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Estimating the Effects of Offsite Power Recovery Time based on Cutset Analysis

Jae Young Yoon*, Dong-San Kim

Korea Atomic Energy Research Institute, Daedeok-daero 989-111, Yuseong-gu, Daejeon, Republic of Korea
**Corresponding author: jyyoon@kaeri.re.kr*

1. Introduction

Conventional probabilistic safety assessment (PSA) needs some assumptions based on expert judgement to evaluate the risk quantitatively, and therefore there have been efforts to estimate risk realistically. Some researches that handle offsite power recovery have been conducted for more practical applications [1-3]. In domestic PSA models, we assume EDGs are failed after running for 8 hours when estimating station blackout (SBO) caused by the running failure of emergency diesel generators (EDGs). It was obtained conservatively by calculating the average failure probability of offsite power recovery during 24 hours. In cases of alternate alternating current DG (AAC-DG), it was not considered how long it was run. Because the offsite power recovery time allowed for preventing core damage is dependent on loss of power loss, the running times of EDGs and AAC-DG are significant factors. This study evaluated the effect of offsite power recovery time in accordance with the running failure time of EDGs and AAC-DG on core damage frequency (CDF) through case studies.

2. Approach

The approach is based on cutsets obtained by evaluating the conventional PSA model, and it was developed to get insights into offsite power recovery timing before modifying the PSA model to apply the effect of offsite power recovery timing. The approach is shown in Fig. 1. At first, the significant cutsets having large Fussell-Vesely (FV) importance are obtained. For each cutset, the failure modes of EDGs and AAC-DG are classified into staring failure and running failure. If there are two EDGs and one AAC-DG in a single unit, there are six failure types as shown in Table 1. Type 1, 2, and 3 do not consider the running failure time of AAC-DG, which means the AAC-DG fails to start, whereas, for type 4, 5, and 6, the failure mode of AAC-DG is running failure. Time intervals which are divided into equal parts are needed to consider various running failure times of EDGs and AAC-DG. The running failure times of EDGs and AAC-DG are determined to the median values of time intervals and allowed offsite power recovery times are also decided. Time fractions at each time interval are assigned by considering the time when AC power is lost. AC power needed to operate safety systems is fully lost when two EDGs and one AAC-DG are failed if the mobile generators are not considered. After that, we recalculate the probability of all cutsets by modifying the failure probability of offsite power recovery as follows.

$$P_1(\text{cutset})=\sum P_0(\text{cutset})*\text{Fraction(I-i)}*P_i(\text{RF})/P_0(\text{RF})$$

P_1(cutset) is a recalculated probability of cutset, P_0(cutset) is an original probability of cutset, Fraction(I-i) is a fraction at the ith interval, P_i(RF) is a new failure probability of offsite power recovery at the ith interval, and P_0(RF) is an old one.

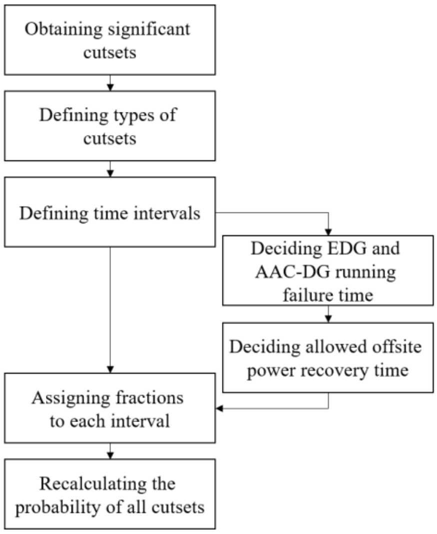

Fig. 1. Flowchart of the approach.

