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DESIGNING OF FAULT-TOLERANT RADIO ELECTRONIC SYSTEMS WITH COMPLEX MAJORITY STRUCTURES

In the paper it is solved the scientific-applied task of increasing degree of adequacy of analytical reliability models of fault-tolerant radio electronic systems (RES) for solving tasks of reliability analysis and parametric synthesis of RES. These RES are based on majority structure. An analytical reliability model of fault-tolerant RES with reconfiguration of majority structure core, which takes into account the changing rules of voting, is developed. Proposed model of fault-tolerant RES allows us to design the RES, which keep on the principle of majority voting after technical systems failures. Two analytical models of reliability of fault-tolerant RES with two-level principle of majority voting are developed. Improved analytical reliability model of maintained fault-tolerant RES based on majority structure with sliding redundancy and fixed rule of vote, allows solving tasks of multivariate analysis (different variants of the algorithm of redundancy using and disaster recovery strategies). This model can solve tasks of reliability parametric synthesis by finding compromises between chosen parameters of fault-tolerant RES and carry out comparative research of their reliability.

Keywords: *reliability, fault-tolerant radio electronic system, majority structure, reliability designing, reconfiguration, disaster recovery strategy, sliding redundancy.*

Introduction

In designing of the systems of responsible destination or critical systems, the one of the difficult and important tasks is to ensure requirements to their reliability. There are critical systems or responsible systems such as: emergency protection system of nuclear power plants [1, 2]; fault-tolerant system TRICON, which is used in emergency protection systems for petrochemical and chemical plants; fire safety systems of floating platforms; fault-tolerant system TMS-1000R, which provides protection and control of gas and steam turbines [3]; vehicle-borne information and control computer systems [4], as well as informational and control systems of military and civil aviation [5]; centralized systems of control subway and rail transport [6-7].

First of all, the insufficient level of reliability such radio electronic systems (RES) can lead to the material losses, and, in the worst case, to even more serious consequences of environmental disasters or human victims.

Ensuring the reliability of such systems on design stage can be provided by selecting and developing of fault-tolerant structures and determining their requirements for maintenance.

Fault tolerant system with the majority redundancy are widely used in designing of critical systems.

There are such typical fault-tolerant configuration of RES with the majority redundancy which are practically used:

– fault-tolerant RES basing on majority structure (MS) with fixed decision rule;

– fault-tolerant RES with reconfiguration of majority structure core;

– fault-tolerant RES with two-level principle of majority voting (fault-tolerant RES using the majority structures embedded in the majority structure).

The main advantages of using such structures are: protection from failures; absence of downtime; simplicity of control and diagnostics.

In practice of designing such structures, it is widely known fault-tolerant system with majority structure "2 out of 3". For such fault-tolerant RES it is used the maintenance of sliding redundancy during continuous performance. Important task is to determine the requirements for the maintenance and sliding redundancy. In the available publications, such systems are used, but the adequacy of the developed models requires significant increase. Particularly there are not taken into account: repair parameters, control and diagnostics, and for the duration of the recovery process exponential distribution law is used.

Fault-tolerant RES with two-level principle of majority voting are used to improve the reliability of information and control systems, onboard systems. However, models and tools that enable reliability analysis of such structures are absent in the literature.

Fault tolerant RES with reconfiguration and adaptive voting element are used during long-term performance for non-maintained systems. The models of fault tolerant-RES with reconfiguration of structure are known in the literature. However, in these models the majority principle of redundancy system is lost after the reconfiguration procedure. An important task is to show the possibilities of fault-tolerant electronic system with reconfiguration of majority structure, provide the principle of majority voting and all its positive qualities.

In addition, important task is to compare the reliability of all variants of configuration of fault-tolerant RES with majority structure. To summarize the above, we can assume that for fault-tolerant RES with complex majority structures the mathematical models either are absent or need substantial improvements in their degree of adequacy.

The actual problem is the task of developing mathematical models to solve problems of reliability designing of non-maintained critical electronic systems with different variants of implementation of fault-tolerant RES basing on the majority structure.

