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RESEARCH ARTICLE

Evaluation of the effectiveness of sliding redundancy of radioelectronic facilities

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Abstract
Objectives. The increased reliability of radioelectronic facilities can be achieved by the application of structural and load redundancy. Structural redundancy is achieved taking into account multiplicity of redundancy and the intensity of failures of elements of radioelectronic facilities, while load redundancy involves an easing of electrical, thermal, and mechanical operating modes of the elements. The choice of a redundancy method is determined according to reliability indicator requirements, which may often be contradictory. Therefore, the problem of how to effectively combine structural redundancy and load redundancy methods is very topical. In long-life radioelectronic facilities, for example, in satellite communication repeater systems, sliding redundancy is applied when limiting mass-dimensional parameters and consequently consumed energy. The aim of the work is to evaluate the efficiency of sliding redundancy according to various reliability indicators when altering redundancy multiplicity, reserve operating mode, element failure intensity, and switching device type.
Methods. To describe the structure of a complex sliding redundancy system, a logical-probabilistic method is used, in which the dependence of the system reliability indicators on the reliability indicators of the elements is formulated as a logical function of operability. Graph-analytical methods are used to compare different variants of reliability logic schemes.
Results. Mathematical models have been obtained to evaluate the effectiveness of sliding reservation. A comparative analysis of the efficiency of sliding redundancy with a loaded and unloaded reserve was carried out in terms failure-free operation probability, as well as gamma-percentage resource, failure rate when changing the fractional multiplicity of the redundancy, and element failure rate. The influence of the reliability of the switching device on the efficiency of the sliding redundancy is considered.
Conclusions. Practical recommendations on the selection of the redundancy mode are presented according to different reliability indices and constructed mathematical models of the sliding redundancy efficiency coefficients. The correlation between the reliability indices of elements and the switching device whose reliability can be discounted, is determined. To increase the efficiency of sliding redundancy of radioelectronic facilities, it is necessary to combine multiplicity of redundancy and the operating mode of the reserve with approaches aimed at reducing the intensity of failure of elements.

Keywords: reliability, radioelectronic facilities, probability of failure-free operation, gamma-percentage resource, failure rate, sliding redundancy

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НАУЧНАЯ СТАТЬЯ

Оценка эффективности скользящего резервирования радиоэлектронных средств

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Резюме
Цели. Повышение надежности радиоэлектронных средств достигается применением структурного и нагрузочного резервирования. Эффективность структурного резервирования зависит от кратности резервирования и от интенсивности отказов элементов радиоэлектронных средств. При нагрузочном резервировании путем облегчения электрических, тепловых и механических режимов работы элементов можно снизить их интенсивности отказов. Выбор способа резервирования определяется требованиями к показателям безотказности, которые часто находятся в противоречии. Поэтому весьма актуальной является проблема эффективного сочетания методов структурного резервирования и способов нагрузочного резервирования. В радиоэлектронных средствах длительного срока действия, например, в ретрансляторах спутниковых систем связи, при ограничении на массогабаритные параметры и потребляемую энергию применяется скользящее резервирование. Цель работы – оценка эффективности скользящего резервирования по различным показателям надежности при изменении кратности резервирования, режима работы резерва, интенсивности отказов элементов и переключающего устройства.
Методы. Для описания структуры сложной системы скользящего резервирования используется логико-вероятностный метод, в котором зависимость показателей надежности системы от показателей надежности элементов формулируется в виде логической функции работоспособности. Для сравнения различных вариантов логических схем надежности применяются графоаналитические методы.
Результаты. Получены математические модели для оценки эффективности скользящего резервирования. Проведен сравнительный анализ эффективности скользящего резервирования с нагруженным и ненагруженным резервом по вероятности безотказной работы, по гамма-процентному ресурсу, по интенсивности отказов при изменении дробной кратности резервирования и интенсивности отказов элементов. Исследовано влияние надежности переключающего устройства на эффективность скользящего резервирования.
Выводы. Построенные математические модели коэффициентов эффективности скользящего резервирования по разным показателям надежности позволяют дать практические рекомендации по выбору режима резерва. Определено соотношение показателей безотказности элементов и переключающего устройства, при котором надежностью переключающего устройства можно пренебречь. Для повышения эффективности скользящего резервирования радиоэлектронных средств необходимо сочетать кратность резервирования, режим работы резерва и способы уменьшения интенсивности отказов элементов.

Ключевые слова: надежность, радиоэлектронное средство, вероятность безотказной работы, гамма-процентный ресурс, интенсивность отказов, скользящее резервирование

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INTRODUCTION

When ensuring the reliability of radioelectronic facilities (REF), a contradiction arises between the need to combine increased system complexity with limited increases in the reliability of the element base, which justifies the search for new solutions. Such indicators as efficiency, durability, availability, survivability, and safety depend on the reliability of complex REFs. Thus, in order to achieve high indicators of REF reliability, requirements according to many indicators must be should satisfied: probability of no-failure operation, average operating time between failure, gamma-percentage resource, intensity of failures, etc. For example, to achieve a given REF efficiency it is necessary to guarantee a certain value of probability of no-failure operation, and to provide durability according to a certain gamma-percentage resource value [1, 2].

