APPLICATION OF SIMPLE APPROXIMATE SYSTEM ANALYSIS METODS FOR RELIABILITY AND AVAILABILITY IMPROVEMENT OF REACTOR WWER-1000

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The method described in this report provides a set of simple, easily understood "approximate" models applicable to a large class of system architectures. Constructing a Markov model of each redundant subsystem and its replacement after that by a pseudo-component develops the approximation models. Of equal importance, the models can be easily understood even of non-experts, including managers, high-level decision-makers and unsophisticated consumers. A necessary requirement for their application is the systems to be repairable and the mean time to repair to be much smaller than the mean time to failure. This is a case most often met in the real practice. Results of the "approximate" model application on a technological system of Kozloduy NPP are presented in this report. The results obtained can be compared quite favorably with the results obtained by using SAPHIRE software.

1. INTRODUCTION

Markov models are the most frequently used tools for analyzing the reliability and availability of complex high reliable systems. The large number of components and possible system states often make detailed models of such systems large and unwieldy to the extent that they are understandable only by their developers or other experts after careful study, and frequently require special software to be solved. Fortunately, a set of simpler, "approximate", but nevertheless highly accurate models can be used for such systems.

A necessary requirement for their application is the systems to be repairable and the mean time to repair to be much smaller than the mean time to failure, a case most often met in the real practice.

Results of the "approximate" model application on a technological system of Kozloduy NPP are presented in this paper.

For comparison, values, calculated using other methods are also presented. The results obtained can be compared quite favorably.

2. THEORETICAL BACKGROUND

2.1.System Model

The system model assumes that the system is a series combination of redundant subsystems. Individual units in the subsystem may fail, be repaired and returned to service without the subsystem failing. However, if too many units fail at the same time, the subsystem fails and the system fails. The number of units that can fail without the subsystem failing determines the subsystem structure [1].

The state transition diagram for a 3-state Markov model of a redundant system with repair is shown on Fig 1. Let us assume that the units are identical with constant failure rate λ. When a unit fails it is repaired at a constant rate μ. If more than one unit has failed the system fails. State S_2 is the state with all units working. We assume that S_2 is the initial state of the system. State S_1 is the state with one unit failed. This state does not distinguish which unit has failed since the system behavior is the same in all cases. State S_0 is the system failed state – it is entered if more than one unit has failed at the same time.

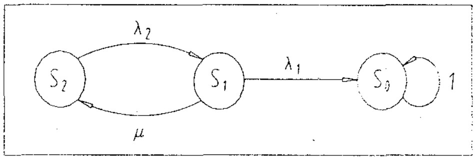

Fig. 1. 3-state Markov model of a parallel system with repair.

With appropriate choices of the transition rates, the model in Figure 1 can represent many system architectures.

2.2. System and Subsystem Availability

When a redundant subsystem fails the entire system fails. Thus, there is an incentive to make the necessary repairs quicker than when making repairs to a single failed unit, which has not caused the entire system to fail. On the other hand, we have assumed that a subsystem fails only when more than one of the redundant units has failed; thus more extensive repairs may be needed. Let μ_{ss} denote this repair rate. Representing the subsystem as a pseudo component having the constant failure rate λ'=1/MTTF (Mean Time To Failure), the subsystem availability, A(t), and its steady state availability, A, can be found by:

$$A(t) = \frac{\mu_{ss}}{\lambda' + \mu_{ss}} + \frac{\lambda'}{\lambda' + \mu_{ss}} e^{-(\lambda' + \mu_{ss})t} \qquad (1)$$

$$A = \frac{\mu_{ss}}{\lambda' + \mu_{ss}}$$

The overall system availability can be calculated as the product of the system availabilities obtained from the equations above.

3. RESULTS

3.1. Application of the "approximate" model on a specific system

As an example let us consider low-pressure safety injection system (LPIS) of units 3 and 4 of Kozloduy NPP consisting of three independent trains [2].

The LPIS is designed to compensate the lost coolant and cool down the core during accidents with large loss of primary coolant.

The system is normally kept in Stand-by State and operates on technological setpoins or operator's request.

The system is based on three pumps, Emergency Water Storage Tank (EWST), valves and pipes. LPIS includes three independent trains. If the equipment of some train fails, the train has to be taken off-line and repaired while the system remains operational. If the downtime period for repair continuous more than 24 hours, the reactor has to be blackout and shutdown. If two trains fail and it is necessary to be repaired, the reactor is also to be shutdown.

Fig. 2a shows the model of a safety injection system and Fig. 2b shows the system model in Fig. 2a with each subsystem collapsed into a pseudo-component [3].

