Приводиться системне оцінювання динаміки функціонування складних технічних систем у реальному режимі часу з урахуванням ресурсу допустимого ризику, що забезпечує їх живучість функціонування у певному інтервалі часу, у якому ступінь ризику і рівень ризику не перевищують допустимих значень. Передбачається раціональне узгодження ресурсів допустимого ризику для критичних показників функціонування з інтегральним показником інформованості про ситуації ризику з урахуванням неусуненого порогового обмеження часу

Ключові слова: стратегія, безпека, живучість, ресурс допустимого ризику, позаштатний режим, ризик, невизначеність

Приводится системное оценивание динамики функционирования сложных технических систем в реальном режиме времени с учетом ресурса допустимого риска, обеспечивающего живучесть функционирования сложных технических систем. Предусматривается рациональное согласование ресурсов допустимого риска для критических показателей функционирования с интегральным показателем информированности о ситуациях риска с учетом неустранимого порогового ограничения времени

Ключевые слова: стратегия, безопасность, живучесть, ресурс допустимого риска, нештатный режим, риск, неопределенность

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SYSTEM EVALUATION OF ENGINEERING OBJECTS' OPERATING TAKING INTO ACCOUNT THE MARGIN OF PERMISSIBLE RISK

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1. Introduction

The strategy for guaranteed security and survivability of complex engineering systems (CES), while taking into account the objectives, timing, resources, and expected results, is determined by the sequence of systemically agreed procedures of the efficiency and safety, characterized by the incompleteness, uncertainty, and ambiguity of information about risk situations, as well as the timeliness of decision-making and unavoidable threshold limiting the time of a transition into an emergency or disaster [1]. The causes for technogenic catastrophes, accidents, social disasters, or other hazards can include the equipment malfunction, failure of engineering systems, violation of equipment operating rules, wrong actions of personnel, non-compliance with safety regulations, and external effects. The requirements for systemic coherence of decisions assume the systemic support of indicators of CES performance, security, guaranteed survivability during specified time of operation.

For complex systems of different nature, the actual problem is a reliable forecasting and timely prevention of abnormal mode situations under the influence of destabilizing factors on the operability, safety, durability, and efficiency in the functioning process, which are detected using the indicators of the risk degree, risk level, and the margin of permissible risk. The latter indicator characterizes the resource defined by the state of the working capacity, security, and survivability for a certain time frame according to the real operating conditions.

2. The analysis of the published data and the problem statement

The principles of control by security and survivability of CES are distinguished by functioning peculiarities of means for technical diagnostics, existing both functional and test type. Functional diagnostic means represent typical monitoring systems used to assess the overall technical state of the object. Test diagnostics means are used to evaluate the technical state of individual elements, components, parts with a specially organized test influences. In [2], the authors described the approach for diagnosing the technical state of a system before a failure, taking into account uncertainties connected with the fault's time, location, and class. Functional diagnostic models are formed based on the analysis of nominal and abnormal operations of sensors. In [3], to diagnose while determining the failure type together with the place and time of its detection, the authors used parity equations build for a specific process. In [4], the authors discussed issues related to a technical condition of the mechanical equipment in the presence of regulators (automatic balancing devices). In [5], using connections between gas turbine components as an example, the authors consider the diagnostic method that allows detecting a fault at the early stage before manifesting itself as a serious malfunction. In [6], the authors considered the problem of tracking and diagnosing malfunctions in complex systems which were characterized by both discrete and continuous variables. On the basis of the constructed using the discussed approach models, various failures are simulated, including the burst in malfunction, incorrect measurement of errors and gradual drift. In [7], the authors considered issues related to designing and creating complex anthropogenic systems which satisfy the required level of guaranteed quality (reliability, durability and safety) under conditions of incompleteness of the original information for forecasting technical systems' conditions. The described concept of information and the statistical approach to the formation of the anthropogenic system structure is based on their information-linguistic description, using the system-morphological methods of formal analysis and variational principles of an experimental random parameter distribution. In [8], the author justifies the significance of the system approach and system analysis principles when forming the evaluating indicators and estimating criteria for the technical condition of systems. In [9], the author uses for the analysis of the anomalous behavior of the system the approach to design the control system with detecting simultaneously the failures of technological equipment elements, making the transition of the control object to one from the secure states. In [10], the author suggests an approach for restoring the efficiency of diagnosed CES elements based on the construction of the optimal test sequence on the given sets of input data. In [11], the authors consider a comprehensive model to control and restore an operation of CES with multilevel structure, describing the processes to control technical condition, search a place of failures and replacement of defective typical replacement elements. The durations to recover CES efficiency on a level of functional components, functional modules, typical replacement elements and system in general are represented in the mark-up stochastic graph by the analytical dependences of the mathematical expectation and variance from the indicators characterizing the control of the technical CES condition, diagnosis, the effectiveness of the spare elements and replace defective typical elements.

Thus, the existing studies are mainly aimed to detect a failure in the CES operation, while a priority is timely detection of the causes and prevention of transition to an abnormal mode, that allows providing the introduction of the margin of permissible risk.

