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다중호기 원전에서 공유 대체교류전원 영향 평가 방법 개발

Development of a Method to Evaluate Shared Alternate AC Power Source Effects in Multi-Unit Nuclear Power Plants

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본 보고서를 2003년도 "위험도 정보 활용 기반 기술 개발"에 관한 기술 보고서로 제출합니다.

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요약문

공유 대체교류전원(Shared alternate AC (AAC) power source)을 가진 다중호기 원전의 발전소정전사고(Station blackout, SBO) 빈도를 적절히 평가하기 위해, 여러 호기에서 동시에 외부전원상실사고(Loss of offsite power, LOOP)시 호기간의 대체교류전원의 복잡한 상호의존성을 고려할 수 있는 방법을 개발하였다. 2호기와 4호기를 가진 원전 각각에 대한 발전소정전사고 빈도 계산 방법을 유도하였고 N호기를 가진 다중호기 원전에 대한 일반식을 유도하였다. 또한 2호기의 경우에 대해 발전소정전사고 빈도 계산을 수행하였다.

다중호기간의 상호의존성이 적절히 모델되지 않을 경우 발전소정전사고 빈도가 저평가 될 수 있고, 공유 대체교류전원과 비상전원의 비상디젤발전기들 사이의 공통원인고장(Common cause failure, CCF)의 특성에 따라 이 상호의존성이 발전소정전사고 빈도에 크게 영향을 미칠 수 있음을 본 연구에서 보여주었다.

공유 대체교류전원을 가진 다중호기 원전의 발전소정전사고 빈도와 이에 의한 노심손상 빈도를 본 연구의 방법으로 효율적으로 계산할 수 있다. 또한 본 연구의 방법은 다중호기의 일반 공유기기의 신뢰도 평가에 확대 적용될 수 있다.

Summary

In order to evaluate accurately a station blackout (SBO) event frequency of a multi-unit nuclear power plant that has a shared alternate AC (AAC) power source, an approach has been developed which accommodates the complex inter-unit behavior of the shared AAC power source under multi-unit loss of offsite power (LOOP) conditions. The approach is illustrated for two cases, 2 units and 4 units at a single site, and generalized for a multi-unit site. Furthermore, the SBO frequency of the first unit of the 2-unit site is quantified.

The SBO frequency at a target unit of probabilistic safety assessment (PSA) could be underestimated if the inter-unit dependency of the shared AAC power source is not properly modeled. The effect of the inter-unit behavior of the shared AAC power source on the SBO frequency is not negligible depending on the common cause failure (CCF) characteristics among AC power sources.

The methodology suggested in the present report is believed to be very useful in evaluating the SBO frequency and the core damage frequency resulting from the SBO event. This approach is also applicable to the probabilistic evaluation of the other shared systems in a multi-unit nuclear power plant.

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1. Introduction

There have been many issues to be solved when performing probabilistic safety assessments (PSA) of multi-unit nuclear power plants [1-3]. One of them is a shared alternate AC (AAC) power source that supplies electric power to any one of multiple units in order to reduce a potential station blackout (SBO) event upon a loss of offsite power (LOOP) event. An additional or swing emergency diesel generator (EDG) is installed to ensure an alternative AC power source as shown in Fig. 1. A brief calculation method [4] had been developed to evaluate the effects of the installation of the additional EDG, which is not based on fault tree technology.

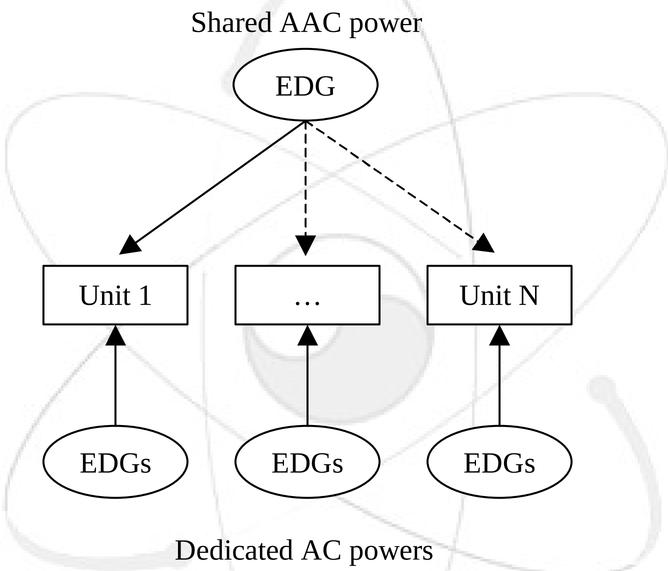


Fig. 1. AC power supply configuration

The LOOP event may occur at a single unit or at all units simultaneously. The complex inter-unit behavior of the shared AAC power source in case of the multi-unit LOOP event makes the probabilistic evaluation of the SBO event a significantly complicated task. The complexity exponentially increases according to the number of the multiple units in a nuclear power plant.

