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OPTIMIZATION PARAMETERS OF THE MAINTENANCE STRATEGY "ON CONDITION" WITH A CONSTANT FREQUENCY OF CONTROL

Abstract

In this article, the optimization parameters of maintenance strategy "on condition" with a constant frequency of control is carried out. During the operation of complex technical objects, as a rule, maintenance is carried out to maintain the required level of object reliability. It is known that the most effective principle of maintenance organization is "maintenance by condition" (MC), according to which maintenance operations are carried out only if it is required by the actual technical condition (TC) of the object. In order to be able to determine the actual TC of an object during operation, it is necessary to develop and "embed" in the object tools for measuring the determining parameters of the most unreliable elements even at the stage of its creation. To do this, the developer needs mathematical models with which to estimate the expected costs of embedding measuring instruments and the expected gain from maintenance during the operation of facility.

Currently, there are no satisfactory models that allow one to obtain such estimates. In this article, an attempt is made to partially fill this gap - models are proposed that allow predicting the indicators of reliability and cost of operating an object, taking into account MC. The article also developed methods to determine the optimal parameters of various maintenance strategies.

The problem is that when developing such facilities, all issues related to maintainability and maintenance should be addressed already at the early stages of the design of the facility. If you do not provide in advance the necessary hardware and software for integrated monitoring of the technical condition (TC) of the object, do not develop and "embed" maintenance technology into the object, then it will not be possible to realize in the future a possible gain in the reliability of object due to maintenance. Since all these issues must be resolved at the stage of creating an object (when the object does not yet exist), mathematical models of the maintenance process are needed, with the help of which it would be possible to calculate the possible gain in the level of reliability object due to maintenance, to estimate the cost costs required for this. Then, based on such calculations, make a decision on the need for maintenance this type of objects and, if such a decision is made, develop the structure of maintenance system, choose the most appropriate maintenance strategy, and determine its optimal parameters.

Keywords: maintenance, actual technical condition, optimization of strategy parameters, technical condition control

Introduction

Complex technical objects in modern society are extremely important. First of all, we are talking about various radio-electronic complexes for military and special purposes, radar stations, automated control systems (air traffic, energy facilities, etc.). The level of reliability such facilities depends on the defense capability of state, economic security, the lives of hundreds and thousands of people.

Such objects belong to the class of recoverable objects of long-term multiple use. They tend to be expensive and require significant maintenance costs. To ensure the required level of reliability during their operation, maintenance is usually carried out, the essence of which is the timely preventive replacement of elements that are in a pre-failure state.

A characteristic feature of complex technical objects for special purposes is the presence in their composition of a large number (tens, hundreds of thousands) of different types components that have different levels of reliability, different patterns of their wear and aging processes. This feature requires a more subtle approach to the organization and planning of maintenance during their operation.

Currently, there is a decline in the number of scientific publications devoted to the maintenance of complex technical objects. One of the reasons for this, in our opinion, is a sharp increase in the level of integration and reliability of components. Thanks to this, the developers of complex equipment managed to solve the issues of ensuring the required level of reliability without significant maintenance costs (or without maintenance at all). However, the same reason (high integration and reliability of components) opened up the possibility of implementing more and more complex equipment with new functions, which was impossible with the old element base. This again objectively leads to problems of ensuring reliability and, therefore, the question of need for maintenance and the choice of optimal strategy for its implementation again becomes relevant.

Unfortunately, currently known mathematical models and methods for calculating the optimal parameters of maintenance processes are not very suitable for application to real technical objects. The main drawback of these models is that they either do not take into account the complex structure of the object at all, or it is possible to take into account only some of the simplest structures [1, 2]. In [3], a comparative analysis of the problems that arise in solving the problems of maintenance “by resource” and “by state” is carried out. An overview of the latest works in the field of maintenance and repair of complex systems is given. In [4], a theoretical generalization of the known mathematical models of TC processes was made. However, these models do not allow one to build methods suitable for practical use on their basis.

Even worse, in our opinion, is the situation with mathematical models of TC processes “by state”. Only a small number of scientific works are devoted to this line of research [5, 6].

Thus, the article solves an urgent scientific problem of developing methods and tools (software) for determining the optimal parameters of the maintenance strategy “by state” of complex technical objects.

Materials and methods

Formalized description of the methodology.

The problem of optimizing the parameters of MC strategy with a constant frequency of control can be represented as follows:

$$T_0(E^*_{\text{то}}, U^*_{\text{то}}, T^*_{\text{к}}) \geq T_0^{\text{тр}}; \tag{1 а}$$

$$c_{\text{уд}}(E^*_{\text{то}}, U^*_{\text{то}}, T^*_{\text{к}}) \to \min\ , \tag{1 б}$$

where $T_0^{\text{тр}}$ - is the given required value of the mean time between failures of the object;

$E^*_{\text{то}}$, $U^*_{\text{то}}$ and $T^*_{\text{к}}$ - are the desired optimal values of the corresponding parameters.

This problem cannot be solved by strict analytical optimization methods, only an approximate solution of the problem is possible. Let us consider a technique for an approximate solution of problem (1) based on the use of ISM and software that implements it (ISMPN program).

If at some step all the elements $E_{\text{то}}$ selected from are exhausted ($k = |E_{\text{то}}|$), then this will mean that the original problem (1) has no solution – specified requirement $T_0^{\text{тр}}$ cannot be met.

If, despite this, the task still remains relevant, then to solve it, you need to:

- increase the level of reliability of the facility;
- expand the set of potentially serviceable elements $E_{\text{то}}$, or
- reduce the required level of object $T_0^{\text{тр}}$ reliability.

Results

The considered technique is implemented by the user (expert) using ISMPN program. To apply the technique, it is necessary, firstly, to create a database for the object for which problem is supposed to be solved, and, secondly, to perform a step-by-step search for a solution in accordance with the technique considered above. At each (*k*-th) step, user needs to perform the following actions (points):

1) add to the subset of serviced elements $E_{\text{то}}^+$ (initially empty) one element taken from the set $E_{\text{то}}$;

2) to perform simulation and find a conditionally optimal solution $\mathbf{STO}_S^+ = \langle E_{\text{то}}^+, U_{\text{то}}^+, T_{\text{к}}^+ \rangle$;

3) determine the achieved value of the mean time between failures T_0^+ and check the fulfillment of the requirement $T_0^+ \geq T_0^{\text{тр}}$. If the requirement is not met, return to step 1 and continue the search process. Otherwise, follow the next (final) point;

4) take the conditionally optimal solution obtained as the optimal solution $\mathbf{STO}_S^+$ of the problem $\mathbf{STO}_S^* = \langle E_{\text{то}}^*, U_{\text{то}}^*, T_{\text{к}}^* \rangle$.

