Multi-Fragmental Markov Models of Information and Control Systems Safety Considering Elimination of Hardware-Software Faults

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Abstract. The information and control systems of Nuclear Power Plant and other safety critical systems are considered as a set of three independent hardware channels including online testing system. Nuclear Power Plant information and control systems design on programmable platforms is rigidly tied to the V-model of the life cycle. Functional safety and availability during its life cycle are assessed using Markov and multi-fragmental models. Multi-fragmental models are used to assess the availability function and proof test period. The multi-fragmental model MICS31 contains an absorbing state in case of hidden faults and allows evaluating risks of "hidden" unavailability. The MICS41 model simulates the "migration" of states with undetected failures into states with detected faults. Results of multi-fragmental modeling (models MICS31 and MICS42) are compared to evaluate proof test period taking into account requirements for SIL3 level and limiting values of hidden fault probabilities.

Keywords: Multi-Fragmental Models, Functional Safety Modeling, Information and Control System, Undetected Software Failure

1 Introduction

For different classes of critical systems (medical equipment, banking systems, road, air, railway transport and nuclear power plants) very strict requirements have been developed. These requirements determine both the system characteristics from the group of non-functional requirements (availability, reliability, safety, etc.) and the content of the life cycle phases. During the development cycle, it is possible to change the architecture of the information and control system (ICS) of the Nuclear Power Plant (NPP) project and correct the parameters of its elements. Such actions require justification, which uses special mathematical models to confirm the fulfillment of design requirements.

This paper discusses the class of the information and control systems on programmable platforms, which are used in the reactor protection system of NPP in normal operation. This class of information and control system is based on the 2oo3 architecture without versioning with the control system and is described in detail in [1,2]. Expansion of the previously reviewed model consists of detailing the diagnostic procedures. This paper discusses the separate diagnosis of hardware and software with DC_{HW} and DC_{SW} parameters (DC is diagnostic coverage). As a separate process, regular proof tests are highlighted, during which latent hardware (HW) and software (SW) faults, that are not detected by the integrated control system, are detected.

Studies carried out in [3] have shown that achievement of the requirements of industrial systems on proof test $T_{Areq} \geq 3$ years' period can be by influencing parameters of the functional safety of SW (reducing an intensity of dangerous SW $\lambda_{D\,S}$ failure or increasing the completeness of control of dangerous SW DC_S failure). For information and control systems on programmable platforms, SW faults (architectural project faults) are entered into the system of bug tracking after their detection and eliminated within a certain time interval. The elimination of the software fault (assuming no new faults are introduced) causes a decrease in SW failure rate, as shown in [4,5]. To adequately display the elimination of SW faults and reduce the failure rate in studies [6], it was suggested to use the mathematical apparatus of multi-fragmental modeling.

At first glance, the elimination of software faults may cause a desire to use the information and control system project with the initial high intensity of dangerous SW failures, because faults will be identified and eliminated over the time. But this decision should be justified by the results of the study of the corresponding models of the information and control system with the elimination of faults causing dangerous SW failures.

In this paper, multi-fragmental models of functioning of the information and control system under the conditions of manifestation of dangerous HW and SW failures and elimination of identified SW faults are studied. For each model, graduated and oriented graphs are constructed; using the Matlab functions, systems of Kolmogorov-Chapman differential equations are constructed and solved. As a result, the values of the proof test T_{Areq} period for the SIL3 level and input parameters are obtained, at which the condition $T_{Areq} \geq 3$ years for industrial systems is satisfied.

2 Approach and Modeling Technique

2.1. Model Specification

In this paper we develop six models using Markov process theory as shown in Table 1. Models MICS01 and MICS02 were studied at the papers [1] with the assumption of manifestation of only dangerous HW failures and only DC_H parameter.

We discuss in this work the separate diagnosis of hardware and software with DC_{HW} and DC_{SW} parameters.