The SBO event has been considered as one of the accidents with a high potential that could lead to core damage in a nuclear power plant. In order to reduce the SBO event related core damage frequency, USNRC issued a regulatory guide requiring utilities to prove the safety of the nuclear power plant by either installing the AAC power source or detailed analysis [5]. As an AAC power source, an additional EDG has been installed in many nuclear power plants. It is a primary means to reduce the potential SBO event after the LOOP event. The additional EDG can supply an AC electric power to the selected Class 1E bus of any one of the multiple units through the realignment of pre-selected breakers. Typical examples of multi-unit nuclear power plants that have a swing EDG are

1. Yonggwang, Ulchin (in Korea), Shinpo (in North Korea), and Lungmen (in Taiwan) nuclear power plants in Asia, and
2. Surry, Zion, Arkansas Nuclear One, North Anna, Calvert Cliffs, and Hatch nuclear power plants in USA.

Some of the nuclear power plants in Asia are under construction. The multi-unit nuclear power plants are using an additional EDG as a shared AC power source among multiple units.

The SBO frequency could be underestimated if the inter-unit dependency of the shared AAC power source upon the simultaneous LOOP event at multiple units is not correctly modeled when performing the PSA of one of the multiple units. This results from ignoring the possibility that the AAC power source could be aligned to another unit and it is completely unavailable at the target unit of a probabilistic evaluation of the SBO event.

In this study, an appropriate method to evaluate accurately the amount of risk resulting from the SBO event of the multi-unit site has been developed. The approach is illustrated for two cases, 2 units and 4 units at a site, and generalized for the *n* multi-unit site in Section 2 where lots of multi-unit LOOP conditions are analyzed to get a general formula. Furthermore, the SBO frequency of the 2-unit site is quantified and the results are explained in Section 3.

2. Analysis Method

In order to develop formulae to quantify the SBO frequency of an *n*-unit site, let us define the followings:

SBO_i = station blackout event at unit *i*

L_i = LOOP event at unit *i* and no LOOP event at the other units

$L_{i_1 \ldots i_m}$ = simultaneous LOOP event at *m* units ($m<n$) and no LOOP event at the other units

$L_{i_1 \ldots i_n}$ = simultaneous LOOP event at all units

S = available or successful state

F = unavailable or failed state

(-) = indefinite state, that is, available or unavailable state

S_i = available dedicated AC power source, that is, at least one available EDG of unit *i*

F_i = unavailable dedicated AC power source of unit *i*

S_{AAC} = available AAC power source

F_{AAC} = unavailable AAC power source

T_i = i^{th} system state

$P(X)$ = probability of an event X

$F(X)$ = frequency of an event X

For example, L_{12} denotes the LOOP event which occurs at units 1 and 2 at the same time but no LOOP event occurs at the other units. A system state consists of AC power source states, that is, a shared AAC power source state and dedicated AC power source states successively. In case of a 2-unit site, the system state can be expressed in two ways as

$$S_{AAC}F_1F_2 = SFF\ . \tag{1}$$

That means the shared AAC power source is available and the dedicated AC power sources of units 1 and 2 are unavailable. The example of a system state with an indefinite state of a 4-unit site is as follows

$$P(S_{AAC}\ F_1F_3F_4) = P(SF\text{-}FF) = P(SFFFF \vee SFSFF) = P(SFFFF) + P(SFSFF) \tag{2}$$

where the system state $S_{AAC}F_1F_3F_4$ or *SF-FF* represents 2 disjoint (mutually exclusive) system states *SFFFF* and *SFSFF*. Similarly, the system state $S_{AAC}F_1F_4$ or *SF--F* denotes 4 disjoint system states *SFFFF, SFFSF, SFSFF,* and *SFSSF*.

2.1. 2-Unit Site

Let us consider a nuclear power plant that has 2 units. Each unit has 2 dedicated EDGs and the site has a shared AAC power source. All possible system states depending on all AC power source states are listed in Table 1.