3. The purpose and objectives of the study

The objective is to develop a technique of systemic evaluation of the real CES operation taking into account the margin of permissible risk.

To achieve this objective, the following tasks have been solved:

– to evaluate the margin of permissible risk for CES operating indicators under the impact of destabilizing factors and uncertainties;

– to coordinate rationally the margin of permissible risk for the CES operating indicators under the impact of destabilizing factors and uncertainties.

4. The development of a technique to prevent a certain abnormal mode situation of real CES operating

4. 1. Mathematical statement of the problem

A sample of values of real operating indicators $y_i \big| i=\overline{1,m}$ and parameters $x_j \big| j=\overline{1,n}$

$$\left\langle Y(t_k)=\left\{Y_i(t_k), i=\overline{1,m}\right\}, X(t_k)=\left\{X_j(t_k), j=\overline{1,n}\right\}, t_k \in D_0\right\rangle$$

is given in the initial time interval $D_0=\left\{t_0 \big| t_0^- \le t_0 \le t_0^+\right\}$ (the length of the interval is set as $\left|D_0\right| = 40 \div 70$). Using the orthogonal polynomials (Legendre polynomials, Chebyshev polynomials, displaced Chebyshev polynomials, and others), on the given sample the functional dependencies

$$\tilde{y}_i = \Phi_i\left(\left\{x_j \big| j=\overline{1,n}\right\}\right), i=\overline{1,m}$$

are restored with acceptable accuracy and constructed in real-time while taking the forecast into account for a period of $D_p=\left\{t_p \big| t_0^+ \le t_p \le t^+\right\}$ with the length, given as

$$0{,}1\cdot\left|D_0 \bigcup D_p\right| \le \left|D_p\right| \le 0{,}25\cdot\left|D_0 \bigcup D_p\right|$$

for the short-term forecast.

The sets of

$$D_Y=\left\langle y_{ir} \le y_{ir}^{perm} \big| i=\overline{1,m}, r=\overline{1,n_r}\right\rangle$$

and

$$D_X=\left\langle x_{jr} \le x_{jr}^{perm} \big| j=\overline{1,n}, r=\overline{1,n_r}\right\rangle$$

are given, where y_{ir}^{perm} and x_{jr}^{perm} are the boundary values of the operating indicators and parameters of CES, characterizing the occurrence of abnormal mode situations, n_r is the number of the following modes types: abnormal, extraordinary, emergency, catastrophic, etc.

For the given $\tilde{y}_i$ at time instances $t_k \in D_0 \bigcup D_p$ the values of $\eta(\tilde{y}_i)\big| i=\overline{1,m}$ risk degree and

$$W(\tilde{y}_i)\big| i=\overline{1,m}$$

risk level are known, which are calculated using the set D_Y. Based on restrictions

$$\eta(\tilde{y}_i) \le \eta_{perm}\left(y_{ir}^{perm}\right),$$

$$W(\tilde{y}_i) \le W_{perm}\left(y_{ir}^{perm}\right) \quad \forall\, i=\overline{1,m}, r\in\left[1,n_r\right]$$

on the functional dependencies

$$\tilde{y}_i = \Phi_i\left(\left\{x_j \big| j=\overline{1,n}\right\}\right), i=\overline{1,m}$$

abnormal mode situations are detected, which corresponds to the set

$$T_R=\left\{\left[t_{fr}^i, t_{rr}^i\right] \big| t_{fr}^i < t_{rr}^i, t_{rr}^i < t_{cr},\right.$$
$$\left. t_{fr}^i, t_{rr}^i \in D_0 \bigcup D_p, r\in\left[1,n_r\right], i=\overline{1,m}\right\},$$

where t_{fr}^i, t_{rr}^i are the time instances for identifying and implementing the solution, t_{cr} is a limit value of decision-making time as an unavoidable threshold time instance. In each interval $\left[t_{fr}^i, t_{rr}^i\right] \subseteq T_R, r\in\left[1,n_r\right], i=\overline{1,m}$ in the real time mode, the values of indices $I_V^i(t_k)$ informedness veracity, $I_C^i(t_k)$ informedness completeness, $I_T^i(t)$ informedness timeliness, and $I_0^i(t_k)$ integral informedness index are evaluated for $\forall\, t_k \in\left[t_{fr}^i, t_{rr}^i\right], k=\overline{1,K}, i=\overline{1,m}$. The informedness indexes of $I_V^i(t)$, $I_C^i(t)$, $I_T^i(t)$, $I_0^i(t)$ as the functions of time are represented by the following formulas [12]:

$$I_V^i(t)=\begin{cases}\hat{I}_V^i\cdot(1+\gamma_i\cdot t), \text{if } \hat{I}_V^i\cdot(1+\gamma_i\cdot t)<1\\ 1, \text{if } \hat{I}_V^i\cdot(1+\gamma_i\cdot t)\ge 1\end{cases}, i=\overline{1,m},$$

