Sensitivity Analysis of Simplified CCF Application in a Fault Tree with the Different Design Configuration

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1. Introduction

In Probabilistic Risk Assessment (PRA) model, a common cause event is defined as the failure or unavailable state of more than one component during the mission time and due to the same shared cause. Common Cause Failure (CCF) results from the coexistence of two main factors, a root cause and a coupling factor (or coupling mechanism) that creates the condition for multiple components to be affected by the same cause. An advanced nuclear power plant has the redundant systems and components for the safe operation. Therefore, the CCF modeling becomes complicated and huge. For the simplicity, the simplified CCF modeling can be used.

In this study, the simplified CCF modeling is incorporated into the fault tree modeling for imaginary train designs with different design configuration, in which the effect of the CCF modeling can be interpreted. The probability of Simplified CCF is calculated based on the alpha factor model introduced in the NUREG/CR-5485 [1].

2. Methods and Results

2.1 Common Cause Impacting Components

The identification of CCCG is the first step to model CCFs. The Common Cause Component Group (CCCG) consist of Common Cause Basic Events (CCBEs) that involves failure of a specific set of components due to a common cause. In the CCCG of size *m*, the number of common cause impacting *k* components $N_k^{(m)}$ is given by,

$$N_k^{(m)} = \binom{m}{k} = {}_mC_k = \frac{m!}{k!(m-k)!},\ 1 \le k \le m \qquad (1)$$

In the formula (1), if *k* is equal to one, the result of $N_1^{(m)}$ means the number of independent failure in CCCG(*m*).

Table I shows the number of common cause impacting *k* components in CCCG size from two to eight. As shown in Table I, the total number of CCBEs is significantly increases with increasing CCCG size.

Table I: The number of common cause impacting *k* components

$N_k^{(m)}$ \ m	2	3	4	5	6	7	8
$N_1^{(m)}$	2	3	4	5	6	7	8
$N_2^{(m)}$	1	3	6	10	15	21	28
$N_3^{(m)}$		1	4	10	20	35	56
$N_4^{(m)}$			1	5	15	35	70
$N_5^{(m)}$				1	6	21	56
$N_6^{(m)}$					1	7	28
$N_7^{(m)}$						1	8
$N_8^{(m)}$							1
Total	3	7	15	31	63	127	255

2.2 Simplified CCF Probability Calculation

The CCF probability developed by Alpha-Factor model is given by,

$$Q_k^{(m)} = \frac{1}{\binom{m-1}{k-1}} \alpha_k Q_t \qquad (2)$$

for a staggered testing scheme.

In the formula (2) Q_t means the total failure probability of each component due to all independent and common cause events. α_k means fraction of the total probability of failure events that occur in the system and involve the failure of *k* components due to a common cause. The Alpha-Factor model develops CCF probability from a set of failure ratios and the total component failure rate.

The Simplified CCF Method is simplification by summing alpha factor in one CCCG. The Simplified CCF probability is given by,

$$Q_S^{(m)} = \sum_{k=i}^{n} \alpha_k Q_t,\ 1 < i < n \le m \qquad (3)$$

for a staggered testing scheme.

In the formula (3), *i* means the start number of simplification group and *n* means the end number of simplification group of CCCGs.

