Modeling and Parameter Estimation of Common Cause Failures by Using the Decomposition Approach

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1. Introduction

Most of the parametric models for common cause failure (CCF) analysis use a symmetry assumption that the probabilities of similar events involving similar components are the same. However, there are many situations in practice in which the CCF events would be expected to exhibit asymmetries [1]. In this study, we derived an analytical formula for the modeling and parameter estimations of asymmetrical CCF events by using the decomposition approach. Different approach without decomposition was introduced to compare the calculation results of system unavailability by using it with those using the decomposition approach.

2. Method

Let us assume that there are three components A, B, and C. They are manufactured by the same company. Two components A and B have the same design features, but component C is designed differently. Some of the sub-components for three systems are the same. Other causes of CCFs such as the maintenance staff and operating environment are the same.

The failure events of each component can be decomposed into two: One is those that come from the same design, operational environment, etc., and the other is those that come from different designs, operation environments, etc. Thus, the total probability of each component can be represented as follows:

Q_T (component C) = $Q_{TCP} + Q_{TIP}$ (1)

Q'_T (component A or B) = $Q'_{TCP} + Q'_{TIP}$ (2)

Where,

Q_T = total failure probability of component C

Q'_T = total failure probability of component A or B

$Q_{TCP} = Q'_{TCP}$ = total failure probability of component A, B, or C due to the same design, operation environments, etc.

Q_{TIP}= total failure probability of component C due to its unique design, operation environments, etc.

Q'_{TIP}= total failure probability of component A or B due to its different design, operation environment, etc. from component C

The probability of a CCF event involving k specific components in a common cause component group (CCCG) of size m for a staggered testing scheme, $Q_k^{(m)}$, is calculated by using the following equation [1]:

$Q_k^{(m)} = (\alpha_k^{(m)} / {}_{m-1}C_{k-1}) * Q_T$ (3)

where,

$Q_T = \sum_{k=1}^{m} {}_{m-1}C_{k-1} * Q_k^{(m)}$ =total failure probability of a component in a CCCG due to all the independent and common cause failure events (4)

$\alpha_k^{(m)} = n_k / \sum_{k=1}^{m} n_k$ =fraction of the total frequency of the failure events that occur in the system involving the failure of k components due to a common cause (5)

Where,

n_k = number of events involving k components in a failed state

With Eq. (3), Q_T and Q'_T of Eqs.(1) and (2) can be represented as follows:

Q_T (component C) = $Q_{1\text{-}TCP} + 2Q_{2\text{-}TCP} + Q_{3\text{-}TCP} + Q_{TIP}$. (6)

Q'_T (component A or B) =
$Q_{1\text{-}TCP} + 2Q_{2\text{-}TCP} + Q_{3\text{-}TCP} + Q'_{1\text{-}TIP} + Q'_{2\text{-}TIP}$……(7)

3. Applications

We applied the method of Section 2 to three emergency diesel generators (EDGs) of Ulchin Unit 3. The Ulchin Unit 3 has two onsite EDGs and one alternate AC (AAC) EDG. The AAC is manually connected to only one 4.16kV Class 1E bus. The EDGs of Unit 3&4 and the AAC are manufactured by the same company, but they are designed differently. In this paper, we call the two onsite EDGs as EDG A and B, and the AAC as EDG C.

3.1 Decomposition approach

Based on the characteristics of the design features and the operation environments of three EDGs A, B, and C, the following assumptions for Eqs (6) and (7) were made:

1) Q_T is approximately equal to Q'_T and Q_{TCP}
2) Q_{TCP} is greater than Q'_{TIP} and Q_{TIP}

Thus, Eqs (6) and (7) can be represented as follows:

Q (EDG C) $\approx Q_1 + 2Q_2 + Q_3$…… ……….(8)

Q' (EDG A or B)

$$\approx Q_1 + 2Q_2 + Q_3 + Q'_{2\text{-TIP}} \quad (9)$$

where,

$$Q_1 = \alpha_1 * Q_T \approx Q_T,$$
$$Q_2 = (\alpha_2 / 2) * Q_T \quad (10)$$
$$Q_3 = \alpha_3 * Q_T$$
$$Q'_{2\text{-TIP}} = \alpha'_{2\text{-TIP}} * Q'_{TIP}$$

By using Eq.(5), $\alpha_{2\text{-TIP}}$ is represented as follows:

