Probability Subtraction Method Implementation into SAREX

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1. Introduction

Since the publication of WASH-1400[1], the first comprehensive probabilistic safety assessment (PSA) for nuclear power plants (NPPs), fault trees have been used to model logic structure consisting of structure, system, and component failures leading to undesired plant state, for example, core damage. To quantify a fault tree, 1) Boolean solution or minimal cut sets (MCSs) is generated, and 2) the probability or frequency of the MCSs is calculated. So far, for most of PSAs, delete-term approximation (DTA) has been used to generate MCSs for a fault tree with negates, and rare event approximation (REA) or minimum cutset upper bound (MCUB) has been used for MCSs probability calculation.

2. Overestimation issues for fault tree with non-rare events

DTA, REA, and MCUB can be used for fault trees with rare events while the overestimation error is tolerable during quantification. However, it is well known that if they are used for fault trees with non-rare events, big overestimation error can be involved [2]. The overestimation error caused by the application of REA or MCUB during MCSs probability calculation can be overcome by converting MCSs into binary decision diagram (BDD). We have dedicated software tools to convert MCSs into BDD, for example, ACUBE or BeEAST. However, at the present time, it is not possible to generate exact Boolean solution for a fault tree with the size of typical single-unit PSA due to the limitation of computing power, even though we have dedicated software tools that can generate exact Boolean solution from a fault tree. Therefore, it is essential to quantify fault trees with a method which can manage the overestimation error caused by the application of DTA if a fault tree has non-rare events in negates.

3. Probability subtraction method

The overestimation error caused by DTA application during MCSs generation can be overcome by using probability subtraction method (PSM) [2]. PSM is a fault tree quantification method to evade negates during quantification using the Eq. (1) below.

A = A(B + /B) = AB + A/B

P(A) = P(AB) + P(A/B) (1)
P(A/B) = P(A) − P(AB)

Where,
A and B are basic events or fault tree gates.
AB and A/B are disjointed.

Eq. (1) can be applied to PSA event tree sequences quantification without DTA application as described below.

With the traditional quantification procedure, accident sequence 5 of Fig. 1 can be quantified 1) by generating MCSs for fault tree gate logic of %K*S*B*/T*/I by applying DTA, and 2) by calculating probability of the MCSs generated.

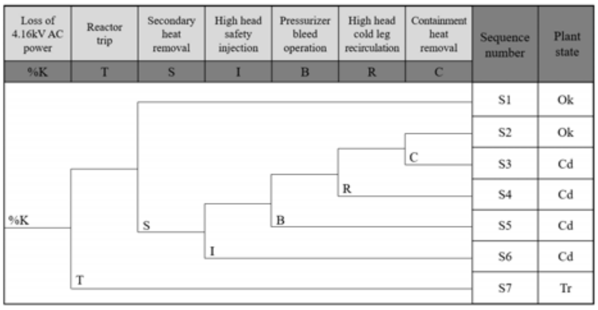

Fig. 1. Event tree

The fault tree gate logic of accident sequence 5 is %K*S*B*/T*/I or %K*S*B*/(T+I) and can be quantified using PSM equation of Eq. (2).

%K*S*B*/(T+I) = %K*S*B - %K*S*B*(T+I)
P[%K*S*B*/(T+I)] = P(%K*S*B) (2)
- P[%K*S*B*(T+I)]

The procedure to calculate accident sequence 5 using PSM is 1) to generate MCSs of fault tree gate logic %K*S*B and %K*S*B*(T+I), 2) to calculate P(%K*S*B) or frequency for MCSs of %K*S*B, and to calculate P[%K*S*B*(T+I)] or frequency for MCSs of %K*S*B*(T+I), and 3) to calculate sequence 5 frequency by subtracting P[%K*S*B*(T+I)] from P(%K*S*B).

4. PSM implementation into SAREX

In SAREX, PSM was implemented to quantify fault tree for event tree accident sequences by providing an option to adopt PSM for event tree quantification as shown on Fig. 2.