For easy development of formulae, the following two LOOP events in Fig. 2 are analyzed

1. LOOP event at only unit 1 (no LOOP event at unit 2) L_1, and
2. LOOP event at both units L_{12}.

Table 1. SBO event dependency on system states (2 units/site, 2 EDGs/unit, 1 AAC/site)

System states						LOOP event at both units		LOOP event at only unit 1	
Index	AAC	DG1A	DG1B	DG2A	DG2B	AAC alignment	SBO event	AAC alignment	SBO event
T1	S	S	S	S	S	-	-	-	-
T2	S	S	S	S	F	-	-	-	-
T3	S	S	S	F	S	-	-	-	-
T4	S	S	S	F	F	2	-	-	-
T5	S	S	F	S	S	-	-	-	-
T6	S	S	F	S	F	-	-	-	-
T7	S	S	F	F	S	-	-	-	-
T8	S	S	F	F	F	2	-	-	-
T9	S	F	S	S	S	-	-	-	-
T10	S	F	S	S	F	-	-	-	-
T11	S	F	S	F	S	-	-	-	-
T12	S	F	S	F	F	2	-	-	-
T13	S	F	F	S	S	1	-	1	-
T14	S	F	F	S	F	1	-	1	-
T15	S	F	F	F	S	1	-	1	-
T16	S	F	F	F	F	2(a), 1(b)	SBO1(a), SBO2(b)	1	-
T17	F	S	S	S	S	-	-	-	-
T18	F	S	S	S	F	-	-	-	-
T19	F	S	S	F	S	-	-	-	-
T20	F	S	S	F	F	-	SBO2	-	-
T21	F	S	F	S	S	-	-	-	-
T22	F	S	F	S	F	-	-	-	-
T23	F	S	F	F	S	-	-	-	-
T24	F	S	F	F	F	-	SBO2	-	-
T25	F	F	S	S	S	-	-	-	-
T26	F	F	S	S	F	-	-	-	-
T27	F	F	S	F	S	-	-	-	-
T28	F	F	S	F	F	-	SBO2	-	-
T29	F	F	F	S	S	-	SBO1	-	SBO1
T30	F	F	F	S	F	-	SBO1	-	SBO1
T31	F	F	F	F	S	-	SBO1	-	SBO1
T32	F	F	F	F	F	-	SBO1, SBO2	-	SBO1

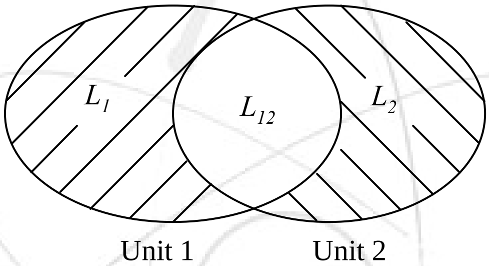
a AAC is aligned to unit 2 (conservative assumption)
b AAC is aligned to unit 1 (non-conservative assumption)
SBOn Station blackout event at unit n
DG1A(B) Electric power from DG1A(B) to bus A(B) at unit 1
DG2A(B) Electric power from DG2A(B) to bus A(B) at unit 2

S Success
F Fail
- Not applicable

For the analysis of the simultaneous LOOP event at both units L_{12}, the two following assumptions or cases are analyzed

1. The AAC power source is aligned to unit 2 (conservative assumption), and
2. The AAC power source is aligned to unit 1 (non-conservative assumption).

Here, the terms, conservative and non-conservative assumptions, are based on the fact that a target unit of the PSA is unit 1. The SBO frequency of unit 1 is underestimated if the inter-unit dependency of the shared AAC power source is ignored, especially in a multi-unit nuclear power plant that has no explicit emergency operational procedure as to how to select a unit to which the AAC power source is aligned in case of the simultaneous LOOP event at both units.



L_1 = LOOP at unit 1 and no LOOP at unit 2
L_2 = LOOP at unit 2 and no LOOP at unit 1
L_{12} = simultaneous LOOP at both units

Fig. 2. LOOP events for 2-unit site

Table 2. SBO event dependency on system states (2 units/site, 1 AAC/site)

System states				LOOP event at both units		LOOP event at only unit 1	
Index	AAC	AC1	AC2	AAC alignment	SBO event	AAC alignment	SBO event
T1	S	F	F	2(a), 1(b)	SBO1(a), SBO2(b)	1	-
T2	F	F	S	-	SBO1	-	SBO1
T3	F	F	F	-	SBO1, SBO2	-	SBO1

a AAC is aligned to unit 2 (conservative assumption)
b AAC is aligned to unit 1 (non-conservative assumption)
ACn Dedicated AC power at unit n
S Success
F Fail
\- Not applicable

