Electrical, Control and Communication Engineering
ISSN 2255-9159 (online)
ISSN 2255-9140 (print)
2022, vol. 18, no. 1, pp. 57–65
https://doi.org/10.2478/ecce-2022-0008
https://content.sciendo.com

Technical Condition Monitoring for Telecommunication and Radioelectronic Systems with Redundancy

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***Abstract* – The telecommunication and radioelectronic systems with redundancy are widely used in different branches of human activity. To provide the necessary reliability level of equipment, the operation system is utilized. That system contains intended use, maintenance, repair, technical condition monitoring, and others. The damages, faults and failures are usually observed during the lifecycle of telecommunication and radioelectronic systems. They can lead to deterioration of equipment technical condition. The deterioration of technical condition can be detected during observation of diagnostic variable and reliability parameter. This article concentrates on the synthesis and analysis of statistical data processing procedure for deterioration detection while operating telecommunication and radioelectronic systems with redundancy. For the purpose of reliability estimation based on different redundancy methods, statistical data processing procedure synthesis was carried out using multiple hypothesis testing and detection criterion. The analysis problem was solved using Monte-Carlo simulation method, which allowed constructing operating characteristics. The obtained results can be used in the process of design and improvement of operation systems for telecommunication and radioelectronic equipment.**

***Keywords* – Detection algorithms, deterioration of technical condition, operation systems, reliability increase, statistical data processing, telecommunication and radioelectronic systems.**

I. Introduction

The telecommunication and radioelectronic systems (TRSs) are widely used in different branches of human activity [1]. To support the given level of operational stability of such equipment, the methods of reliability increase are used [2]. These methods are implemented during the stages of designing, manufacturing and maintenance of TRS. The main methods are as follows: reasonable choice of TRS operation principles; usage of reliable schemes; usage of the most reliable elements and their mode of operation; actions increasing serviceability; TRS redundancy.

There are five types of redundancy in scientific literature: informational, structural, functional, loaded and time redundancy [3], [4]. The main method of reliability provision in civil aviation is structural redundancy. If the methods of structural redundancy are used, it means that reliability growth is achieved by including redundant elements performing the same functions as basic elements.

There are whole-system and segregate redundancy. Whole-system redundancy method supposes redundancy of the whole system. In the case of the basic system failure, its functions are executed by a similar redundant system. Segregate redundancy method supposes redundancy of separate system components.

Redundant elements can be switched on in two ways. There are continuous and standby redundancies.

During the continuous redundancy, two basic components are steady switched on. They operate in the same mode. The main advantage is simplicity and absence of time stoppage in operation. Disadvantage is an increased consumption of the redundant element resource.

During the standby redundancy, redundant elements are switched on only if basic elements of the system fail. The main advantage is that if redundant elements are in unloaded condition, their resource is kept. It results in a decrease in power consumption. There is an opportunity to use one redundant element for redundancy of several single-type elements. Disadvantage is a necessity to use switches and control systems.

Depending on operation conditions of redundant elements, there are three operating modes: loaded, reduced, and unloaded.

In the loaded mode, redundant elements operate just as basic ones since the start of system operation. The consumption of its resource is the same as in basic elements.

The reduced mode is characterised by small loads of redundant elements before the failure of basic elements. The consumption of its resource is slight.

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In the unloaded mode, the consumption of redundant element resource is little.

During intended use of TRS, different processes are implemented with the purpose to increase operation efficiency. These processes are as follows: maintenance, repair, continuation of life service, and others [5], [6]. The main actions during operation process implementation contain parameter monitoring, technical condition control, diagnostics, serviceability recovery, measuring and others. The above-mentioned processes and actions are the basic components of TRS operation system [7].

During TRS operation, the statistical data on reliability parameters and diagnostic variables are observed.

The damages, faults and failures of TRS are observed during the equipment lifecycle. They can lead to deterioration of equipment technical condition. The deterioration is associated with occurrence of non-stationarity in the dataset of reliability parameters and diagnostic variables [8]. In scientific literature, sufficient attention is paid to deteriorated system research, but TRS with redundancy is not considered enough.

This article is an extended version of the report [9] presented at IEEE Workshop on Microwave Theory and Techniques in Wireless Communications (MTTW 2021).

II. Literature Review and Problem Statement

The deterioration of technical condition has also a negative effect on maintenance costs and, therefore, on operation efficiency [10]. Change of technical condition can lead to an increase in the number of maintenance procedures [11], [12]. The experience of TRS intended use shows that the technical condition change research is an important scientific and practical problem [8], [13]–[15].