Table I: Failure Types with two EDGs and one AAC-DG

	EDGA		EDGB		AAC-DG	
Failure Mode	Start	Run	Start	Run	Start	Run
Type 1		O		O	O	
Type 2	O			O	O	
Type 3		O	O		O	
Type 4		O		O		O
Type 5	O			O		O
Type 6		O	O			O

3. Case study

The case studies were performed to verify the application of the approach. The model used in the case studies is a multi-unit PSA model including two OPR-1000 type reactor which had been developed in previous research [4]. The significant cutsets having an FV importance greater than 0.9 caused by EDG running failure (SBOR) were analyzed. At first, the cutsets were classified into Type 1, 2, and 3 excluding the effect of AAC-DG. Because the offsite power recovery considered in significant cutsets is failure of offsite power recovery within 7 hours of AC power loss, the allowed offsite power recovery time was determined to be the running failure time of EDGs plus 7 hours as shown in Table II. The cases are defined by the number of intervals.

Table II: Definition of cases without the effect of AAC-DG

	Time Interval	EDGs Running Failure Time	Offsite Power Recovery Time (+7h)
Original	0h~24h	8h	15h
Case 1 (24h/2)	0h~12h 12h~24h	6h 18h	13h 25h
Case 2 (24h/3)	0h~8h 8h~16h 16h~24h	4h 12h 20h	11h 19h 27h
Case 3 (24h/4)	0h~6h 6h~12h 12h~18h 18h~24h	3h 9h 15h 21h	10h 16h 22h 28h
Case 4 (24h/6)	0h~4h 4h~8h 8h~12h 12h~16h 16h~20h 20h~24h	2h 6h 10h 14h 18h 22h	9h 13h 17h 21h 25h 29h

To recalculate the probability of cutsets, it is needed to decide the fractions assigned to each time interval. The fractions were assigned considering two EDGs in a single-unit since most significant cutsets under SBO initiating event are caused by the core damage in a single-unit. For Case 1 and Type 1 cutsets, an early time interval (I-1) means both EDG A and B fail at an early time interval, whereas a late time interval (I-2) means one of two EDGs fails at a late time interval. If one EDG fails at I-1 and the other EDG fails at I-2, the AC power fails at I-2. The fractions of Case 1 are decided as follows.

Fraction (Case 1 & Type 1 & I-1)
=1/2 (EDG A (I-1)) * 1/2 (EDG B (I-2)) = 1/4

Fraction (Case 1 & Type 1 & I-2)
=1/2 (EDG A (I-1)) * 1/2 (EDG B (I-2)) + 1/2 (EDG A (I-2)) * 1/2 (EDG B (I-1)) + 1/2 (EDG A (I-2)) * 1/2 (EDG B (I-2)) = 3/4

The fractions for Cases 1~4 and Type 1~3 are provided in Table III.

Table III: Fractions of cases for Type 1, 2, and 3 cutsets

	Time Interval	Fractions		
		Type 1	Type 2	Type 3
Original	All	-	-	-
Case 1	I-1 I-2	1/4 3/4	1/2 1/2	1/2 1/2
Case 2	I-1 I-2 I-3	1/9 3/9 5/9	1/3 1/3 1/3	1/3 1/3 1/3
Case 3	I-1 I-2 I-3 I-4	1/16 3/16 5/16 7/16	1/4 1/4 1/4 1/4	1/4 1/4 1/4 1/4
Case 4	I-1 I-2 I-3 I-4 I-5 I-6	1/36 3/36 5/36 7/36 9/36 11/36	1/6 1/6 1/6 1/6 1/6 1/6	1/6 1/6 1/6 1/6 1/6 1/6

The probabilities of cutsets were recalculated by multiplying fractions corresponding to the type of cutsets and time interval and replacing the failure probability of offsite power recovery with a new one estimated in Table II. The failure probability of offsite power recovery that was log-normal fitted with the data which is obtained from domestic experience is shown in Fig. 2 [4].

