Conference Paper

Complex for Modeling the Reliability of Reactor Plant Systems by the Monte Carlo Method

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Abstract

The article considers the main models incorporated in the developed software package for modeling reliability indicators of nuclear reactor unit (RF) complex technical systems by the Monte Carlo method. Approaches to organization of system state determination on the layout basis into groups, principles of accounting for dependent failures and incomplete recovery are described.

Two distribution laws are provided as ones for a random time distribution to failure of the modeled system single element. Relations are given for the generation of random time to failure when using these distributions.

Since the most of reactor safety systems operate in standby mode, a separate consideration is given to the organization of systems operating simulations in standby mode. It is important that the elements of such systems are periodically tested, and this periodicity can be different for different elements of the one system. Tests / testing availability of safety systems significantly affects the evaluation of their performance indicators. Therefore, the developed program complex takes into account the tests availability and their different frequency for individual elements of one system. The implementation description of accounting for periodic testing in the framework of reliability modeling is also given in this paper.

The various types' features of recovery are considered, in terms of their account at modeling. So, for example, instant recovery of some elements of the system and random for others, are possible. A specific attention is paid to the principles of accounting for different types of recovery in the modeling, together with the influence of dependent failures. Estimates of reliability indicators depend significantly on the types of recovery, and if the different nature of the recovery time and the time of its start is not taken into account, there may be a significant distortion of the modeling results.

Incomplete recovery's estimation is made on a base of the relatively simple heuristic model described in this paper. The use of the proposed incomplete recovery model is provided for modeling the reliability of the system.

The operation principle of the developed calculation code for modeling the reliability of NPP complex technical systems is precisely described, taking into account all the specified features.

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1. Introduction

In the nuclear industry, significant attention given to the tasks of ensuring and managing the reliability of complex technical systems. Since NPP realize potentially dangerous technology, reliability indicators (RI) determine not only economic efficiency units, but also their safety properties.

Nuclear reactor systems RI can be estimated reliably only in the end of the facility's operation and the limit state' attainment in order to have definite realizations of random variables characterizing its reliability [1]. Thanks to them it is possible to determine correctly the mean time to failure of the restorable object, the average recovery time, the number of failures, etc. However, this is not the most rational approach, and its application to NPP systems is often impossible, since most equipment and systems have not yet reached a operating lifetime.

An alternative to full-scale testing and evaluation of actual operational data about the elements and systems' reliability are methods of structural reliability modeling on the base of statistical modeling (the Monte-Carlo method).

When modeling real technical systems RI one should take into account: it has a complex mode of operation, the duration of recovery is random and there is dependence between failure elements. In such cases, the use of the methodology for constructing failure trees is difficult, and the obtained estimates are "optimistic". It is also difficult to estimate the reliability of the system characteristics, which elements have incomplete recovery (element is not restored to 100%).

The initiated program complex allows solving the problems stated above, e.g.:

- to calculate the elements and systems' RI, on basis on their reliability data and structural scheme of the system;
- to take into account dependencies between the failures of individual elements when modeling RI's estimates;
- to consider the incomplete recovery of individual elements when modeling RI's estimates;

- to assign different options to estimate the recovery duration after the independent failure and to model a nature of the after-failure recovery.

The program complex was prepared on the base of Python programming language [2]. When calculating the RI statistical tests (Monte Carlo method) count methodology was used [3-4] with a help of reliability structural charts [5-7].

2. Prerequisites for modeling the reactor plant systems' reliability

A specific feature of RI is their functional and numerical characteristics of random variables, such as [1]:

- operating time of the object to failure (operating time to failure for non-renewable elements);
- the recovery efficiency of the object after the failure (duration of unplanned, emergency repairs);
- the number of failures of the restored object for the considered interval of operation.

Using a Monte-Carlo method (MCM) is reasonable if there's a probabilistic analysis of complex real processes providing the structural features of the system [7-8]. The process of the system functioning within MCM is a stream of random events which are changes in the state of the system occurring at random times. The change in the state of the system is due to the resulting failures and recovery of its parts and elements [1].