Consider the technology for performing each of these items.

1. Formation of a set of serviced elements $E_{\text{то}}^+$.

Open the ISMPN program in Database mode. On the Object composition and structure page, select an element in the object constructive structure tree to be included in set $E_{\text{то}}^+$. Then, in the table that displays data on the selected object, in the PW (recovery sign) column, enter the value "in" (serviced element) for this element.

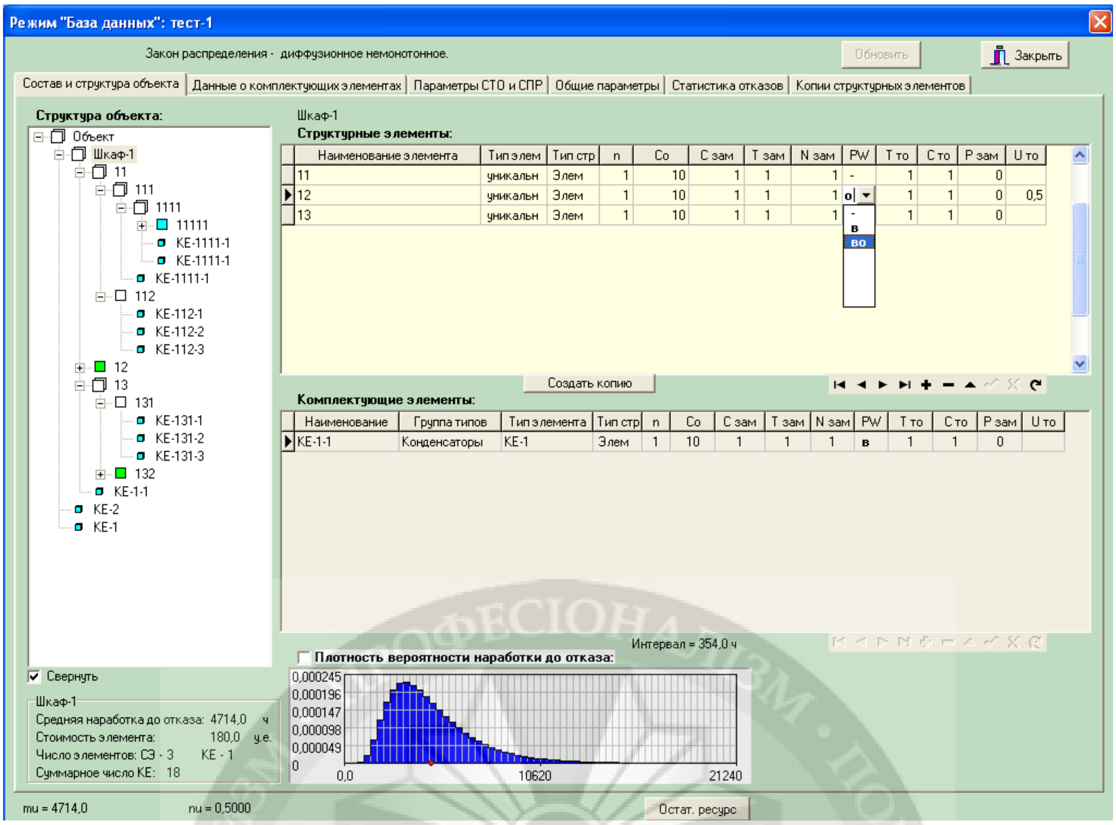
All elements for which the attribute "in" is set will be automatically included in the current set of serviced elements $E_{\text{то}}^+$.

The set of potentially serviceable elements $E_{\text{то}}$ is determined by the user in advance, before the start of calculations by this method.

2. Formation of a conditionally optimal solution $\mathbf{STO}_S^+$.

Calculations in order to determine the conditionally optimal solution are performed in the following sequence:

- open the ISMPN program in TC Study mode | Variation Uto+Tk. (Fig. 1 shows the view of PC screen after the completion of the calculations);
- introduce boundaries and intervals for varying the frequency of control $T_{\text{к}}$ and the level of maintenance $u_{\text{то}k}$. The parameters of periodicity $T_{\text{к}}$ variation are selected in such a way as to find the minimum of function $c_{\text{уд}}^+(T_{\text{к}})$ with sufficient accuracy. The range of variation $u_{\text{то}k}$ is recommended to be set to [0.1; 0.9], variation interval – 0.05;
- press the Start and run simulation button.



Закон распределения - диффузионное немонотонное.

Шкаф-1

Структурные элементы:

Наименование элемента	Тип элем	Тип стр	n	Co	C зам	T зам	N зам	PW	T то	C то	P зам	U то
11	уникальн	Элем	1	10	1	1	1	-	1	1	0	
12	уникальн	Элем	1	10	1	1	1	о	1	1	0	0,5
13	уникальн	Элем	1	10	1	1	1		1	1	0	

Комплектующие элементы:

Наименование	Группа типов	Тип элемента	Тип стр	n	Co	C зам	T зам	N зам	PW	T то	C то	P зам	U то
КЕ-1-1	Конденсаторы	КЕ-1	Элем	1	10	1	1	1	в	1	1	0	

Интервал = 354,0 ч

☐ **Плотность вероятности наработки до отказа:**

☑ Свернуть

Шкаф-1
Средняя наработка до отказа: 4714,0 ч
Стоимость элемента: 180,0 у.е.
Число элементов: СЭ - 3 КЕ - 1
Суммарное число КЕ: 18

mu = 4714,0
nu = 0,5000

Fig. 1 Entering the attribute “in” for element “12”

All elements for which the attribute “in” is set will be automatically included in the current set of serviced elements $E^{+}_{\text{то}}$.

The set of potentially serviceable elements $E_{\text{то}}$ is determined by the user in advance, before the start of calculations by this method.