$$I_C^i(t)=\begin{cases}\hat{I}_C^i\cdot(1+\delta_i\cdot t), \text{if } \hat{I}_C^i\cdot(1+\delta_i\cdot t)<1\\ 1, \text{if } \hat{I}_C^i\cdot(1+\delta_i\cdot t)\ge 1\end{cases}, i=\overline{1,m},$$

$$I_T^i(t)=\begin{cases}\hat{I}_T^i\cdot(1-\theta_i\cdot t^2), \text{if } \theta_i\cdot t^2<1\\ 0, \text{if } \theta_i\cdot t^2\ge 1\end{cases}, i=\overline{1,m},$$

$$I_0^i(t)=I_V^i(t)\cdot I_C^i(t)\cdot I_T^i(t). \quad (1)$$

The parameters of $\hat{I}_V^i$, $\hat{I}_C^i$, $\hat{I}_T^i$ for the functions in (1) characterize preliminary evaluations of the informedness veracity index, informedness completeness index, and informedness timeliness index. The evaluations of $\hat{I}_V^i$ and $\hat{I}_C^i$ are obtained by expert evaluation using the seven-level scale, presented in [12]. The evaluations of $\hat{I}_T^i$ are calculated while taking into account the maximum values of the informedness veracity of

$$I_{V_m}^i\left(t_{V_m}^i\right)=\max_{t_k\in\left[t_{fr}^i,t_{rr}^i\right]} I_V^i(t_k)$$

and informedness completeness of

$$I_{C_m}^i\left(t_{C_m}^i\right)=\max_{t_k\in\left[t_{fr}^i,t_{rr}^i\right]} I_C^i(t_k)$$

reached at time instances

$$t_{V_m}^i, t_{C_m}^i \in\left[t_{fr}^i, t_{rr}^i\right]\subset T_R, k\in[1;K].$$

The formula for $\hat{I}_T^i$ is $\hat{I}_T^i=0{,}5\cdot(1+R_i), i=\overline{1,m}$, where R_i characterizes the time resource to implement early a decision on functional dependency $\tilde{y}_i$ and is defined by time instance values of $t_{V_m}^i$, $t_{C_m}^i$ according to $I_{V_m}^i\left(t_{V_m}^i\right)$ and $I_{C_m}^i\left(t_{C_m}^i\right)$. Due to the dependence of indexes I_V^i and I_C^i on time R_i is calculated as

$$R_i=\frac{\max\left\{t_{V_m}^i, t_{C_m}^i\right\}-t_{fr}^i}{t_{rr}^i-t_{fr}^i}.$$

The coefficients of γ_i, δ_i, θ_i characterize the change of dynamics for informedness indexes $I_V^i(t)$, $I_C^i(t)$, and $I_T^i(t)$, respectively. In [12], these coefficients are evaluated using formulas $\gamma_i=e^{\hat{I}_V^i}\cdot\hat{a}_i\cdot 0{,}05$, $\delta_i=e^{\hat{a}_i}\cdot\hat{I}_C^i\cdot 0{,}5$, $\theta_i=(\hat{a}_i+\gamma_i)\cdot\hat{I}_T^i\cdot 10^{-5}$ $\forall i=\overline{1,m}$ which were determined as result of computational experiment, where $\hat{a}_i$ is an evaluation of an influence of parameters

$$X_j(t_k)\Big|j=\overline{1,n},\ t_k\in\left[t_{fr}^i,t_{rr}^i\right], i=\overline{1,m}$$

on indicators $\tilde{y}_i$ during abnormal mode situations, using the formula

$$\hat{a}_i=\max_{t_k\in\left[t_{fr}^i,t_{rr}^i\right]}\left\{1-\prod_{j=1}^{n}\left[1-\eta\left(X_j(t_k)\right)\right]\right\}, i=\overline{1,m},$$

where $\eta\left(X_j(t_k)\right)$ is the risk degree, caused by the influence of parameters $X_j(t_k)\Big|j=\overline{1,n},\ t_k\in\left[t_{fr}^i,t_{rr}^i\right], i=\overline{1,m}$ and evaluated using the restrictions of the set D_X.

For the current value of $\tilde{y}_i$, the rational level value for the integral informedness index is evaluated, providing the recognition situations of specified CES operating mode; it is expressed by the formula

$$I_0^-=\min_{i\in[1,m]}\left\{\overline{I_0^i(t_k)}\right\}, t_k\in\left[t_{fr}^i,t_{rr}^i\right], k=\overline{1,K}, t_{rr}^i<t_{cr},$$

where

$$\overline{I_0^i(t_k)}=\frac{1}{K}\cdot\sum_{t_k\in\left[t_{fr}^i,t_{rr}^i\right]} I_0^i(t_k), i=\overline{1,m}$$

is the average values of the integral informedness index in the time interval $\left[t_{fr}^i,t_{rr}^i\right]\subset T_R, i\in[1,m]$. The time intervals

$$\left[t_{s_1r}^i,t_{s_2r}^i\right]\subseteq\left[t_{fr}^i,t_{rr}^i\right]\subset T_R, i\in[1,m]$$

