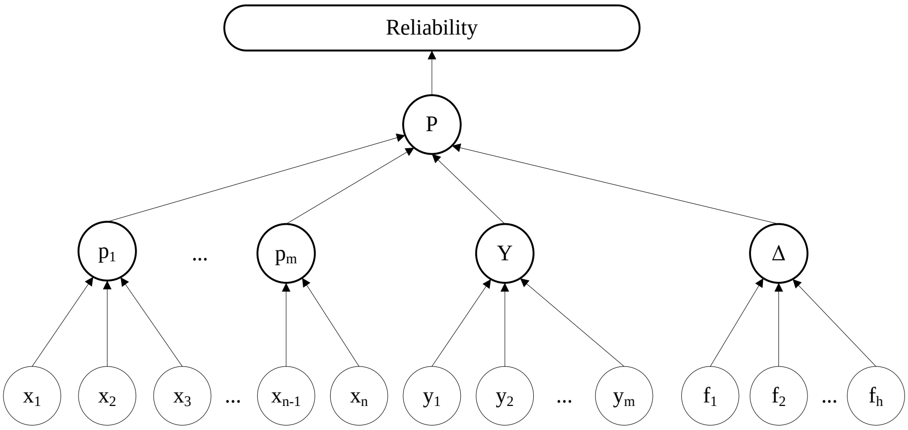


Fig. 3. Hierarchy of factors affecting the reliability of the CTS

For linguistic variables and external factors, ranges of their values are formed.

When developing HES designed to implement antifault control, expert opinions are taken into account when choosing technical criteria for the structural parts of the CTS, the values of which are taken into account based on the degree of their impact on the operability of the CTS.

Separately for linguistic variables and external factors, expert KB are formed on the basis of the «if-then» rules, where, taking into account the values of linguistic and external variables, set the value of the general linguistic variable (table 1) and the errors in calculations (table 2), respectively.

Table 1

Fuzzy knowledge base for linguistic variables

y_1	y_2	…	y_m	Y
H	H	…	H	H
M	AM	…	M	BM
…	…	…	…	…
L	L	…	L	L

Table 2

Fuzzy knowledge base for external variables

f_1	f_2	…	f_h	Δ
H	H	…	H	H
H	AM	…	BM	M
…	…	…	…	…
L	L	…	L	L

In table 1 and table 2 H, M, L – high, medium and low value of the variable, respectively; AM, BM – the value of the variable above and below the average, respectively.

The coefficients of calculation assessments of the operability are selected by experts using the Saaty pair comparison method [13].

As a result of the calculations, we obtain the weight coefficients for calculation assessments of the operability, taking into account the values of the general linguistic variable (table 3).

In Table 3 $w_{Y1},...,w_{Y5}$ – weight coefficients of the general linguistic variable for different values of Y; $w_{11},...,w_{m5}$ – weight coefficients of calculation assessments of the operability for different values of Y.

Taking into account the carried out researches, operability at the moment of time is calculated by the formula

$$P(t_i)=\Delta(t_i)\left(w_{Yj}\cdot Y(t_i)+w_{1j}\cdot p_1(t_i)+w_{2j}\cdot p_2(t_i)+...+w_{mj}\cdot p_m(t_i)\right) \quad (9)$$

Table 3

Weighting factors of calculation assessments of the operability and the general linguistic variable Y, taking into account the values of Y

The value of Y	Y	p_1	p_2	$\dots$	p_m
H	w_{Y1}	w_{11}	w_{21}	$\dots$	w_{m1}
AM	w_{Y2}	w_{12}	w_{22}	$\dots$	w_{m2}
M	w_{Y3}	w_{13}	w_{23}	$\dots$	w_{m3}
BM	w_{Y4}	w_{14}	w_{24}	$\dots$	w_{m4}
L	w_{Y5}	w_{15}	w_{25}	$\dots$	w_{m5}

At the same time, the NN is trained, which is used to calculate the calculation assessments of the operability, as well as the operability of the CTS.

To limit the search space, the target error function of the NN, using the least squares method [14], is minimized

$$E(w)=\frac{1}{2}\sum_{j=1}^{p}\left(y_j-d_j\right)^2, \qquad (10)$$

where y_j – value of the j-th output of the NN;

d_j – target value of j-th output;

p – number of neurons in the output layer.