Development of reliability model of non-maintenance fault-tolerant electronic systems with reconfiguration of majority structure

The reliability of non-maintained RES for long-term performance is provided by the use of fault-tolerance, MS with fixed decision rule and sliding redundancy of technical systems (TS) in core [8]. In the paper [9] long-term performance of fault-tolerant RES is provided by procedure of core reconfiguration of MS. Fault-tolerant RES with the "2 of 3" structure after the failure of two TS in core is reconfigured, then the last operable TS continues working. Fault tolerant RES with the "3 out of 5" structure the after the failure of three TS in core continues working as a fault-tolerant RES with single redundancy. In these variants of reconfiguration procedures, the fault-tolerant RES loses the positive qualities of the majority principle, namely: the protection against failure; absence of downtime in case of TS failure; simplicity of control procedures and diagnosis. Models of these systems are developed with the assumption, that the voting element is faultless. This causes an absolute reliability reconfiguration procedure, that in turn reduces the adequacy of the proposed models. The proposed model doesn't consider the possibility of the sliding redundancy using.

Practical interest has the reconfiguration procedure of MS core, which allows us to keep on the majority principle when TS number in core decreases. However, in certain publications about fault-tolerant RES with MS are absent models for evaluation of efficiency of this reconfiguration procedure.

List of procedures, which form the behavior of fault-tolerant RES after failure of technical system in core

In developing the model of fault-tolerant RES there are counted its reliability behavior representing the following list of procedures.

The procedure 1. Detection of failed TS in the core and disable it.

The procedure 2. Connection of TS from hot redundancy to the core. This procedure gives the alternative of connection or non-connection of TS from hot redundancy to the core as result of switch failure. The number of redundant TS doesn't change when TS doesn't connect to the core. If connection is successful, failed TS is replaced in the core.

The procedure 3. Switching of TS from cold redundancy to the hot redundancy. This procedure is characterized by duration, which determines the time spent on software loading. The procedure can be successful and unsuccessful.

The procedure 4. Reconfiguration of MS core. This procedure involves changing the rule of voting in adaptive voting element (AVE) and correspondingly changing in the number of TS in core. Two variants of conditions of reconfiguration procedure launching core of MS are considered.

1. In the first version, the reconfiguration of MS core occurs after the first failure of any TS in the core when there is no connection with redundant TS or sliding redundancy is exhausted. The disagreement detector sends the command to AVE to reconfigure after detection of inoperability of TS in the core and establishment of the fact that it is not fault but failure. Then inoperable TS turns off, one operable TS is transferred to the redundancy and the core changes the decision rule. For example, if 9 TS are in the core, so decision rule was "5 out of 9", then after reconfiguration 7 TC are in the core and decision rule is changed to "4 out of 7". The AVE gives alternative correspondingly with keeping and not keeping of reconfiguration of MS core. In other case, fault tolerant RES loses the ability to reconfigure, but ensures operability until the core will be equal to ((n-1)/2) TS, where n always is an odd natural number.

2. In the second version, the reconfiguration of MS core is carried out before critical state when the number of TS in the core is the minimum for proper operation of the MS, i.e. ((n+1)/2). For fault-tolerant configurations of RES if the core of MS has an odd number of TS, one TS core is transferred to the sliding redundancy. For example, if the core has 7 TS, decision rule is "4 out of 7", then after reconfiguration the core has 3 operable TS and decision rule is changed to "2 out 3". In other case, fault tolerant RES continues to operate unchanged and it

goes into critical failure when the next TS fails in the core.

Development of structural-automatic model of fault-tolerant RES with reconfiguration of majority structure core

Model was developed by technology [10], which allows automation the development of graph of states and transitions. It is important for solving problems of multivariate analysis and parametric synthesis. A software module ASNA-1 provides the practical use of this technology.

This technology is presentation of the researched object in the form of structural- automatic model (SAM). For SAM development of fault-tolerant RES it is carried out: definition of basic events which occur and are caused by reliability behavior algorithm; determining of the state vector components; determining of the conditions and circumstances, when the basic events occur; calculation of formulas of basic events intensities; formation of rules modification of the state vector component of fault tolerant RES.

The developed SAM as formalized presentation of the research object is input in software module ASNA-1, which builds graph of states and transitions, basing on which, system of Kolmogorov-Chapman differential equations is formed. Reliability indexes (probability of faultless work and MTTF) of fault-tolerant RES is determined by numerical method using MathCAD or MathLab.

Mathematical model of fault-tolerant RES with reconfiguration of majority structure core

The model takes into account the following parameters, namely: n – initial number of TS in core of MS; m – initial number of TS in cold redundancy; λ – failure rate; Prec – probability of successful reconfiguration; Ph – probability of successful TS connection from hot redundancy to the core; Pc – probability of successful TS connection from cold redundancy to the hot redundancy; Th – mean time of TS connection from hot redundancy to MS core; Tc – mean time of TS connection from cold redundancy to hot redundancy; Trec – mean time of MS core reconfiguration.