REF efficiency and reliability indicators have much in common. Many problems related to justification of reliability requirements and the development of reliability assurance programs, as well as the selection of maintenance, control and operation systems, can be considered in terms of efficiency research problems. Examples of such problems include the following:

- determination of reasonable development time;
- selecting the optimal range of REF;
- selecting the best combination of REF design parameters;
- selecting from several logical reliability diagrams the diagram which provides operability at the highest number of failures of any of its elements;
- comparison of redundancy methods and construction topologies.

Assessment of efficiency of redundant REF is typically carried out by comparing redundancy types for different reliability indicators. For this purpose, a coefficient of efficiency [1] is introduced, which shows which type of redundancy is more effective according to the investigated reliability index.

All reliability indicators or criteria are connected by single-valued mathematical models, since the desire to satisfy several criteria at once often leads to contradictory requirements, including excessive redundancy, depending on the redundancy multiplicity. For this reason, the choice of a reliability assurance method essentially depends on the criterion used. Therefore, structural redundancy is used to provide probability of no-failure operation [2–6], while load redundancy is used to provide mean time between failures of the long-lasting system [1, 3, 7]. In practice, it is often necessary to combine structural and load redundancy the methods.

In complex systems, various kinds of failures occur [1, 8], all having a random character. In calculations, the independence of these failures is assumed. Their influence can be estimated by different mathematical models: for example, for sudden failures of elements at a constant failure rate, the exponential model is used, while the normal distribution is used to analyze the influence of gradual failures. However, gradual failures due to ageing change the probability of occurrence of sudden failures and failures, complicating the analysis of REF reliability [9, 10].

The high efficiency of satellite communication networks [11–13] is due to the creation of repeaters when using them in sliding redundancy, significantly increasing reliability along with a relatively small gain in weight, size, and energy consumption [3]. One, two, or more redundant elements can be used to ensure the redundancy of individual elements, each of which can be connected in place of any of the main elements. For example, in the sliding redundancy of onboard transmitters or their power amplifiers, the reserve can be loaded and unloaded [14, 15]. For modern geostationary communication satellites, the multiplicity of sliding redundancy of transmitters (ratio of the number of working and redundant transmitters) can vary from 1/5 to 1/2[1] [4].

When using loaded or hot redundancy, there is no need to activate or allow the redundant device to operate in active loaded standby mode, as would be the case unloaded or cold redundancy. For this reason, sliding redundancy with loaded redundancy increases system availability and responsiveness, but also increases operating costs

[1] Dinges S.I., Ivanyushkin R.Yu., Kozyrev V.B., et al. *Radio transmitting devices.* Textbook for universities. Ivanyushkin R.Yu. (Ed.). Moscow: Goryachaya liniya – Telekom; 2021. 1150 p. (in Russ.). ISBN 978-5-9912-0774-4.

because such a structure requires additional power and a more complex switching device. It is noted in [4, 5, 15] that in non-loaded reserve substitution redundancy, the automatic control and switching machine reduces the probability of fault-free operation of the redundant system, but no recommendations are given for the selection of the fault-free performance of the switching device. Therefore, the issue of increasing the reliability and efficiency of sliding redundancy, closely related to the choice of redundancy multiplicity and reserve operation mode, and with the provision of faultlessness indicators of the switching device, which do not reduce the reliability of the system as a whole, is relevant.

FAILURE PROBABILITY AND GAMMA-PERCENT LIFETIME OF SLIDING REDUNDANCY DIAGRAMS

The structural diagram of sliding redundancy reliability with multiplicity m/n is shown in Fig. 1.

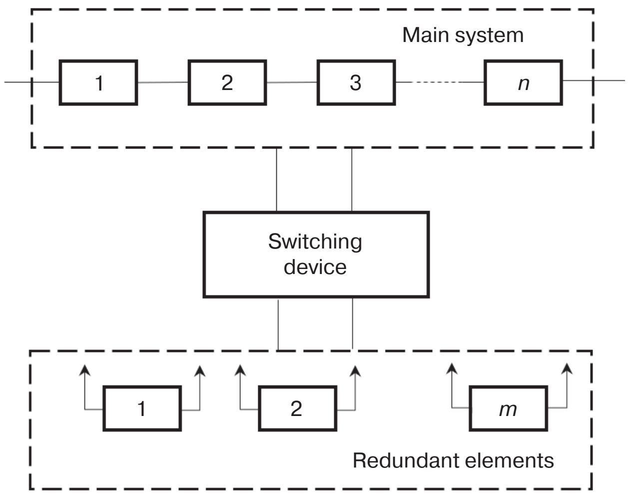

Fig. 1. Structural diagram of sliding redundancy reliability with multiplicity m/n

For a diagram with unloaded redundancy and a redundancy factor of $1/n$, the dependence of probability of no-failure operation on time is described by the expression[2]:

$$P_1(t) = \left(n\frac{\lambda}{\lambda_k} + 1\right)e^{-n\lambda t} - n\frac{\lambda}{\lambda_k}e^{-(\lambda_k + n\lambda)t}, \quad (1)$$

where λ is the failure rate of the main and redundant elements; n is the number of elements of the main system; λ_k is the failure rate of the switching device.

