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A method to improve cutset probability calculation in probabilistic safety assessment of nuclear power plants

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ABSTRACT

In order to calculate the more accurate top event probability from cutsets or minimal cut sets (MCSs) than the conventional method that adopts the rare event approximation (REA) or min cut upper bound (MCUB) calculation, advanced cutset upper bound estimator (ACUBE) software had been developed several years ago and shortly became a vital tool for calculating the accurate core damage frequency of nuclear power plants in probabilistic safety assessment (PSA).

Usually, the whole cutsets in the industry PSA models cannot be converted into a Binary decision diagram (BDD) due to the limited computational memory. So, the ACUBE selects the major cutsets whose probabilities are larger than the others, and then converts the major cutsets into a BDD in order to calculate more accurate top event probability from cutsets.

This study (1) suggests when and where the ACUBE should be employed by predicting the amount of overestimation of the top event probability depending on the cutset structure, (2) explains the details of the ACUBE algorithm, and (3) demonstrates the efficiency of the ACUBE by calculating the top event probability of some PSA cutsets.

1. Introduction

1.1. Fault tree analysis

Fault tree analysis is extensively and successfully applied to the risk assessment of safety critical systems such as nuclear, chemical, and aerospace systems. The fault tree analysis has been used together with an event tree analysis in probabilistic safety assessment (PSA) of nuclear power plants. In PSA, cutsets or minimal cut sets (MCSs) for accident sequences are generated from a set of fault trees and event trees. Each cutset represents an accident sequence that might result in the undesired condition such as core damage. An accident sequence represents successive failures of components or systems after an initiating event. For the safe design and operation of nuclear power plants, various PSAs are performed such as internal, external, full-power, low-power, and shutdown PSAs including online-risk monitoring [1]. The cutset quantification is a very important task through these various PSAs.

Most of the fault tree analysis methods and softwares for PSA are based on the cutset-based algorithm. They generate cutsets from a fault tree by using the traditional Boolean algebra or Zero-suppressed binary decision diagram (ZBDD) algorithm [2,3] and calculate the top event probability from the cutsets. Although the cutset-based fault tree analysis has played an important role in PSA for a nuclear power plant, it is a very complex and time-consuming activity to calculate cutsets, perform the post-processing of cutsets, calculate the top event probability from the processed cutsets, and calculate importance measures from the processed cutsets (see Section 1.2).

In the PSA industry, cutsets can be produced and manipulated by a number of PSA tools such as CAFTA software [4]. PSA softwares that are widely used in the nuclear industry are CAFTA, RiskSpectrum, and RiskMan [5]. Regulatory PSA software in the USA is SAPHIRE [6]. Each PSA tool employs one of the dedicated cutset generation algorithms. One of them is Fault Tree Reliability Evaluation eXpert (FTREX) [2,3] that is the most popular fault tree solver in the USA.

1.2. Approximations in the fault tree analysis

Uncertainty in PSA of nuclear power plants could be classified into (1) parameter uncertainty, (2) model uncertainty, (3) completeness uncertainty, and (4) quantification uncertainty. Uncertainty sources in PSA are classified into the first three groups [7]. The importance of identifying, characterizing and displaying the uncertainty in the risk analyses was widely recognized, and the appropriate understanding and treatment of uncertainty is an important component of risk analyses for complex systems [8].

This study was performed for minimizing the quantification uncertainty. More specifically, this study focuses on the overestimated probability calculation with given cutsets. Since the

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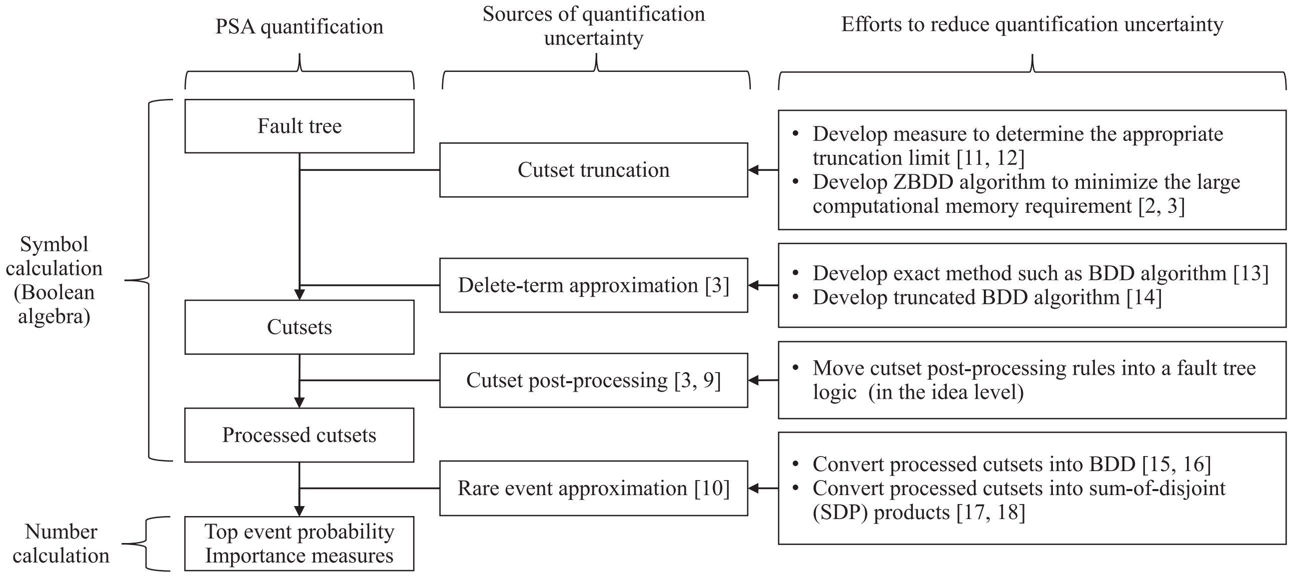