Mathematical model of fault-tolerant RES with reconfiguration of majority structure core for the first version of start conditions of reconfiguration procedure is presented in the form of linear homogeneous differential equations of the first order (1). The mathematical model is formed by the graph of states and transitions, which has the following parameters: 29 states and 79 transitions.

$$\begin{cases} \dfrac{dP_1(t)}{dt} = -7\lambda \cdot P_1(t); \\ \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \\ \dfrac{dP_{10}(t)}{dt} = -\left(\dfrac{P_{rec}}{T_{rec}} + \dfrac{1-P_{rec}}{T_{rec}}\right) \cdot P_{10}(t) + \\ +\lambda \cdot P_8(t) + \dfrac{P_h}{T_h} \cdot P_{14}(t) + \dfrac{1}{T_h} \cdot P_{15}(t); \\ \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \\ \dfrac{dP_{29}(t)}{dt} = -\dfrac{1}{T_h} \cdot P_{29}(t) + 3\lambda \cdot P_{20}(t). \end{cases} \quad (1)$$

Comparison of fault-tolerant RES reliability: with MS reconfiguration and without MS reconfiguration

The researched results are presented in Fig. 1. Research were conducted for these parameters: initial number of TS in MS core n = (5, 7, 9); failure rate λ = 100 failures /106 hours; mean time of TS connection from hot redundancy to MS core Th = 0,0001 h; mean time of TS connection from cold redundancy to hot redundancy Tc = 0,01 h; mean time of MS core reconfiguration Trec = 0,01 h; probability of successful reconfiguration Prec = 0,999; probability of successful TS connection from hot redundancy to the core Ph = 0,999; probability of successful TS connection from cold redundancy to hot redundancy Pc = 0,999.

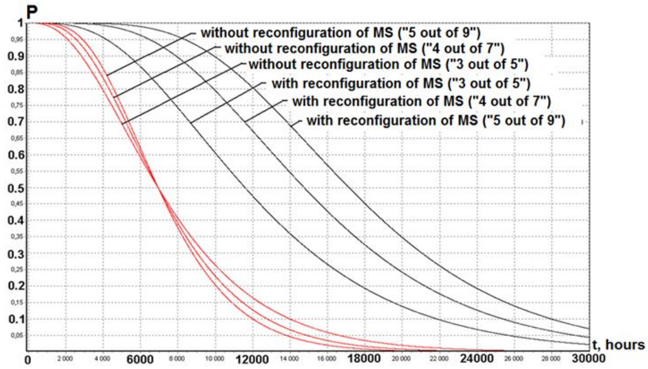

Fig. 1. The probability of faultless work of fault-tolerant RES with reconfiguration and fault-tolerant RES with fixed decision rule depending on the duration of RES performance

Research demonstrates that the usage of fault-tolerant RES with reconfiguration of MS in comparison with fault-tolerant RES with fixed decision rule improves the reliability (mean time before failure): to fault-tolerant RES with MS "5 out of 9" in 2,4 times (or by 140%); to fault-tolerant RES with MS "4 out of 7" in 2,1 times (or by 110%); to fault-tolerant RES with MS "3 out of 5" in 1,6 times (or by 60%). This confirms the efficiency of reconfiguration procedure for the MS core of non-maintained RES.

Determination reliability of RES based on model with reconfiguration core of MS

Research were conducted at these parameters: initial number of TS in MS core n = 7; initial number of TS in cold redundancy m = 1; failure rate λ = 100 failures /106 h; mean time of TS connection from hot redundancy to MS core Th = 0,0001 h; mean time of TS connection from cold redundancy to hot redundancy Tc = 0,1 h; mean time of MS core reconfiguration Trec = 0,01 h; probability of successful reconfiguration Prec = 0,999. The research results are presented in Fig. 2.