Fig. 2. SAREX option for PSM selection

As shown on Eq. (2), to quantify event tree sequences with PSM, MCSs generation and probability calculation should be performed for failure gate combination or %K*S*B and for failure-success gate combination or %K*S*B*(T+I). The linked fault tree for failure gate combination and failure-success gate combination is generated in the TREE folder as is the same for the existing quantification method in SAREX. The MCSs for failure gate combination and failure-success gate combination are generated in the CUTSET folder as shown on Fig. 3.

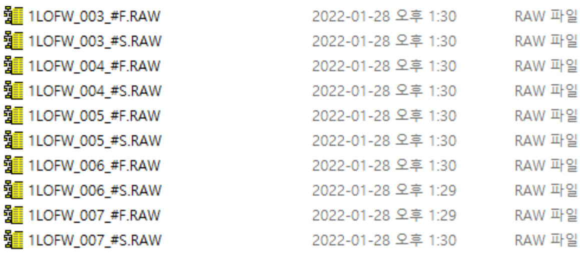

Fig. 3. MCSs generated by PSM application

The MCSs probability is calculated using MCUB at the current version of SAREX. If MCSs conversion into BDD for accurate PSM application is necessary, it should be done manually.

5. Application area

As described in the previous section, PSM was suggested to reduce overestimation error for the fault tree with non-rare events in negates. Therefore, PSM can be best utilized for a fault tree with non-rare events in negates. The specific areas that PSM can be effectively applied to, are as follows.

5.1 Plant damage state event tree

Due to the peculiar structure of plant damage state event tree (PDS ET), the frequency of PDS ET sequences is often overestimated compared to the equivalent one of level 1 event tree sequence. The causes of the frequency difference and methods to adjust the difference were described in detail in reference [3].

5.2 Internal event PSA

So far, non-rare events have hardly been modeled in internal event PSA. However, recent PSAs have non-rare events for equipment failure and human failure event related to FLEX. Therefore, it is necessary to check the possibility of the overestimation error during internal event PSA quantification. If necessary, PSM can be used to reduce the overestimation error.

5.3 Fire PSA

In general, the state-of-the-art fire PSA has a lot of non-rare events representing fire-induced spurious operation. The typical probability of the fire-induced spurious operation is from 0.3 to 0.6. Therefore, in many fire induced scenarios, the application of DTA, REA, or MCUB may cause big overestimation error. In this situation, PSM is suggested to use.

5.4 Seismic PSA

In general, a number of non-rare events have been modeled in seismic PSA. So far, several seismic PSA specific quantification methods have been suggested and used. However, as the number of non-rare events or seismic induced failure events increases, it is very difficult to apply the existing seismic PSA specific quantification methods. It is believed that PSM can be best applied to seismic PSA.

6. Conclusions and future works

In this paper, 1) the limitation of traditional fault tree quantification methods was described, 2) the PSM characteristics were explained, and 3) PSM implementation into SAREX and its application area were explained.

As was explained in the previous section, SAREX can generate MCSs for failure gate combination and failure-success gate combination. It calculates MCSs probability or frequency using MCUB. Therefore, if MCSs conversion into BDD for accurate PSM application is necessary, it should be done manually with the current version of SAREX. Because PSM can be best utilized for the fault tree with non-rare events in negates, it is necessary to incorporate a module to calculate more accurate probability of MCSs with non-rare events such as ACUBE or BeEAST.

REFERENCES

[1] U.S. NRC, Reactor safety study, WASH-1400, November, 1975.

[2] S.K. Park, W.S. Jung, Probability subtraction method for accurate quantification of seismic multi-unit probabilistic safety assessment, Nuclear Engineering and Technology, Vol. 53, 2021.

[3] S.K. Park, W.S. Jung, Methods for frequency gap adjustment between level 1 and PDS sequences, Transactions of the Korean Nuclear Society Autumn Meeting, 2020.