The network is trained by the gradient descent method. At each iteration the change in weight occurs according to the formula

$$\Delta w_{ij}=-\eta\cdot\frac{\partial E}{\partial w_{ij}}, \qquad (11)$$

where η – learning speed parameter.

When developing KB of HES, critical values are set for each variable that directly affect the performance of the CTS, taking into account their individual parameters, when values of which are reached, the operation mode of the CTS becomes emergency (table 4).

For each variable, as well as for operability, the value at which the CTS goes into the emergency mode is set individually [15].

Table 4

Values of the parameters of the CTS variables

Variable	Values of the parameters	
	Non-emergency mode	Emergency mode
V_1	$[a_{1}...b_1]$	$> b_1$
V_2	$[a_{2}...b_2]$	$< a_2$
…	…	…
V_m	$[a_{m}...b_m]$	$(< a_m) \vee (> b_m)$
P	$[a_{p}...b_p]$	$< a_P$

In addition, according to the data is predicted to operability the system, by analyzing the time series of the technical state of the CTS on the basis of changing the characteristics of its variables with a specified time interval.

The interval between fixing the values is TI. During each fixation of values, the operability of the CTS is determined, as well as all previously undetected equipment failures.

For the entire life cycle of the L system, a time frame is calculated

$$L:((0,TI)(TI,2\cdot TI)(2\cdot TI,3\cdot TI)...((T-1)\cdot TI,T\cdot TI)), \tag{12}$$

where $T=\frac{L}{TI}$.

During each t-th period $((t-1)\cdot TI, t\cdot TI)$, a certain interval of time, where $t=(1,T)$, the system's actions are described by a system of ordinary differential equations

$$\frac{dV(t)}{dt}=V(t)\cdot M \tag{13}$$

where $V(t)=(v_1(t),v_2(t)...v_T(t))$ – the probability vector of the system under consideration in a certain state;

M – matrix of system transitions from one state to another, containing the transition coefficients between states [16]

$$M=\begin{pmatrix} \lambda_{11} & ... & \lambda_{1T} \\ ... & ... & ... \\ \lambda_{T1} & ... & \lambda_{TT} \end{pmatrix} \tag{14}$$

After that, the influence functions (IF) of the factors are formed on the probability of an emergency situation.

IF are formed on the basis of statistics and expert assessments.

When one of the possible values $x(t)$ IF of the factor X_j is obtained, the remaining values of the IF are established by the expert's evaluation in paired comparisons of the relative influences of this factor on the occurrence of basis events (BE). When knowledge of IF is formed, n_j tuples of the form [17] are created for each pair (factor X_j, BE «a^r») in the KB

$$\left(r, j, x_t, f_j^r(x_t)\right) \tag{15}$$

where $r \in \{R\}$ – set of BE indexes;

$j \in \{J\}$ – set of factors indices that affect the BE;

n_j – the number of possible values of the factor X_j;

x_t – one of the possible values of X_j;

$f_j^r(x_t)$ – the value of the influence function of the factor X_j on the BE «a^r», when $X_j = x_t$.

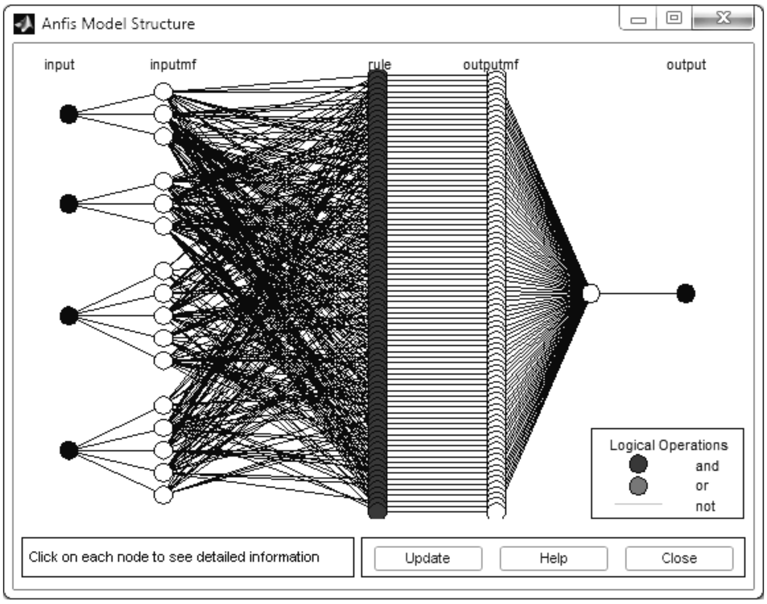
Research results. With the help of the Fuzzy Logic Toolbox, the scheme of fuzzy NN was visualized, as well as the surface of the fuzzy output of the operability of the CTS for a particular case, taking into account the values of calculated assessments p_1 and p_2, the general linguistic variable Y and the error F (fig. 4).