1. Formation of a conditionally optimal solution $\mathbf{STO}^{+}_{S}$.

Calculations in order to determine the conditionally optimal solution are performed in the following sequence:

- open the ISMPN program in TC Study mode | Variation Uto+Tk. (Fig. 1 shows the view of the PC screen after the completion of the calculations);
- introduce boundaries and intervals for varying the frequency of control $T_{\text{к}}$ and the level of maintenance. The parameters of periodicity $T_{\text{к}}$ variation are selected in such a way as to find the minimum of the function $c^{+}_{\text{уд}}(T_{\text{к}})$ with sufficient accuracy. The range of variation $u_{\text{то}\,k}$ is recommended to be set to [0.1; 0.9], variation interval – 0.05;
- press the Start and run simulation button.

After the simulation is completed, the graphs of the functions $u^{+}_{\text{то}\,k}(T_{\text{к}})$, $c^{+}_{\text{уд}}(T_{\text{к}})$, $T^{+}_{0}(T_{\text{к}})$ and $K^{+}_{\text{ти}}(T_{\text{к}})$, will be displayed, as shown in fig. 1. $T^{+}_{0}(T_{\text{к}})$ and $K^{+}_{\text{ти}}(T_{\text{к}})$ – are functions of the corresponding indicators and obtained with the optimal vector $U^{+}_{\text{то}}$.

If it turned out that the function $c^{+}_{\text{уд}}(T_{\text{к}})$ does not have a pronounced minimum (the minimum is obtained at the edge of the range $[T_{\text{к}1}, T_{\text{к}2}]$), it is necessary to change the boundaries and accordingly, $T_{\text{к}1}$ and $T_{\text{к}2}$ re-execute the simulation.

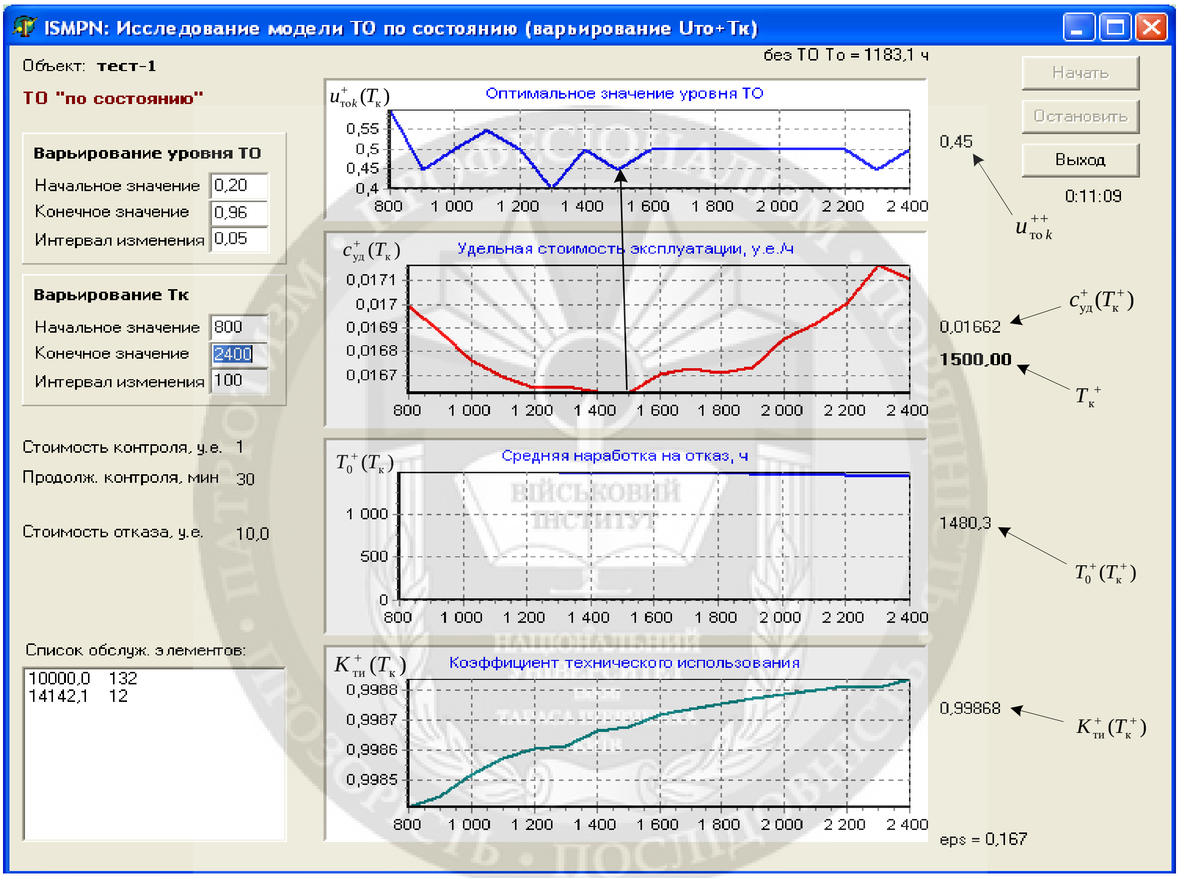
- according to graph $c^{+}_{\text{уд}}(T_{\text{к}})$, the optimal value $T^{+}_{\text{к}}$ is found that satisfies the condition (4);

- according to schedule $u^{+}_{\text{то}k}(T_{\text{к}})$, the value of TC $u^{++}_{\text{то}k}$ level corresponding to the optimal value $T^{+}_{\text{к}}$ is determined (expression (5));
- according to schedule $T^{+}_{0}(T_{\text{к}})$, value of the mean time between failures achieved in the current step is determined $T^{+}_{0} = T_{0}\,(T^{+}_{\text{к}})$.

The found optimal value $T^{+}_{\text{к}}$ and the corresponding values $u^{++}_{\text{то}k}$, $c^{+}_{\text{уд}}$, T^{+}_{0} and $K^{+}_{\text{ти}}(T_{\text{к}})$, are displayed on the right, next to the graphs.