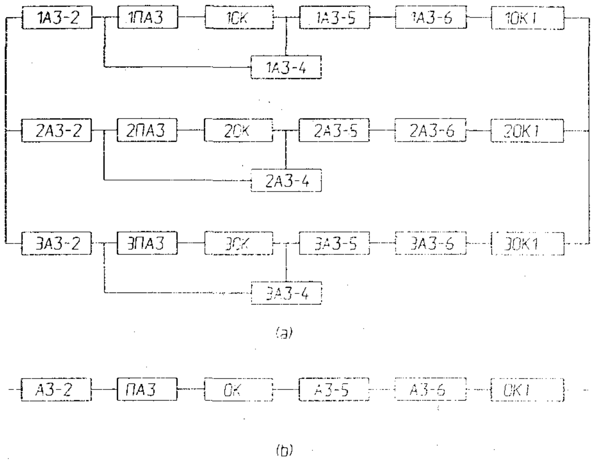

Fig.2.Reliability model of a safety injection system of units 3&4 of KNPP (a) and its pseudo-component "approximation" (b)

3. 2. Approximation Formulas

Formulas for calculating the MTTF and failure rate of various types of redundant subsystem for a case when the ratio is $\mu/\lambda>100$, are given in Table 1. They are simpler, but less accurate approximations compared with the equations used for cases when the ratio is $\mu/\lambda>10$.

Table 1. Simplified expressions for MTTF and failure rates for pseudo component representing a parallel subsystem, $\mu\lambda>100$.

	BASIC APPROXIMATION*	
System structure	MTTF	λ'
2-unit standby $\lambda_1=\lambda$, $\lambda_2=\lambda$	$\frac{\mu}{\lambda^2}$	$\frac{\lambda^2}{\mu}$
2-unit parallel $\lambda_1=2\lambda$, $\lambda_2=\lambda$	$\frac{\mu}{2\lambda^2}$	$\frac{2\lambda^2}{\mu}$
3-unit TMR $\lambda_1=3\lambda$, $\lambda_2=2\lambda$	$\frac{\mu}{6\lambda^2}$	$\frac{6\lambda}{\mu}$
n-unit (n–1)-out-of-n:G $\lambda_1=n\lambda$, $\lambda_2=(n-1)\lambda$	$\frac{\mu}{n(n-1)\lambda^2}$	$\frac{n(n-1)\lambda^2}{\mu}$
n-unit k-out-of-n:G $\lambda_1=i\lambda$,	$\frac{(k-1)!}{n!}\frac{1}{\lambda}\left[\frac{\mu}{\lambda}\right]^{n-k}$	$\frac{n!}{(k-1)}\lambda\left[\frac{\lambda}{\mu}\right]^{n-k}$

*λ = Equipment (unit) failure rate, μ is its repair rate

3.3 Calculations

Assuming constant failure and repair rates and using the expression for the Triple Modular Redundant (TMR) system in Table 1 we have obtained the results presented in Table 2. For MTTR we have accepted 24 hours, i.e. $\mu=0.0417$ repairs/hour.

Table 2. Input data and results

Equipment	λ (Equipment failure rate)	MTTF [h] For the pseudo-component	λ' [1/h] For the pseudo-component	Ass Availability	Qss Unavailability
1÷3 AZ-2	$3.00x10^{-7}$	$7.69x10^{10}$	$1.30x10^{-11}$	1.0000	0.0000
1÷3 PAZ-3	$7.80x10^{-5}$	$1.14x10^{6}$	$8.74x10^{-7}$	0.9999	0.0001
1÷3 OK	$5.00x10^{-7}$	$2.78x10^{10}$	$3.60x10^{-11}$	1.0000	0.0000
1÷3 AZ-4	$2.80x10^{-6}$	$8.86x10^{8}$	$1.13x10^{-9}$	0.9999	0.0001
1÷3 AZ-5	$9.20x10^{-6}$	$8.20x10^{7}$	$1.22x10^{-8}$	0.9999	0.0001
1÷3 AZ-6	$9.20x10^{-6}$	$8.20x10^{7}$	$1.22x10^{-8}$	0.9999	0.0001
1÷3 OK1	$5.00x10^{-7}$	$2.78x10^{10}$	$3.60x10^{-11}$	1.0000	0.0000

Where Ass and Qss are the availability and unavailability of the subsystems, represented as pseudo-components.

For the availability of the whole system, we obtain:

A = 0.9996

3.4. Comparison with other analytical models results

For a comparison of the applicability of the results obtained by means of the method presented here, the same system is investigated by Fault Tree Analysis (FTA) method. The FTA model is built in correspondence with the common practice and boundary conditions. Both basic modes of a system operation are modeled, i.e. system operation at the three trains availability and a system operation at a train taken off-line for 24 hours. The same reliability characteristics have been used as input data for failures of the system equipment. The analysis is done by SAPHIRE software, developed by Los Alamos National Laboratory.

The comparison of the results of different methods application is presented in Table 3.

Table 3. Values obtained for A and Q

Procedure	Availability (A)	Unavailability (Q)
SAPHIRE	0.9996	$3.93x10^{-4}$
Approximation model	0.9996	0.0004

As it can be seen, for $\mu/\lambda>100$ the results obtained can be compared quite favorably.

4. CONCLUSIONS

Models of complex systems are really complex. As a result detailed models used to determine the availability and reliability of such systems are often too complex to be readily understood and a simpler, easily understood model is often more useful. In this paper we have described a set of relatively simple, "approximate", but nevertheless, highly accurate models for such systems.

The models as described above have rather simple representations and can be easily implemented with simple calculations. The results obtained can be compared quite favorably with the results obtained by using SAPHIRE software.

5. REFERENCES

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