When the redundancy multiplicity is $1/n$, the expression for the time dependence of the probability of faultless operation of a sliding redundancy diagram with loaded redundancy can be obtained without taking into account the reliability of the switching device [1]:

$$P_2(t) = e^{-n\lambda t}\left[1 + n\left(1 - e^{-\lambda t}\right)\right]. \quad (2)$$

The expression for the probability of failure-free operation of a sliding redundancy diagram with a redundancy factor of 2/3 can also be obtained without taking into account the reliability of the switching device [1]:

- for an unloaded redundancy diagram

$$P_3(t) = e^{-3\lambda t}\left(1 + 3\lambda t + 4.5\lambda^2 t^2\right), \quad (3)$$

- for a loaded redundancy diagram

$$P_4(t) = e^{-3\lambda t}\left(10 + 6e^{-2\lambda t} - 15e^{\lambda t}\right). \quad (4)$$

Figure 2 illustrates dependencies (1) and (2) for $n = 2$ and $n = 4$ at different failure intensities of the main and redundant elements. For a diagram with unloaded reserve, a switching device failure rate $\lambda_k = 10^{-8}$ h^{-1} is assumed when constructing the dependencies of Fig. 2.

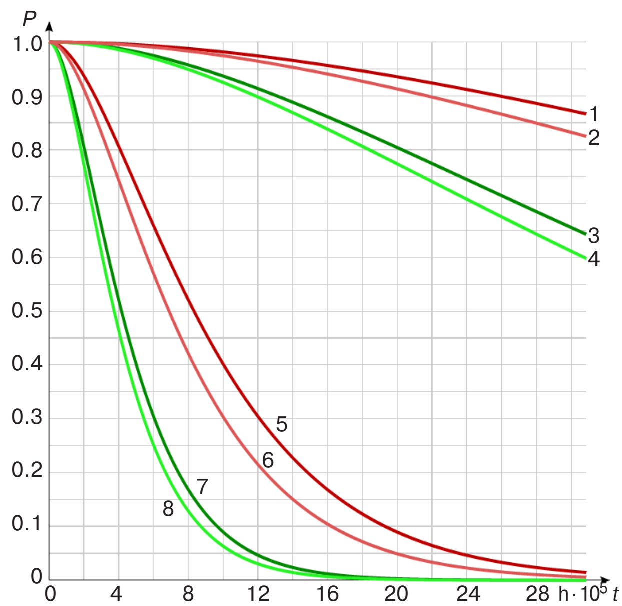

Fig. 2. Time dependencies of the probability of failure-free operation of the sliding redundancy diagram: 1, 2, 3, 4: $\lambda = 10^{-7}$ h^{-1}; 5, 6, 7, 8: $\lambda = 10^{-6}$ h^{-1}; 1, 3, 5, 7: unloaded redundancy; 2, 4, 6, 8: loaded redundancy; 1, 2, 5, 6: redundancy multiplicity 1/2; 3, 4, 7, 8: redundancy multiplicity 1/4

According to the graphs depicted in Fig. 2, unloaded redundancy provides a higher probability of no-failure operation, even when taking into account the reliability of the switching device. For example, for the unloaded reserve with $\lambda = 10^{-6}$ h^{-1} and $\lambda_k = 10^{-8}$ h^{-1} at redundancy

[2] Yanshin A.A. *Theoretical foundations of EVA design, technology and reliability*: textbook for universities. Moscow: Radio i svyaz'; 1983. 128 p. (in Russ.).

multiplicities 1/4 and 1/2, the probability of non-failure operation for time $4 \cdot 10^5$ h is respectively 0.52 and 0.8. In the case of application of the loaded redundancy, the corresponding probability values of no-failure operation are 0.46 and 0.74, respectively.

From the graphs given in Fig. 2, we can determine the index of durability-gamma percent resource [2] of the redundancy diagrams. At use of elements with intensity of failures $\lambda = 10^{-7}$ h^{-1}, the gamma-percent resource of the scheme with unloaded redundancy is $1.3 \cdot 10^6$ h at multiplicity of redundancy 1/4 and $2.6 \cdot 10^6$ h at multiplicity of redundancy 1/2. The corresponding values of gamma-percent resource of the diagram with loaded redundancy are $1.2 \cdot 10^6$ and $2.2 \cdot 10^6$ h, respectively. In other words, the diagram with unloaded redundancy is more durable.

It also follows from the dependencies of Fig. 2 that the gamma-percent resource of any of the diagrams under consideration deteriorates by an order of magnitude when the failure rate of the main and redundant elements increases to $\lambda = 10^{-6}$ h^{-1}.

Figure 3 shows the graphs of time dependencies of no-failure operation probability of the diagram with unloaded redundancy having multiplicity of redundancy 1/4 and 1/2, $\lambda = 10^{-7}$ h^{-1} at different failure rates of the switching device constructed in accordance with expression (2).