for searching the additional information by a decision maker, where $I_0^i(t_k)\ge I_0^i(t_k)$, are used to define the margin of permissible risk in order to prevent the situations of corresponding abnormal mode. The margin of permissible risk is implemented in the time interval

$$\left[t_{a_1r}^i,t_{s_2r}^i\right], t_{s_1r}^i\le t_{a_1r}^i<t_{s_2r}^i, i\in[1,m]$$

with endpoints $t_{a_1r}^i, t_{s_2r}^i$, which correspond to the values $\tilde{y}_i\left(t_{a_1r}^i\right)$ with

$$\eta_i\left(\tilde{y}_i\left(t_{a_1r}^i\right)\right)<\eta_i\left(\tilde{y}_i\left(t_{s_2r}^i\right)\right),\ W_i\left(\tilde{y}_i\left(t_{a_1r}^i\right)\right)<W_i\left(\tilde{y}_i\left(t_{s_2r}^i\right)\right)$$

and $\tilde{y}_i\left(t_{s_2r}^i\right)$ with $I_0^i\left(t_{s_2r}^i\right)\ge I_0^-$. The expression for the margin of permissible risk is written in the following form:

$$R_i^{perm}=\left\{\frac{\left|\left[t_{a_1r}^i,t_{s_2r}^i\right]\right|}{\left|\left[t_{s_1r}^i,t_{s_2r}^i\right]\right|}:\eta_i\left(\tilde{y}_i\left(t_{a_1r}^i\right)\right)<\eta_i\left(\tilde{y}_i\left(t_{s_2r}^i\right)\right),\right.$$
$$W_i\left(\tilde{y}_i\left(t_{a_1r}^i\right)\right)<W_i\left(\tilde{y}_i\left(t_{s_2r}^i\right)\right),$$
$$\left.I_0^i\left(t_{s_2r}^i\right)\ge I_0^-,\ r\in\left[1,n_r\right], i=\overline{1,m}\right\}. \quad (2)$$

On the time intervals $\left[t_{a_1r}^i,t_{s_2r}^i\right], r\in\left[1,n_r\right], i\in[1,m]$, a coordination for the margin of permissible risk R_i^{perm} for $\tilde{y}_i$,

$$I_0^i(t_k)\ge I_0^-, t_k\in\left[t_{s_1r}^i,t_{s_2r}^i\right]\subset T_R, i=\overline{1,m}$$

is realized; it is evaluated by the value R_c^{perm} with the time interval

$$\left[t_{ca_1}^r,t_{cs_2}^r\right]\subset\bigcup_{i\in[1,m]}\left[t_{a_1r}^i,t_{s_2r}^i\right], r\in\left[1,n_r\right],$$

where the prevention of the abnormal mode situation r is guaranteed. The lower endpoint of the interval $\left[t_{ca_1}^r,t_{cs_2}^r\right]$ is defined as

$$t_{ca_1}^r=\min_{i=\overline{1,m}}\left\{t_{a_1r}^i\right\}.$$

The upper endpoint of this interval is defined by the formula

$$t_{cs_2}^r=\min_{i=\overline{1,m}}\left\{t_{s_2r}^i\right\}$$

taking into account the relation $I_0\left(t_{s_2r}^i\right)\ge I_0^-, i=\overline{1,m}, r\in\left[1,n_r\right]$. The value R_c^{perm} for the margin of permissible risk is defined by the length of the interval

$$\left[\min_{i=\overline{1,m}}\left\{t^i_{a_1r}\right\},\min_{i=\overline{1,m}}\left\{t^i_{s_2r}\right\}\right].$$

The formula for R_c^{perm} is written as follows:

$$R_c^{perm}=\left\{\frac{\left\|\left[\min_{i=\overline{1,m}}\left\{t^i_{a_1r}\right\},\min_{i=\overline{1,m}}\left\{t^i_{s_2r}\right\}\right]\right\|}{\left\|\left[\min_{i=\overline{1,m}}\left\{t^i_{s_1r}\right\},\min_{i=\overline{1,m}}\left\{t^i_{s_2r}\right\}\right]\right\|}: I_0^i\left(t^i_{s_2r}\right)\geq I_0^-, t^i_{a_1r}\in\left[t^i_{s_1r},t^i_{s_2r}\right], r\in\left[1,n_r\right], i=\overline{1,m}\right\}. \quad (3)$$

The task consists in evaluating and rationally coordinating the margin of permissible risk R_i^{perm} $\forall\tilde{y}_i, i=\overline{1,m}$ for abnormal mode situations, which are implemented during time intervals

$$\left[t^i_{a_1r},t^i_{s_2r}\right]\subset T_R, r\in\left[1,n_r\right] i=\overline{1,m}.$$