Table 1. Functional safety models of the information and control system NPP

General characteristics of the model	Model specification	Conventional notions
A) Markov model for evaluating the functional safety of the information and control system with an absorbing state	- three groups of states (without manifestation of SW fault, with detected SW failure and with undetected SW failure) - there is one absorbing state (output only after the proof test)	$M_{ICS}01$
B) Markov model for evaluating the functional safety of the information and control system with the migration of hidden failures	- three groups of states (without manifestation of SW fault, with detected SW failure and with undetected SW failure) - there is no absorbing state (after the manifestation of the undetected failure, its "migration" is possible before the proof test)	$M_{ICS}02$
C) Multi-fragmental models for evaluating functional safety of the information and control system with incomplete elimination of design faults	- several fragments, in each fragment there are three groups of states - there is the absorbing state in each fragment (output only after the proof test)	$M_{ICS}31$
	- several fragments, in each fragment there are three groups of states - there are no absorbing states (after the manifestation of the undetected failure, its "migration" is possible before the proof test)	$M_{ICS}41$
D) Multi-fragmental models for evaluating functional safety of the information and control system with incomplete elimination of design faults	- several fragments, in the first fragments there are three groups of states - in the last fragment, there are two groups of states, since all SW faults are eliminated - there is the absorbing state in each fragment (output only after the proof test)	$M_{ICS}32$
	- several fragments, in the first fragments there are three groups of states - in the last fragment, there are two groups of states, since all SW faults are eliminated - there are no absorbing states (after the manifestation of the undetected failure, its "migration" is possible before the proof test)	$M_{ICS}42$

The assumptions during models building are as follows:

- the events of failures and restoration of hardware channels and software (until the fault is eliminated) constitute of the simplest flows (stationary, ordinary and without aftereffect), with the corresponding constant λ_{HW}, λ_{SW} (failure rate) and μ_{HW}, μ_{SW} (recovery intensity) parameters;
- the system uses identical hardware channels with the same failure rates;
- the failure rate of the majority body and the control system is negligibly small and these systems are assumed to be absolutely reliable in the considered model;
- the model considers only dangerous failures of hardware channels of the information and control system and SW information and control system, the intensity of

the dangerous failures is estimated according to the method [2] and data obtained for similar systems [9] as $\lambda_{D\,HW} = 0.497 * \lambda_{HW}$; $\lambda_{D\,SW} = 0.476 * \lambda_{SW}$;

- when diagnosing a part of dangerous failures, the intensity of detected dangerous failures is $\lambda_{DD\,HW} = \lambda_{D\,HW} * DC_{HW}$, and the intensity of undetected dangerous failures.

2.2. Multi-Fragmental Model for Evaluating the Functional Safety of the Information and Control System with the Absorbing States

MICS31 multi-fragmental model is improved in comparison with MICS01 and contains absorbing states in each fragment. The application of the multi-fragmental principle [6] allows us to adequately make the model of the elimination of design faults with the subsequent decrease in the intensity of dangerous SW failures. The graduated graph of the model is presented in Fig.1. The two-fragmental model describing the operation of the information and control system, in the course of which one design fault is eliminated, is considered. Each fragment of the model contains 25 states: S0 ... S24 in the initial F0 fragment and S25 ... S49 in the final F1 fragment. The initial operation of the system is described by the change of states, as in MICS01 model, but after detecting the dangerous SW failure, which manifests itself with $\lambda_{D\,S\,0}$ intensity, the mechanism for its elimination is initiated, after which the system goes into the new fragment of F1 states, which is modeled by the corresponding S18 → S25, S19 → S26, S20 → S28, S21 → S29, S22 → S31, S23 → S32, S24 → S33 transitions with $\mu_{SR} > \mu_S$ intensity.

In the new fragment, the system functions in the same way as described for MICS01 model [1] (taking into account the “shift” of state numbering by 25). At the same time, in F1 fragment, the intensity of the manifestation of dangerous SW failures is equal to $\lambda_{D\,S\,1}$, and is defined as:

$$\lambda_{DSi} = \lambda_{DSi-1} - \Delta\lambda_{DS} \tag{1}$$

Since design faults remain in the system, after manifestation and detection of the dangerous SW failure, the system restarts to eliminate its consequences of μ_S intensity, which is modeled by S41 → S25, S42 → S26, S44 → S28, S45 → S29,S47 → S31, S48 → S32, S49 → S33 transitions.