From the results of visualization of the work of HES it follows that the operability is greatest at high values of the calculated assessments and the general linguistic variable, and is lowest with high error assessments. The obtained data represent a fairly reliable level of diagnostics, as well as further prediction of the CTS reliability state on the basis of these data.

Below is a table of CTS operability values in the time series $z(t)$ as a result of diagnosing the values of the input variables with the help of the HES (table 5).

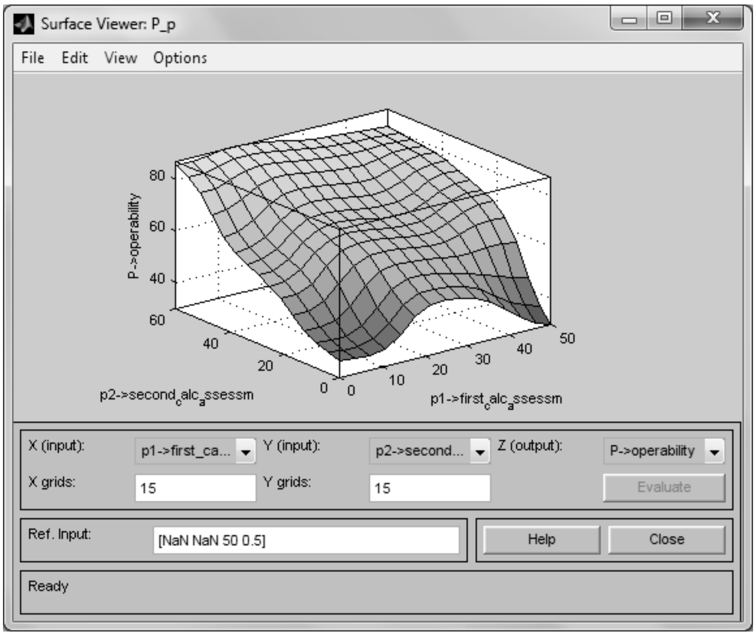
With the help of Matlab – Network / Data Manager, the CTS data is predicted on the basis of time series analysis [18].

As a result, the operability of system was calculated on the basis of the predicted data (table 6). According to the received data for the time series $z(t_1) - z(t_4)$, the average error of the network is 2,4973, which, in parti-cular, speaks of a sufficiently high accuracy of the forecast of the technical parameters of the CTS.



Click on each node to see detailed information

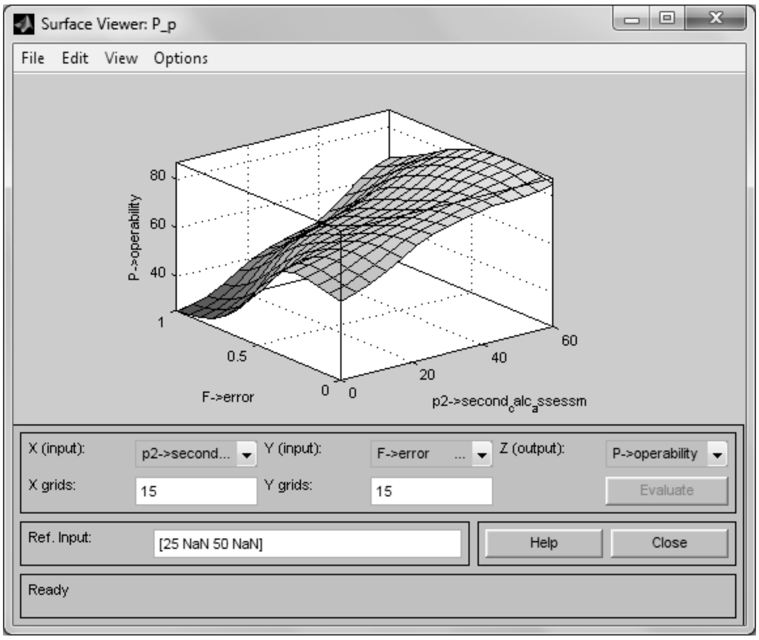
a)