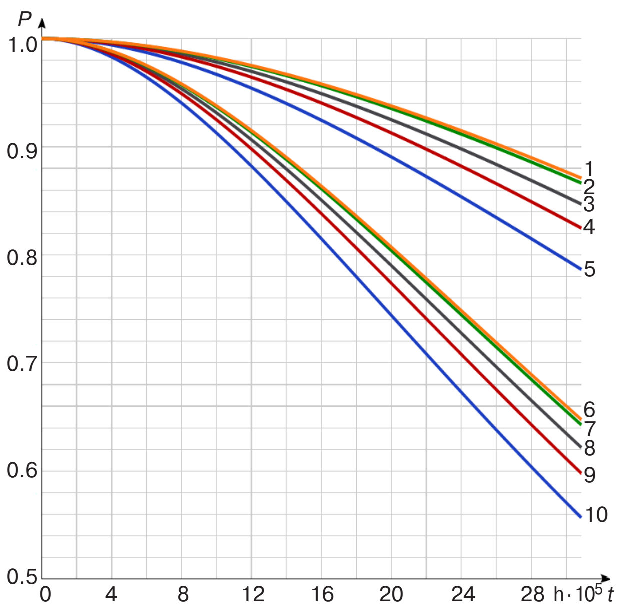

Fig. 3. Time dependencies of the probability of failure-free operation of the diagram with unloaded redundancy: 1, 2, 3, 4, 5: redundancy multiplicity 1/2; 6, 7, 8, 9, 10: redundancy multiplicity 1/4; 1, 6: $\lambda_k = 10^{-9}$ h^{-1}; 2, 7: $\lambda_k = 10^{-8}$ h^{-1}; 3, 8: $\lambda_k = 5 \cdot 10^{-8}$ h^{-1}; 4, 9: $\lambda_k = 10^{-7}$ h^{-1}; 5, 10: $\lambda_k = 2 \cdot 10^{-7}$ h^{-1}

The effect of switching device reliability on the durability of a sliding redundancy diagram with unloaded redundancy can be estimated on the basis of the graphs given in Fig. 3. For example, when a switching device with failure rates of $2 \cdot 10^{-7}$ h^{-1}, $5 \cdot 10^{-8}$ h^{-1}, and 10^{-8} h^{-1}, respectively, is used in a scheme with 1/4 redundancy multiplicity, the gamma percent resource is $1.1 \cdot 10^6$, $1.24 \cdot 10^6$, and $1.3 \cdot 10^6$ h, respectively. The corresponding values of gamma percent resource for a scheme with 1/2 redundancy multiplicity are $1.9 \cdot 10^6$, $2.4 \cdot 10^6$, and $2.6 \cdot 10^6$ h, respectively. It follows from the closeness of curves 1 and 2, as well as 6 and 7, that the reliability of the switching device has almost no effect on the durability of the unloaded sliding redundancy diagram at a ratio $\lambda/\lambda_k > 10$.

REDUNDANCY EFFICIENCY COEFFICIENT BY PROBABILITY OF FAILURE-FREE OPERATION

Let us analyze the effect of the state of redundancy in sliding redundancy on the efficiency of redundancy using the coefficient of redundancy efficiency K_p on the probability of the failure-free operation:

$$K_\text{p}(t) = \frac{P_1(t)}{P_2(t)}.$$

For a redundancy multiplicity of 1/2 according to (1) and (2), the efficiency factor is defined by the expression:

$$K_{\text{p}\,1/2}(t) = \frac{2\dfrac{\lambda}{\lambda_k}\left(1 - e^{-\lambda_k t}\right) + 1}{3 - 2e^{-\lambda t}}.$$

For a redundancy multiplicity of 1/4, the formula for the efficiency factor is as follows:

$$K_{\text{p}\,1/4}(t) = \frac{4\dfrac{\lambda}{\lambda_k}\left(1 - e^{-\lambda_k t}\right) + 1}{5 - 4e^{-\lambda t}}.$$

For a redundancy multiplicity of 2/3 without taking into account the reliability of the switching device, the formula for the coefficient of effectiveness by the probability of failure-free operation according to (3) and (4) is as follows:

$$K_{\text{p}\,2/3}(t) = \frac{1 + 3\lambda t + 4.5\lambda^2 t^2}{10 + 6e^{-2\lambda t} - 15e^{-\lambda t}}.$$

Figure 4 illustrates the time dependencies of the redundancy effectiveness coefficient for a switching device failure rate 10^{-8} h^{-1}, redundancy multiplicities 1/2 and 1/4, and different element failure rates. Figure 5 depicts graphs of the dependence on time of the redundancy effectiveness coefficient for a redundancy multiplicity of 2/3 at different element failure intensities.