The moment of each individual element's failure is calculated on the basis of its reliability data. The parameters of no-failure operation's distribution law are an initial data on the element's reliability. The program complex (PC) can use one of the two distribution laws: exponential and Weibull [9].

Choosing these two types of non-failure distribution law is based on the fact that failures of highly reliable systems' elements should be rare. The individual elements are often complex technical devices, consisting of the nodes' set. Failure's flows of such elements will be subject to the extreme values' central theorem (described by Frechet distributions) [10-11]. There are three forms for Frechet distributions: the negative time for exponential distribution, the intermediate form for Weibull distribution; the limiting form is the distribution of Gumbel. The latter was not used when designing the program because of unassailability to get the limited (steady) failure's flow state.

RF systems can have a simple or complex mode of operation [12]. For a simple mode of operation, the periods of work and downtime, caused by the need to restore elements after a failure (periods of unscheduled emergency repairs), are typical.

The complex mode of operation is typical for reactor emergency systems, nuclear power plant safety systems, which are in a stand-by mode most of the time. During this stand-by period an element does not perform its basic functions, but should be absolutely ready to be used as intended. This need (to use it) occurs at random times when a no-failure operation of the system is required and this guarantees a successful execution of its functions. There can be latent failures at downtime; they can be detected at the moments of system element's scheduled testing or when it's time to perform some functions by an element. The most frequently detected failures during testing are failures to claim [1].

The paper considers modelling of the following RIs:

- mean time between failures T_{mbf} (mean time between failures);
- the average recovery time T_{ar};
- probability to respond promptly (quickly) to the demand $P_{\mathrm{o.s.t}}\ (t)$;
- availability ratio R_{av}.

3. Principles to organize a reliability modeling of NPP systems by the Monte Carlo method

The program complex consists of some parts:

- a connection unit for the internal modules and Python libraries
- functions' unit
- a unit to connect files with the original data,
- the main part (unit)
- a unit to calculate RI on the base of modeled data and a file recording of the results.

The database is organized in two files. The first file provides information about general data on the system and its elements. The second one provides data on the structural scheme of the system. The files have a format «*.json», which is convenient to fill in and read when running of a program and during its operation.

The structure of the main part depends on the modeled mode of operation. The program flow runs as many times as the tests are set in its basic data.

The data obtained in the modeling are stored in a file in a format «*.xlsx» the format of Microsoft Excel). Due to these data it is possible to estimate single and complex RI for simple and complex systems, recoverable and non-recoverable equipment.

3.1. Recreating the structural scheme in modeling

The structural block diagram of reliability is made on the basis of project information about the system, in which purposes, principle of functioning, modes of operation are specified. Elements can be connected to serial, parallel and mixed connections [13-15].

Recover of the structural block diagram is realized by combining the elements in groups of connection type in the developed PC [16]. A group can consist of elements and / or subgroups. An important and specific feature is that the elements may be present in different groups at a time if it does not interfere with the general logic (e.g., when an element is one for three groups, but each group has a reserve). Thus it can be considered the effect of one element on several groups at once. This approach solves the problem of modeling such bridge structures or where there is no definite division type of compound elements.

The joining of elements in a group can be serial or parallel. For example, according to Fig. 1 the «group 1» consists of elements «e1», «e2»; «group 2» consists of «e3», «e4», «e5». The group, when modeling, is presented as a "virtual" element, for which the concept of failure is also applicable. For example, Fig. «group 0» is composed of the parallel elements «group 1», «group 2», thus they can be regarded as virtual elements.

For groups with parallel connection of elements a criterion of failure as the number of operable elements, which is necessary for successful operation group (system) (e.g., 2 working items-of- 3 «group 2») can be specified.

Code for analyzing a structural block diagram is given in *ASS* function with a passed list of failed elements. The function returns the result in the form of a list with elements which led to system's failure. If the list is without elements - the system did not fail, if it contains the element numbers - the system failed.