Fig. 1. Efforts to reduce PSA quantification uncertainty.

current PSA fault trees have a huge size and the number of cutsets grows exponentially with the size of a fault tree, cutset-based fault tree solvers employ approximations in order to overcome high memory requirements and a long computing time. Fig. 1 explains PSA quantification stages, the sources of quantification uncertainty in each stage, and the efforts to overcome or reduce the quantification uncertainty. As shown in Fig. 1, the sources of quantification uncertainty are (1) cutset truncation that is designed to minimize huge memory requirement, (2) delete-term approximation that simulates negates in a fault tree [3], (3) cutset post-processing that manipulates cutsets for reflecting the reality [3,9], and (4) rare event approximation (REA) [10] that minimizes the complexity of the top event probability calculation.

The sources of quantification uncertainty and the efforts to reduce the quantification uncertainty are summarized as follows: First, during the cutset calculations of gates in a fault tree, a truncation is performed to discard cutsets that have lower probabilities than the given truncation limit. The quantification uncertainty from the truncation was a great concern in the PSA industry [11,12]. The truncation of cutsets might result in significantly underestimated top event probability, and thus inaccurate importance measures. The efforts for reducing the quantification uncertainty from the cutset truncation have focused on (1) developing measures that estimate the amount of truncated cutset probabilities and (2) developing an efficient algorithm that facilitates the application of a very low truncation limit. Considerable progresses had been made by developing truncation measures [11,12] to determine acceptably low truncation limit, and the ZBDD algorithm [2,3] was developed to minimize the large computational memory requirement for the efficient cutset generation from a fault tree and compact cutset storage.

Second, the delete-term operation [3] was adopted as an approximation to simulate negates in a fault tree that are gates in the successful state. In order to directly solve negates without using this approximation, the binary decision diagram (BDD) algorithm [13,14] was developed.

Third, the post-processing of cutsets [3,9] is performed after generating cutsets from a fault tree. This post-processing of cutsets is performed in order to delete a physically impossible cutset that has mutually exclusive events and to take into account recovery actions for an accident sequence and the dependencies among the recovery actions. In order to avoid the quantification uncertainty that is from the tricky and non-logical cutset manipulation, some researchers in the US Electric Power Research Institute are thinking of moving cutset recovery rules into a fault tree model.

Fourth, the rare event approximation in Section 3.1 is employed for calculating the approximate top event probability and importance measures by assuming small event probabilities. Its replacement is MCUB in Section 3.2. As explained in Section 4, these two approximations may significantly overestimate top event probability when basic event probabilities are not small, cutsets are share many common events, or cutsets have successful events. In order to avoid this overestimation of the top event probability, the cutsets are converted into a BDD structure [15,16] or sum-of-disjoint (SDP) products [17,18], and then the exact top event probability is calculated by the BDD or SDP products.

1.3. *Objectives and structure of the paper*

This study focuses on the overestimated probability calculation with given cutsets among various sources of quantification uncertainty. In order to calculate the accurate top event probability from cutsets rather than improving the direct probability calculation from a fault tree, the author of this paper developed advanced cutset upper bound estimator (ACUBE) software [15,16] supported by the US Electric Power Research Institute. The ACUBE development was an effort to reduce the quantification conservatism that is caused by the rare event approximation or MCUB calculation in the top event probability and importance measure calculations from given cutsets.

The handling of the approximations in Section 1.2 that are introduced by truncating cutsets and handling of fault tree negations are not part of this study. This study focuses on the way to minimize or eliminate the adverse effect from the rare event approximation that induces the overestimated top event probability.

This paper aimed at three objectives. (1) The first objective is to suggest an appropriate method to classify the types of cutsets in order to predict the amount of the overestimated top event probability by looking at the cutset structure such as event probabilities and event states in the cutsets. (2) The second objective is to find an appropriate target area in PSA where the ACUBE calculation should be applied. In this study, it was the top event probability calculation with the cutsets that have high probability events or successful events. (3) The third objective is to show the ACUBE effectiveness by comparing ACUBE and min cut upper bound (MCUB) calculation results with real PSA cutsets.