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Simplification of transition state diagrams via Generalized Perturbation Theory in the Markovian reliability analysis of aging safety systems

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ABSTRACT

This work presents a proposal to simplify state transition diagrams in Markovian reliability analyses for large systems and subsequent calculation of their mean unavailability, considering that at least one component is aging. Two proposals are presented to circumvent the loss of the Markovian property: the method of stages and the method of supplementary variables. The method chosen was the latter because it presents the advantage of a standard solution, requiring only the updating of system equations and initial condition for each new case. Failure rates will be modeled by the two parameter Weibull distribution. The criterion used for simplifying state transition diagrams is the derivative of the integral quantity in non-null elements of the state transition matrix. To do so, these derivatives are obtained by the Generalized Perturbation Theory (GPT), which makes extensive use of the principle of importance conservation. The simplification proposed using the GPT formalism can be considered a good approximation for the original diagram to calculate the mean system unavailability and its relative error is negligible.

1. Introduction

The Nuclear Regulatory Commission (NRC) issued on December 1991 rules and associated documentation describing how a licensee must demonstrate that a plant can keep operating for 20 additional years after the expiration of the 40-year license. These rules were established in DOE (1991), environmental protection requirements and DOE (1995), technical requirements, being named license renewal.

In the quest for understanding aging phenomena the International Atomic Energy Agency (IAEA) has sponsored several programs and projects related to the aging of nuclear power plants, focusing on the aging management in long-term reliability and economic aspects of the licensed life extension of nuclear power plants. The results of these programs are presented in a number of technical reports. Standing out among these are IAEA (1992a,b, 1999) dealing, respectively, with a methodology for aging management, a guide to the collection of operational and maintenance data for the management and evaluation of aging mechanisms.

In Brazil, Angra 1 nuclear power plant completed 30-year of operating license in 2014. The plant, Westinghouse manufactured, had its license ruled by the standard CNEN (1984) and based on the NRC model (regulatory guides for standardized review), the time of 40 years was considered as a basis for 1984 being scheduled a review authorization every 10 years to ratify or rectify its terms. This ensures a periodicity of the safety assessment review licensing keeping the basis described therein.

The analysis of qualified life extension has two approaches, one deterministic and another probabilistic and they complement each other. The evaluation based on deterministic methods defines the difference between the item current state and that in the qualifying phase but it does not define the probability that it works properly for a period beyond its qualified life.

There is not in Brazil a formalized approach to treat the extension of the operating license beyond 40 years. In fact, Brazil follows the law of the country of origin of the reactor design. However, the Interim Operation Authorization (AOP) provides various programs that seek an Angra 1 project update in relation to the international trend, as, for example: fire protection program, environmental qualification program for electrical equipment, program maintenance efficiency and review program of technical specifications (Saldanha and Frutuoso e Melo, 2012).

Abbreviations: AOP, Interim Operation Authorization; CNEN, Brazilian Nuclear Commission of Nuclear Energy; DOE, US Department of Energy; GPT, Generalized Perturbation Theory; IAEA, International Atomic Energy Agency; NRC, US Nuclear Regulatory Commission.

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This paper presents an approach to analyze the behavior of nuclear power plant equipment. Because they can undergo aging, these devices present difficulties in modeling and analyzing the sensitivity and importance regarding the attributes of interest, in this case, reliability estimates in the context of useful life extension and considering the development of probabilistic safety assessments for licensing purposes.

Computational resources available are an important feature to be considered in system reliability analysis of large industrial facilities when working with systems with a large number of components. The computational capacity may be a factor of interest, because of the need, in many cases, to consider dependencies between failure events, besides the large number of system states to be considered.

It is well known that the solution of a Markovian reliability model for obtaining time-dependent and steady-state system probabilities can be simplified if certain sets of states can be combined to form single states, Kemeny and Snell (1960), Singh and Billinton (1977), and Endrenyi (1980). Papazoglou and Gyftopoulos (1978) and Papazoglou (1988) discuss this feature and present practical applications in which system symmetries are explored. These symmetries give rise to superstates, which result from symmetrical states merging. One possibility for this case is the existence of similar components in the analyzed system. Suppose, for example, that components A and B are similar control valves. The state for which A is failed and B is on is quite similar to the one for which A is on and B is failed. These two states are eligible for merging and, thus, make a superstate. In this case, the mergeability approach will not be useful as will be clear for the case study to be discussed in this paper, due to the lack of system symmetries.