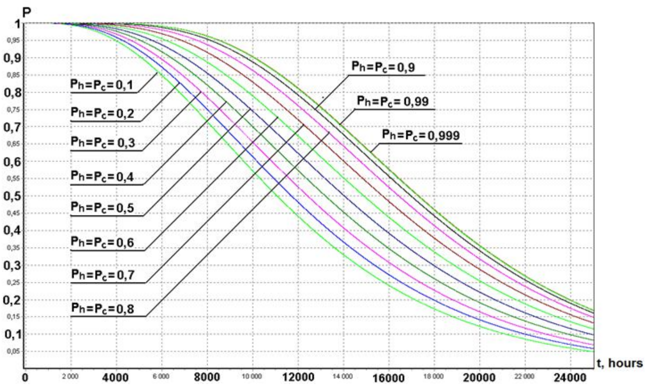

Fig. 2. The probability of faultless work of fault-tolerant RES with reconfiguration depending on the duration of its performance for different values of P_h i P_c

Research showed (Fig. 2) that for high reliability of non-maintained RES the values of probability of successful TS connection to the core and successful TS connection from cold redundancy to hot redundancy should not be lower than 0,99. Higher requirements for switch does not provide significant increase of reliability indexes.

Development of reliability models of non-maintained electronic systems with two-level principle of majority voting

To ensure high level of reliability of RES of critical application, in work [11] it is shown the block diagram of fault-tolerant RES using three majority structures embedded in majority structure. In this publication it is called "fault-tolerant RES with parallel-hybrid redundancy". The system includes: N cores, each of which includes M operating units (technical systems) and voting element. Such fault-tolerant RES are used for design of control systems.

However, in known publications, which deal with the problem of designing fault-tolerant RES, the models using two-level principle of majority voting are absent. Therefore, the task of developing such models of fault-tolerant RES is very actual. For solving this problem two models of fault-tolerant RES using two-level principle of majority voting were developed, limit performance is determined by two rules: the first case the fault-tolerant RES is inoperable after critical failure in 2 core; in the second case the fault-tolerant RES is inoperable after critical failure in the last core. These models take into account the sliding redundancy, which is formed from operable TS after VE core failure or 2 TS in one core.

Configuration fault-tolerant of RES with two-level principle of majority voting

The fault-tolerant of RES (block diagram is presented in Fig. 3) consist of: three cores, each of them includes 3 TS; redundant TS (appears in the process of fault-tolerant

RES performance); the disagreement detector for detecting failed TS (DD1); the disagreement detector for detecting failed cores (DD2); voting elements for 1-st, 2-nd and 3-rd core (VE1, VE2, VE3); finite voting element (FVE); switch.

Accordingly, the signal is sent from each output from VE to KVE. The initial number of TC in each core is equal to three and decisions rule of each VE is fixed.

Localization of failed TS in the core. Control of TS performance in the core is carried out by DD1. This disagreement detector performs the comparison at each step of output signal from VE in the core (VE1, VE2, VE3) with the signal from the output of each TS. Disagreement of one TS signal with VE output signal in the most cases indicates on software fault in this TS, because the fault rate exceeds the failure rate. If you find disagreement, the TS testing starts. If the testing detects fault, TS software restarts and then continues as part of the core. Otherwise, DR1 sends signal that TS in the core is inoperable. After that the detected failed TS is disconnected from the core and the redundant TS connects (if it is available).

Localization of failed core of fault-tolerant RES. Control of the cores of fault tolerant RES carried out by DD2. This disagreement detector performs the comparison of output signals from VE1, VE2, VE3 with the signal from the output from KVE. If they don't match, DD2 sends the signal about inoperation on corresponding core of fault-tolerant RES, as a result of lack of TS for correct performance of the core, i.e., when in the core it is one operable TS or when voting element (VE1, VE2, VE3) fails. After that the transfer of remained operable TS from the core to sliding redundancy or other cores, where the TS number is less than initial.