The change of technical condition can be considered in terms of change-point study [16]. The change-point occurs in form of variable transition from stationary to non-stationary state. During the change-point study, two problems can be distinguished: 1) problem of detection and 2) problem of reliability parameter evaluation. These problems are associated with: 1) decision-making about occurrence of non-stationary state in the variable trend and 2) constructing optimal estimates for model parameters after occurrence of non-stationary state in the variable trend.

Literature review gives the possibility to conclude that mathematical tools for the change-point study are methods of hypothesis testing, theory of statistical parameter estimation, methods of random variable transformation, approximation methods, deep learning and others [17]–[20]. The necessity to use these tools in the case of TRS operation is substantiated in [21]. Previous research of this article authors is associated with the study of procedures to detect technical condition deterioration using: 1) posteriori analysis approach with known in advance sample size [22]; 2) Neyman-Pearson criterion and techniques of threshold calculation according to Bellman approach with iterative accumulation of sample size [23]; 3) sequential analysis by A. Wald [24]. The mentioned procedures were studied in case of non-redundant TRS operation.

The reliability analysis for redundant TRS with limitation of absence of technical condition deterioration was considered in [25]. It should be noted that the redundant TRS are usually researched in literature in the case of normal operation without change of technical condition.

The aim of the article is the synthesis of procedure to detect technical condition deterioration in case of operation of redundant TRS during failure rate monitoring. This procedure aims at correct decision-making on the technical condition change and an increase in the TRS operation efficiency.

III. Reliability Analysis of Deteriorating TRS with Redundancy

The research is associated with operation of telecommunication and radioelectronic systems with redundancy as shown in Fig. 1.

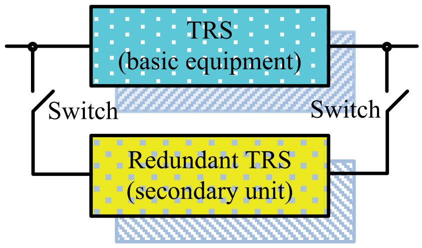

Fig. 1. TRS with redundancy.

Let us suppose that redundant equipment is characterised by reduced mode. The switch connects redundant TRS only in the case of failure occurrence in the basic TRS. The probability of failure-free operation of switch is equal to one. Therefore, the switch cannot fault.

Let us assume that the repair process is carried out only when a redundant TRS fails.

The different probability distributions can describe the time of failure occurrence. The TRS operates in normal mode before deterioration of technical condition. Such a mode assumes a constant failure rate. In this paper, the authors use the limitation about the simplest type of probability density function (PDF) for time between failures in case of normal operation. Such type of PDF corresponds to exponential distribution. Moreover, let us assume that basic and redundant TRSs are identical, so they have the same failure rate λ before deterioration.

According to these limitations, the PDF of time between failures for basic and redundant TRSs can be presented as follows:

$$f(t_1) = \lambda e^{-\lambda t_1} h(t_1)\,,\ f(t_2) = \lambda e^{-\lambda t_2} h(t_2)\,, \qquad (1)$$

where $h(t)$ is a step function, times t_1 and t_2 correspond to the failure occurrence moments for basic and redundant TRS, respectively. The failure rate in PDFs (1) after occurrence of technical condition deterioration for corresponding TRS will be equal to λ_{det}.

Let us consider the model of technical condition deterioration. The model supposes observing for discrete failures of TRS with redundancy. The total quantity of the observed failures (sample size) is n. As TRS with redundancy consists of two TRSs, there are two possible change-points. The first change-point can occur in a basic or redundant TRS. The number of failure k_1 corresponds to time moment of the technical condition deterioration occurrence in one of the TRSs. The number of failure k_2 corresponds to time moment of the technical condition deterioration occurrence in another TRS.

In a general case, time moments of the technical condition deterioration occurrence are unknown in advance random variables. These variables can be characterised by different PDFs.

There are three conditions of TRS with redundancy for the described model of deterioration:

1) operation in the normal mode (in this case, a failure rate for each TRS is constant and equal to initial value λ);
2) technical condition deterioration for one of TRSs (in this case, a failure rate for one of TRSs is equal to λ and for another is equal to λ_{det});
3) technical condition deterioration for both TRSs (a failure rate changes value to λ_{det} for basic and redundant TRSs).

Let us consider the evaluation for reliability parameters for deteriorating TRS with redundancy.