Here, the corresponding values of risk degree and risk level do not exceed

$$\eta_i\left(\tilde{y}_i\left(t^i_{s_2r}\right)\right) \text{ and } W_i\left(\tilde{y}_i\left(t^i_{s_2r}\right)\right)$$

values in a finite time instance of the interval

$$\left[t^i_{s_1r},t^i_{s_2r}\right]\subset T_R\ \forall i=\overline{1,m}$$

to search the additional information, and the integral informedness index values

$$I_0^i\left(t_k\right), t_k\in\left[t^i_{s_1r},t^i_{s_2r}\right]\subset T_R$$

are no lower than

$$I_0^-=\min_{i\in[1,m]}\left\{\overline{I_0^i\left(t_k\right)}\right\}, t_k\in\left[t^i_{fr},t^i_{rr}\right].$$

4. 2. The mathematical models to evaluate and rationally coordinate the values of the permissible risk margin

The mathematical model to evaluate the values for margin of permissible risk $R_i^{perm}\Big|i=\overline{1,m}$ is implemented based on the relation (2) in the following form:

$$R_i^{perm}=\frac{\max\limits_{t_k^i\in\left[t^i_{s_1r},t^i_{s_2r}\right]}\left\{\left|\left[t^i_k,t^i_{s_2r}\right]\right|, t^i_k\in\left[t^i_{s_1r},t^i_{s_2r}\right]\subset T_R, t^i_k<t^i_{s_2r}\right\}}{\left|\left[t^i_{s_1r},t^i_{s_2r}\right]\right|},$$

$$r\in\left[1,n_r\right], i=\overline{1,m} \quad (4)$$

with the restrictions

$$\eta_i\left(\tilde{y}_i\left(t^i_k\right)\right)<\eta_i\left(\tilde{y}_i\left(t^i_{s_2r}\right)\right), W_i\left(\tilde{y}_i\left(t^i_k\right)\right)<$$
$$<W_i\left(\tilde{y}_i\left(t^i_{s_2r}\right)\right), t^i_k\in\left[t^i_{s_1r},t^i_{s_2r}\right],\ r\in\left[1,n_r\right], i=\overline{1,m}, \quad (5)$$

$$I_0^i\left(t^i_{s_2r}\right)\geq I_0^-,\ r\in\left[1,n_r\right], i=\overline{1,m}. \quad (6)$$

The notation $\left|\left[t^i_k,t^i_{s_2r}\right]\right|$ in (4) characterizes the length of the time interval with endpoints, which correspond to values of $\tilde{y}_i\left(t^i_k\right)$ and $\tilde{y}_i\left(t^i_{s_2r}\right)$.

Based on the relation (3), that was intended to coordinate the margin of permissible risk $R_i^{perm}\Big|i=\overline{1,m}$, the mathematical model is implemented in the following form:

$$R_c^{perm}=\frac{\left\|\left[\min_{i=\overline{1,m}}\left\{t^i_{a_1r}\right\},\min_{i=\overline{1,m}}\left\{t^i_{s_2r}\right\}\right]\right\|}{\left\|\left[\min_{i=\overline{1,m}}t^i_{s_1r},\min_{i=\overline{1,m}}t^i_{s_2r}\right]\right\|},$$

$$t^i_{a_1r}\in\left[t^i_{s_1r},t^i_{s_2r}\right], r\in\left[1,n_r\right], i=\overline{1,m} \quad (7)$$

with the restrictions

$$t^i_{s_1r}\leq t^i_{a_1r}<t^i_{s_2r}, t^i_{s_1r}, t^i_{s_2r}\in T_R,$$
$$r\in\left[1,n_r\right], i=\overline{1,m}, \quad (8)$$

$$I_0^i\left(t^i_{s_2r}\right)\geq I_0^-, r\in\left[1,n_r\right], i=\overline{1,m}. \quad (9)$$

The mathematical models are used in the basis of a computational algorithm of CES operating while taking into account the margin of permissible risk.

4. 3. The algorithm of a system evaluation and rational coordination of the permissible risk margin

The algorithm is represented by the procedure sequence to implement mathematical models described in (4)–(6), (7)–(9).

– Forming the set

$$T_R=\left\{\left[t^i_{fr},t^i_{rr}\right]\Big|\ t^i_{fr}<t^i_{rr}, t^i_{rr}<t_{cr},\right.$$
$$\left.t^i_{fr},t^i_{rr}\in D_0\bigcup D_p, r\in\left[1,n_r\right], i=\overline{1,m}\right\}$$

of intervals for time t^i_{fr} to form and time t^i_{rr} to implement the decision for the r-th abnormal mode situations related to $\tilde{y}_i$ based on restrictions

$$\eta\left(\tilde{y}_i\right)\leq\eta_{perm}\left(y_{ir}^{perm}\right),\ W\left(\tilde{y}_i\right)\leq W_{perm}\left(y_{ir}^{perm}\right).$$

– Determining $\hat{I}^i_V$, $\hat{I}^i_C$, $\hat{I}^i_T$ preliminary evaluations of the informedness veracity index, informedness completeness index, and informedness timeliness index, respectively, while taking into account the opinions of a group of experts based on the 7-level scale of ratings.