In this Section, the target unit of the probabilistic evaluation of the SBO frequency is unit 1 and the conservative assumption is employed to avoid the underestimation of the SBO frequency of unit 1. Possible 32 system states depending on AC power sources are listed in

Table 1. 5 system states in Table 1 that might result in the SBO event at unit 1 could be simplified as 3 system states in Table 2. The states T_1 and T_3 in Table 2 are identical to the states T_{16} and T_{32} in Table 1, respectively, and the state T_2 in Table 2 represents the states T_{29}, T_{30}, and T_{31} in Table 1.

If a plant is in state T_1 in Table 2 when a LOOP event at only unit 1 occurs, the available AAC power source supplies electric power to unit 1. However, unit 1 has no available AC power source if the plant is in state T_2 or T_3 in Table 2. Hence, the SBO frequency of unit 1 for the LOOP event at only unit 1 is

$$\begin{aligned} & F(L_1) \times P(T_2 \vee T_3) \\ &= F(L_1) \times P(FFS \vee FFF) \\ &= F(L_1) \times P(FF\text{-}) \\ &= F(L_1) \times P(F_{AAC}F_1)\ . \end{aligned} \tag{3}$$

The SBO frequency of unit 1 for the LOOP event at both units is

$$\begin{aligned} & F(L_{12}) \times P(T_1 \vee T_2 \vee T_3) \\ &= F(L_{12}) \times P(SFF \vee FFS \vee FFF) \\ &= F(L_{12}) \times P(SFF \vee FF\text{-}) \\ &= F(L_{12}) \times \{P(S_{AAC}F_1\, F_2) + P(F_{AAC}F_1)\}\ . \end{aligned} \tag{4}$$

If the plant is in state T_1 in case of the simultaneous LOOP event at both units, unit 1 has no available power source since the AAC power source is aligned to unit 2. Furthermore, the AAC power source is unavailable if the plant is in state T_2 or T_3.

The SBO frequency of unit 1 is obtained by adding the SBO frequencies in Eqs. (3) and (4) as

$$\begin{aligned} & F(SBO_1) \\ &= F(L_1) \times P(F_{AAC}F_1) + F(L_{12}) \times \{ P(S_{AAC}F_1\, F_2) + P(F_{AAC}F_1) \} \\ &= \{ F(L_1) + F(L_{12}) \} \times P(F_{AAC}F_1) + F(L_{12}) \times P(S_{AAC}F_1\, F_2) \\ &= F(L_1 \vee L_{12}) \times P(F_{AAC}F_1) + F(L_{12}) \times P(S_{AAC}F_1\, F_2) \\ &= F(L) \times P(F_{AAC}F_1) + F(L_{12}) \times P(S_{AAC}F_1\, F_2) \qquad (5) \\ &\le F(L) \times P(F_{AAC}F_1) + F(L) \times P(S_{AAC}F_1\, F_2) \qquad (6) \end{aligned}$$

where the LOOP event, L, is a union of the disjoint LOOP events, L_1 and L_{12}, as

$$L = L_1 \vee L_{12}\ . \tag{7}$$

2.2. 4-Unit Site

Let us consider a nuclear power plant that has 4 units and a shared AAC power source. Table 3 has 15 possible system states that might result in a SBO event of unit 1 where the SBO events in case of a LOOP event at all units are illustrated. The system states are determined according to the states of the AC power sources, that is, the shared AAC power source and dedicated AC power sources. Table 3 is constructed based on conservative and non-conservative assumptions that are similar to the assumptions in Section 2.1 as

1. the AAC power source is aligned to the last unit that requires an alternate AC power (conservative assumption), and
2. unit 1 has the first opportunity to use the AAC power source (non-conservative assumption).