To address the issue of modeling large systems, Tagaragi et al. (1985) proposed a method for reducing the number of states in the state transition diagram in a Markovian reliability analysis by making use of ineffective edges, which can be cut with little influence on the system failure probability.

Another model was presented by Gandini (1989) who proposed to make edge cutting off by using the Generalized Perturbation Theory (GPT) and the probability of the system being in each state as the integral quantity.

The objective of this paper is to investigate an alternative way, which has as a theoretical basis the methodology employed by Tagaragi et al. (1985). Like Tagaragi et al., we will also use as an integral parameter the system average unavailability plus the methodology reported by Gandini (1989) who proposed to make the edge cutting analysis by considering GPT, with the help of the importance concept in order to obtain the derivatives that will aid in cutting the less important edges and simplify the system state transition diagram.

In an earlier paper, we discussed the application of the Generalized Perturbation Theory to the sensitivity analysis of the accident rate of plants equipped with protective channel systems (Frutuoso e Melo et al., 1998).

This paper is organized as follows. Section 2 discusses what happens with the Markovian model when at least one of the system components undergoes ageing. Section 3 addresses the application of the Generalized Perturbation Theory to the sensitivity analysis of state transitions.

The numerical solution of the differential equations that are modeled to estimate the system reliability attributes is the subject of Section 4. The numerical solution of the equations that govern the importance functions is discussed in Section 5. The analysis of the derivatives for the cutoff analysis of the state transition diagram is performed in Section 6.

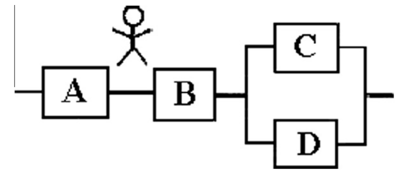

Fig. 1. Block diagram for the case study (Tagaragi et al., 1985).

The results obtained after cutting off the original state transition diagram are presented and discussed in Section 7. Finally, Section 8 displays the conclusions reached so far.

2. Loss of the Markovian property

Vicente et al. (2014) proposed a simplification method of state transition diagrams for large systems by using the principle of importance conservation and the relationship of source reciprocity of the Generalized Perturbation Theory and found that the simplified diagram is a good approximation to the original diagram. If so, the reliability analysis is done with the help of the simplified diagram. This study considered constant failure rates for all components and the Markovian model applies. Extending the method application, it was also considered the hypothesis that at least one component has increasing failure rate over time. To this end, component B was chosen and the associated failure times were modeled by a Weibull distribution.

The system general characteristics are the same as those used in Vicente et al. (2014):

(i) The system is composed by four components/pumps;
(ii) We have a series system with two components/pumps and a parallel system with two components/pumps and both systems communicate;
(iii) The system is serviced by a repair crew;
(iv) System failure rates are lesser than their repair rates, which is a common situation in practice;
(v) Components A and B have higher repair priority than components C and D;
(vi) The repair strategy between components A and B and also between components C and D is first in, first out (see Fig. 1).

We present in Table 1 the failure and repair rates that will be used in this work, which are the same used in Vicente et al. (2014), except that component B is assigned a time dependent failure rate.

As shown in Table 1, we will consider now that the failure rate of component B will be a function of the mission time (x), being modeled by a Weibull distribution for which β is the shape parameter and δ is the scale parameter. The state transitions considered are the same used by Vicente et al. (2014). Fig. 2 shows the new state transition diagram, where the time-dependent transition rate of component B is explicitly displayed.

The solution of the problem mentioned above can be obtained by two methods: the method of stages and the method of supple-

Table 1
Input data considering that component B is aging.

Component	Failure rate (h^{-1})	Repair rate (h^{-1})
A	$\lambda_1 = 1.0 \times 10^{-5}$	$\mu_1 = 1.0 \times 10^{-2}$
B	$\lambda(x) = \frac{\beta}{\delta} \times \left(\frac{x}{\delta}\right)^{\beta-1}$	$\mu_2 = 2.0 \times 10^{-2}$
C	$\lambda_3 = 1.0 \times 10^{-4}$	$\mu_3 = 1.0 \times 10^{-2}$
D	$\lambda_4 = 5.0 \times 10^{-4}$	$\mu_4 = 2.0 \times 10^{-3}$