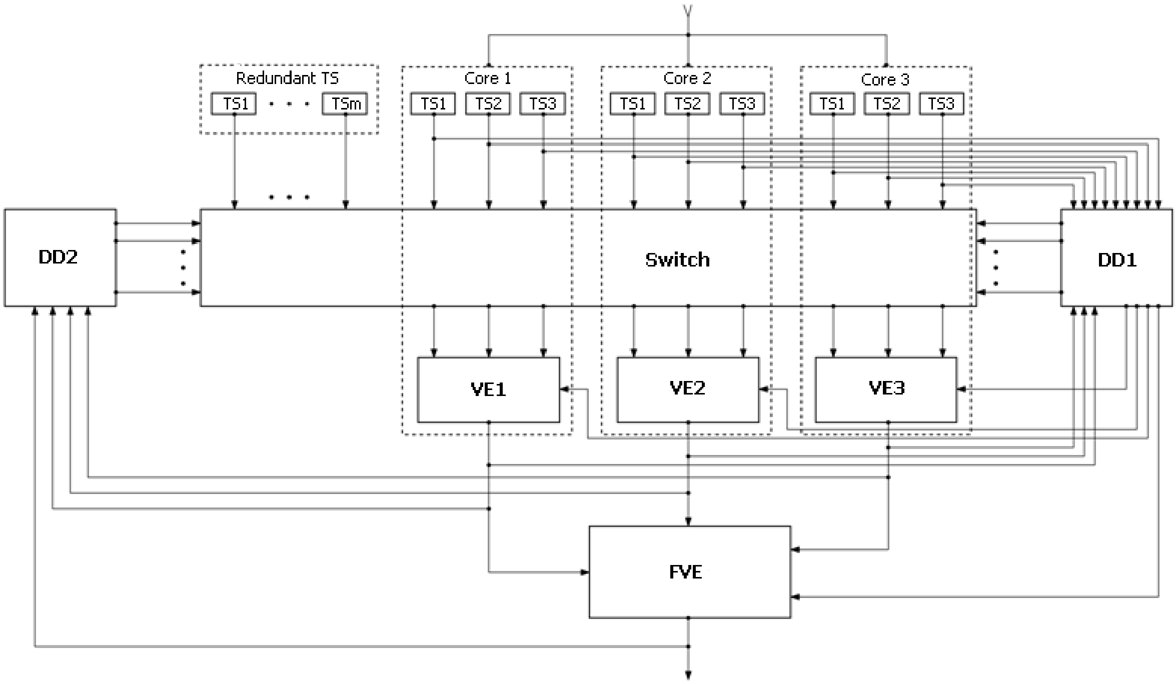

Fig. 3. Block diagram of fault-tolerant RES the two-level principle of majority voting

Solving problems of reliability design of fault-tolerant RES with two-level principle of majority voting

For this configuration fault-tolerant RES with two-level principle of majority voting two reliability models were developed, according to presented methods in paragraph 2.3.

1. Investigation of the probability of failure of RES depending on the duration of its performance. In this study, we are talking about fault-tolerance RES with majority three structures embedded in majority structure. This RES is inoperable after critical failure of 2 cores. Mathematical model of fault-tolerant RES is a system of linear homogeneous differential equations consisting of 80 equations. Calculations were carried out for these parameters of fault-tolerant RES: initial number of TS in each core is equal to 3; failure rate of TS in the core is = 0,0001 1/h; the mean time of connection TS from the sliding redundancy to the core is T = 0,1 h.

Research results of probability of faultless work of fault-tolerant RES depending on duration of its performance for different values of the ratio of the VE failure rate and TS failure rate in the core are shown in Figure 4. The nature of dependencies suggests the feasibility of study of dependence of the mean time to failure of fault-tolerant RES and VE failure rate to TS failure in the core.

2. Investigation of mean time of faultless work of fault-tolerant RES with two-level principle of majority voting. This RES is inoperable after critical failure of 2 cores. Research results of mean time to failure fault-tolerant RES depending on the ratio of the VE failure rate and TS failure rate in the core are shown in Figure 5.

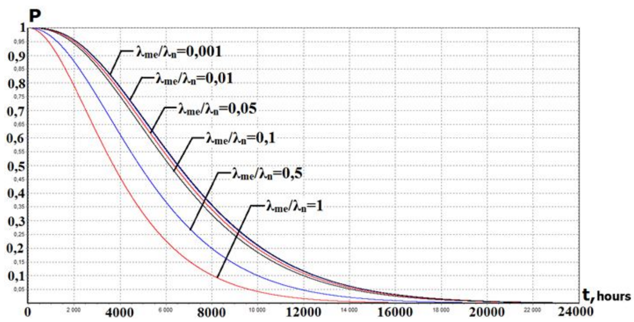

Fig. 4. The probability of faultless work of fault-tolerant RES with two-level principle of majority voting depending on the duration of its performance

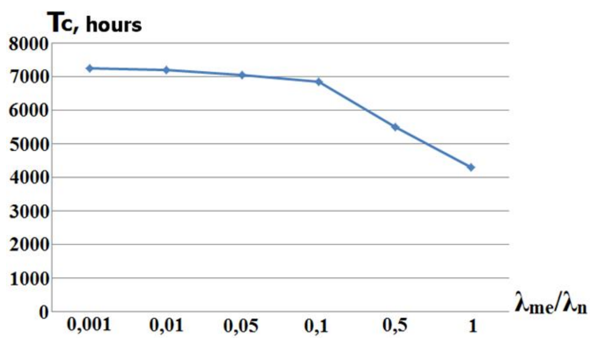

Fig. 5. Mean time to failure fault-tolerant RES depending on the ratio of the VE failure rate and TS failure rate in the core