Table 3. SBO event dependency on system states (4 units/site, 1 AAC/site)

System states						LOOP event at all units	
Index	AAC	AC1	AC2	AC3	AC4	AAC alignment	SBO event
T1	S	F	S	S	F	4(a), 1(b)	SBO1(a),SBO4(b)
T2	S	F	S	F	S	3(a), 1(b)	SBO1(a),SBO3(b)
T3	S	F	S	F	F	4(a), 1(b)	SBO1(a),SBO3,SBO4(b)
T4	S	F	F	S	S	2(a), 1(b)	SBO1(a),SBO2(b)
T5	S	F	F	S	F	4(a), 1(b)	SBO1(a),SBO2,SBO4(b)
T6	S	F	F	F	S	3(a), 1(b)	SBO1(a),SBO2,SBO3(b)
T7	S	F	F	F	F	4(a), 1(b)	SBO1(a),SBO2,SBO3,SBO4(b)
T8	F	F	S	S	S	-	SBO1
T9	F	F	S	S	F	-	SBO1,SBO4
T10	F	F	S	F	S	-	SBO1,SBO3
T11	F	F	S	F	F	-	SBO1,SBO3,SBO4
T12	F	F	F	S	S	-	SBO1,SBO2
T13	F	F	F	S	F	-	SBO1,SBO2,SBO4
T14	F	F	F	F	S	-	SBO1,SBO2,SBO3
T15	F	F	F	F	F	-	SBO1,SBO2,SBO3,SBO4

a AAC is aligned to the failed last unit (conservative assumption)
b AAC is aligned to unit 1 (non-conservative assumption)
ACn Dedicated AC power at unit n
SBOn Station blackout event at unit n
S Success
F Fail
\- Not applicable

Let the target unit of the evaluation of the SBO frequency be unit 1 under the conservative assumption. The SBO frequency of unit 1 for the LOOP event at only unit 1 (no LOOP event at the other units) is

$$F(L_1) \times P(T_8 \vee \ldots \vee T_{15}) = F(L_1) \times P(FF\text{---}) \quad (8)$$

where the system state *FF---* represents the 8 disjoint system states T_8 to T_{15}.

The SBO frequency at unit 1 for the simultaneous LOOP event at units 1 and 2 (no LOOP event at the remaining units) is

$$F(L_{12}) \times P(T_4 \vee T_5 \vee T_6 \vee T_7 \vee T_8 \vee \ldots \vee T_{15})$$
$$= F(L_{12}) \times P(T_4 \vee T_5 \vee T_6 \vee T_7 \vee FF\text{---})\ . \qquad (9)$$

The SBO event at unit 1 occurs in case of the simultaneous LOOP event at units 1 and 2 when the system is in one of the system states T_4 to T_{15} in Table 3. If the system is in one of the system states T_4 to T_7, there is no available AC power source at unit 1 since the dedicated AC power source of unit 1 is unavailable and the available AAC power source is aligned to unit 2 (conservative assumption). If the system is in one of the states T_8 to T_{15}, unit 1 has no available power source since the dedicated AC power source of unit 1 and the shared AAC power source are unavailable.

Similarly, the SBO frequencies for the simultaneous LOOP event at unit 1 and another unit (no LOOP event at the other units) are

$$F(L_{13}) \times P(T_2 \vee T_3 \vee T_6 \vee T_7 \vee T_8 \vee \ldots \vee T_{15})$$
$$= F(L_{13}) \times P(T_2 \vee T_3 \vee T_6 \vee T_7 \vee FF\text{---}) \qquad (10)$$

$$F(L_{14}) \times P(T_1 \vee T_3 \vee T_5 \vee T_7 \vee T_8 \vee \ldots \vee T_{15})$$
$$= F(L_{14}) \times P(T_1 \vee T_3 \vee T_5 \vee T_7 \vee FF\text{---})\ . \qquad (11)$$

The SBO frequencies for the simultaneous LOOP event at three units, that is, at unit 1 and another two units (no LOOP event at the remaining unit) are

$$F(L_{123}) \times P(T_2 \vee T_3 \vee T_4 \vee T_5 \vee T_6 \vee T_7 \vee T_8 \vee \ldots \vee T_{15})$$
$$= F(L_{123}) \times P(T_2 \vee T_3 \vee T_4 \vee T_5 \vee T_6 \vee T_7 \vee FF\text{---}) \qquad (12)$$

$$F(L_{124}) \times P(T_1 \vee T_3 \vee T_4 \vee T_5 \vee T_6 \vee T_7 \vee T_8 \vee \ldots \vee T_{15})$$
$$= F(L_{124}) \times P(T_1 \vee T_3 \vee T_4 \vee T_5 \vee T_6 \vee T_7 \vee FF\text{---}) \qquad (13)$$

$$F(L_{134}) \times P(T_1 \vee T_2 \vee T_3 \vee T_5 \vee T_6 \vee T_7 \vee T_8 \vee \ldots \vee T_{15})$$

$$= F(L_{134}) \times P(T_1 \vee T_2 \vee T_3 \vee T_5 \vee T_6 \vee T_7 \vee FF\text{---}) \ . \quad (14)$$