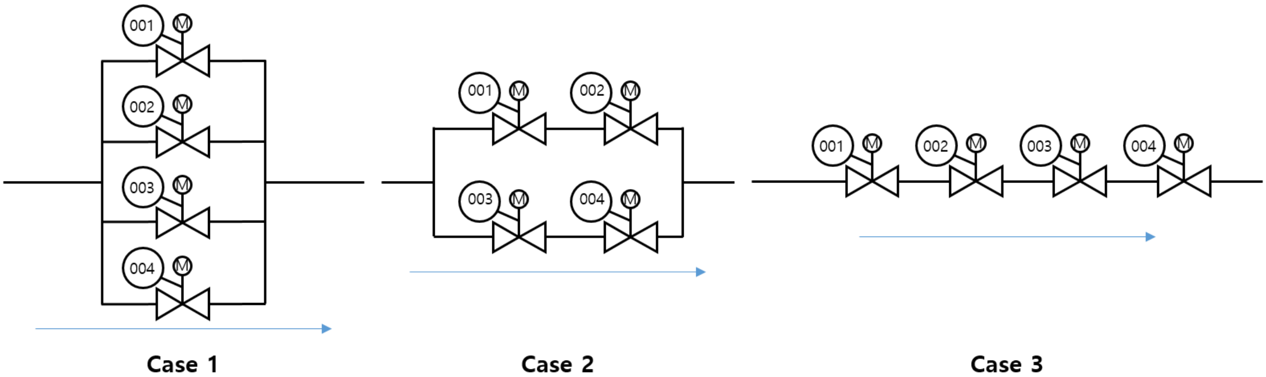

Fig. 1. Three cases composed to four valves

2.3 Case for Comparison of CCF calculation

Case 1, 2 and 3 in Fig. 1. are three models for comparison of General and Simplified CCF calculation Method. The three case of the system configuration consist of four same Motor Operated Valves (MOVs) is assumed as like follows:

The Case 1 shows that the MOVs are arranged in parallel. The failure of all the four valves will cause the train failure. Therefore, the impact of common cause failure is higher than failure of each component.

The Case 2 shows that two lines are arranged in parallel, on which each line contains two MOVs in series. The failure of three or more valves will cause the train failure, also failure of two valves that one in each line will cause the train failure.

The Case 3 shows that the MOVs are arranged in series. The failure of only one valve will cause the train failure. Therefore, the impact of common cause failure is lower than failure of each component.

For the comparison of each case, it is assumed as follow.

- The MOVs are tested staggered.
- Fail to Open failure mode is considered only.

The fail to open probability of each MOV is referred from Component Reliability Data Sheets 2015 Update [2], it is 4.21E-04 that corresponds Q_t in formula (2). The alpha factor of generic demand CCF distribution is referred from CCF Parameter Estimations 2010 [3], it is shown in Table II that shows general CCF probability calculation by formula (2).

Table II: Data of General CCF Calculation (Method1)

Alpha Factor		CCF Parameter	$Q_k^{(4)}$
α_1	9.75E-01	-	-
α_2	1.54E-02	5.13E-03	2.16E-06
α_3	6.50E-03	2.17E-03	9.13E-07
α_4	3.37E-03	3.37E-03	1.42E-06

2.4 Comparison of CCF Calculation Method

The CCF probabilities of each model are calculated by three methods.

Method1. Base Model
- General CCF Calculation Method

Method2. 1-Simplified Model
- 2/4+3/4+4/4 CCF: Simplified CCF Method
- In formula (3), *i*=2, *n*=4

Method3. 2-Simplified Model
- 2/4 CCF: General CCF Calculation Method
- 3/4 + 4/4 CCF: Simplified CCF Method
- In formula (3), *i*=3, *n*=4

The CCF probability of Method1 for base model is shown in Table II. The results of Simplified CCF Calculation Method2 and Method3 are shown in Table III and Table IV.

Table III: Data of 1-Simplified CCF Calculation (Method2)

<table>
<tr><th colspan="2">Alpha Factor</th><th>CCF Parameter</th><th>$Q_S^{(4)}$</th></tr>
<tr><td>α_1</td><td>9.75E-01</td><td>-</td><td>-</td></tr>
<tr><td>α_2</td><td>1.54E-02</td><td rowspan="3">2.53E-02*</td><td rowspan="3">1.06E-05*</td></tr>
<tr><td>α_3</td><td>6.50E-03</td></tr>
<tr><td>α_4</td><td>3.37E-03</td></tr>
</table>

Note. * Calculated by Simplified Method

Table IV: Data of 2-Simplified CCF Calculation (Method3)

<table>
<tr><th colspan="2">Alpha Factor</th><th>CCF Parameter</th><th>$Q_S^{(4)}$</th></tr>
<tr><td>α_1</td><td>9.75E-01</td><td>-</td><td>-</td></tr>
<tr><td>α_2</td><td>1.54E-02</td><td>5.13E-03</td><td>2.16E-06</td></tr>
<tr><td>α_3</td><td>6.50E-03</td><td rowspan="2">9.87E-03*</td><td rowspan="2">4.15E-06*</td></tr>
<tr><td>α_4</td><td>3.37E-03</td></tr>
</table>