– Forming the sets of values for the informedness veracity index

$$I_V=\left\{I_V^i\left(t_k\right)\Big|t_k\in\left[t^i_{fr},t^i_{rr}\right], i=\overline{1,m}\right\},$$

the informedness completeness index

$$I_C=\left\{I_C^i\left(t_k\right)\Big|t_k\in\left[t^i_{fr},t^i_{rr}\right], i=\overline{1,m}\right\},$$

the informedness timeliness index

$$I_T=\left\{I_T^i\left(t_k\right)\Big|t_k\in\left[t^i_{fr},t^i_{rr}\right], i=\overline{1,m}\right\},$$

the integral informedness index

$$I_0=\left\{I_0^i\left(t_k\right)\Big|t_k\in\left[t^i_{fr},t^i_{rr}\right], i=\overline{1,m}\right\}$$

using the formulas from (1).

– Determining

$$I_0^-=\min_{i\in[1,m]}\left\{\overline{I_0^i\left(t_k\right)}\right\}\forall\ t_k\in\left[t^i_{fr},t^i_{rr}\right], k=\overline{1,K}, r\in\left[1,n_r\right],\ i=\overline{1,m}$$

that characterizes the rational level of the integral informedness index.

– Determining the time intervals of

$$\left[t^i_{s_1r}, t^i_{s_2r}\right] \subseteq \left[t^i_{fr}, t^i_{rr}\right] \subset T_R,\ r \in \left[1, n_r\right],\ \ i = \overline{1,m}$$

to search the additional information on decision making by a decision maker taking into account the conditions

$$I^i_0(t_k) \geq I^-_0,\ t_k \in \left[t^i_{s_1r}, t^i_{s_2r}\right],\ r \in \left[1, n_r\right],\ i = \overline{1,m}\ \ \forall\, \tilde{y}_i,\ i = \overline{1,m}$$

related to the integral informedness index.

– Determining the time intervals of

$$\left[t^i_{a_1r}, t^i_{s_2r}\right] \subseteq \left[t^i_{s_1r}, t^i_{s_2r}\right] \subset T_R,\ r \in \left[1, n_r\right],\ i = \overline{1,m}$$

based on the mathematical model of (4)–(6), where the margin of permissible risk is implemented.

– Determining based on the mathematical model (7)–(9) the time interval of $\left[t^r_{ca_1}, t^r_{cs_2}\right]$, where the coordinated margin of permissible risk

$$R^{perm}_i\ \forall \tilde{y}_i = \Phi_i\left(\left\{x_j \middle| j = \overline{1,n}\right\}\right),$$

$$I^i_0(t_k) \geq I^-_0,\ t_k \in \left[t^i_{a_1r}, t^i_{s_2r}\right],\ r \in \left[1, n_r\right],\ i = \overline{1,m}$$

evaluated as R^{perm}_c is implemented.

5. Application of the algorithm for the operation process of water supply system under destabilizing factors and various types of uncertainties

The described technique of the system evaluation and coordination for the margin of permissible risk is implemented using a water supply system (WSS) as an example, where the water level in the reservoir and the water pressure at the water inlet of a technological object are used as indicators; the values of these indicators characterize the state of the system at each time instance during its operating. The malfunctions or the failures of WSS equipment, external influences may cause a technogenic accident or social collapse. In the initial time interval $D_0 \subset [93; 451]$, with the given length of $|D_0| = 73$, the values of mentioned earlier indicators during WSS operating correspond to the state of a deep-well pump; the forecast period represents the interval $D_p = [74; 88]$. The real values of these operating indicators on restored and constructed in real time functional dependencies

$$\tilde{y}_i = \Phi\left(\left\{x_j \middle| j = \overline{1,4}\right\}\right),\ i = \overline{1,2},$$

while taking into account the forecast for the time interval D_p, correspond to the values of risk degree and risk level.

Fig. 1 displays actual values of indicators y_1 and y_2 versus time (curves 1 and 2). The permissible values of operating indicators in abnormal and emergency situations constitute

$$y^{perm}_1 = \{39;\ \ 2\},\ \ y^{perm}_2 = \{100;\ \ 50\}$$

respectively. In corresponding to operating indicators permissible values of the risk degree constitute

$$\eta\left(y^{perm}_1\right) = \{0{,}003; 1{,}0\},\ \ \eta\left(y^{perm}_2\right) = \{0{,}002; 1{,}0\};$$

permissible values of the risk level constitute

$$W\left(y^{perm}_1\right) = \left\{9 \cdot 10^{-6}; 0{,}949\right\},\ \ W\left(y^{perm}_2\right) = \left\{2 \cdot 10^{-6}; 0{,}5\right\}.$$