The SBO frequency of unit 1 for the LOOP event at all units is

$$F(L_{1234}) \times P(T_1 \vee T_2 \vee \ldots \vee T_7 \vee T_8 \vee \ldots \vee T_{15})$$
$$= F(L_{1234}) \times P(T_1 \vee T_2 \vee \ldots \vee T_7 \vee FF\text{---}) \ . \quad (15)$$

Since the SBO frequency of unit 1 is the sum of all SBO frequencies in Eqs. (8) to (15), it could be obtained by arranging the added SBO frequencies in Eqs. (8) to (15) as

$$\begin{aligned}
&F(SBO_1) \\
&= F(L) \times P(FF\text{---}) \\
&+ F(L_{14} \vee L_{124} \vee L_{134} \vee L_{1234}) \times P(T_1) \\
&+ F(L_{13} \vee L_{123} \vee L_{134} \vee L_{1234}) \times P(T_2) \\
&+ F(L_{13} \vee L_{14} \vee L_{123} \vee L_{124} \vee L_{134} \vee L_{1234}) \times P(T_3) \\
&+ F(L_{12} \vee L_{123} \vee L_{124} \vee L_{1234}) \times P(T_4) \\
&+ F(L_{12} \vee L_{14} \vee L_{123} \vee L_{124} \vee L_{134} \vee L_{1234}) \times P(T_5) \\
&+ F(L_{12} \vee L_{13} \vee L_{123} \vee L_{124} \vee L_{134} \vee L_{1234}) \times P(T_6) \\
&+ F(L_{12} \vee L_{13} \vee L_{14} \vee L_{123} \vee L_{124} \vee L_{134} \vee L_{1234}) \times P(T_7) \qquad (16)
\end{aligned}$$

$$\begin{aligned}
&\leq F(L) \times P(FF\text{---}) + F(L) \times P(T_1 \vee T_2 \vee \ldots \vee T_7) \\
&= F(L) \times P(FF\text{---}) + F(L) \times P(SFSSF \vee SFSF\text{-} \vee SFF\text{--}) \qquad (17) \\
&\leq F(L) \times P(FF\text{---}) + F(L) \times P(SF\text{--}F \vee SF\text{-}F\text{-} \vee SFF\text{--})\} \\
&= F(L) \times P(F_{AAC}F_1) + F(L) \times \{ P(S_{AAC}F_1F_2) + P(S_{AAC}F_1F_3) + P(S_{AAC}F_1F_4) \} \qquad (18)
\end{aligned}$$

where the LOOP event, L, is a union of disjoint events as follows

$$L = L_1 \vee L_{12} \vee L_{13} \vee L_{14} \vee L_{123} \vee L_{124} \vee L_{134} \vee L_{1234} \ . \quad (19)$$

and the system states T_1 to T_{15} are disjoint one another.

2.3. N-Unit Site

By generalizing the results in Sections 2.1 and 2.2, the SBO frequency of unit i is inducted as

$$F(SBO_i) \le F(L) \times P(F_{AAC}F_i) + F(L) \times \sum_{j \ne i} P(S_{AAC}F_i\, F_j) \quad (20)$$

where $P(F_{AAC}F_i)$ denotes the system state probability of an unavailable shared AAC power source and an unavailable AC power source of unit i. $P(S_{AAC}F_iF_j)$ indicates the probability of an available AAC power source and unavailable AC power sources of units i and j. By multiplying the conditional core damage probability of SBO event $CCDP_{SBO}$ to Eq. (20), the core damage frequency resulting from the SBO event could be conservatively evaluated as

$$CDF(SBO_i) \le F(L) \times \{ P(F_{AAC}F_i) + \sum_{j \ne i} P(S_{AAC}F_i\, F_j) \} \times CCDP_{SBO}\,. \quad (21)$$

Table 4. Main data [6]

LOOP frequency (number/year), $F(L)$	6.15E-02
EDG failure to start (demand failure), Q_t	1.40E-02

Table 5. MGL parameters for CCF of EDG failure to start [7]

MGL parameters	Common cause component group		
	m =2	m =4	m =5
$1-\beta$	9.69E-01	9.64E-01	9.64E-01
$\beta\ (\rho_1)$	3.12E-02	3.63E-02	3.65E-02
$\gamma\ (\rho_2)$		6.27E-01	6.65E-01
$\delta\ (\rho_3)$		5.01E-01	6.56E-01
$\varepsilon\ (\rho_4)$			5.61E-01

where $Q_k = \frac{1}{{}_{m-1}C_{k-1}} \times \prod_{i=1}^{k} \rho_i \times (1-\rho_{k+1}) \times Q_t$ and $\rho_{m+1} = 0$