In all fragments of MICS31 model, there are absorbing states: S17 in F0 fragment and S42 in F1 fragment.

The availability function taking into account dangerous failures is defined as (2):

$$\begin{aligned} A(t) &= P_0(t) + P_1(t) + P_3(t) + \\ &+ P_{25}(t) + P_{26}(t) + P_{28}(t). \end{aligned} \tag{2}$$

Baseline conditions: $t = 0$, $P_0(0) = 1$, $P_1(0) \ldots P_{49}(0) = 0$.

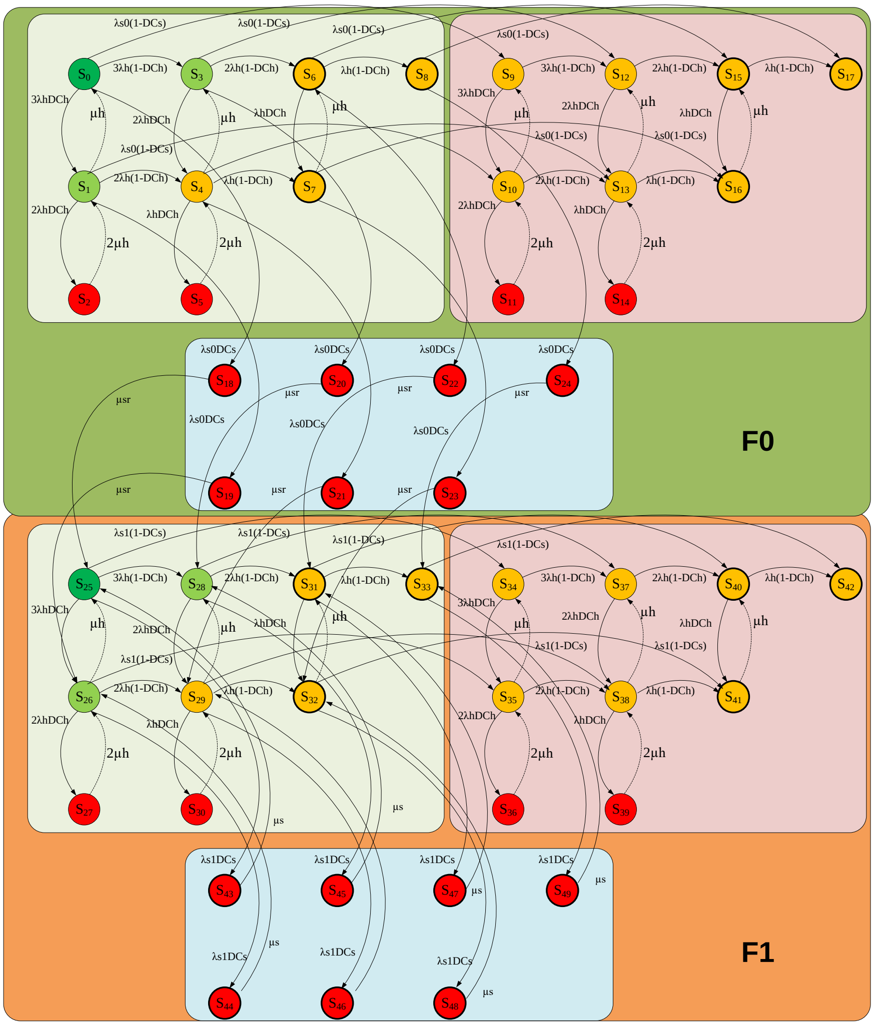


Fig. 1. Marked graph of ICS model with absorbing states and elimination one SW fault

2.3. Multi-Fragmental Model for Evaluating the Functional Safety of the Information and Control System with the Migration of Failures

In MICS41 multi-fragmental model, the assumption of the “migration” of hidden failures into decisive ones, described earlier for MICS02 model, was adopted. There are no absorbing states on the graduated graph of the model (Fig. 2). Transitions from the undetected dangerous failure state are simulated without additional measures (proof test). This model also deals with the elimination of the decisive DC SW after its manifestation. This is modeled as in MICS31 model by S18 → S25, S19 → S26, S20 → S28, S21 → S29, S22 → S31, S23 → S32, S24 → S33 transitions with μ_{SR}

intensity. In the last F1 fragment, system recovery after the dangerous SW failure is performed by restarting with μs intensity without its elimination.