- obtained values $U^{+}_{\text{то}}$ and $T^{+}_{\text{к}}$ are taken as the values of the corresponding parameters of the conditionally optimal solution:

$$\mathbf{STO}^{+}_{S} = \left\langle E^{+}_{\text{то}}, U^{+}_{\text{то}}, T^{+}_{\text{к}} \right\rangle.$$



Объект: тест-1

ТО "по состоянию"

Варьирование уровня ТО

Начальное значение 0,20

Конечное значение 0,96

Интервал изменения 0,05

Варьирование Тк

Начальное значение 800

Конечное значение 2400

Интервал изменения 100

Стоимость контроля, у.е. 1

Продолж. контроля, мин 30

Стоимость отказа, у.е. 10,0

Список обслуж. элементов:

10000,0 132
14142,1 12

0:11:09

eps = 0,167

Fig. 2 PC screen view showing function graphs $u^{+}_{\text{то}}(T_{\text{к}})$, $c^{+}_{\text{уд}}(T_{\text{к}})$, $T^{+}_{0}(T_{\text{к}})$ and $K^{+}_{\text{ти}}(T_{\text{к}})$

1. Evaluation of the results obtained at *k*-th step of solving the problem.

Based on the mean time between failures obtained $T^{+}_{0} = T_{0}(\mathbf{STO}^{+}_{S})$ in the current step, the condition is checked $T^{+}_{0} \geq T^{\text{тр}}_{0}$.

If the condition is met, then the conditionally optimal solution $\mathbf{STO}^{+}_{S}$ obtained is accepted as the final solution of the problem:

$$\mathbf{STO}^{*}_{S} := \mathbf{STO}^{+}_{S}.$$

The process of finding a solution in this case is completed.

Otherwise, if $T^{+}_{0} < T^{\text{тр}}_{0}$, it is necessary to return to point 1, add one more serviced element to the set $E^{+}_{\text{то}}$ and repeat the calculations.

We will illustrate the application of the technique on the example of the test object Test-1. The object has 15 recoverable elements. For example, let's set that potentially serviced among them are the 5 least reliable elements, the data on which are given in table. Since all elements are connected (in the sense of reliability) in series, the coefficient of variation in the distribution of operating time to failure of serviced elements is the same as for elements of the lower level, i.e. $\nu_i = 1$.

Table 1

Characteristics of potentially serviceable elements of object Test-1

Element number	Element name	Средняя наработка до отказа $T_{\text{ср}i}$, h
1	132	10000
2	12	14142
3	11111	14142
4	КЕ-131-1	20000
5	КЕ-131-2	20000

For simulation, we set the following parameters:

$T_{э}$ = 20 years; $c_{п}^{0}$ = 10 c.u./h; $\varepsilon^{\text{тр}}$ = 0.2; $N_{I}^{\max}$ = 500;

We will perform the calculations in sequence in accordance with the considered technology.

1. At the 1st step, we include the element 132 in the set $E_{\text{то}}^{+}$: $E_{\text{то}}^{+}$ ={132}.
2. Open ISMPN program in TC Research | Variation Uto+Tk and set the following variation parameters:

- for $u_{\text{то}}$: $u_{\text{то}} \in [0{,}1;\ 0{,}9]$; $\Delta u_{\text{то}}$ = 0,05;
- for $T_{\text{к}}$: $[T_{\text{к}1}, T_{\text{к}2}]$ = [800 h, 2400 h]; $\Delta T_{\text{к}}$ = 100 h.

After that, we will make a simulation. On fig. 3 shows results of the simulation.

According to the graph of the function $c_{\text{уд}}^{+}(T_{\text{к}})$, we find its minimum and the conditionally optimal value corresponding to it $T_{\text{к}}^{+}$. Then, according to the graph $u_{\text{то}1}^{+}(T_{\text{к}})$, we find the conditionally optimal value of $u_{\text{то}1}^{++} = u_{\text{то}1}^{+}(T_{\text{к}}^{+})$. As a result, we get:

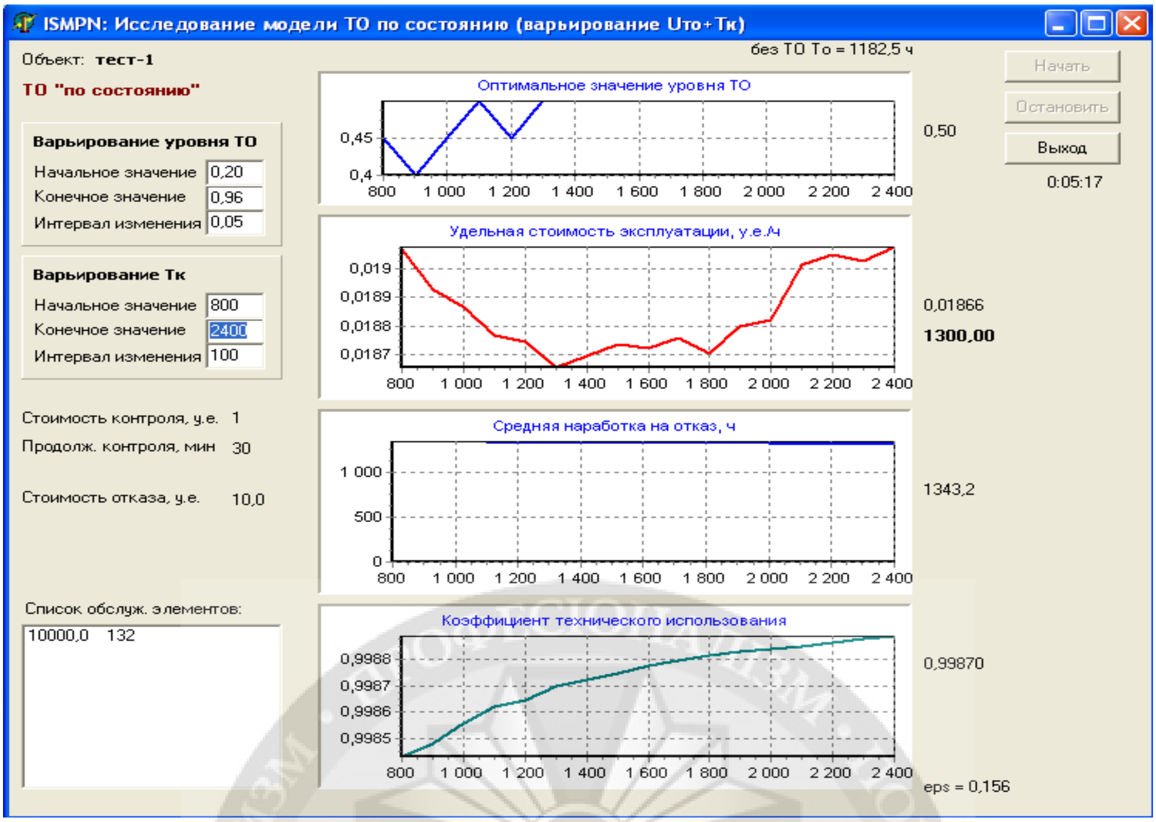
$T_{\text{к}}^{+}$ = 1300 h; $u_{\text{то}1}^{++}$ = 0,5.