Table 1
Mean time to failure fault-tolerant RES depending on the ratio of the VE failure rate and TS failure rate in the core

Fault-tolerant RES with two-level principle of majority voting which is inoperable after critical failure of 2 cores						
T_c, h	4282	5485	6840	7034	7193	7229
λ_{me}/λ_n	1	0,5	0,1	0,05	0,01	0,001

The results show that the reliability index (mean time to failure) increases on 2558 hours or in 60% while VE failure rate decreases (the parameter range of 0..11). further reduce of the VE failure rate (VE1, VE2, VE3) does not significantly increase the reliability index. The usage of VE1, VE2, VE3 with failure rate lower than λ_{me} = 0,00001 1 / h is not appropriate for given fault-tolerant RES.

Development of reliability models of maintained fault-tolerant radioelectronic systems with majority and sliding redundancy

When for development of maintained critical fault-tolerant RES it is necessary to provide the required level of reliability, the fault-tolerant RES with fixed decision rule of MS is used [12]. Reliability of these RES during long-term performance is increased by using sliding redundancy of TS and appropriate maintenance strategy [13].

Above for the construction reliability models of fault-tolerant RES it was assumed that the duration of all processes, which occur in the system, has exponential distribution. With this assumption the intensity of events flow is constant in time values. To improve the adequacy of models, and therefore the accuracy of the reliability indexes, it should be taken into account the actual distribution laws. In reality, the duration of the recovery process, which includes spent time for the arrival of repair crew and duration of repair, has the distribution law may similar to the Erlang distribution of 4-th order. Therefore, the second phase of the transformation graph uses the Erlang phases. The main essence of this method is that each transition of inhomogeneous Markov model is replaced by group of fictitious states, transitions between which are stationary. So developed homogeneous Markov model is close to the real system.

Description of recovery strategies

For the studied fault-tolerant RES during its performance the maintenance with recovery strategy is provided.

Repair crew is located far from the object, that makes significant impact on the repairman arrival time and reliability indexes. Therefore, the actual problem is the choice of such moment of time when repair crew receives a call and go to the object. This paper shows the impact on the reliability indexes of two limiting options of calling the repair crew:

1. Repair crew is call when instant TS failure lead to catastrophic failure (sliding redundancy is empty and number of operable TS n the core is minimal).
2. Repair crew is call after first TS failure in the MS core.

In the developed model repair crew capabilities are presented as follows:

- when the repairman arrives to the object, he carries out recovery of all inoperable TS of fault-tolerant RES. Recovered TS supply MS core and sliding redundancy;
- number of repairman interventions (repairs) is limited, due to the number of available spare repair kits, which are allocated for maintenance of fault-tolerant RES;
- duration of recovery work at whole includes directly the repair duration and repairman time spent for arriving to the object.

In the time interval after calling the repair crew and to the moment of repairman arrival to the object (before repair) the TS failure is possible. The probability of TS failure in the MS core during repair (replacement) of failed modules is not considered. According to the task of the study the models of fault-tolerant RES, according to the first and the second variants of calling the repair crew, were developed.

The developed model takes into account the following parameters, namely: n – initial number of TS in core of MS; m – initial number of TS in cold redundancy; r –maximum number of spare TS in stock to replace (repair) defective TS; λ – failure rate; Pc – probability of successful TS connection from cold redundancy to MS core; Tc – mean time of TS connection from cold redundancy to MS core; Trem – mean time to repair of TS; Tp –mean time required to arrival repair service; K – component, which determines the order of Erlang law.

Comparison of the reliability indexes of fault-tolerant RES for the first maintenance strategy, estimated for exponential distribution law and Erlang distribution law of 4-th order

Calculations were carried out for these parameters of fault-tolerant RES: n = 5; m = 2; λ_n = 1000 failures/10^6 h; r = 8; T_c = 0,1 h; T_{rem} = 0,1 h; T_p = 1 h;

$\mu = 1/(V4 \cdot T_{rem} + T_p)$ – intensity of inoperable TS recovery.