Note. * Calculated by Simplified Method

Table V: Result of CCF Calculation Method Comparison for Each Case

	Case 1		Case 2		Case 3	
Method	Prob.	Deviation	Prob.	Deviation	Prob.	Deviation
Method1 ; Base Model	1.42E-06	-	1.44E-05	-	1.70E-03	-
Method2 ; 1-Simplified	1.06E-05	+650%	1.14E-05	-21%	1.70E-03	-0.43%
Method3 ; 2-Simplified	4.15E-06	+193%	1.35E-05	-6%	1.70E-03	-0.05%

In the Table III, the Simplified CCF probability is applied one CCF event on behalf of seven CCF events for CCCG(2), CCCG(3) and CCCG(4).

In the Table IV, the Simplified CCF is calculated by the sum of α_3 and α_4. It is applied one CCF event on behalf of four CCF events for CCCG(3) and CCCG(4). On the other hand, CCF probability for CCCG(2) is applied three CCF events like base model.

2.5 Results of Comparison

Table V shows the result of three CCF Calculation Method comparison for each case. The analysis results of each case by the methods are described as follow.

<u>Case 1. MOVs are arranged in parallel</u>

Failure probability using Method1 is 1.42E-06. When using Method2, failure probability is estimated to be 1.06E-05 (increase by 650% in base model). When using Method3, failure probability is estimated to be 4.15E-06 (increase by 193% in base model).

In this case, the deviations of probability for CCFs are the highest, because the impact of the CCF events is dominant for parallel configuration failure. When using Method2, the Simplified CCF event is the only event of common cause failure. Thus, the Simplified CCF calculation method is very conservative in Case 1.

<u>Case 2. 2 lines are arranged in parallel that contains 2 MOVs are arranged in series</u>

Failure probability using Method1 is 1.44E-05. When using Method2, failure probability is estimated to be 1.14E-05 (decrease by 21% in base model). When using Method3, failure probability is estimated to be 1.35E-05 (decrease by 6% in base model).

In this case, the deviations of probability for CCFs are quietly high, because of insufficient consideration of CCF events. Failure of two or more valves except for two valves failure in same line causes the failure of this case. It is not considered sufficiently when using Simplified Method.

For example, CCF event of V001/V002 and failure of V003 causes the failure of Case 2. However, this failure is not considered in Method2 because one Simplified CCF event is considered only. Thus, the Simplified CCF calculation method is estimated lower than base model in Case 2.

<u>Case 3. MOVs are arranged in series</u>

Failure probability using Method1 is 1.70E-03. When using Method2, failure probability is estimated to be 1.70E-03 (decrease by 0.43% in base model). When using Method3, failure probability is estimated to be 1.70E-03 (decrease by 0.05% in base model).

In this case, the deviations of probability for CCFs are the lowest, because the impact of each component failure is higher than CCF events for series configuration failure. When using Simplified Method, the results are very similar with Method1. Thus, the Simplified CCF calculation method has been well applied in Case 3.

3. Conclusions

In this study, the sensitivity study has been performed to understand the effectiveness of the Simplified CCF modeling. The impact of CCF event depends on train designs.

In the parallel configuration model like Case 1, the Simplified CCF Calculation is estimated to be very conservative. On the other hand, when the components are placed in series like Case 2 and Case 3, it is estimated to be non-conservative because the CCF events are less considered.

A PRA for an advanced nuclear power plant includes a lot of CCCGs that consist of many components due to its redundant design. If the Simplified CCF Calculation Method is applied to PRA model in these conditions, it is necessary to consider very cautiously.

REFERENCES

[1] Mosleh, A., INEEL, Guidelines on Modeling Common-Cause Failures in Probabilistic Risk Assessment, NUREG/CR-5485, 1999.

[2] U.S. Nuclear Regulatory Commission, Component Reliability Data Sheets 2015 Update, 2017.

[3] U.S. Nuclear Regulatory Commission, CCF Parameter Estimations 2010, 2012.