According to the schedule $T_{0}^{+}(T_{\text{к}})$, we determine the achieved value of the mean time between failures T_{0}^{+} = 1343 h.

As a result of the calculations performed at the 1st step, we obtain the following conditionally optimal solution:

$\mathbf{STO}_{S}^{+} = \left\langle E_{\text{то}}^{+}, U_{\text{то}}^{+}, T_{\text{к}}^{+} \right\rangle = \left\langle \{132\}, \{0{,}5\}, 1300\,\text{h} \right\rangle$.

3. Taking into account the fact that the specified requirement for object reliability $T_{0}^{+} \geq T_{0}^{\text{тр}}$ = 1500 h is not fulfilled with the received MC $\mathbf{STO}_{S}^{+}$ parameters, it is necessary to perform the next step of search.


ISMPN: Исследование модели ТО по состоянию (варьирование Uто+Тк)

Объект: **тест-1**

ТО "по состоянию"

без ТО To = 1182,5 ч

Варьирование уровня ТО

Начальное значение 0,20
Конечное значение 0,96
Интервал изменения 0,05

Варьирование Тк

Начальное значение 800
Конечное значение 2400
Интервал изменения 100

Стоимость контроля, у.е. 1
Продолж. контроля, мин 30

Стоимость отказа, у.е. 10,0

Список обслуж. элементов:

10000,0 132

0,50

0,01866
1300,00

1343,2

0,99870

eps = 0,156

0:05:17

Fig. 3 Graphs of functions $u^{+}_{\text{то}}(T_{\text{к}})$, $c^{+}_{\text{уд}}(T_{\text{к}})$, $T^{+}_{0}(T_{\text{к}})$ and $K^{+}_{\text{ти}}(T_{\text{к}})$ for $E^{+}_{\text{то}}=\{132\}$ $(\nu_i = 1)$

But before that, it is necessary to open the database and for element 132 enter the conditionally optimal value of the TC $u^{++}_{\text{то}1}$ level obtained for it. The value $u^{++}_{\text{то}1}$ = 0.5 must be entered in Uto column for element 132, as shown in fig. 3.

After that, you can perform the next (2nd) step of finding a solution.

1. At the 2-nd step, we add the element 12 to the set $E^{+}_{\text{то}}$. As a result, we get set $E^{+}_{\text{то}}$ = {132, 12}.
2. Open the ISMPN program in the Research TC | Varying Uto + Tk and perform calculations in accordance with the technology discussed above. After calculations at the 2nd step, we obtain the following conditionally optimal solution:

$$\mathbf{STO}^{+}_{S} = \left\langle E^{+}_{\text{то}}, U^{+}_{\text{то}}, T^{+}_{\text{к}} \right\rangle = \left\langle \{132,12\};\ \{0{,}5;0{,}4\}, 1300\,\text{h} \right\rangle.$$

3. At 2-nd step, the mean time between failures T^{+}_{0} = 1485 hours is obtained. If this value also does not satisfy the specified requirement $T^{\text{тр}}_{0}$, then the next step is performed.

In table. Table 2 shows the results of calculations obtained in 5 steps of the search performed for all serviced elements available in the set $E_{\text{то}}$ (see Table 1).

Let the requirement for the reliability level $T^{\text{тр}}_{0}$ = 1500 h be set for the object Test-1. Then, based on the data obtained, we determine the following optimal MC parameters:

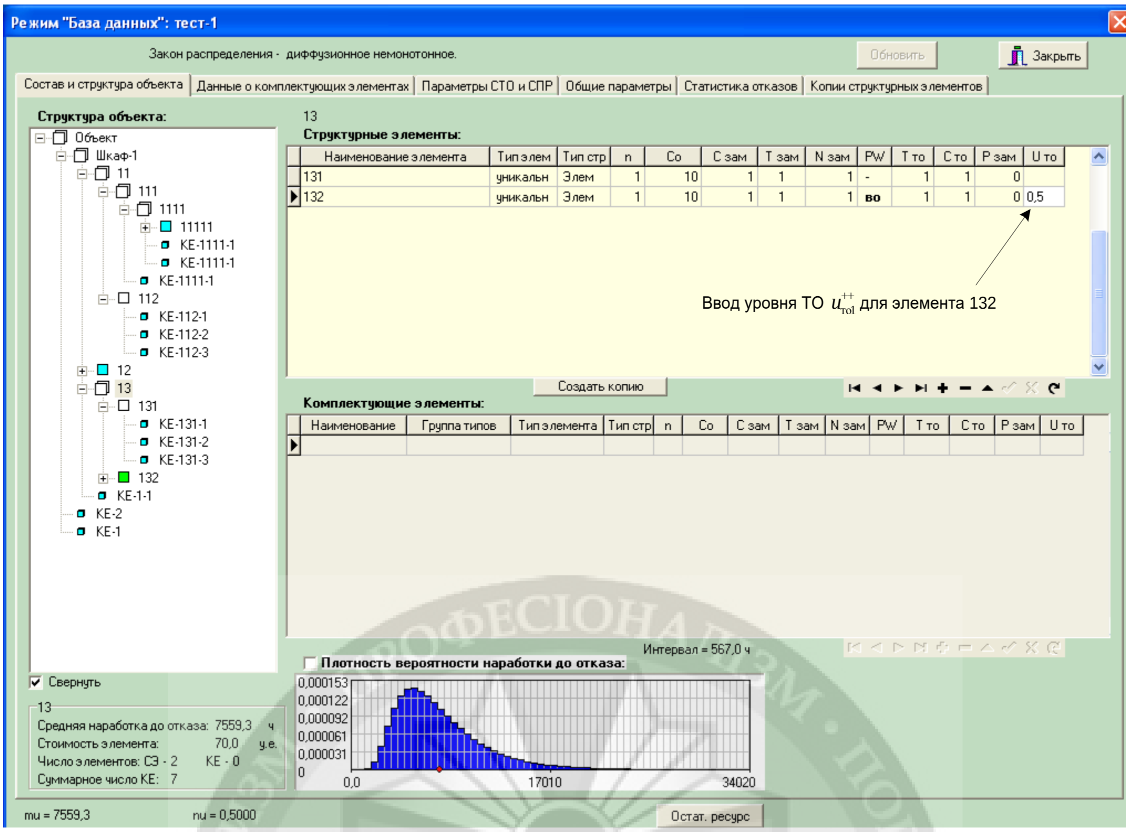
$$\mathbf{STO}^{*}_{S} = \mathbf{STO}^{+}_{S} = \left\langle \{132,12,11111\};\ \{0{,}5;0{,}4;0{,}5\}, 1200\,h \right\rangle.$$