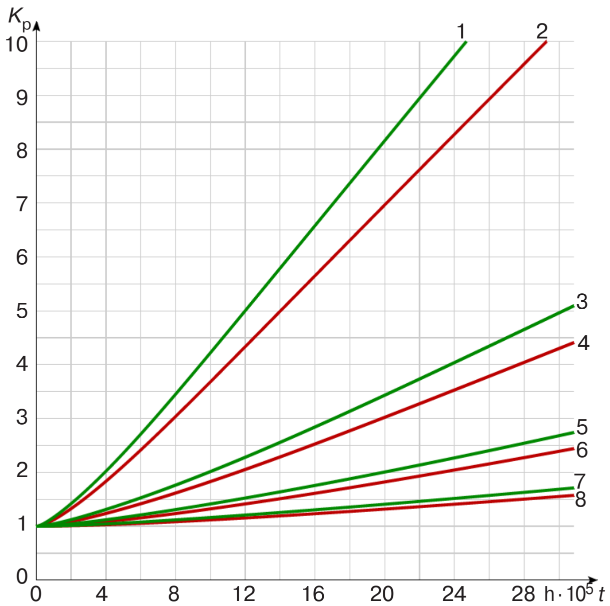

Fig. 4. Time dependencies of the redundancy efficiency coefficient on the probability of failure-free operation:
1, 2: $\lambda = 5 \cdot 10^{-6}$ h^{-1}; 3, 4: $\lambda = 2 \cdot 10^{-6}$ h^{-1};
5, 6: $\lambda = 10^{-6}$ h^{-1}; 7, 8: $\lambda = 5 \cdot 10^{-7}$ h^{-1};
1, 3, 5, 7: redundancy multiplicity 1/4;
2, 4, 6, 8: redundancy multiplicity 1/2

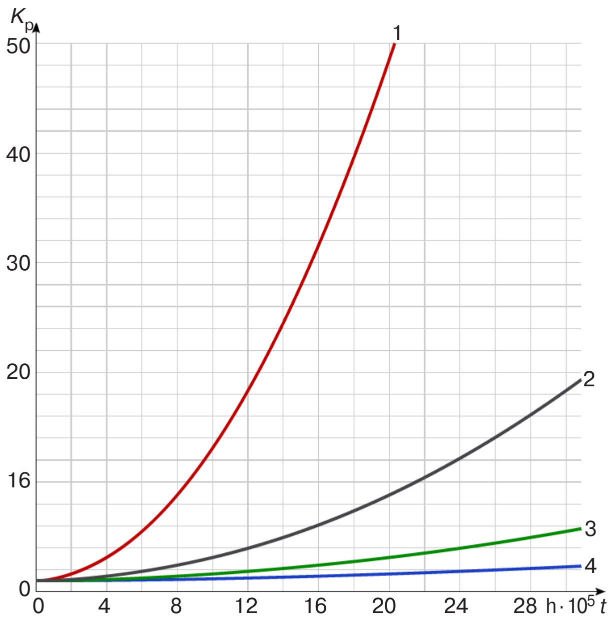

Fig. 5. Time dependencies of the redundancy effectiveness coefficient on the probability of failure-free operation for the redundancy multiplicity of 2/3.
1: $\lambda = 5 \cdot 10^{-6}$ h^{-1}; 2: $\lambda = 2 \cdot 10^{-6}$ h^{-1};
3: $\lambda = 10^{-6}$ h^{-1}; 4: $\lambda = 5 \cdot 10^{-7}$ h^{-1}

Analysis of the graphs of Fig. 4 and Fig. 5 shows that the coefficient of efficiency of the probability of the failure-free operation increases with time, as well as with the increase of λ. Thus, for example, for the time of 10^6 h and $1.4 \cdot 10^6$ h at a redundancy multiplicity of 1/4 $\lambda = 5 \cdot 10^{-6}$ h^{-1} and $\lambda_k = 10^{-8}$ h^{-1} the coefficient of efficiency is equal to 4.2 and 5.8, respectively. When the redundancy multiplicity is 1/2, the similar values of K_p are 3.7 and 5.0. In case of the decrease of the failures rate down to $\lambda = 10^{-6}$ h^{-1} for the time of 10^6 h and the redundancy multiplicities 1/4 and 1/2, the efficiency coefficient is equal to 2.0 and 1.8, respectively.

In the case of application of the redundancy multiplicity 2/3 at $\lambda = 5 \cdot 10^{-6}$ h^{-1} for the time 10^6 h and $1.4 \cdot 10^6$ h, the redundancy efficiency coefficient is equal to 13.3 and 24.5, respectively (Fig. 5). At decrease of intensity of failures down to $\lambda = 10^{-6}$ h^{-1}, corresponding values of K_p are equal to 1.7 and 2.2, respectively.

FAILURE RATE OF SLIDING REDUNDANCY DIAGRAMS

One of the main indicators of the reliability of REF is the failure rate. Let's investigate how the failure rate of sliding redundancy diagrams with loaded and unloaded redundancy changes for different values of λ and λ_k when the redundancy multiplicity is being changed.