3. Application

The SBO frequency of the first unit of a 2-unit site is quantified. The site has 5 EDGs, that is, each unit has 2 EDGs and the site has a shared additional EDG as an AAC power source. The fault trees for the SBO frequency in Eq. (6) or (20) are developed as shown in Figs. 3 through 5. The basic fault trees and event data are from Ulchin Unit 3&4 PSA report [6]. The main data are listed in Tables 4 and 5. The AAC power source is connected to Class 1E bus B of units 1 and 2 as shown in Fig. 5.(c). The following three cases of a common cause failure (CCF) group are evaluated:

1. one CCF group of 5 EDGs, {DG1A, DG1B, DG2A, DG2B, AAC},
2. one CCF group of 4 EDGs, {DG1A, DG1B, DG2A, DG2B}, and
3. two CCF groups of 4 EDGs, {DG1A, DG1B} and {DG2A, DG2B}.

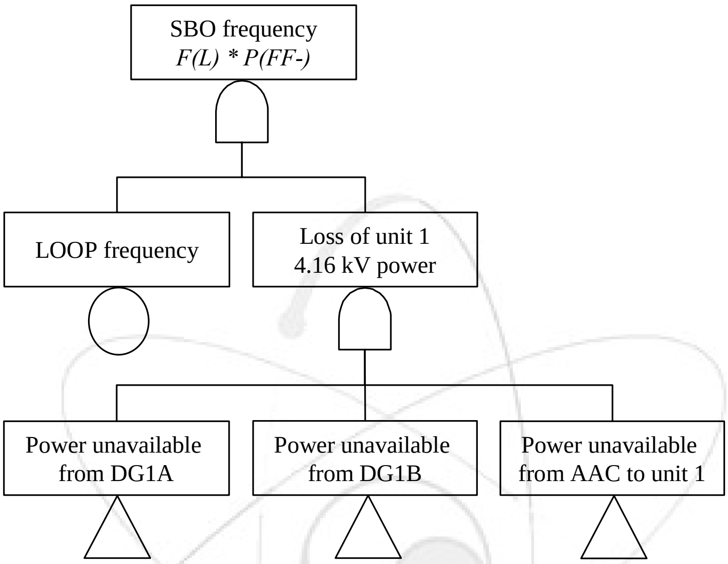


Fig. 3. Fault tree for SBO frequency (*F(L)* × *P(FF-)*)