With the obtained optimal MC $\mathbf{STO}^{*}_{S}$ parameters, the following values of indicators will be provided:

$T_0(\mathbf{STO}^{*}_{S})$ = 1660 h;

$c_{\text{уд}}(\mathbf{STO}^{*}_{S})$ = 0,01461 c.u./h;

$K_{\text{ти}}(\mathbf{STO}^{*}_{S})$ = 0,99851.



Закон распределения - диффузионное немонотонное.

13

Структурные элементы:

Наименование элемента	Тип элем	Тип стр	n	Co	C зам	T зам	N зам	PW	T то	C то	P зам	U то
131	уникальн	Элем	1	10	1	1	1	-	1	1	0	
132	уникальн	Элем	1	10	1	1	1	во	1	1	0	0,5

Ввод уровня ТО $u_{\text{то}l}^{++}$ для элемента 132

Комплектующие элементы:

Наименование	Группа типов	Тип элемента	Тип стр	n	Co	C зам	T зам	N зам	PW	T то	C то	P зам	U то

Интервал = 567,0 ч

☐ **Плотность вероятности наработки до отказа:**

13
Средняя наработка до отказа: 7559,3 ч
Стоимость элемента: 70,0 у.е.
Число элементов: СЭ - 2 КЕ - 0
Суммарное число КЕ: 7

mu = 7559,3
nu = 0,5000

Fig. 4 Enter maintenance $u_{\text{то}k}^{++}$ level for element 132

Table 2

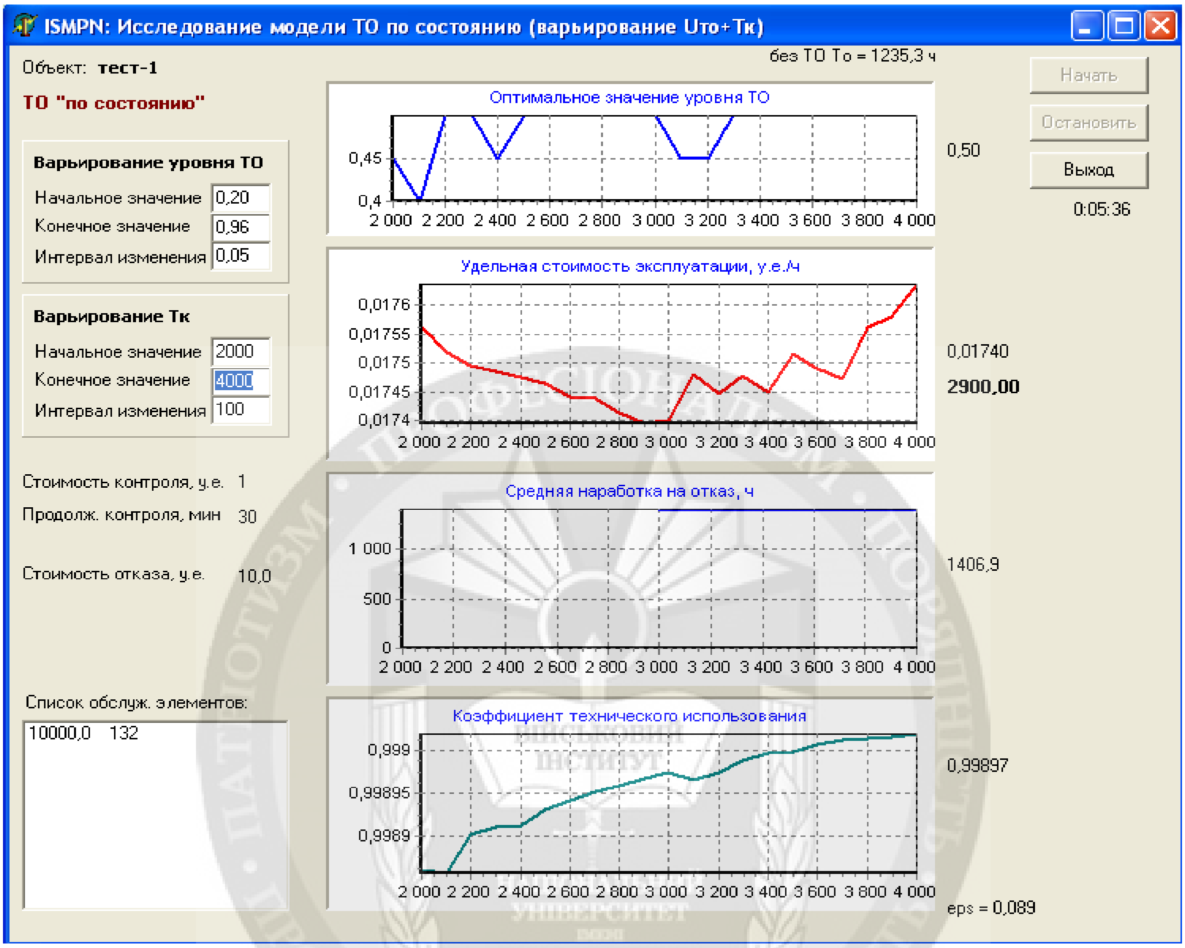
Calculation results of conditionally optimal MC parameters for object Test-1 ($\nu_i = 1$)

Step number k	Conditionally optimal parameters **STO**$_S^+$			Values of indicators obtained with conditionally optimal parameters **STO**$_S^+$			
	$E_{\text{то}}^+$	$u_{\text{то}k}^{++}$	$T_{\text{к}}^+$, h	T_0^+, h	$c_{\text{уд}}^+$, c.u./h	$K_{\text{ти}}^+$	ε
1	{132}	0,5	1300	1343	0,01866	0,99870	0,156
2	{132, 12}	0,4	1300	1485	0,01663	0,99861	0,171
3	{132, 12, 11111}	0,5	1200	1660	0,01461	0,99851	0,180
4	{132, 12, 11111, KE-131-1}	0,65	1300	1808	0,01361	0,99850	0,182
5	{132, 12, 11111, KE-131-1, KE-131-2}	0,65	1200	1988	0,01266	0,99847	0,198

The relative error of the simulation results at which these results were obtained is $\varepsilon = 0.180$.