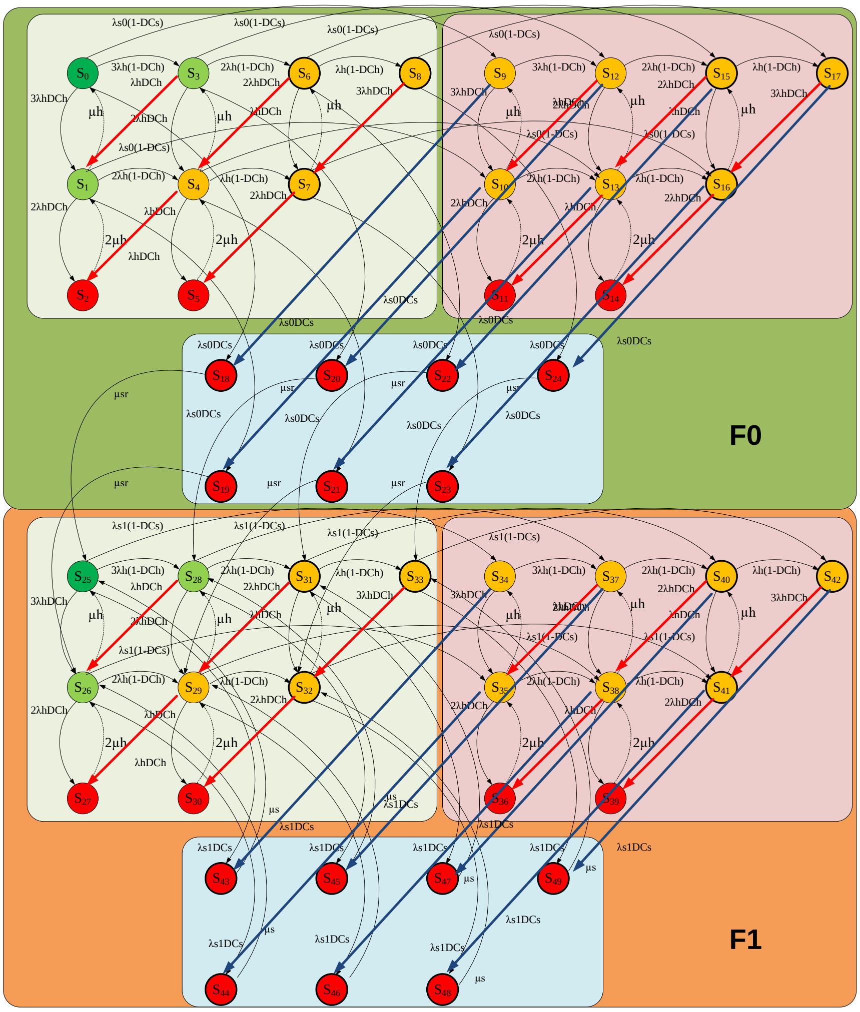


Fig. 2. Marked graph of multi-fragmental ICS model with the migration of hidden failures MICS41

The number and nature of the states of the MICS41 model graph are identical to the previous MICS31 model. In addition to the MICS31 model, transitions have been added that simulate the migration of hidden HW failures: S3→S1, S4→S2, S6→S4, S7→S5, S8→S7, S12→S10, S13→S11, S15→S13, S16→S14, S17→S6; transitions that simulate the migration of hidden SW failures: S9→S18, S10→S19, S12→S20, S13→S21, S15→S22, S16→S23, S17→S24 (for initial fragment F0). For F1 fragment migration of hidden HW failures is presented in transitions S28→S26, S29→S27, S31→S29, S32→S30, S33→S32, S37→S35, S38→S36, S40→S38, S41→S39, S42→S41; migration of hidden SW failures is presented in transitions S34→S43, S35→S44, S37→S45, S38→S46, S40→S47, S41→S48, S42→S49.