The analysis of the structural block diagram begins with an analysis of the failure of those groups that include the failed elements. The faulty groups which were found are becoming "virtual" elements. A cycle of serial analysis is run in order to find out the influence of each "virtual" element on the group which it belongs (analysis is made from a more nested to a less nested group). Each time, in case of failure of this group, it becomes the new "virtual" element and then the higher group is analyzed in the hierarchy, and so on.

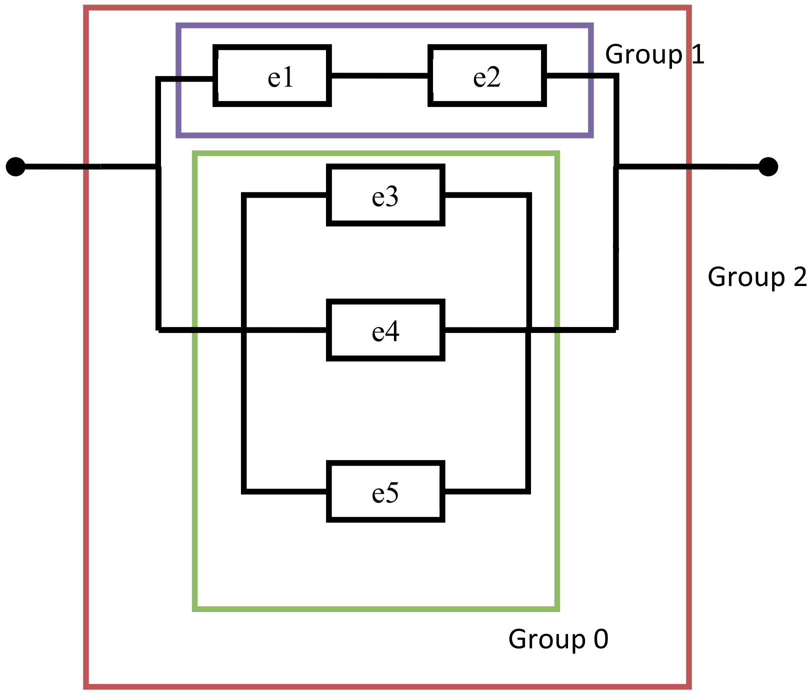

Figure 1: An example of elements' combining into groups of reliability structural block diagram.

If the number of the last failed group is zero, it is considered the system to have failed. A list of the elements that caused the system's failure is created (in the groups that led to the failure of Group 0). If neither of the initially failed groups fails the system, then the system is considered not to fail. The list of elements that caused the system's failure is formed empty.

Thus, the analysis algorithm of the block diagram can model structures with a high degree of nesting, memorize faulty groups and exclude from analysis groups with no detected failure.

3.2. Modeling the independent failure of an individual element

Failures of elements occur at random times. The interval before the onset of a new failure is modeled using a pseudo-random number generator in the following sequence:

1. "Draw" uniformly distributed random numbers R_i in the range from 0 to 1;

2. A time till his failure t_i is calculated (estimated) due to type of no-failure operation's time distribution law and its parameters.

Getting a random time interval with a predetermined distribution law $f(t)$ and uniformly distributed number R_i in the interval (0, 1) is a result of a solution to equation with respect to t_i:

$$R_i = \int_0^{t_i} f(t)dt = F(t_i).$$

This equality with $f(t) > 0$ specifies the one correspondence between the variables R_i and $t_{i,}$ and allows to obtain a random number corresponding to an arbitrary distribution law $f(t)$ of the random number, distributed uniformly on the interval (0, 1).

In the case of the exponential distribution law it is:

$$t_i = -\frac{1}{\lambda} \cdot \ln(1 - R_i) \tag{1}$$

For the Weibull distribution law it is:

$$t_i = -\frac{1}{\lambda} \cdot (-\ln(1 - R_i))^{\frac{1}{\alpha}} \tag{2}$$

3.3. Modeling the dependent failure of an individual element

Dependence between failures of elements can considerably worsen properties of system's reliability in comparison with the similar system where it is not observed. Taking into account this dependence can significantly increase the assessment of the likelihood (probability) of failures. [17]

There are many techniques for modeling dependent failures. The developed program complex accounts dependent failures by using the coupling coefficient $K_{i,j}$. The use of more complex models for dependent failures is another research topic and requires a separate research work.