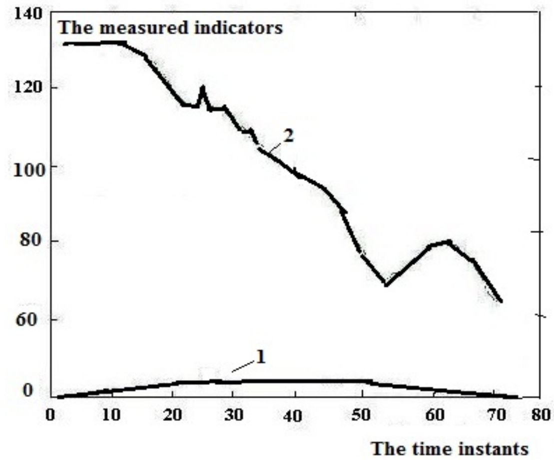

Fig. 1. The actual values of indicator y_1 for the water level in the reservoir versus time (curve 1) and indicator y_2 for the water pressure in the inlet of the technological object (curve 2) during WSS operating related to the state of the deep-well pump

Using the sample $\left\langle Y(t_k), X(t_k) \middle| t_k \in D_0 \right\rangle$ of measured operating indicators and parameters for WSS, the functional dependencies $\tilde{y}_1$ for the water level in the reservoir and $\tilde{y}_2$ for the water pressure in the inlet of the technological object are restored with the approximation accuracy, which came to 4,03–4,11 percentagewise, based on displaced Chebyshev polynomials of the 11-th degree. Wherein $\tilde{y}_1$ and $\tilde{y}_2$ are considered as the functions of the parameters in set X, including the total water consumption, pressure at the pump's discharge, quantity of working pumps, speed of the controlled pump. The forecast is made for the interval $D_p = [74; 88]$.

On the time interval

$$T_R = [1; 79] \subset D_0 \bigcup D_p = [1; 88]$$

during the water supply system operation, the abnormal situations are detected concerning $\tilde{y}_1$ and $\tilde{y}_2$, that transitioned at time $t_{cr} = 80$ into an emergency situation with the risk level $W\left(\tilde{y}_2(t_{cr})\right) = 0{,}5308 > 0{,}5$ for $\tilde{y}_2$. At time $t = 79$, the value of the indicator $\tilde{y}_1$ reached $\tilde{y}_1(t = 79) = 37{,}21$ m with the risk degree of $3 \cdot 10^{-3} < \eta(\tilde{y}_1) = 0{,}048 < 1{,}0$ and the risk level of

$$9 \cdot 10^{-6} < W(\tilde{y}_1) = 0{,}0333 < 0{,}949;$$

the value of the indicator $\tilde{y}_2$ reached $\tilde{y}_2(t = 79) = 60{,}7$ m with the risk degree of $2 \cdot 10^{-3} < \eta(\tilde{y}_2) = 0{,}786 < 1{,}0$ and the risk level of

$$2 \cdot 10^{-6} < W(\tilde{y}_2) = 0{,}4442 < 0{,}5.$$

In the finite time of the interval $D_p = [74; 88]$, the value of $\tilde{y}_1(t = 88) = 36{,}58$ m was reached with the risk degree of

$$3 \cdot 10^{-3} < \eta(\tilde{y}_1) = 0{,}135 < 1{,}0$$

and the risk level of

$$9\cdot 10^{-6} < W(\tilde{y}_1) = 0{,}035 < 0{,}949\,,$$

that corresponded to an abnormal situation; the indicator value of $\tilde{y}_2(t=88) < 50\ \mathrm{m}$ was reached with the risk degree of $\eta(\tilde{y}_2)=1{,}0$ and the risk level of $W(\tilde{y}_2)=0{,}5308$, that corresponded to an emergency situation. The time intervals of

$$\left[t^{i}_{s_1}, t^{i}_{s_2}\right]\Big| i=\overline{1,2}=\left\{\left([5;56],[3;56]\right),\left([5;60],[22,79]\right)\right\}\subset T_R=[1;79],$$

obtained in accordance with $I_0^i \ge I_0^- = \{0{,}965;0{,}863\}$ for $\tilde{y}_1$ and $\tilde{y}_2$, are intended for searching the additional information on decision making by a decision maker. On the curves 1 and 2 of Fig. 2 that illustrate the changes of the integral informedness indices I_0^1 and I_0^2, respectively, versus time over the time interval $T_R=[1;79]$, taking into account opinions of experts, the search for the additional information on decision making is performed in the time intervals of [3; 56] and [22; 79] with $I_0^i \ge I_0^- = 0{,}863,\ i=\overline{1,2}$.