4 Simulation and Comparative Analysis

The calculation of the availability indicators is performed for the input data from Table 2. To construct the matrix of the Kolmogorov-Chapman system of differential equations, we use the matrix A function [8]. The Kolmogorov solution was performed in the Matlab system using the ode15s method [9] for the time interval of [0 ... 50000] hours. The results of the solution are presented in the graphical form in Fig. 3.

Table 2. Values of input parameters of simulation processing

#	**Parameter**	**Base value**
1	λ_{Dh}	46.04622e-6 (1/hour)
2	DCh	0.9989
3	μ_h=1/MRTh	1/8 = 0.125 (1/hour)
4	λ_{Ds}	6.27903e-6 (1/hour)
5	DCs	0.9902
6	μ_s=1/MRTs	10 (1/hour)
7	μ_{sr}	1/24=0.04167 (1/hour)
8	$\Delta\lambda_{Ds}$	1.5697575e-06 (1/hour)

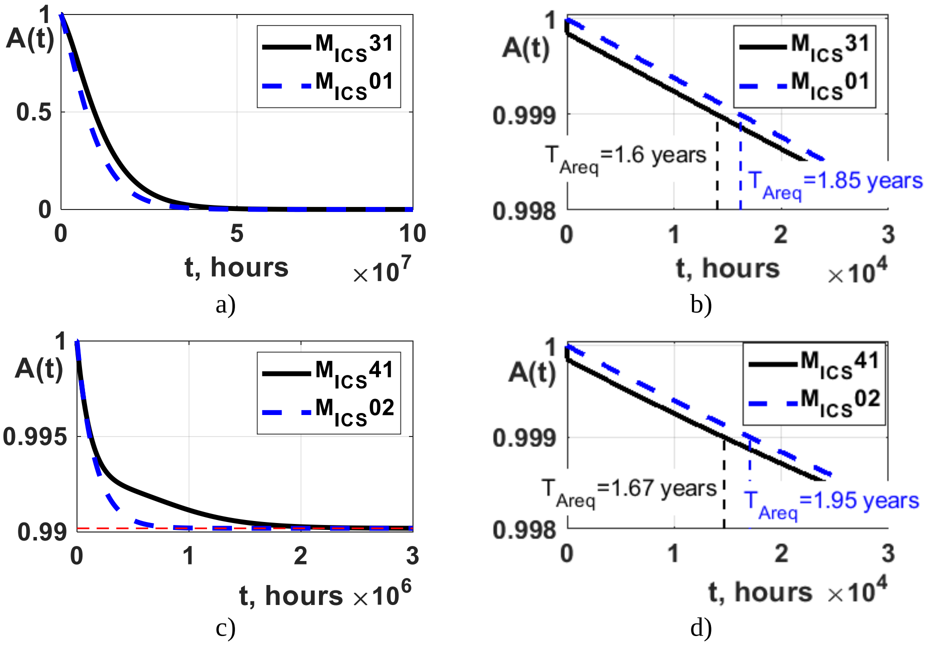


Fig. 3. The results of modeling of availability function of models $M_{ICS}31$ (a), $M_{ICS}41$ (c) and determining T_{Areq} interval with an error ξ=1e-6 (b,d)

The presence of absorbing states in MICS31 model causes the availability function behavior similar to MICS01 model - it's striving to zero. But it is obvious that the elimination of design faults slows the decrease in availability to zero. The decrease in the level of availability below 0.999 occurs after 13992 hours or 1.6 years. This value is worse than in MICS01 model and does not meet the standard for industrial systems in 3 years or 26298 hours.