Obtained results (Fig. 6) show that the reliability index (mean time to failure), which was determined without regard to actual distribution law for the recovery duration, is underestimated about 20% for the level of probability equal to 0,9.

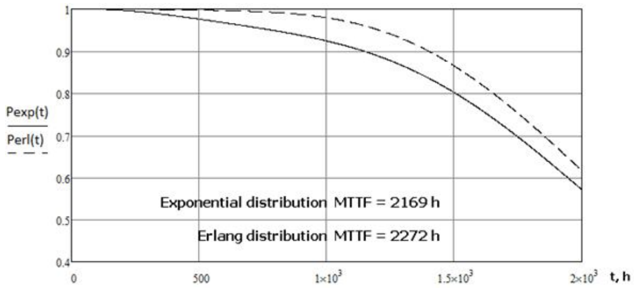

Fig. 6. Mean time to failure fault-tolerant RES depending on the duration of its exploitation

Comparison of three configurations of fault-tolerant radio electronic systems basing on majority structure

It is necessary to compare the reliability of these variants of non-maintained fault-tolerant RES, which are equivalent in terms of the TS number (all RES variants have 9 TS) 1 - fault-tolerant RES using two-level principle of majority voting – three MS embedded in MS with rule "2 out of 3"; 2 - fault-tolerant RES using three MS embedded in MS with rule "1 out of 3"; 3 - fault-tolerant RES with reconfiguration of core "5 out of 9"; 4 - fault-tolerant RES with reconfiguration of core "4 of 7" (2 TS are redundant); 5 - fault-tolerant RES with reconfiguration of core "3 out of 5" (4 TS are redundant).

The results (Fig. 5) of comparisons show that the best reliability for a given set of input parameters is provided by fault-tolerant RES with reconfiguration of MS core "3 out of 5" plus 4 TS in redundancy.

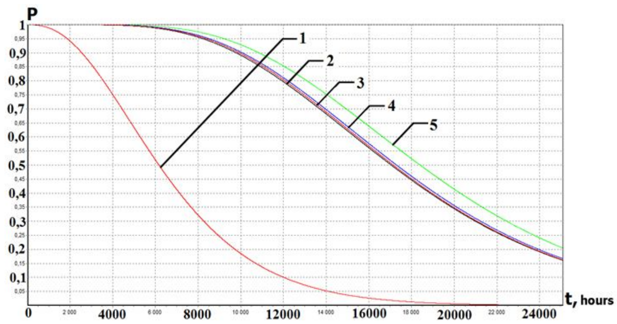

Fig. 7. Comparison of the reliability of fault-tolerant RES with reconfiguration of MS core and fault-tolerant RES using two-level principle of majority voting

It is necessary to determine the minimum number of repairs TS for repair service for ability to provide the probability value failure Rb.r. = 0,9 in the range of 10,000 operating hours for failover RES structure based on the majority of the "2 of 3".

The research reliability of fault-tolerant RES with majority structure "2 out of 3" for different number of repair

Necessary to determine a minimum number repairs of TS to predict for repair service that fault tolerant RES with majority structure "2 out of 3" could provide value probability uptime R = 0,9 in the range of operation 10000 hours.

Calculations of performed under such parameter values: n = 3; λn = 1·10-4 1/hour; Tp = 3 hours; Trem = 0,3 hour. Research results are presented in Fig. 8.

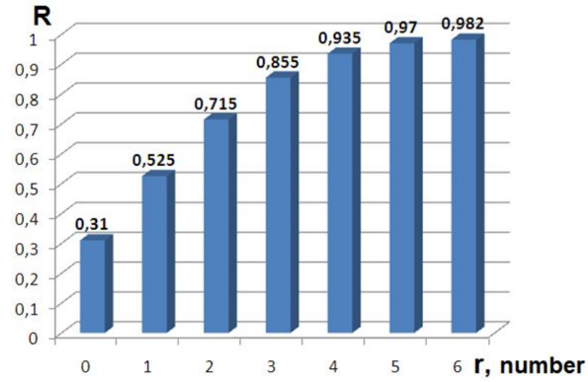

Fig. 8 The dependence of the probability failures work fault tolerant RES with MS "2 out of 3" (in the range of 10,000 hours) on the number of repairs

The results of research have shown that in order to provide a given level of reliability for repair service should provide at least 4 repairs, for a given input parameters.