The PDF of time between failures for TRS with redundancy is calculated in such a way. The time t of failure occurrence is equal to the sum of t_1 and t_2. Therefore, the PDF will be the following:

$$f(t) = \int_0^t f(t_1) f(t_2)\Big|_{t_2 = t - t_1} dt_1 . \quad (2)$$

For the case of operation in the normal mode, the PDF (2) corresponds to Erlang distribution

$$f(t) = \int_0^t \lambda e^{-\lambda t_1} \lambda e^{-\lambda(t - t_1)} dt_1 = \lambda^2 \int_0^t e^{-\lambda t_1} e^{-\lambda(t-t_1)} dt_1 =$$
$$= \lambda^2 \int_0^t e^{-\lambda t} dt_1 = \lambda^2 e^{-\lambda t} \int_0^t dt_1 = \lambda^2 t e^{-\lambda t} . \quad (3)$$

There are two cases after occurrence of technical condition deterioration for one of TRSs:

1) the first change-point is observed in the basic TRS, then the PDF (2) will take a form

$$f(t) = \int_0^t \lambda_{det} e^{-\lambda_{det} t_1} \lambda e^{-\lambda(t-t_1)} dt_1 = \lambda\lambda_{det} \int_0^t e^{-\lambda_{det} t_1} e^{-\lambda(t-t_1)} dt_1 =$$
$$= -\frac{\lambda\lambda_{det}}{\lambda_{det} - \lambda} e^{-\lambda t} e^{-t_1(\lambda_{det} - \lambda)} \Bigg|_0^t = \frac{\lambda\lambda_{det}}{\lambda_{det} - \lambda}\left(e^{-\lambda t} - e^{-\lambda_{det} t}\right). \quad (4)$$

2) the first change-point is observed in the redundant TRS, then the PDF (2) will be

$$f(t) = \int_0^t \lambda e^{-\lambda t_1} \lambda_{det} e^{-\lambda_{det}(t-t_1)} dt_1 = \lambda\lambda_{det} \int_0^t e^{-\lambda t_1} e^{-\lambda_{det}(t-t_1)} dt_1 =$$
$$= -\frac{\lambda\lambda_{det}}{\lambda - \lambda_{det}} e^{-\lambda_{det} t} e^{-t_1(\lambda - \lambda_{det})} \Bigg|_0^t = \frac{\lambda\lambda_{det}}{\lambda_{det} - \lambda}\left(e^{-\lambda t} - e^{-\lambda_{det} t}\right). \quad (5)$$

Equations (4) and (5) give the same PDF. Therefore, PDF (2) after occurrence of technical condition deterioration for one of TRSs can be presented as follows:

$$f(t) = \frac{\lambda\lambda_{det}}{\lambda_{det} - \lambda}\left(e^{-\lambda t} - e^{-\lambda_{det} t}\right). \quad (6)$$

The PDF of times between failures after occurrence of technical condition deterioration for both TRSs can be presented as follows:

$$f(t) = \int_0^t \lambda_{det} e^{-\lambda_{det} t_1} \lambda_{det} e^{-\lambda_{det}(t-t_1)} dt_1 = \lambda_{det}^2 \int_0^t e^{-\lambda_{det} t_1} e^{-\lambda_{det}(t-t_1)} dt_1 =$$
$$= \lambda_{det}^2 \int_0^t e^{-\lambda_{det} t} dt_1 = \lambda_{det}^2 e^{-\lambda_{det} t} \int_0^t dt_1 = \lambda_{det}^2 t e^{-\lambda_{det} t} . \quad (7)$$

Mean time between failures for three conditions of TRS with redundancy will be:

1) normal mode

$$T_0 = \frac{2}{\lambda}; \quad (8)$$

2) deterioration of one of TRSs

$$T_0 = \frac{2k_1 - 2}{n\lambda} + \frac{(n - k_1)(\lambda + \lambda_{det})}{n\lambda\lambda_{det}}; \quad (9)$$

3) deterioration for both TRSs

$$T_0 = \frac{2k_1 - 2}{n\lambda} + \frac{(k_2 - k_1)(\lambda_1 + \lambda_{det})}{n\lambda\lambda_{det}} + \frac{2n - 2k_2 + 2}{n\lambda_{det}} . \quad (10)$$

Let us calculate the basic parameters of reliability based on statistical simulation. The origin data are as follows:

– initial value of failure rate $\lambda = 5 \cdot 10^{-4}$ h^{-1};
– failure rate after change-point $\lambda_{det} = 10^{-3}$ h^{-1};
– number of failure for the first deterioration occurrence $k_1 = 20$;
– number of failure for the second deterioration occurrence $k_2 = 40$;
– sample size $n = 50$;
– time between repairs is exponentially distributed;
– repair rate $\lambda_r = 10^{-1}$ h^{-1};
– quantity of reiteration $m = 1000$.