This solution was obtained under the condition that the coefficient of variation of random time to failure ν_i for all elements of the object is the same and equal to 1. It is an interesting question: how will the optimal MC parameters change in the case of smaller values of ν_i. This issue seems important because many elements of real technical objects are characterized by the distribution of time to failure, which has a coefficient of variation that is significantly less than 1 (see table 3). To study this issue, we will make calculations for the object Test-1, obtained under the condition that the coefficient of variation ν_i for all elements is 0.5.

On fig. 6 shows the graphs of functions $u^{+}_{\text{то}}(T_{\text{к}})$, $c^{+}_{\text{уд}}(T_{\text{к}})$, $T^{+}_{0}(T_{\text{к}})$ and $K^{+}_{\text{ти}}(T_{\text{к}})$, obtained at the first step of calculations for the set $E^{+}_{\text{то}}$ ={132} at ν_i =0,5.



ISMPN: Исследование модели ТО по состоянию (варьирование Uто+Тк)

Объект: **тест-1**

ТО "по состоянию"

Варьирование уровня ТО

Начальное значение 0,20
Конечное значение 0,96
Интервал изменения 0,05

Варьирование Тк

Начальное значение 2000
Конечное значение 4000
Интервал изменения 100

Стоимость контроля, у.е. 1
Продолж. контроля, мин 30
Стоимость отказа, у.е. 10,0

Список обслуж. элементов:
10000,0 132

без ТО То = 1235,3 ч
0,50
0,01740
2900,00
1406,9
0,99897
eps = 0,089
0:05:36

Fig. 5 Graphs of functions $u^{+}_{\text{то}}(T_{\text{к}})$, $c^{+}_{\text{уд}}(T_{\text{к}})$, $T^{+}_{0}(T_{\text{к}})$ and $K^{+}_{\text{ти}}(T_{\text{к}})$ for $E^{+}_{\text{то}}$ ={132} (ν_i =0,5)

Table 3 shows the obtained conditionally optimal MC $\mathbf{STO}^{+}_{S}$ parameters and the corresponding values of the indicators T^{+}_{0}, $c^{+}_{\text{уд}}$ and $K^{+}_{\text{ти}}$.

According to the data obtained in table 3, and taking into account that $T^{\text{тр}}_{0}$ = 1500 h, for the case ν_i = 0.5, we obtain the following solution to problem (4):

$$\mathbf{STO}^{*}_{S} = \mathbf{STO}^{+}_{S} = \left\langle \{132,12\};\ \{0{,}5;0{,}5\}, 2900\,\text{h} \right\rangle .$$

This results in the following values:

$T_0(\mathbf{STO}^{*}_{S})$ = 1553 h;

$c_{\text{уд}}(\mathbf{STO}^{*}_{S})$ = 0,01541 c.u./h;

$K_{\text{ти}}(\mathbf{STO}^{*}_{S})$ = 0,99892 (ε = 0,099).

Using the Test-1 test object as an example, let's consider another question: what is MC process in the case of a strategy with a constant control frequency, and what are the characteristics of this process.

Table 3

Calculation results of conditionally optimal MC parameters for object Test-1 ($\nu_i = 0{,}5$)

Step number k	Conditionally optimal parameters **STO**$_S^+$			Values of indicators obtained with conditionally optimal parameters **STO**$_S^+$			
	$E^+_{\text{то}}$	$u^{++}_{\text{то}k}$	$T^+_{\text{к}}$, ч	T^+_0, ч	$c^+_{\text{уд}}$, у.е./ч	$K^+_{\text{ти}}$	ε
1	{132}	0,5	2900	1405	0,01740	0,99897	0,089
2	{132, 12}	0,5	2900	1553	0,01541	0,99892	0,099
3	{132, 12, 11111}	0,5	3000	1738	0,01340	0,99888	0,100
4	{132, 12, 11111, КЕ-131-1}	0,65	2700	1896	0,01248	0,99884	0,107
5	{132, 12, 11111, КЕ-131-1, КЕ-131-2}	0,45	2900	2086	0,01154	0,99881	0,113

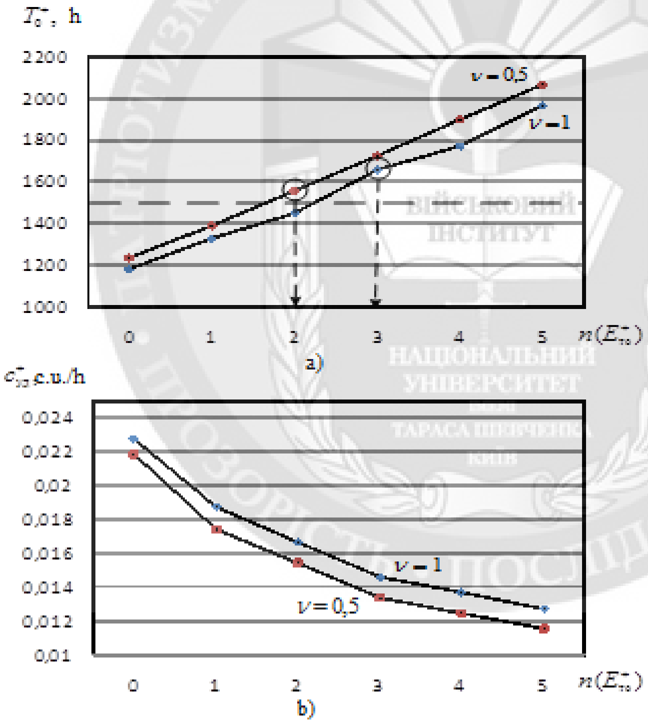


Fig. 6 Graphs of the dependence of indicators T_0^+ and $c^+_{\text{уд}}$ on the number of serviced elements $n(E^+_{\text{то}})$ for various values ν_i

It is obvious that this is a random process that occurs at discrete times, multiple of the frequency of control $T_{\text{к}}$. At each of these moments of time, TC of *i*-th element from the set $E^*_{\text{то}}$ is performed $p_{\text{то}i}$ with probability.

