Application of SDP/CUTREE Code to NPP PSAs

Jong Soo Choi
Korea Institute of Nuclear Safety, 19 Guseong-dong Yuseong-gu Daejeon 305-338
k209cjs@kins.re.kr

1. Introduction

The computer code package, CUTREE [1,2], was developed for accurate calculation of top event probability and importance measures in minimal cut sets (MCS)-based fault tree analyses. The CUTREE code package consists of five independent computing modules: SDP, CFA, TE, TE-IS and RM-IM. SDP/CUTREE is a code for exact MCS quantification based on the concept of "sum of disjoint products" [3,4]. To have a better understanding of the SDP/CUTREE code, its accuracy and applicability to NPP PSAs have been tested. This study is described herein and representative results of the SDP calculations are presented.

2. Methods and Results

In this section, some of the techniques used to quantify MCSs and the proposed method to apply the SDP/CUTREE code to NPP PSAs are described.

2.1 MCS Quantification Methods

In PSAs for nuclear power plants (NPPs), outputs are computed from a set of limited MCSs, $\{\mathbf{K}_i \mid i = 1, \ldots, m\}$ mainly by using approximations as follows:

- Rare Event Approximation (RE):

$$P(MCS)_{RE} = \sum_{i=1}^{m} P(K_i) \geq P(MCS)_{Exact} \quad (1)$$

- Min Cut Upper Bound Approximation (MCUB):

$$P(MCS)_{MCUB} = 1 - \prod_{i=1}^{m} \{1 - P(K_i)\} \geq P(MCS)_{Exact} \quad (2)$$

The exact probability of the union of all the MCSs, $P(MCS)_{Exact}$, is theoretically calculated by the following inclusion exclusion expansion (In-Ex)

$$\begin{aligned} P(MCS)_{Exact} &= \sum_{i=1}^{m} P(K_i) - \sum_{1 \le i < j \le m} P(K_i K_j) \\ &+ \sum_{1 \le i < j < k \le m} P(K_i K_j K_k) - \cdots \\ &+ (-1)^{m-1} P(K_1 K_2 \cdots K_m). \end{aligned} \quad (3)$$

$P(MCS)_{Exact}$ is also calculated by the sum of disjoint product algorithm (SDP) [3].

2.2 Accuracy of SDP/CUTREE

The accuracy of the SDP/CUTREE code is tested on an example tree. This example is the tree for the AFWS of Kori unit 3&4, which contains 613 gates and 677 basic events. Table 1 gives MCS quantification results using the rare-event approximation, the SDP/CUTREE code and the inclusion-exclusion expansion for 4 different cut-off value (C_v) cases. Figure 1 shows the comparison results among different MCS quantification methods for the $C_v = 10^{-8}$ cases.

Table 1. MCS quantification results for example tree

C_v	# of MCS	*RE*	*SDP*	*In-Ex* with first 3 terms	*In-Ex* with first 5 terms
10^{-6}	14	2.266E-4	2.233E-4	2.233E-4	2.233E-4
10^{-7}	55	2.361E-4	2.315E-4	2.315E-4	2.315E-4
10^{-8}	230	2.416E-4	2.359E-4	2.359E-4	2.359E-4
10^{-9}	806	2.436E-4	2.374E-4	2.375E-4	

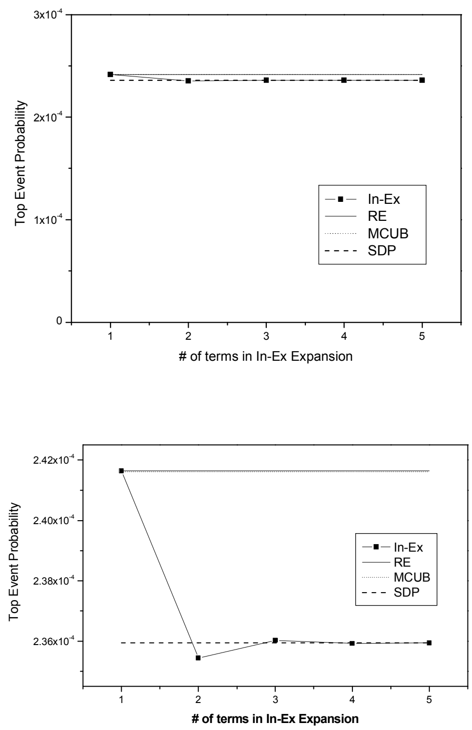

Figure 1. Comparison of MCS quantification methods

2.3 Proposed Quantification Method for NPP PSAs

All NPP PSA models have the following characteristics:

Initiating events (IE): mutually exclusive
Basic events (BE): mutually independent
Core-damaged sequences (SQ): mutually exclusive

Mutually exclusive events and mutually independent events have the following characteristics:

If events, $\{B_i \mid i = 1, \ldots, n\}$ are mutually exclusive,

$$\Rightarrow P\left[\bigcup_{i=1}^{n} B_i\right] = \sum_{i=1}^{n} P(B_i)$$

$\Rightarrow P(B_i \cap B_j) = 0$ for any pairs of different events.