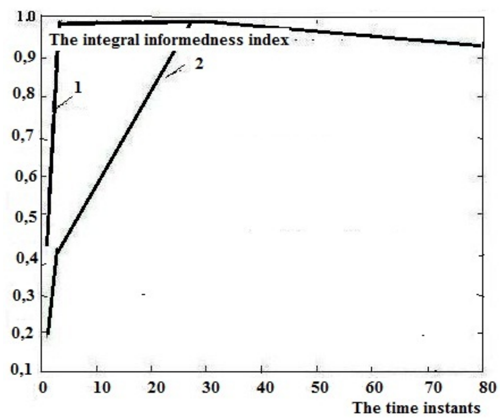

Fig. 2. The integral informedness indices versus time for WSS operating indicators (curves 1 and 2 are for $\tilde{y}_1$ and $\tilde{y}_2$, respectively) over the time interval that precedes time t_{cr}

Based on the mathematical model presented in (4)–(6) in the time intervals

$$\left[t^{i}_{s_1}, t^{i}_{s_2}\right]\Big| i=\overline{1,2}=\left\{\left([5;56],[3;56]\right),\left([5;60],[22,79]\right)\right\}\subset T_R=[1;79]$$

the time intervals of

$$\left[t^{i}_{a_1r}, t^{i}_{s_2r}\right]\Big| i=\overline{1,2}=\left\{\left([5;56],[3;56]\right),\left([50;60],[78;79]\right)\right\}$$

are selected, which can be used to prevent the situations of abnormal mode. The values for the margin of permissible risk, implemented in the specified time intervals, were $R_1^{perm}=\{1{,}0;\ \ 1{,}0\}$ for $\tilde{y}_1$ and $R_2^{perm}=\{0{,}182;0{,}0175\}$ for $\tilde{y}_2$. On the curves 1 and 2 (Fig. 3) of functional dependencies $\tilde{y}_1$, $\tilde{y}_2$, correspondingly, the time intervals of [3; 56], [78; 79] are highlighted, that are used to prevent an abnormal situation for $\tilde{y}_1$ and an emergency situation for $\tilde{y}_2$. In the specified intervals, the values of the integral informedness index are $I_0^i \ge I_0^- = 0{,}863,\ \ i=\overline{1,2}$; values for the margin of permissible risk are $R_i^{perm}=\{1{,}0;\ \ 0{,}0175\},i=\overline{1,2}$.

The coordinated values for the margin of permissible risk as $R_1^{perm}=\{1{,}0;\ \ 1{,}0\}$ for $\tilde{y}_1$ and $R_2^{perm}=\{0{,}182;0{,}0175\}$ for $\tilde{y}_2$, computed based on the mathematical model, which presented in (7)–(9), while taking into account $I_0^-=\{0{,}965;0{,}863\}$, are implemented in the time intervals of {[5;56]; [3;56]}; the values for coordinated margin of permissible risk were $R_c^{perm}=\{1{,}0;1{,}0\}$. The declared time intervals can be used to implement the guaranteed prevention of an abnormal situation for $\tilde{y}_1$ and an emergency situation for $\tilde{y}_2$.

The research of proposed technique was carried out on the example of the real functioning of the water supply system with the indicators characterizing the state of the system at each time instants of the operating period. As the result of systemic evaluation in operating the technical object in real-time there are detected the situations of specified abnormal mode with unavoidable threshold restriction of t_{cr}. The margin of permissible risk for operating indicators and its coordinated value, obtained while taking into account the integral informedness indices, guarantee the prevention of certain abnormal mode. On the above example, the operation of water supply system is provided by the transition from the abnormal situation to the nominal situation and from the emergency situation to the abnormal situation. In further studies, there is envisaged to evaluate the margin of permissible risk by a vector measure implemented for types' variety of abnormal mode.

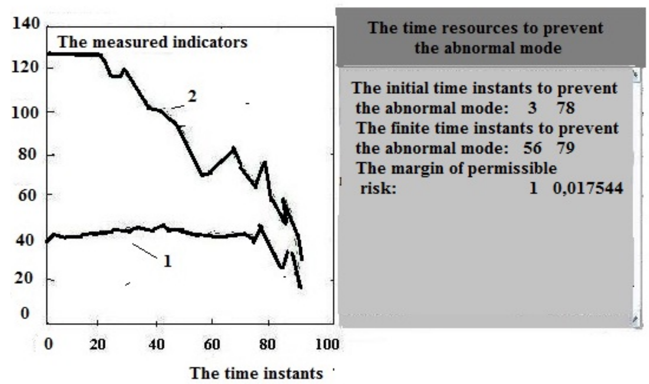

Fig. 3. The values of time resources to prevent the abnormal mode for WSS operating indicators (curve 1 and 2 for $\tilde{y}_1$ and $\tilde{y}_2$, correspondingly) in a time interval, which precedes t_{cr}

6. Conclusions

As a result of studies:

– for each CES operating indicator, the margin of permissible risk is evaluated with the implementation in the time intervals, using them to prevent the situations of the specific abnormal conditions;

– the coordinated margin of permissible risk value is evaluated for CES operating indicators with the implementation in the time interval using as a guarantee to prevent the situation of the specific abnormal conditions.

The proposed technique is intended for system evaluation of real CES operating taking into account the margin of permissible risk. A distinctive feature of this technique is the usage of the principle to timely detect and eliminate the causes for the situations of abnormal mode under the influence of destabilizing factors and different type uncertainties.

The guaranteed prevention of the specified abnormal mode situation is implemented by the coordination for the margin of permissible risk in a given time interval in order to maintain the required indicator values for CES operating in a normal mode while taking into account the integral informedness index about situations and unavoidable threshold time limit at time t_{cr}.

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