For research purposes, ISMPN program has built-in procedures that allow accumulating statistics on the number and frequency of maintenance of various elements over a given period of operation of the facility. According to the accumulated statistics, estimates of indicators are calculated:

$\overline{T}_{\text{то}\,i}$ - average frequency of maintenance *i*-th element;

$\nu_{\text{то}\,i}$ - coefficient of variation randoms periodicity of TO *i*-th element;

$\overline{n}_{\text{то}\,i}$ - average number of maintenance of *i*-th element, which is performed during a given period of operation of the object $T_{\text{э}}$.

In table 4 shows the estimates of these indicators obtained in the simulation example under consideration for the object Test-1.

Table 4

Characteristics of the random process MS of object Test-1
with optimal parameters of the maintenance strategy $\mathbf{STO}_S^*$

Service items	ν_i =1			ν_i = 0,5		
	$\overline{T}_{\text{то}i}$, h	$\nu_{\text{то}i}$	$\overline{n}_{\text{то}i}$	$\overline{T}_{\text{то}i}$, h	$\nu_{\text{то}i}$	$\overline{n}_{\text{то}i}$
132	5533	0,83	30,2	6480	0,40	25,9
12	7447	0,86	22,2	8501	0,41	19,7
11111	7420	0,86	22,3	-	-	-

Conclusions

1. Optimized parameters of MC strategies are:
- set of serviced elements $E_{\text{то}}$;
- vector of TC $U_{\text{то}}$ levels, in which each element $e_i \in E_{\text{то}}$ is assigned the optimal TC $u_{\text{то}i} \in U_{\text{то}}$ level;
- fixed periodicity of control $T_{\text{к}}$ (for conditional maintenance) or coefficient γ (for adaptive maintenance).

2. The parameter γ has the meaning of a relative value that links the changing frequency of control $T_{\text{к}}$ with the current estimate of the average time to failure of the object $\tilde{T}_{\text{ср}}$. With adaptive MC, the frequency of control $T_{\text{к}}$ is calculated by the formula $T_{\text{к}} = \gamma \tilde{T}_{\text{ср}}$, where the score $\tilde{T}_{\text{ср}}$ is determined by the results of measuring determining parameters.

3. Parameters $E_{\text{то}}$ and $U_{\text{то}}$ are common for MC strategies. The difference between the “state maintenance” and “adaptive maintenance” strategies is only in the method of determining the frequency of control $T_{\text{к}}$.

4. The optimal number of serviced elements has decreased. Instead of 3 elements to be served at ν_i = 1, now if ν_i = 0.5, it is enough to serve only 2 elements;

5. Significantly increased the optimal frequency of control $T_{\text{к}}^*$ (instead of $T_{\text{к}}^*$ = 1200 hours obtained value $T_{\text{к}}^*$ = 2900 hours).

Figure 7 shows graphs of the functions of indicators T_0^+ and $c_{\text{уд}}^+$ depending on the number of serviced elements $n(E_{\text{то}}^+)$. The graphs clearly illustrate the trend of improving performance T_0^+ and $c_{\text{уд}}^+$ with a decrease in the coefficient of variation ν_i.

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ОПТИМІЗАЦІЯ ПАРАМЕТРІВ СТРАТЕГІЇ ТЕХНІЧНОГО ОБСЛУГОВУВАННЯ «ПО СТАНУ» З ПОСТІЙНОЮ ПЕРІОДИЧНІСТЮ КОНТРОЛЮ

Анотація

У цій статті проводиться оптимізація параметрів стратегії технічного обслуговування «за станом» з постійною періодичністю контролю. У процесі експлуатації складних технічних об'єктів, зазвичай, проводиться технічне обслуговування (ТО) підтримки необхідного рівня безвідмовності об'єкта. Відомо, що найефективнішим принципом організації ТО є «ТО станом» (ТОС), відповідно до яким операції ТО проводяться лише тому випадку, якщо цього вимагає фактичний технічний стан (ТС) об'єкта. Для того, щоб у процесі експлуатації була можливість визначати фактичний ТС об'єкта, необхідно ще на етапі його створення розробити та вбудувати в об'єкт засоби для вимірювання параметрів, що визначаються найбільш ненадійних елементів. Для цього розробнику необхідні математичні моделі, за допомогою яких можна було б оцінити очікувані витрати на вбудовування засобів вимірювання та очікуваний виграш від проведення ТО у процесі експлуатації об'єкта.

В даний час відсутні задовільні моделі, що дають змогу отримувати такі оцінки. У цій статті зроблено спробу частково заповнити цю прогалину – запропоновано моделі, що дозволяють прогнозувати показники надійності та вартості експлуатації об'єкта з урахуванням ТГС. У статті також розроблено методики, що дають змогу визначати оптимальні параметри різних стратегій ТО.

Проблема полягає в тому, що при розробці таких об'єктів усі питання, пов'язані з ремонтопридатністю та технічним обслуговуванням, повинні вирішуватися вже на ранніх

етапах проектування об'єкта. Якщо не передбачити заздалегідь необхідні апаратні та програмні засоби вбудованого контролю технічного стану (ТС) об'єкта, не розробити і не вбудувати в об'єкт технологію проведення ТО, то реалізувати в майбутньому можливий виграш у безвідмовності об'єкта за рахунок проведення ТО не вдасться. Оскільки всі ці питання повинні вирішуватися на етапі створення об'єкта (коли об'єкта ще немає), необхідні математичні моделі процесу ТО, за допомогою яких можна було б прорахувати можливий виграш у рівні безвідмовності об'єкта за рахунок проведення ТО, оцінити необхідні вартісні витрати. Потім на підставі таких розрахунків прийняти рішення про необхідність проведення ТО для цього типу об'єктів і, якщо таке рішення прийнято, розробити структуру системи ТО, вибрати найбільш прийнятну стратегію ТО, визначити її оптимальні параметри.

Ключові слова: технічне обслуговування, фактичний технічний стан, оптимізація параметрів стратегії, контроль технічного стану