The simulation results for constructing PDF (6) of time between failures are shown in Fig. 2.

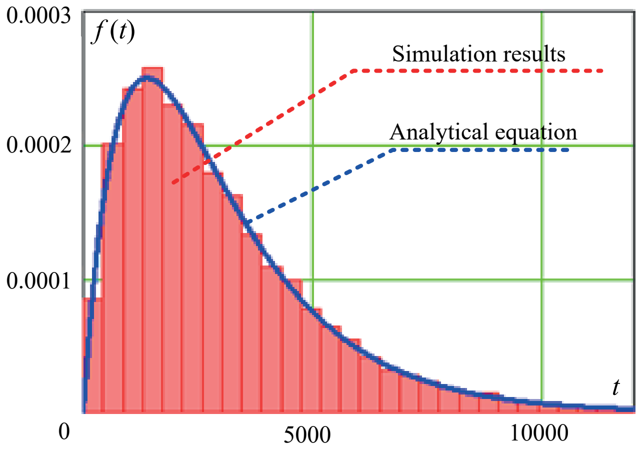

Fig. 2. PDF (6) of time between failures.

Visual analysis of graphs in Fig. 2 and calculated chi-squared test usage prove the coincidence of simulation results with analytical formula (6).

The mean time between failures during normal operation according to (8) is equal to 4000 h for the initial dataset. Results of calculation based on (10) for the case of deterioration for both TRSs are shown in Fig. 3.

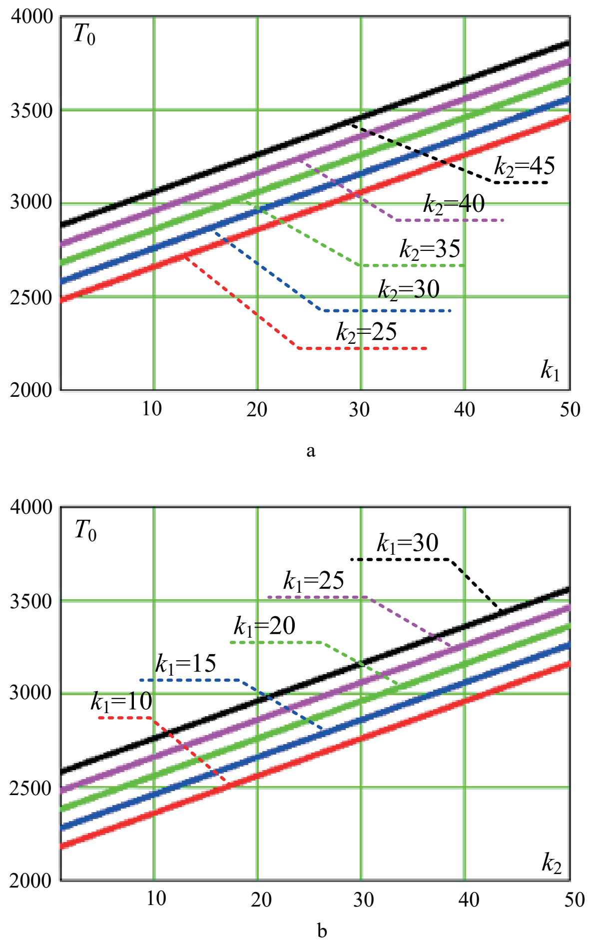

Fig. 3. The dependence of mean time between failures on the moment of the first (a) and second (b) deterioration occurrences.

The analysis showed that earlier occurrence of deterioration decreased the value of mean time between failures.

The PDF of mean time between failures for the initial dataset is shown in Fig. 4. The central limit theorem of probability theory gives the possibility to make conclusion about approximately normal nature for PDF of mean time between failures.

The PDF of steady-state availability is shown in Fig. 5.

After the comparative analysis of calculation results for TRS operation with and without redundancy in case of technical condition deterioration, the probability characteristics of steady-state availability were obtained. These characteristics are given in Table I.