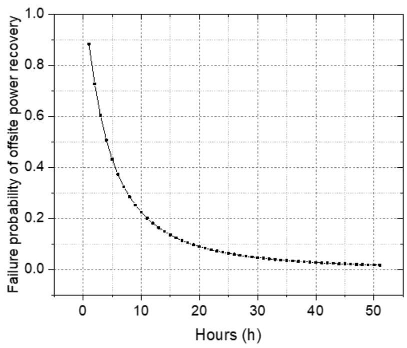

Fig. 2. Failure probability of offsite power recovery

In addition, there are special types of cutsets that were obtained when the EDGs are failed in both units. The fractions for special types were determined by multiplying the fractions provided in Table III twice. For Case1, if the failure modes of EDGs are Type 1 in both units, the fraction at I-1 is 1/16 (=1/4*1/4) and the fraction at I-2 is 15/16. If the failure modes of EDGs are Type1 in one unit and Type 2(or3) in one unit, the fraction at I-1 is 1/8 (=1/4*1/2) and the fraction at I-2 is 7/8. If the failure modes of EDGs are Type 2 in both units, the fraction at I-1 is 1/4 (=1/2*1/2) and the fraction at I-2 is 3/4. After that, the types of cutsets including AAC-DG running failure are transferred to Type 4, 5, and 6. The running failure time of AAC-DG is additionally considered with running failure time of EDG. In this study, two time intervals are considered for AAC-DG running failure. Table IV shows Case 1 with AAC-DG running failure as an example.

Table IV: Case1 with the effect of AAC-DG

	Time Interval		AAC-DG Running Failure Time	Offsite Power Recovery Time (+7h)
	EDG	AAC-DG		
Case1_1 (with AAC-DG)	0h~ 12h	0h~ 12h	12h (6h+6h)	19h
	0h~ 12h	12h~ 24h	24h (6h+18h)	31h
	12h~ 24h	0h~ 12h	24h (18h+6h)	31h
	12h~ 24h	12h~ 24h	36h (18h+18h)	43h

Table V shows the results of case studies which represent the core damage frequency (CDF) induced by SBOR. The original CDF (SBOR) obtained from AIMS-PSA software [5] is 1.42E-06 and it is reduced by about 28~29% through case studies. Dividing 24 hours into some intervals for the EDGs that fail to run reduced CDF, but the number of time intervals is not important except for a tiny decrease trend of CDF according to the number of intervals. Considering two time intervals for the AAC-DG that fails to run also reduced CDF (SBOR) by 47%, which is caused by the reduced probability of offsite power recovery failure according to increase of allowed offsite power recovery time. As a future work, it is needed to estimate the effect of the number of time intervals for the AAC-DG running failure. AAC-DG affects core damage when EDGs fail to start (SBOS), and therefore it is also necessary to examine the effect of running failure time of the AAC-DG after SBOS happens.

Table V: Results of case studies

w/o AAC-DG	CDF (SBOR)	Reduction Rate	with AAC-DG	CDF (SBOR)	Reduction Rate
Original	1.42 E-06				
Case1	1.02 E-06	28.29%	Case 1_1	7.58 E-07	46.77%
Case2	1.01 E-06	28.81%	Case 2_1	7.55 E-07	46.94%
Case3	1.01 E-06	29.07%	Case 3_1	7.54 E-07	47.05%
Case4	1.01 E-06	29.31%	Case 4_1	7.53 E-07	47.13%

4. Conclusions

The effect of offsite power recovery time was estimated based on cutset analysis under SBO event induced by the EDGs and AAC-DG running failure. The first step of the approach is obtaining the significant cutsets and classifying them into various failure types according to failure modes of EDGs and AAC-DG. After that, time intervals are defined by dividing 24 hours into equal parts to consider various EDGs and AAC-DG running failure times. The failure times of EDGs and AAC-DG are decided at each interval, and allowed offsite power recovery time and its failure probability are estimated. The probabilities of cutsets are recalculated by using the time fractions assigned to each time interval. Through case studies using a multi-unit PSA model, it was confirmed that the division of EDGs and AAC-DG running failure time into some intervals reduced the CDF, whereas the number of intervals is negligible to CDF.

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