If the redundancy multiplicity is equal to $1/n$, the failure rate of the scheme with unloaded redundancy is determined by the expression:

$$\lambda_1(t) = -\frac{dP_1(t)}{dt}\Big/P_1(t) = \frac{n\lambda\left(n\frac{\lambda}{\lambda_k}+1\right)\left(1-e^{-\lambda_k t}\right)}{n\frac{\lambda}{\lambda_k}\left(1-e^{-\lambda_k t}\right)+1}, \quad (5)$$

and for a diagram with a loaded redundancy the failure rate is determined by the expression:

$$\lambda_2(t) = -\frac{dP_2(t)}{dt}\Big/P_2(t) = \frac{n\lambda(n+1)\left(1-e^{-\lambda t}\right)}{n\left(1-e^{-\lambda t}\right)+1}. \quad (6)$$

In the case of a redundancy multiplicity of 2/3, the equations for the failure rate are as follows:

- for the diagram with unloaded redundancy

$$\lambda_3(t) = -\frac{dP_3(t)}{dt}\Big/P_3(t) = \frac{27\lambda^3 t^2}{2+6\lambda t+9\lambda^2 t^2}, \quad (7)$$

- for the diagram with loaded redundancy

$$\lambda_4(t) = -\frac{dP_4(t)}{dt}\Big/P_4(t) = \frac{30\lambda\left(1+e^{-2\lambda t}-2e^{-\lambda t}\right)}{10+6e^{-2\lambda t}-15e^{-\lambda t}}. \quad (8)$$

From the equations (5)–(8) it follows that for all considered sliding redundancy diagrams at $t = 0$ the failure rate is equal to zero, while when the failure rate is equal to $n\lambda$, the failure rate is the same as for a non-redundant system. Such systems are referred to as ageing.

The dependencies of failure rate on the time of sliding redundancy schemes with redundancy multiplicity of 1/2, 1/4, and 2/3 at $\lambda = 10^{-6}$ h^{-1} are given in Fig. 6. When constructing the dependencies, the value of the switching device failure rate $\lambda_k = 10^{-8}$ h^{-1} was taken for a diagram with unloaded redundancy for multiplicity of redundancy 1/2 and 1/4.

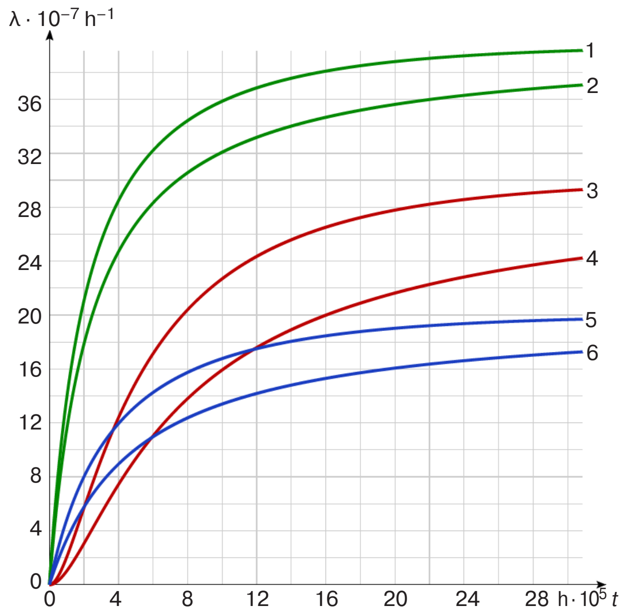

Fig. 6. Dependencies of failure rate on time of sliding redundancy diagrams:
1, 2: multiplicity of redundancy 1/4;
3, 4: multiplicity of redundancy 2/3;
5, 6: multiplicity of redundancy 1/2;
1, 3, 5: loaded redundancy;
2, 4, 6: unloaded redundancy

For comparing the failure intensities of systems with various redundant multiplicities, we will introduce an ageing rate indicator—time of achievement by intensity of failures of level 0.9 from the maximum time, i.e., when redundancy already practically does not influence intensity of failures. The table shows the values of this time determined by equations (5)–(8) and graphs of Fig. 6 values of this time in hours for some values of λ at different variants of redundancy.

Increasing the reliability of REF, in particular satellite communication systems, is associated with an increase in the active life and is determined by functional and structural solutions, allowing to postpone the processes of ageing and degradation of elements and systems as a whole. From the equations (5)–(8), as well as the graphs presented in Fig. 6 graphs and Table data it follows that

- it is possible to slow down the ageing process of the systems of sliding redundancy with unloaded and loaded redundancy at different multiplies of redundancy by application of load redundancy;
- the ageing rate of the considered schemes with sliding redundancy depends on the redundancy multiplicity and is smaller for the multiplicity of 2/3.

CONCLUSIONS

The considered methodology for determining the efficiency of sliding redundancy using mathematical models of the probability of failure-free operation and intensity of failures allows us to draw the following conclusions:

1. Diagram of sliding redundancy with unloaded redundancy is more effective than the diagram with loaded redundancy even when taking into account the intensity of failures of the switching device. Moreover, the efficiency of sliding redundancy with unloaded redundancy increases with time, as well as with the increase of the failure rate of the main and redundant elements.
2. If the ratio of element failure rate to switchgear failure rate is greater than 10, the reliability of the switchgear has almost no effect on the durability of the unloaded sliding redundancy diagram.
3. Combination of load redundancy to reduce the failure rate of elements and structural redundancy makes it possible to achieve a decrease in the ageing rate of systems with sliding redundancy, i.e., to extend the duration of redundancy with