Conclusions

As part of this task, the following scientific and practical results are obtained:

- new reliability model of fault-tolerant RES with of reconfiguration of the core of majority structure was developed. This model takes into account the change of the decision rules and appropriate reconfiguration of the core majority structure, the presence of sliding redundancy of technical systems in the core, unreliable work of the voting element and switch;

- two new analytical reliability models of fault-tolerant RES with two-level principle of majority voting are developed. The marginal efficiency of RES is defined by two rules: in the first case the fault-tolerant RES is inoperable after critical failure of 2 cores; in the second case the fault-tolerant RES is inoperable after critical failure in the last core. These models take into account unreliable work of the voting element and the sliding redundancy, which is formed from remained TS after failure of voting element in the core or failure of 2 technical systems in one core;

- analytical reliability model basing on fault-tolerant RES with considering of recovery strategy was improved. The duration of the recovery is distributed according to Erlang distribution low of 4th order;

- the models fault tolerant RES with majority principle of redundancy are allowing to solve the problem of reliability designing electronic systems of long-term continuous operation with a given level of reliability.

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ПРОЕКТИРОВАНИЕ ОТКАЗОУСТОЙЧИВЫХ РАДИОЭЛЕКТРОННЫХ СИСТЕМ СО СЛОЖНЫМИ МАЖОРИТАРНИМИ СТРУКТУРАМИ

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В работе решена актуальная научно-прикладная задача повышения степени адекватности надежностных аналитических моделей отказоустойчивых РЭС предназначенных для решения задач надежностного анализа и параметрического синтеза. Отказоустойчивые радиоэлектронные системы построены на основе мажоритарной структуры. Разработано надежностною аналитическую модель отказоустойчивой РЭС с реконфигурацией ядра мажоритарной структуры, которая учитывает изменение правила принятия решения. Предложенная модель отказоустойчивой системы позволяет проектировать РЭС, которые смогут сохранить мажоритарный принцип голосования после отказа отдельных технических систем. Разработаны две надежностные аналитические модели отказоустойчивой РЭС с двухуровневым принципом мажоритарного голосования. Усовершенствованная надежностная аналитическая модель обслуживаемой отказоустойчивой РЭС на основе мажоритарной структуры со скользящим резервированием и фиксированным правилом голосования, позволяет решать задачи многовариантного анализа (обусловленные различными вариантами реализации алгоритма использования резерва и стратегии аварийного восстановления). Эта модель позволяет решать задачи надежностного параметрического синтеза путем нахождения компромиссных решений при выборе параметров отказоустойчивой РЭС и проводить сравнительные исследования их надежности.

Ключевые слова: надежность, отказоустойчивость радиоэлектронная система, мажоритарная структура, надежностное проектирование, реконфигурация, стратегия аварийного восстановления, скользящее резервирование.

ПРОЕКТУВАННЯ ВІДМОВОСТІЙКИХ РАДІОЕЛЕКТРОННИХ СИСТЕМ ІЗ СКЛАДНИМИ МАЖОРИТАРНИМИ СТРУКТУРАМИ

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В роботі розв'язана актуальна науково-прикладна задача підвищення ступеня адекватності надійнісних аналітичних моделей відмовостійких РЕС призначених для розв'язання задач надійнісного аналізу та параметричного синтезу. Відмовостійкі радіоелектронні системи побудовані на основі мажоритарної структури. Розроблено надійнісну аналітичну модель відмовостійкої РЕС з реконфігурацією ядра мажоритарної структури, яка враховує зміну правила прийняття рішення. Запропонована модель відмовостійкої системи дає змогу проектувати РЕС, які зможуть зберегти мажоритарний принцип голосування після відмови окремих технічних систем. Розроблено дві надійнісні аналітичні моделі відмовостійкої РЕС з дворівневим принципом мажоритарноного голосування. Удосконалена надійнісна аналітична модель обслуговуваної відмовостійкої РЕС на основі мажоритарної структури з ковзним резервуванням та фіксованим правилом голосування, дозволяє розв'язувати задачі багатоваріантного аналізу (обумовлені різними варіантами реалізації алгоритму використання резерву та стратегії аварійного відновлення). Ця модель дозволяє вирішувати задачі надійнісного параметричного синтезу шляхом знаходження компромісних рішень при виборі параметрів відмовостійкої РЕС і проводити порівняльні дослідження їх надійності.

Ключеві слова: надійність, відмовостійка радіоелектронна система, мажоритарна структура, надійнісне проектування, реконфігурація, стратегія аварійного відновлення, ковзне резервування.

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