TABLE I

COMPARISON OF STEADY-STATE AVAILABILITY CHARACTERISTICS

Redundancy	Minimum	Maximum	Mean	Deviation	Skewness
No	0.987	0.996	0.993	0.001525	−0.589
Yes	0.995	0.998	0.997	0.000561	−0.449

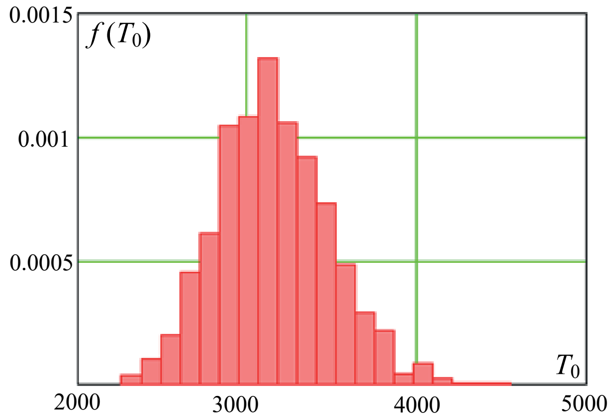

Fig. 4. The PDF of mean time between failures.

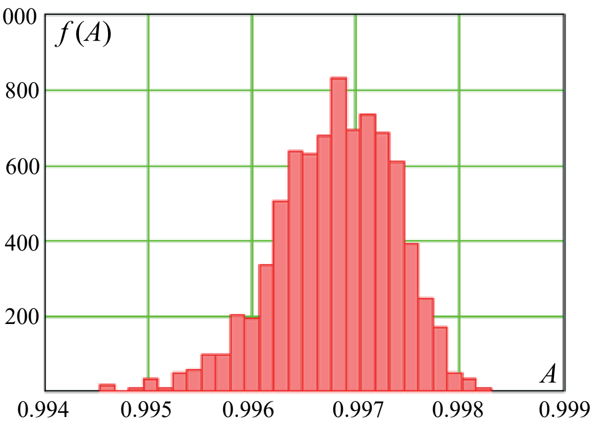

Fig. 5. The PDF of steady-state availability.

Data in Table I show that using redundancy in the case of deterioration increases the mean value of steady-state availability and decreases the corresponding standard deviation. The PDF of steady-state availability has the negative skew and cannot be approximated by the normal distribution.

Graphical dependences for steady-state availability in the case of deteriorating TRS operation with and without redundancy are shown in Fig. 6.

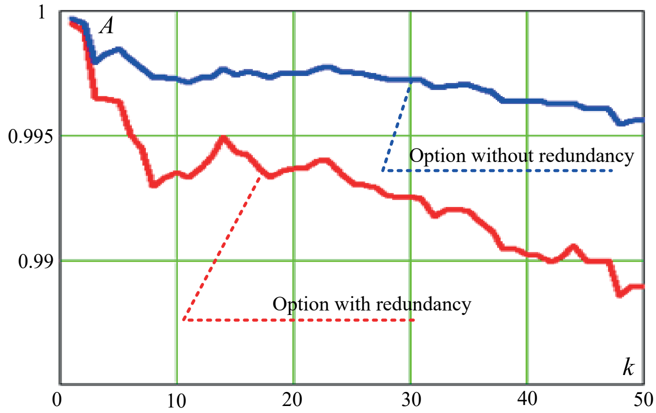

Fig. 6. The comparison of the steady-state availability for TRS with and without redundancy.

IV. Synthesis of Detection Procedure

The problem of timely detection of possible technical condition deterioration is one of the most important in reliability and operation theory.

Let us consider the procedure for detection of TRS technical condition deterioration. This procedure uses the theory of multiple hypothesis testing and Neyman-Pearson criterion.

During hypothesis testing, it is necessary to introduce the hypothesis and alternatives:

– hypothesis H_0 is normal mode of TRS operation without deterioration,
– alternative H_1 is technical condition deterioration for one of TRSs,
– alternative H_2 is technical condition deterioration for both TRSs.