The coefficient (index) is given by experts and takes values from 0 to 1. The value «0» indicates that the influence of i-th on j-th element is absent, and the value «1» means that a failure of i-th element leads to a significant failure of j-th.

A failure moment of time for the j-th element due to failure of i-th is estimated according to the following algorithm:

1) it is determined whether there is dependence between the failed i-th element and the unfailed j-th element;

2) if there is a dependence ($K_{i,j} > 0$), the condition (3) is checked and if the last is fulfilled there is a dependent failure of j-th element:

$$F_j(t_i) > (1 - K_{i,j}) \cdot R_j, \tag{3}$$

wherein $F_j(t_i)$ - a value of the j-th element's failure probability at the time of i-th element failure; R_j - probability of j-th element's failure, ie, $R_j = F_j(t_i)$.

The relationship between failures $K_{i,j}$ is assumed to be linear. This is due to the fact that the $K_{i,j,}$ as was mentioned above, is determined by experts who estimate how i-th element's failure will affect the probability of j-th element failure.

3.4. Modeling recovery duration

After modeling the occurrence of failure recovery duration of the i-th element is modeled.

Duration of recovery can be specified by one of three options:

- an instant (immediate) recovery;
- an occasional duration;
- a determined, constant duration of recovery;
- discrete, predefined time intervals.

In the modelling of instant recovery, it is assumed to be an immediate element's performance recovery after a failure. This means a complete substitution of the element by the new one.

When calculating random duration of the i-th element's recovery a random normally distributed number is generated (truncated normal distribution is used). This number is further scaled in accordance with parameters predetermined for $i-$th element (mean and standard deviation). Modelling the random recovery duration is used when it is certainly (obviously) impossible to guess how long it will take to repair an element.

Modeling this recovery duration in the form of a predetermined time interval refers to the known (certain) time interval required for the element's repair.

A recovery of dependent failed element can be realized in the developed complex in three ways:

- after recovery of the element caused dependent failure;
- in parallel with recovery of the element caused dependent failure;
- at the same time with an element caused dependent failure.

3.5. Modeling incomplete recovery

In world practice, when analyzing the reliability of repaired objects, it is considered that after recovery the object is restored to 100%. In fact, in most cases, when repairing complex equipment it is impossible to replace or repair its components so that it does not affect its reliability in the future. The item is restored to a certain percentage of its original state. Accounting for incomplete recovery brings the conditions of modeling to reality.

When developing program complex the most realistic method of obtaining information about incomplete recovery i–th element is used, it's a expert evaluation method. For that purpose a coefficient $k_{\text{rec},i}$ is applied, it belongs to the range from 0 to 1.

At the beginning of modeling all the elements have the 100% level of serviceability, i.e. $k_{\text{rec},i}$ = 1. After each recovery the element's serviceability decreases by some amount $\Delta_{\text{rec},i}$, which also lies in the interval [0, 1].

$$k^{l+1}_{\text{rec},i} = k^{l}_{\text{rec},i} - \Delta_{\text{rec},i}, \tag{4}$$

where l- number of recovery (l = 0,..., n); i- element's number; - $k^{l}_{\text{rec},i}$ coefficient got from the registration of the previous incomplete recovery; $k^{l+1}_{\text{rec},i}$- coefficient of incomplete recovery after a new failure.

When the $k_{\text{rec},i}$ reaches a certain point $k^{\lim}_{\text{rec},i}$, after which the element's recovery becomes useless, it is replaced with a new one. For this element - $k_{\text{rec},i}$ = 1 (100%).

Defining of the time to failure in incomplete recovery is performed using the following equation:

$$F_i(t_i) = R_i \cdot k^{l+1}_{\text{rec},i}. \tag{5}$$

Coefficients $k^{\lim}_{\text{rec},i}$ and $\Delta_{\text{rec},i}$ are defined with the help of expert evaluation method.