If events are mutually independent,

$$\Rightarrow P\left[\bigcup_{i=1}^{n} B_i\right] \leq \sum_{i=1}^{n} P(B_i)$$

$\Rightarrow P(B_i \cap B_j) = P(B_i) \cdot P(B_j)$ for any pairs of i and j.

Then, the exact core damage frequencies (CDF) can be calculated by using the following equations:

$$F(CD)_{Exact} = \sum_{all\ IE} F(CD \mid IE)_{Exact} \quad (4)$$

$$F(CD \mid IE)_{Exact} = F(IE) \times \sum_{all\ SQ-IE} P(CD \mid SQ)_{Exact} \quad (5)$$

$$P(CD \mid SQ) = P\left[\bigcup_{all\ MCSs} (MCS - SQ)\right] + TE(SQ) \quad (6)$$

The exact MCS quantification for each core damaged sequence, $P\left[\bigcup_{all\ MCSs} (MCS - SQ)\right]$, can be performed by using the SDP/CUTREE code and the truncation error evaluation for each core damaged sequence, *TE(SQ)*, can be performed by using the TE/CUTREE code or the TE-IS/CUTREE code. In the proposed method for exact PSA quantification, we additionally need Boolean equations of all core-damaged sequences.

2.4 Application of SDP/CUTREE to UCN 5&6 PSA

The example PSA model is the internal event CDF model for Ulchin unit (UCN) 5&6, which was published in 2002 and is summarized as follows:

Number of initiating events (IE): 16
Number of basic events (BE): 1139
Number of core-damaged sequences (SQ): 242
Number of minimal cut sets (MCS): 8164
CDF (using rare event approx.): 7.277E-6 /RY

Table 2 provides MCS re-quantification results for all core-damaged sequences for the UCN 5&6 internal CDF model by using the SDP/CUTREE code.

Table 2. MCS quantification results for UCN 5&6 PSA('02)

IE	# of SQ	*RE*	*SDP*	Cons. of RE
ILL	5	9.275E-7	9.258E-7	100.19%
IML	4	6.240E-7	6.228E-7	100.19%
ISL	18	1.505E-6	1.503E-6	100.11%
ISGTR	21	6.142E-7	6.108E-7	100.56%
ILSSB	17	2.090E-7	2.073E-7	100.85%
ILOFW	16	1.219E-6	1.215E-6	100.31%
ILOCV	16	2.301E-8	2.291E-8	100.41%
ILOCCW	16	8.667E-8	8.565E-8	101.19%
ILOKV	16	6.365E-10	6.324E-10	100.65%
ILODC	16	3.550E-7	3.498E-7	101.49%
ILOOP	16	4.478E-7	4.465E-7	100.30%
ISBO	22	2.710E-7	2.709E-7	100.03%
IGTRN	16	3.912E-7	3.885E-7	100.69%
IATWS	41	3.357E-7	3.357E-7	99.99%
IISL	1	1.770E-9	1.770E-9	100.00%
IRVR	1	2.660E-7	2.660E-7	100.00%
Total	242	7.277E-6	7.254E-6	100.33%

CDF: Core damage frequency (/RY)

3. Conclusion

This paper focuses on the accuracy and applicability to NPP PSAs of the SDP/CUTREE code and shows the possibility of exact PSA quantification without approximation and truncation errors in the field of NPP PSAs.

REFERENCES

[1] J. S. Choi, N. Z. Cho, A Practical Method for Accurate Quantification of Large Fault Trees, Reliability Engineering and System Safety, in press.

[2] J. S. Choi, N. Z. Cho, NurapT-2006-03, A User's Manual of the CUTREE Code Package for Minimal Cutset-Based Fault Tree Analysis, Ver. 1.0, KAIST, Department of Nuclear and Quantum Engineering, June 2006.

[3] J. S. Choi, N. Z. Cho, Exact Minimal Cutset Quantification Using Equivalent Sum of Disjoint Products, Transactions of the Korean Nuclear Society Spring Meeting Chuncheon, Korea, May 25-26 2006.

[4] A. Rauzy, New Algorithms for fault trees analysis, Reliability Engineering and System Safety, Vol.40, p.203, 1993.