According to the Eqs. (3), (6) and (7), the PDFs for H_0, H_1 and H_2 can be presented as follows:

$$f(t/H_0)=\lambda^2 te^{-\lambda t}h(t)\,; \tag{11}$$

$$f(t/H_1)=\begin{cases}\lambda^2 te^{-\lambda t}h(t),\ \text{if}\ 0<k<k_1,\\ \dfrac{\lambda\lambda_{\text{det}}}{\lambda_{\text{det}}-\lambda}\left(e^{-\lambda t}-e^{-\lambda_{\text{det}}t}\right)\ h(t),\ \text{if}\ \ k\ge k_1;\end{cases} \tag{12}$$

$$f(t/H_2)=\begin{cases}\lambda^2 te^{-\lambda t}h(t),\ \text{if}\ 0<k<k_1,\\ \dfrac{\lambda\lambda_{\text{det}}}{\lambda_{\text{det}}-\lambda}\left(e^{-\lambda t}-e^{-\lambda_{\text{det}}t}\right)\ h(t),\ \text{if}\ k_1\le k<k_2,\\ \lambda_{\text{det}}^2 te^{-\lambda_{\text{det}}t}h(t),\ \text{if}\ \ k\ge k_2,\end{cases} \tag{13}$$

where k is the current number of failure.

The next step is the computation of decisive statistics. In this case, these statistics are formed based on likelihood ratio determination. The multiple decision-making scheme corresponds to double hypothesis testing:

– hypothesis testing between hypothesis H_0 and alternative H_1,
– hypothesis testing between hypothesis H_0 and alternative H_2.

The first likelihood ratio is

$$\Lambda_1(\vec{t}_n,\,\lambda,\lambda_{\text{det}},k_1)=\frac{\prod_{i=1}^{n}f(t_i/H_1)}{\prod_{i=1}^{n}f(t_i/H_0)}=$$

$$=\frac{\prod_{i=1}^{k_1-1}\lambda^2 t_i e^{-\lambda t_i}\prod_{i=k_1}^{n}\frac{\lambda\lambda_{\text{det}}}{\lambda_{\text{det}}-\lambda}\left(e^{-\lambda t_i}-e^{-\lambda_{\text{det}}t_i}\right)}{\prod_{i=1}^{n}\lambda^2 t_i e^{-\lambda t_i}}=$$

$$=\prod_{i=k_1}^{n}\frac{\lambda_{\text{det}}}{\lambda}\frac{1}{\lambda_{\text{det}}-\lambda}\frac{1}{t_i}\left(1-e^{-(\lambda_{\text{det}}-\lambda)t_i}\right)=$$

$$=\left(\frac{\lambda_{\text{det}}}{\lambda}\frac{1}{\lambda_{\text{det}}-\lambda}\right)^{n-k_1+1}\prod_{i=k_1}^{n}\frac{1-e^{-(\lambda_{\text{det}}-\lambda)t_i}}{t_i}\,. \tag{14}$$

The second likelihood ratio is

$$\Lambda_2(\vec{t}_n,\,\lambda,\lambda_{\text{det}},k_1,k_2)=\frac{\prod_{i=1}^{n}f(t_i/H_2)}{\prod_{i=1}^{n}f(t_i/H_0)}=$$

$$=\frac{\prod_{i=1}^{k_1-1}\lambda^2 t_i e^{-\lambda t_i}\prod_{i=k_1}^{k_2-1}\frac{\lambda\lambda_{\text{det}}}{\lambda_{\text{det}}-\lambda}\left(e^{-\lambda t_i}-e^{-\lambda_{\text{det}}t_i}\right)\prod_{i=k_2}^{n}\lambda_{\text{det}}^2 t_i e^{-\lambda_{\text{det}}^2 t_i}}{\prod_{i=1}^{n}\lambda^2 t_i e^{-\lambda t_i}}=$$

$$=\frac{\left(\lambda_{\text{det}}/\lambda\right)^{2n+2-k_2-k_1}}{\left(\lambda_{\text{det}}-\lambda\right)^{k_2-k_1}}\prod_{i=k_1}^{k_2-1}\frac{1-e^{-(\lambda_{\text{det}}-\lambda)t_i}}{t_i}\prod_{i=k_2}^{n}e^{-(\lambda_{\text{det}}-\lambda)t_i}\,. \tag{15}$$

Eqs. (14) and (15) correspond to decisive statistics. The obtained decisive statistics depend on dataset of times between failures $\vec{t}_n$ with a predetermined value of total quantity of observed failures n, initial value of failure rate for normal mode λ and failure rate after deterioration occurrence λ_{det} that is necessary to detect. The numbers of possible occurrence of deterioration sequentially change in the range from 1 to n. Due to this fact, the first decisive statistics is one-dimensional array with size of n samples, and the second decisive statistics is two-dimensional array with $n\times n$ size.