3.6. Modeling the system operation process which is working in a complex mode

Much attention is given to modeling and system's modeling algorithms with a simple working mode, the review is given in the papers [1, 8, 9, 18, 19]. Therefore, this article focuses on modeling the system operation process which is working in a complex mode.

Figure 2 is a timing diagram showing schematically the process of operation of such a system, where the following notations (symbols) are:

$\tau^k_{0,\,i}$, $\tau^k_{r,\,i}$ - duration of no-failure operation and recovery for the k-th element, respectively (i - fault number, k = 1,..., n);

$T^k_{fl,\,i}$- point of time when a k–th element's latent failure occurs;

$M^k_{fl,i}$, $M^k_{rec,i}$ - time of a failure and recovery detection for the k–th element, respectively;

$M^k_{test,\,j}$- point of time for the j-th sampling (testing) of the k-th element (j = 1,... J);

$M^{k,dep}_{fl,\,i}$- point of time of dependent failure detection for the k th element;

I^k_{fl} - the time interval between failures of the k-th element.

S_i– point of time when system's state changes in $M^k_{fl,\,i}$;

$I^{sys}_{fl,q}$- the time interval between failure of the system during the waiting period;

$M^{sys}_{rec,q}$- point in time of recovery during the waiting period;

[T_{start}, T_{finish}]- the interval of time when the system performs its functions;

τ^k_{fl} - the time interval before a failure of the k–th element on the interval [0, T_{finish}];

$M^k_{fl,i}$ - failure and recovery time for the k–th element on the interval [T_{start}, T_{finish}];

I^k_{fl} - time interval from the start of k-th element's application to its failure [$T^k_{start,\,fl}$] on the interval [T_{start}, T_{finish}];

S'_i- point of time when system's state changes M^k_{fl} on the interval [T_{start}, T_{finish}];

$I^{sys'}_{fl,\,l}$ - the time interval before system's failure on the interval [T_{start}, T_{finish}];

M^n_{rec}, $M^{sys'}_{rec,\,l}$ - point of time for the k–th element and system's recovery, respectively, after a period [T_{start}, T_{finish}] (l- the number of failure).

System's operating process is composed of two-time domains – a standby mode and a mode with no recovery (a possibility to recover is absent).

The first domain [0, T_{start}] is divided into periods between elements testing (checking). It is possible to detect latent failures (on request), and failure detection (for example type «flow») here.

The second domain [T_{start}, T_{finish}] means the system's elements are introduced simultaneously into operation and the elements' recovery is not possible during this period. System's failure is determined by consecutive failures of elements in a specific interval. Failed elements' recovery is possible only after period's ending.

