Development of Unavailability Estimation Method Considering Various Operating States of Dynamic Systems

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1. Introduction

A dynamic system can be defined as a system which has a state at any given time which can be represented by a point in an appropriate state space. In order to analyze the dynamic systems, various failure mechanisms with time requirements such as the failure orders of sub-components and the changes of system states with time need to be modeled and quantitatively estimated. Since the conventional static fault tree analysis has imitations when applied to the dynamic systems, two types of dynamic fault tree methods have been developed. Dugan et al. proposed four dynamic gates to handle failure mechanisms composed of sequence-dependent events [2] and Cepin and Mavko proposed the use of house events to handle failure mechanisms of dynamic systems which have various operating states with time [3]. However, modeling a fault tree from a complex system is a cumbersome task even for the experts who is familiar to it, and demands a great amount of attention and caution to avoid errors. In order to model complex systems more conveniently from system block diagrams compared to the fault tree, a reliability graph with general gates (RGGG) was developed by introduction of general gates to a conventional reliability graph [4]. The RGGG is an easy-to-modeling method as powerful as fault tree. It was also improved to analyze the dynamic failure mechanisms composed of sequence-dependent events with the addition of dynamic nodes [5].

In this paper, unavailability assessment method for dynamic systems which have various operating states is proposed using the RGGG method. To achieve this, a novel concept of reliability matrix for the RGGG is introduced and Bayesian Networks are used for the quantification.

2. Dynamic RGGG with reliability matrix

The configuration or failure mechanism of a system can be changed with time if the system has several operational states. In nuclear power plants, the system configuration changes during equipment test and maintenance. The conventional fault tree and the RGGG have limitations to consider the effect of the configuration change. The dynamic fault tree was developed to analyze the dynamic systems of which the configuration changes using house events and house events matrix. In this section, the RGGG method is extended to consider the changes of operating states with time, since it allows more intuitive and easier system modeling compared to the fault tree method.

2.1 Reliability matrix

As the house events and house events matrix are used in the dynamic fault tree, a reliability matrix is proposed for one RGGG to express various system configurations which change with time. The reliability matrix is newly introduced to the conventional RGGG to handle the changes of the system configurations. The reliability matrix for the arcs in the RGGG is constructed as follows:

$$\left\| RM_{at} \right\| = \left\| \begin{matrix} r_{11} & r_{12} & \cdots & r_{1T} \\ r_{21} & \cdots & & \\ \cdots & & r_{nt} & \cdots \\ r_{N1} & \cdots & & r_{NT} \end{matrix} \right\|$$

The variable r_{nt} in the reliability matrix refers to the reliability of the arc a_n at time t. The variable N and T refer to the number of the arcs and time periods, respectively. Therefore, the number of rows in the matrix represents a number of arcs in the model which are modeling the behavior of a certain system configuration as a function of time. And the number of columns represents the number of time periods in which mutually different system configuration exist. By determining the reliability of each arc according to the system configuration during each period, the change of the system configuration with time can be modeled with one RGGG.

The quantitative analysis for estimating the system reliability during each period and system unavailability during the total process time can be conducted using Bayesian networks in the same way as the conventional RGGG.

2.2 Qualitative and quantitative analysis using reliability matrix

2.2.1 Varying number of inputs

The reliability matrix can be used for the RGGG to express more operational modes of an equipment modeled as an input of OR node and AND node. Fig. 1 shows the change of the operating state that the equipment modeled in the arc 2 (*a*2) which is an input of OR node is not considered in the model during the period 2 (p_2).

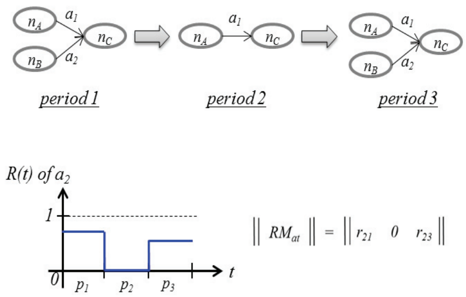

Fig. 1. Modeling of the varying number of inputs with OR node during the period *2*.

The probability table for node C (n_c) is shown in Fig. 2(a). As the reliability of a_2 (r_2) is set to *0* during the period 2, the probability table for node C is transformed into Fig. 2(b) and it can be used as the probability table for node C during the period 2.

(a)

	$y_A = 1$		$y_A = 0$	
	$y_B=1$	$y_B=0$	$y_B=1$	$y_B=0$
$y_C=1$	$r_1+r_2-r_1r_2$	r_1	r_2	0
$y_C=0$	$1-(r_1+r_2-r_1r_2)$	$1-r_1$	$1-r_2$	1

↓ $r_2 = 0$ (period 2)

(b)

	$y_A = 1$		$y_A = 0$	
	$y_B=1$	$y_B=0$	$y_B=1$	$y_B=0$
$y_C=1$	r_1	r_1	0	0
$y_C=0$	$1-r_1$	$1-r_1$	1	1

Fig. 2. Change of the probability table for node *C* during the period *2*.

In a similar manner, the varying number of inputs with AND node can be expressed using the reliability matrix. If we assume the node C in Figure 1 is AND node, the difference with OR node is that the reliability of the a_2 is set to be *1* during the period 2, so that only the a1 is considered as an input of node C.

2.2.2 Change of k-out-of-n logic

Redundant channels are often employed in standby critical systems for safety critical applications [5]. The *k*-out-of-*n* logic is a widely adopted configuration for trip signal generations in nuclear power plants and the trip logic changes during surveillance tests such as sensor and channel tests. As *n* decreases to *n-1* during a channel test, *k* may decrease to *k-1* or may remain the same.

A. *k*-out-of-*n* logic to *(k-1)*-out-of-*(n-1)* logic

From a reliability standpoint, it can be understood that the channel under test is always able to transmit trip signals when needed. Therefore, the reliability of the channel under test is set to be *1* in the reliability matrix.

B. *k*-out-of-*n* logic to *k*-out-of-*(n-1)* logic

From a reliability standpoint, it can be understood that the channel under test breaks down and cannot transmit trip signals when needed. Therefore, the reliability of the channel under test is set to be *0* in the reliability matrix.

3. Discussions and conclusions

In this paper, in order to analyze dynamic systems which have various operating states with time using one RGGG, the reliability matrix is introduced and the various operation modes are modeled by the RGGG with the reliability matrix. With the conventional RGGG, for the unavailability analysis of a system which has *k* operation modes during total process time, *k* RGGG should be drawn and the probability tables for all the nodes in each RGGG should be determined with reliabilities of the arcs. On the other hand, with the proposed reliability matrix, only one RGGG is able to express all the operation modes during total process time and the probability tables for all the nodes do not have to be revised according to each operation mode. The replacement of reliability data of arcs according to the predefined reliability matrix has same effect as changing the equations in the probability tables. The proposed method provides much easier way to model and analyze the changes of operating states with time and understand the actual structure of the system compared to the dynamic fault tree with house events.

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