To make decision on technical condition deterioration occurrence, it is necessary to compute the decision-making thresholds V_1 and V_2. Let us suppose that PDFs of decisive statistics correspond to normal distribution. It allows finding mathematical expectation and standard deviation for two decisive statistics. If conditional probability α of the first type error is known, thresholds can be calculated using next equations:

$$\int_{V_1}^{\infty} f(\Lambda_1 / H_0) d\Lambda_1 = \alpha, \quad \int_{V_2}^{\infty} f(\Lambda_2 / H_0) d\Lambda_2 = \alpha. \qquad (16)$$

There are the following decisions:

1) acceptance of hypothesis H_0 if

$$\Lambda_1(\vec{t}_n, \lambda, \lambda_{\det}, k_1) < V_1;$$

2) acceptance of alternative H_1 if

$$\Lambda_1(\vec{t}_n, \lambda, \lambda_{\det}, k_1) \geq V_1 \text{ and } \Lambda_2(\vec{t}_n, \lambda, \lambda_{\det}, k_1, k_2) < V_2;$$

3) acceptance of alternative H_2 if

$$\Lambda_1(\vec{t}_n, \lambda, \lambda_{\det}, k_1) \geq V_1 \text{ and } \Lambda_2(\vec{t}_n, \lambda, \lambda_{\det}, k_1, k_2) \geq V_2.$$

The graphical chart of decision-making about TRS technical condition is shown in Fig. 7.

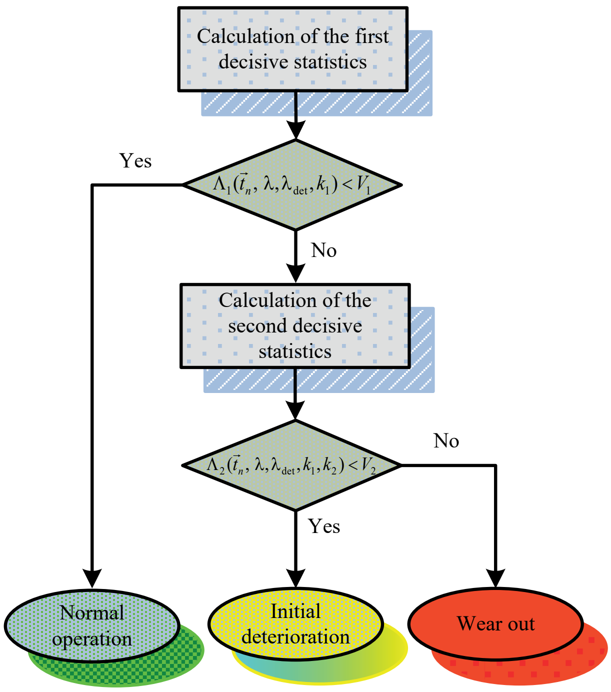

Fig. 7. The graphical chart of decision-making about TRS technical condition.

V. Analysis of Detection Procedure

The main task for detection procedure analysis consists of operating characteristic constructing. In a general case, the operating characteristic shows the probability D of correct detection dependence on a real value of failure rate $\lambda_{\det}$ after deterioration occurrence. Let us assume that there is a need of only event of initial deterioration detection, the operating characteristic can be calculated as follows:

$$D = \int_{V_1}^{\infty} f(\Lambda_1 / H_0) d\Lambda_1. \qquad (17)$$

Let us consider the problem of the operating characteristic constructing based on Monte-Carlo simulation method.

The data for simulation is listed in Section III. The decision-making thresholds are calculated for the probability of the first type error $\alpha = 0.1$.

The imitation procedure contains the next segregate operations:

1. Forming initial statistics on times between failures for operation in the normal mode, for the case of technical condition deterioration for one of TRSs and for the case of technical condition deterioration for both TRSs. Examples of three datasets for deteriorating TRS with redundancy are shown in Fig. 8.
2. Computation of decision-making thresholds using (16).
3. Computation of two decisive statistics. The first decisive statistics trends for different moments of deterioration occurrence are shown in Fig. 9.

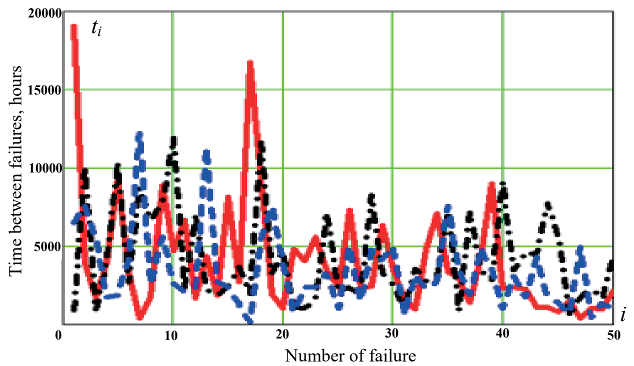

Fig. 8. Examples of three datasets for deteriorating TRS with redundancy.