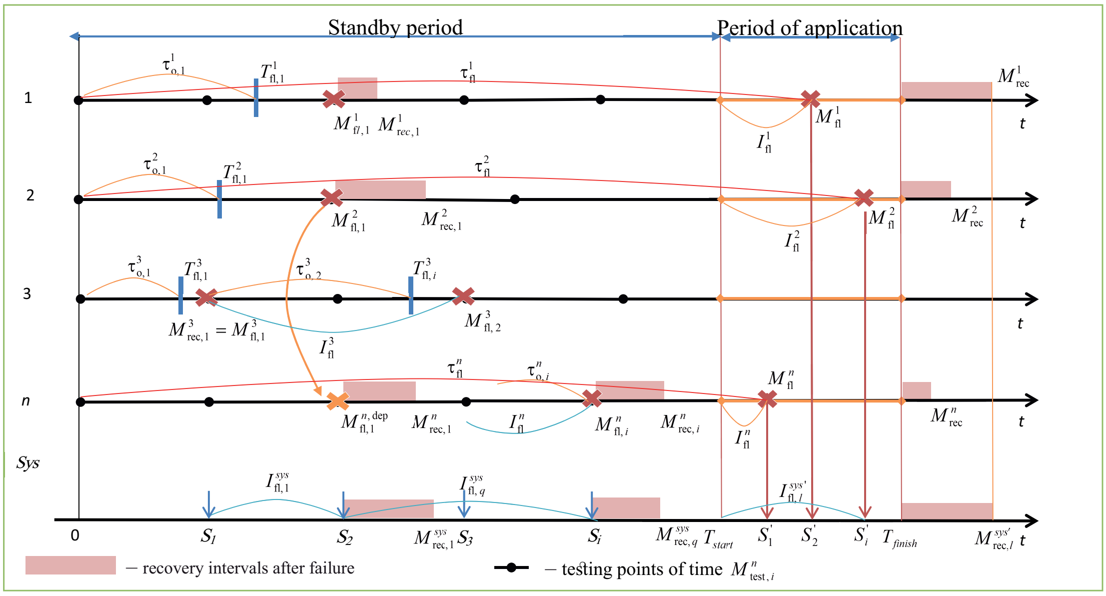

Figure 2: Timing diagram schematically showing the system operating in a complex mode consisting of n elements.

The values that characterize the system and its element's operation at standby period, are related by:

$$
\begin{gathered}
T^k_{\text{fl},\,1} = \tau^k_{>,\,1},\\
T^k_{\text{fl},\,i} = M^k_{\text{rec},\,i} + \tau^k_{>,\,i},\\
M^k_{\text{fl},\,i} = M^k_{\text{test},\,j},\ \text{if}\ M^k_{\text{test},\,j-1} < T^k_{\text{fl},\,i} = M^k_{\text{test},\,j},\\
M^k_{2,\,i} = M^k_{\text{fl},\,i} + \tau^k_{\text{r},\,i},\\
M^{k,\text{dep}}_{\text{fl},\,i} = M^k_{\text{fl},\,i},\\
M^{k,\text{dep}}_{\text{rec},\,i} = M^{k,\text{dep}}_{\text{fl},\,i} + \tau^{k,\text{dep}}_{\text{r},\,i},\\
I^k_{\text{fl}} = M^k_{\text{fl},\,i} - M^k_{\text{fl},\,i-1},\\
S^{\text{sys}}_{\text{fl},\,i} = M^k_{\text{fl},\,i},\\
I^{\text{sys}}_{\text{fl},\,q} = M^k_{\text{fl},\,i} - S^{\text{sys}}_{\text{fl},\,q-1},\\
M^{\text{sys}}_{\text{rec},\,i} = \max(M^k_{\text{rec},\,i}).
\end{gathered}
\tag{6}
$$

The values characterizing the system and elements' operation during application period, are related by:

$$M_{\text{fl}}^{k} = \tau_{\text{fl}}^{k},$$
$$M_{\text{rec}}^{k} = T_{\text{finish}} + \tau_{\text{r}}^{k},$$
$$M_{\text{fl}}^{k,\,\text{dep}} = M_{\text{fl}}^{k},$$
$$I_{\text{fl}}^{k} = M_{\text{fl}}^{k} - T_{\text{start}}, \tag{7}$$
$$S_{\text{fl},\,i}^{\text{sys}'} = M_{\text{fl}}^{k},$$
$$I_{\text{fl},\,l}^{\text{sys}'} = S_{\text{fl},\,l}^{\text{sys}} - T_{\text{start}},$$
$$M_{\text{rec},\,l}^{\text{sys}'} = \max(M_{\text{rec}}^{k}).$$

Consider the sequence of simulation tests and elements of the system in standby mode.

Before the simulation is performed preparing the initial conditions to start the cycle, which is executed until the time of the previous sampling system M_{start} is less than or equal to the time system monitoring T_A. Before starting a cycle M_{start} = 0.

For each element, the latent time of failure is modeled $T_{\text{fl},i}^{k}$ in accordance with relations (6) (in the simulation of the first failure in all elements of the system are listed). If $T_{\text{fl},\,i}^{k}$ longer follow-up period of the system T_A, then the element is eliminated from the simulation under this test. If all the elements were eliminated from the study, it will be terminated. For the $(i+1)$ failures is considered incomplete recovery when determining the probability of failure for those elements for which this is necessary.