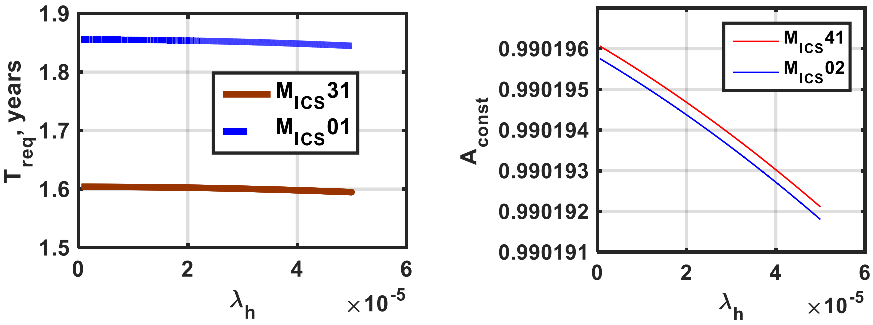
The availability function of MICS41 model is approaching to the stationary value of 0.9901, at that it goes into the established mode on 10^6 hours later than the result of the single-fragment MICS02 model. The decrease in the level of availability below 0.999 occurs after 14666 hours or 1.67 years. This value is worse than in MICS02 model and does not meet the standard for industrial systems in 3 years or 26298 hours.

For MICS31 and MICS41 models, the additional studies were conducted to determine the values of the input parameters at which $T_{Areq} \geq 26298$ hours. The intervals for changing the input parameters are the same as for MICS01 model and are shown in Table 3.

Table 3. Variable input parameters of the ICS model

#	Variable parameter	Designation	Values series
1	The rate of dangerous hardware failures	$\lambda_{D\ H}$	[0.05…5]e-5 (1/hour)
2	Diagnosing dangerous hardware failures control completeness	DC_H	[0..1]
3	Diagnosing dangerous software failures control completeness	DC_S	[0..1]

Cyclic scripts for Matlab were built to calculate the models. The results of the research are shown as graphical dependences in Fig. 4 – Fig. 6.

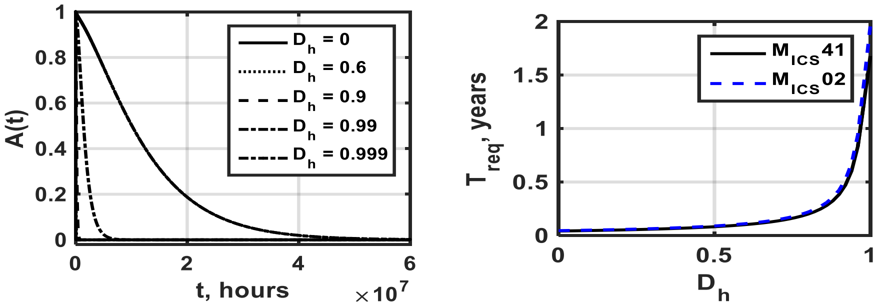


a) b)

Fig. 4. Graphs for determining the T_{Areq} interval of MICS31 models (a) and the established value of the availability function of MICS41 model (b) for different values of the input $\lambda_{D\ H}$ parameter

The results of the influence of values of the input $\lambda_{D\ H}$ parameter on the behavior of the availability function of MICS31 model are shown in Fig.4 (a). With the decrease in the intensity of dangerous failures of HW, the reduction in availability to zero slows down. But taking into account the scale on the horizontal axis (10^8 hours), this result is not applicable in practice.

The results of the influence of values of the input λ_{DH} parameter on the established value of the function of MICS02 model are shown in Fig. 4 (b). With the decrease in the intensity of dangerous HW failures, A_{const} increases insignificantly (6 decimal places), which cannot be used for practical application. The result presented in Fig. 4(b) is also practically not interesting since a change of λ_{DH} by two orders of magnitude does not allow assuring $T_{Areq} \geq 26298$ hours' condition.

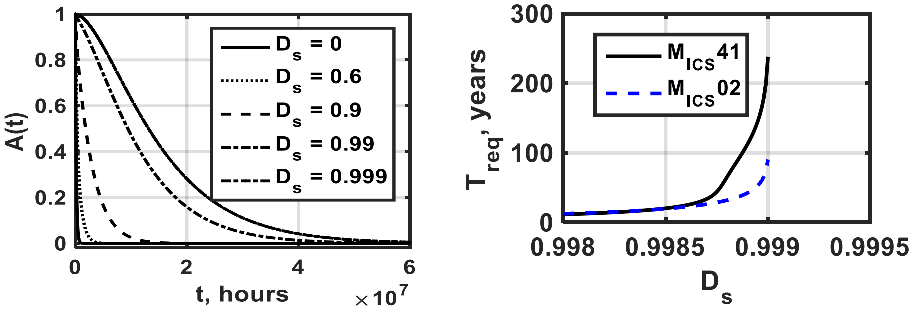


a)

b)