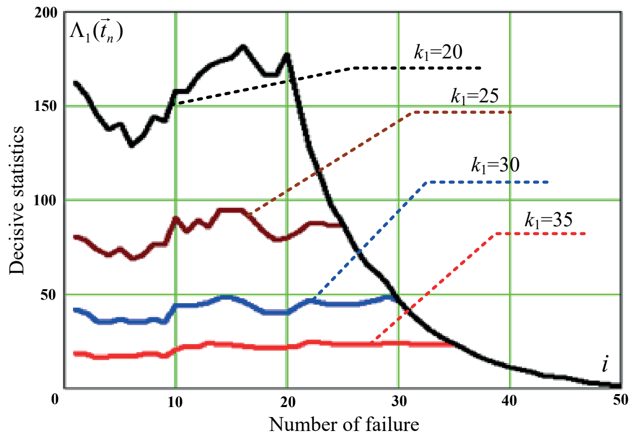

Fig. 9. The first decisive statistics trends for different moments of deterioration occurrence.

Visual analysis of dependencies in Fig. 9 gives the possibility to select two segments: 1) increasing linear segment during operation in the normal mode; 2) decreasing parabolic segment after technical condition deterioration occurrence.

4. The operating characteristic constructing. The operating characteristic dependencies for different moments of deterioration occurrence are shown in Fig. 10.

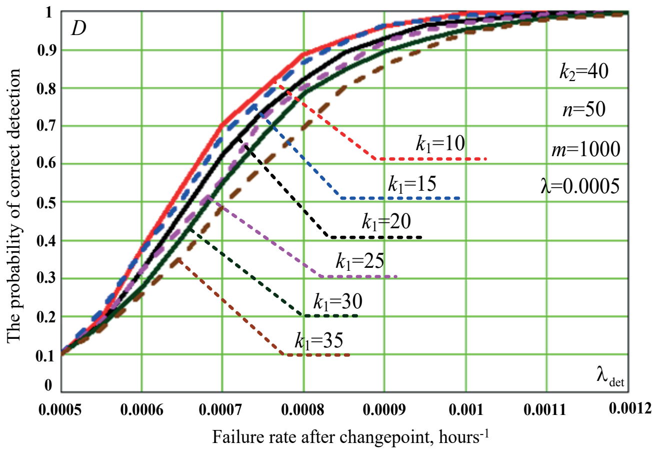

Fig. 10. Operating characteristics for different moments of initial deterioration occurrence.

The analysis of operating characteristics in Fig. 10 shows that the probability of correct detection is in the range from 0.943 to 0.993 depending on time moment of initial deterioration occurrence and in case when a failure rate increases twice as much after change-point. The operating characteristics do not depend on the value of failure during normal mode and have the same growing tendencies while constructing on dimensionless axis λ_{det}/λ. The time moment of initial deterioration occurrence decreasing tends to improve detecting properties for the proposed procedure of data processing.

VI. Conclusion

The change-point is an objective process during operation of arbitrary equipment. It is caused by occurrence of failures, damages and faults, equipment component aging, influence of environmental conditions and others. In scientific literature, insufficient attention is paid to the change-point study, especially while operating TRS with redundancy. This paper has considered the problem of technical condition deterioration analysis for TRS with redundancy. The obtained analytical equations give the possibility to evaluate the reliability properties for TRS. In a general case, the change-point process makes an effect on decreasing such reliability parameters as mean time between failures, probability of failure-free operation and steady-state availability.

The presented approach to synthesis and analysis of data processing procedure allows detecting the technical condition deterioration. The synthesis of detection procedure uses Neyman-Pearson criterion and the theory of multiple hypothesis testing. The analysis of detection procedure concentrates on operating characteristic constructing based on Monte-Carlo simulation method.

The future research areas are associated with analytical calculations of operating characteristic for a change-point detector and the study of the reliability properties of TRS with redundancy considering the features of repair process.

The obtained results can be used in the process of design and improvement of operation systems for telecommunication and radioelectronic equipment.

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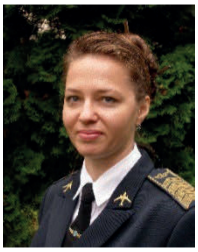

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