Table. Ageing rate of a redundant system

λ, h^{-1}	Redundancy multiplicity					
	1/2		1/4		2/3	
	Loaded redundancy	Unloaded redundancy	Loaded redundancy	Unloaded redundancy	Loaded redundancy	Unloaded redundancy
10^{-6}	$1.38 \cdot 10^6$	$4.36 \cdot 10^6$	$1.03 \cdot 10^6$	$2.22 \cdot 10^6$	$1.75 \cdot 10^6$	$6.29 \cdot 10^6$
$5 \cdot 10^{-7}$	$2.79 \cdot 10^6$	$8.93 \cdot 10^6$	$2.02 \cdot 10^6$	$4.17 \cdot 10^6$	$3.51 \cdot 10^6$	$12.7 \cdot 10^6$

unloaded and loaded redundancy. The best results are obtained by the diagram with fractional multiplicity of 2/3.

Thus, to improve the efficiency of the long-life REF sliding redundancy, it is necessary to combine the multiplicity of redundancy with the reserve operating mode and ways to reduce the intensity of failure of elements.

Authors' contributions

T.E. Gelfman—research idea, scientific editing.

A.P. Pirkhavka—conducting research, writing the text of the article.

REFERENCES

1. Polovko A.M., Gurov S.V. *Osnovy teorii nadezhnosti* (*Fundamentals of Reliability Theory*). St. Petersburg: BKhV-Peterburg; 2008. 704 p. (in Russ.). ISBN 978-5-94157-541-1
2. Gelfman T.E., Pirkhavka A.P., Skripachev V.O. Analysis of the effectiveness of methods for ensuring the reliability of a communication satellite transponder. *Russ. Technol. J.* 2023;11(1):51–59. https://doi.org/10.32362/2500-316X-2023-11-1-51-59
3. Sevastyanov N.N., Andreev A.I. *Osnovy upravleniya nadezhnost'yu kosmicheskikh apparatov s dlitel'nymi srokami ekspluatatsii* (*Fundamentals of Reliability Management of Spacecraft with Long Service Life*). Tomsk: TGU; 2015. 266 p. (in Russ.). ISBN 978-5-94621-460-5
4. Saleh J.H., Hassan R., Torres-Padilla J.P., Hastings D.E., Newman D.J. Impact of subsystem reliability on satellite revenue generation and present value. *Journal of Spacecraft and Rockets*, 2005;42(6):1122–1129. https://doi.org/10.2514/1.13137
5. Gelfman T.E., Kalmykov M.N., Serditov A.A., Chuev E.A., Bogachev V.N., Kharitonov A.Yu. Reliability of space communication systems. In: *Fundamental Problems of Radioengineering and Device Construction. Proceedings of the International Scientific and Technical Conference "INTERMATIC 2012"*. 2012;12(6):157–161 (in Russ.).
6. Kislaev A.G., Khropov A.N. Optimal redundancy as a method for improving the reliability of space communication systems. *Fundamental Problems of Radioengineering and Device Construction. Proceedings of the International Scientific and Technical Conference "INTERMATIC 2010"*. 2010;10(3):109–112 (in Russ.).
7. Zhadnov V.V. Calculation assessment of durability indicators of spacecrafts and systems electronic means. *Nadezhnost' i kachestvo slozhnykh system = Reliability and Quality of Complex Systems.* 2013;2:65–73 (in Russ.). Available from URL: https://nikas.pnzgu.ru/files/nikas.pnzgu.ru/zhadnov_65_73.pdf
8. Yampurin N.P., Baranova A.V. *Osnovy nadezhnosti elektronnykh sredstv* (*Fundamentals of Reliability of Electronic Means*). Moscow: Akademiya; 2010. 240 p. (in Russ.). ISBN 978-5-7695-5908-2
9. Alyoshin V.F., Kolobov A.Yu., Petrov J.A. Challenging issues for predicting and validating reliability of sustained spacecraft operation. *Nauka i obrazovanie: nauchnoe izdanie MGTU im. N.E. Baumana = Science and Education of Bauman MSTU.* 2015;6:31–41 (in Russ.). Available from URL: https://www.elibrary.ru/item.asp?id=23852897