Further, for each simulated moment of latent failure $T_{\text{fl},\,j}^{k}$ to k–th element is checked condition:

$$M_{\text{test},j-1}^{k} < T_{\text{fl},i}^{k} < M_{\text{test},j}^{k} \& M_{\text{test},j}^{k} = M_{\text{finish}}.$$

If it is satisfied, it is considered that the element has a latent failure $T_{\text{fl},\,j}^{k}$ in the interval $[M_{\text{test},\,j-1}^{k}, M_{\text{test},\,j}^{k}]$. Between the previous and current testing of $M_{\text{test},\,j}^{k}$ this element, which enters the system at the time of sampling M_{finish}. The hidden element failures considered to be detected at a time $M_{\text{test},\,j}^{k}$. Such verification is introduced due to the fact that the sampling frequency of the elements may be different (once a month, once a year), but the minimum period between the multiple sampling.

After, item numbers added to the list regardless refused. For them, the simulated recovery duration $\tau_{\text{rec},\,j}^{k}$, recovery time$M_{\text{rec},\,i}^{k}$ is determined by the time interval between the detection of a failure I_{fl}^{k}, according to suitable their expressions from (6) and the serial number of failure. For regardless self-failed elements of the formulas (6) are determined by the time of failure $M_{\text{fl},i}^{k,\text{det}}$, the time of recovery $M_{\text{rec},\,q}^{\text{sys}}$, the time between failures, failure number.

Runs analysis of the system. If the system failed, then it is determined at time of failure S_i (it is equal to the time of failure detection elements during testing), the interval between failures $I_{\text{fl},\,q}^{\text{sys}}$, by the relations (6), fault number.

For all elements of the following time points simulate sampling system between $M_{\text{test},\,j}^{k}$ and $M_{\text{test},\,j-1}^{k}$. The value of the previous time the sampling system is overridden $M_{\text{start}} = M_{\text{finish}}$. Checking if the loop condition.

After the simulation of the system in standby mode is modeled during its application. Referring to Figure 2, this region $[T_{\text{start}}, T_{\text{finish}}]$. Simulation run separately. Consider the structure of the main part of the program for one test (in this case, the test - a simulation of the system operation in the operating mode cannot be restored).

The sequence of the algorithm:

1. With the help of a random number generator is played uniformly distributed random number P_{sys} - the probability of the system to go from standby to operating mode. In fact it is the likelihood of a situation for which the system must respond.

2. Calculated at time T_{start} and T_{finish} from the following relations

$$T_{\text{start}} = P_{\text{sys}} \cdot T_A,$$

$$T_{\text{finish}} = T_{\text{start}} + t_a,$$

Where T_A - the existence of the system; t_a - the duration of the system will perform its functions.

1. For each element of simulated time of the first (and only) failure M_{fl}^{k}.

2. Among the elements whose failure falls on $[T_{\text{start}}, T_{\text{finish}}]$, is determined by the element with minimum failure time - the first failed element.

3. From the failed component establishes a relationship failed elements. For these elements a new time of failure is recorded.

4. Checks for a system failure due to failed elements.

5. If the system is not denied, it is checked whether there was a failure of the other element after the already proven.

6. In case of failure, the failed element are performed for step 5. After that number of the failed element and regardless failed elements are added to the elements, failures which are already installed. Performed step 6.

7. Items 5 - 9 are repeated until the system fails or runs out faulty elements in the interval. In the event of failure of the system to save the number of its failure and the time of failure of time in accordance with the formulas (7).

8. For the system elements and slots to failure record is the same, by the relations (2 - 6) $I_{\text{fl}, l}^{\text{sys}'}$, I_{fl}^{k} respectively.

9. Duration of recovery is modeling, also recovery time points for the elements and systems, in accordance with (7). It should again be noted that the recovery of the elements and the system is modeled only after completion of the period of application in the case of necessity and possibility.

After modeling for both periods RI are evaluated for all tests.

4. Conclusion

It should be noted, that implemented model of the individual elements' functioning and their relationships, in terms of reliability in the developed program complex, allow to obtain estimates of reliability indices which are very close to reality. In addition, the designed complex allows to obtain characteristics unavailable in the majority of software, for example, maintainability and durability characteristics of the analyzed system.

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