X (input): p1->first_ca...
Y (input): p2->second...
Z (output): P->operability
X grids: 15
Y grids: 15
Ref. Input: [NaN NaN 50 0.5]
Ready

b)

Fig. 4. Visualization of the scheme of fuzzy NN (a), surface of fuzzy conclusion with calculation assessments p_1 and p_2 (b), error F and calculation assessment p_2 (c), error F and general linguistic variable Y (d)



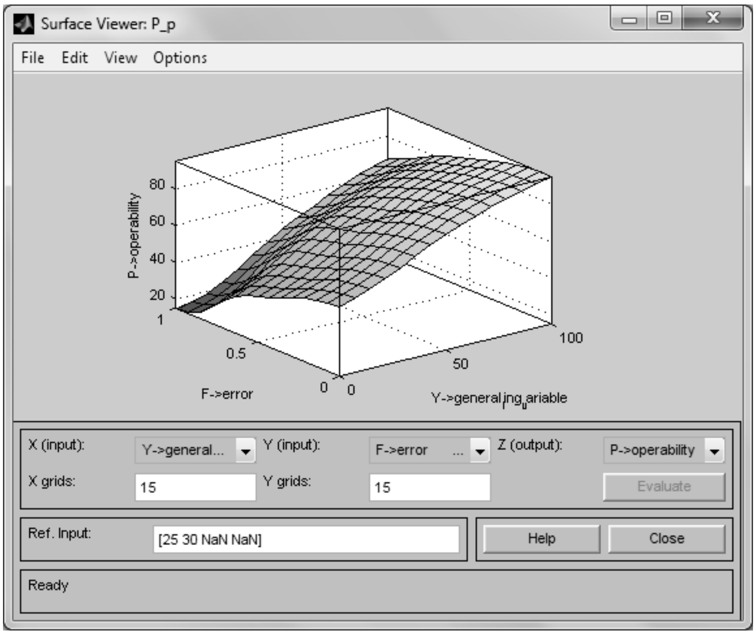
X (input): p2->second... Y (input): F->error ... Z (output): P->operability

X grids: 15 Y grids: 15

Ref. Input: [25 NaN 50 NaN]

Ready

c)



X (input): Y->general... Y (input): F->error ... Z (output): P->operability

X grids: 15 Y grids: 15

Ref. Input: [25 30 NaN NaN]

Ready

d)

Fig. 4. Continuation

Table 5

Values of the variables and operability of the CTS

Variable	Time series $z(t)$			
	$z(t_1)$	$z(t_2)$	$z(t_3)$	$z(t_4)$
p_1	30	10	20	35
p_2	60	50	40	55
Y	67.3178	50.0202	47.5608	50.0576
F	0.4636	0.4281	0.500	0.4187
P	89.6603	83.4636	72.8506	82.1741

Table 6

Forecasting results, as well as the calculated operability of the CTS

Variable	Time series $z(t)$
	$z(t_5)$
p_1	35
p_2	40
Y	67,3178
F	0,4194
P	82,3703

Conclusions. As a result of the research, a method of antifault control of the CTS was developed with the help of the HES. The developed method uses the advantages of various methods for antifault control of CTS, based on the NN and fuzzy logic.

This makes it not only universal for different types of ship's CTS, but at the same time it is also quite accurate, given that it takes into account, in addition to the CTS data, also external factors, as well as self-learning of the NN.

Data of diagnostics and prediction of technical parameters of the CTS for a particular case were also obtained. The average forecast error was 2,4973, which indicates a rather high efficiency of the developed method.

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Стаття надійшла до редакції 01.09.2017