СПИСОК ЛИТЕРАТУРЫ

1. Половко А.М., Гуров С.В. *Основы теории надежности*. СПб.: БХВ-Петербург; 2008. 704 с. ISBN 978-5-94157-541-1
2. Гельфман Т.Э., Пирхавка А.П., Скрипачев В.О. Анализ эффективности методов обеспечения надежности ретранслятора спутника связи. *Russ. Technol. J.* 2023;11(1):51–59. https://doi.org/10.32362/2500-316X-2023-11-1-51-59
3. Севастьянов Н.Н., Андреев А.И. *Основы управления надежностью космических аппаратов с длительными сроками эксплуатации*. Томск: ТГУ; 2015. 266 с. ISBN 978-5-94621-460-5
4. Saleh J.H., Hassan R., Torres-Padilla J.P., Hastings D.E., Newman D.J. Impact of subsystem reliability on satellite revenue generation and present value. *Journal of Spacecraft and Rockets*, 2005;42(6):1122–1129. https://doi.org/10.2514/1.13137
5. Гельфман Т.Э., Калмыков М.Н., Сердитов А.А., Чуев Е.А., Богачев В.Н., Харитонов А.Ю. Надежность систем космической связи. В сб.: *Фундаментальные проблемы радиоэлектронного приборостроения. Материалы Международной научно-технической конференции «INTERMATIC – 2012»*. 2012;12(6):157–161.
6. Кислаев А.Г., Хропов А.Н. Оптимальное резервирование, как метод повышения надежности систем космической связи. *Фундаментальные проблемы радиоэлектронного приборостроения. Материалы Международной научно-технической конференции «INTERMATIC – 2010»*. 2010;10(1–3):109–112.
7. Жаднов В.В. Расчетная оценка показателей долговечности электронных средств космических аппаратов и систем. *Надежность и качество сложных систем.* 2013;2:65–73. URL: https://nikas.pnzgu.ru/files/nikas.pnzgu.ru/zhadnov_65_73.pdf
8. Ямпурин Н.П., Баранова А.В. *Основы надежности электронных средств*. М.: Академия; 2010. 240 с. ISBN 978-5-7695-5908-2
9. Алешин В.Ф., Колобов А.Ю., Петров Ю.А. Проблемные вопросы прогнозирования и подтверждения надежности космических аппаратов длительного функционирования. *Наука и образование: научное издание МГТУ им. Н.Э. Баумана*. 2015;6:31–41. https://www.elibrary.ru/item.asp?id=23852897
10. Kofanov Y.N., Lvov B.G., Meleh N.A., Sotnikova S.Y. Reliability of space infocommunications equipment. In: *Proceedings of the 2018 International Conference*

10. Kofanov Y.N., Lvov B.G., Meleh N.A., Sotnikova S.Y. Reliability of space infocommunications equipment. In: *Proceedings of the 2018 International Conference “Quality Management, Transport and Information Security, Information Technologies”* (*IT&QM&IS*). IEEE. 2018. P. 354–357. https://doi.org/10.1109/ITMQIS.2018.8525088
11. Jung S., Choi J.P. End-to-end reliability of satellite communication network systems. *IEEE Systems Journal*. 2021;15(1):791–801. https://doi.org/10.1109/JSYST.2020.2980760
12. Jung S., Choi J.P. Reliability of small satellite networks with software-defined radio and enhanced multiple access protocol. *IEEE Transactions on Aerospace and Electronic Systems.* 2021;57(3):1891–1902. https://doi.org/10.1109/TAES.2021.3050652
13. Gelfman T.E., Pirkhavka A.P. The operational readiness factor of satellite communication networks. *Russ. Technol. J.* 2022;10(1):35−40 (in Russ.). https://doi.org/10.32362/2500-316X-2022-10-1-35-40
14. Askinazi G.B., Bykov V.L., Dyachkova M.N., et al. *Sputnikovaya svyaz’ i veshchaniye:* spravochnik (*Satellite Communication and Broadcasting.* Handbook). Kantor L.Ya. (Ed.). Moscow: Radio i svyaz’; 1988. 344 p. (in Russ.).
15. Mehmet N., Selman D., Hasan H.E., Cenk S. Reliability and cost focused optimization approach for a communication satellite payload redundancy allocation problem. *International Journal of Electrical, Electronic and Communication Sciences*, 2018;11.0(5). https://doi.org/10.5281/zenodo.1316576

10. Kofanov Y.N., Lvov B.G., Meleh N.A., Sotnikova S.Y. Reliability of space infocommunications equipment. In: *Proceedings of the 2018 International Conference “Quality Management, Transport and Information Security, Information Technologies”* (*IT&QM&IS*). IEEE. 2018. P. 354–357. https://doi.org/10.1109/ITMQIS.2018.8525088
11. Jung S., Choi J.P. End-to-end reliability of satellite communication network systems. *IEEE Systems Journal*. 2021;15(1):791–801. https://doi.org/10.1109/JSYST.2020.2980760
12. Jung S., Choi J.P. Reliability of small satellite networks with software-defined radio and enhanced multiple access protocol. *IEEE Transactions on Aerospace and Electronic Systems.* 2021;57(3):1891–1902. https://doi.org/10.1109/TAES.2021.3050652
13. Гельфман Т.Э., Пирхавка А.П. Коэффициент оперативной готовности спутниковых сетей связи. *Russ. Technol. J.* 2022;10(1):35−40. https://doi.org/10.32362/2500-316X-2022-10-1-35-40
14. Аскинази Г.Б., Быков В.Л., Дьячкова М.Н. и др. *Спутниковая связь и вещание:* справочник; ред. Л.Я. Кантор. М.: Радио и связь; 1988. 344 с.
15. Mehmet N., Selman D., Hasan H.E., Cenk S. Reliability and cost focused optimization approach for a communication satellite payload redundancy allocation problem. *Int. J. Electrical, Electronic and Communication Sciences*. 2018;11.0(5). https://doi.org/10.5281/zenodo.1316576

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