Fig. 5. Charts of the availability function of MICS31 model (a), interval T_{Areq} of MICS41 model (b) for different values of input parameter DC_H

The value of the input DC_H parameter of MICS31 model affects the speed of the transition of the availability function to the established value: with the increase in DC_H from 0.99 to 0.999, the descent of availability to zero slows down by $4 * 10^7$ hours. The value of the input DC_H parameter of MICS41 model practically does not affect the speed of the transition of the availability function to the established value. On the other hand, the change in DC_H from 0 to 1 also causes a change in A_{const} within [0...0.9902]. The result presented in Fig.5 (b) is also important for practice, since after modeling it becomes obvious that the increase in DC_H to 1 does not allow to ensure $T_{Areq} \geq 26298$ hours' condition (as in MICS31 model).



a)

b)

Fig. 6. Charts of availability function of MICS31 model (a), interval determination T_{Areq} MICS41 model (b) for different values of the input parameter DC_s

The results of the influence of values of the input DC_S parameter on the behavior of the availability function of MICS31 model are shown in Fig.6 (a). With the increase in the test coverage of dangerous SW failures by the order of magnitude (from DC_S = 0.99 to DC_S = 0.999, etc.), the availability function goes to zero level several times slower (from $5 * 10^7$ to $6 * 10^7$ hours). The following result is important for practice: starting from DC_S = 0.9947 value, $T_{Areq} \geq 26298$ hours' condition is provided.

The results of the influence of values of the input DC_S parameter on the behavior of the availability function of the model are shown in Fig.6 (b). The dependence of A_{const} on DC_S for MICS41 model is linear and is not shown in the graph. With $DC_S = 1 \rightarrow A_{const} = 0.9999924$. The value satisfying the requirements of SIL3 ($A_{const} = 0.99909$) is achieved at DC_S = 0.9991. Theoretically, this allows us to talk about systems without a proof test, but from the practical point of view, it is very difficult and costly to achieve such level of control completeness.

The results are shown in Fig.6 (b) illustrate the maintenance of $T_{Areq} \geq 3$ years' condition starting from DC_S = 0.9942 value. And what is more interesting, in Fig. 6(b) it is shown that in DC_S = [0.998 ... 0.9991] interval the multi-fragmental MICS41 model over the proof test period significantly benefits the single-fragmental MICS02 model.

5 Conclusions

In the article, the multi-fragmental model architecture for information and control systems of NPP 2oo3 is presented with occurred HW and SW faults and eliminating of hidden faults.

Analysis of the obtained results of modeling the availability of the information and control systems of NPP architecture with partially eliminating of design faults has shown that:

a) for the multi-fragmental MICS31 model with absorbing the decrease in the availability function to zero is significant. For typical values of input parameters (Table 2), the fulfillment of SIL3 requirements is guaranteed in [0 ... 1.6 years] interval. The increase in the interest $T_{proof\ test}$ interval of up to 3 years is possible with the increase in the control completeness to detect dangerous SW failures to DC_S = 0.9947 level and higher;

b) the multi-fragmental MICS41 model is characterized by the decrease in the availability function to the stationary A_{const} value. For typical values of input parameters (Table 2), the fulfillment of SIL3 requirements is guaranteed in [0 ... 1.67 years] interval. The increase in the interest $T_{proof\ test}$ interval of up to 3 years is possible with the increase in the control completeness to detect dangerous SW failures to DC_S = 0.9942 level. Starting from DC_S = 0.9991, SIL3 requirements are guaranteed to be fulfilled without additional proof tests.

The developed mathematical models make it possible to assess the fulfillment of the requirements for the functional safety of the designed information and control system. Application of the developed models is advisable in specific time counts tied to the phases of the V-model of the project life cycle (and possibly to the separate layer of the V-model).

The future step includes: it is necessary to put in order and regulate the operations of choosing one of several models for the specific design phase, tight time reference to the beginning/end of the life cycle phase, substantiation of assumptions, changes in the structure and parameters of models in one method.

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