$\alpha'_{2\text{-TIP}} = n'_{2\text{-TIP}} / (n'_{1\text{-TIP}} + n'_{2\text{-TIP}})$

Where,

$n'_{2\text{-TIP}}$ = number of CCF events involving EDG A & B in a CCCG of size two by excluding that involving EDG A, B, and C

In general, the number of failure events is proportional to the failure probability, $Q'_{2\text{-TIP}}$ of Eq.(10) can be represented as follow:

$$Q'_{2\text{-TIP}} = \alpha'_{2\text{-TIP}} * Q'_{TIP}$$
$$\approx (n'_{2\text{-TIP}}/(\sum_{k=1}^{m} n_k))*(Q_T/Q'_{TIP}) * Q'_{TIP}$$
$$\approx \alpha'_2 * Q_T = Q'_2 \quad (11)$$

Where,

$$\alpha'_2 = n'_{2\text{-TIP}} / (\sum_{k=1}^{m} n_k) \quad (12)$$

Thus, Q'_T of Eq. (7) can be represented as the following equation:

Q'_T (EDG A or B)

$$\approx Q_1 + 2Q_2 + Q_3 + Q'_2 \quad (13)$$

3.2 Different approach without decomposition

Without the decomposition of the failure events, we can represent the total failure probability of each EDG as follows:

$$Q(\text{EDG C}) = Q_1 + Q_{AC} + Q_{BC} + Q_{ABC}$$
$$= Q_1 + 2Q_2 + Q_3 \quad (14)$$
$$Q(\text{EDG A or B}) = Q_1 + Q_{AC\ or\ BC} + Q_{AB} + Q_{ABC}$$
$$= Q_1 + Q_2 + Q''_2 + Q_3 \quad (15)$$

where,

$Q''_2 \approx \alpha''_2 Q_t$ =probability of a CCF event involving EDG A and B (16)

$\alpha''_2 = n''_2/(n''_1 + n''_2)$ (17)

n''_2 of Eq.(17) is a number of CCF events involving EDG A & B in a CCCG of size three including CCF events involving EDG A, B, and C. As shown in Eqs (8), (13), (14), and (15), formulas for calculating the unavailability of a EDG C in Subsections 3.1 and 3.2 are the same but those of EDG A or B are different.

3.3 Estimations of the alpha parameters and common cause failure probability

With the ICDE [2] data, we estimated the alpha parameters and calculated the CCF probabilities by using Eqs (5), (10), (11), (12), (16) and (17). The probabilities of the events of "fail to start" and "fail to run" for the EDG of Ulchin Unit 3 were estimated as 4.49E-2 and 5.76E-2, respectively. Table 1 shows the estimation results of the alpha parameters and CCF probabilities. With the data of Table 1, the EDG system unavailability of the 1 out of 3 success criterion except for the supporting systems was calculated. By using the decomposition approach, it was calculated as 2.654E-3. By using Eqs. (14) and (15), it was calculated as 2.664E-3.

Table 1. Estimation results of alpha factors and CCF probabilities

Maximum likelihood estimator	Fails to start		Fails to run	
	Alpha factor (α_k)	Failure probability (Q_k)	Alpha factor (α_k)	Failure probability (Q_k)
α_2 , Q_2	9.95E-3	2.23E-4	7.88E-3	2.27E-4
α_3 , Q_3	8.49E-3	3.81E-4	8.16E-3	4.7E-4
α'_2 , Q'_2	5.31E-3	2.38E-4	2.74E-3	1.58E-4
α''_2 , Q''_2	9.91E-3	4.45E-4	8.18E-3	4.71E-4

4. Conclusions

In this paper, we derived an analytical formula for the modeling and parameter estimations of asymmetrical CCF events. The derived formula was applied to three EDGs of Ulchin Unit 3. Different approach without decomposition was introduced to compare the estimation results of the EDG unavailability. There is a negligible difference in the calculation results. Depending on the data available and the system analysts' preference, the CCF events can be modeled differently and their parameters can also be estimated differently.

Acknowledgements

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References

[1]. U.S. NRC, Guidelines on Modeling Common-Cause Failures in Probabilistic Risk Assessment, NUREG/CR-5485, Nov. 1998.

[2] OECD Nuclear Energy Agency, "International Common-cause Failure data Exchange, ICDE General Coding Guidelines", NEA/CSNI/R (2004)4, January 2004