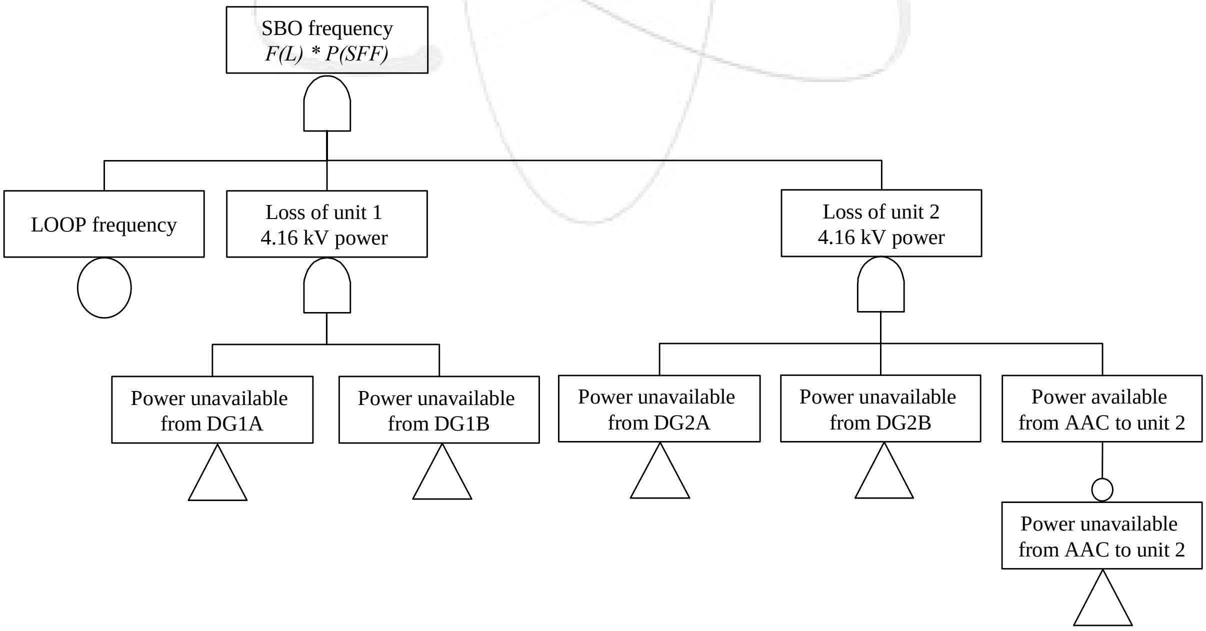
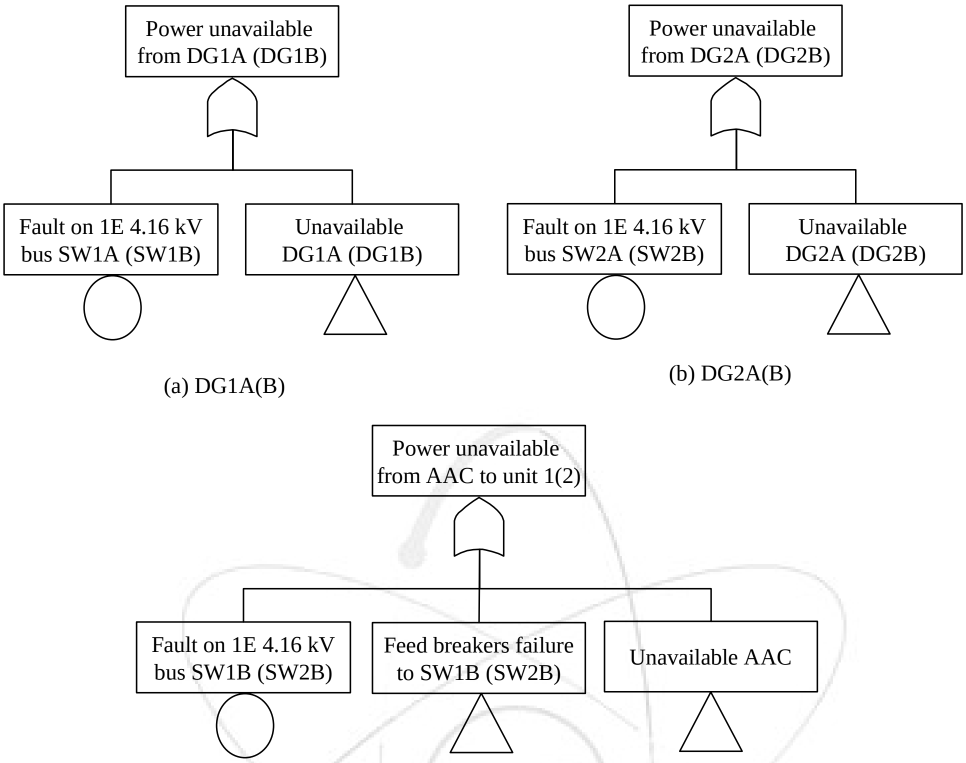


Fig. 4. Fault tree for SBO frequency (*F(L)* × *P(SFF)*)



(a) DG1A(B) (b) DG2A(B)

(c) AAC

Fig. 5. Fault trees for AC power sources

The CCF quantities are calculated using the multiple Greek letter (MGL) method. The MGL data for CCF of EDGs in Table 5 are from Ref. [7]. Common cause component groups, m=5, m=4, and m=2 in Table 5, are for Cases 1, 2, and 3, respectively. The CCF group depends on the plant-specific design and operational characteristics. Normally, the AAC power supply is totally independent of the offsite and onsite power sources. The AAC power source is electrically, physically, mechanically, and environmentally isolated from the offsite and onsite power sources. The AAC power source is protected against the effects of weather-related events that may initiate the loss of offsite power events. Therefore, the CCF groups of Cases 2 and 3 are more realistic than that of Case 1.

The calculation is performed using fault tree quantifiers [8,9]. The results are summarized in Table 6 and depicted in Fig. 6. For the exact evaluation of the negate for the available AAC power source in the fault tree $F(L) \times P(S_{AAC}F_1F_2)$ in Fig. 4, no approximation method such as the delete-term procedure (See Appendix A) is used. As shown in Table 6, if Cases 1 and 2 have no AAC power source, they are identical.

The installation of the AAC power source in Case 3 significantly reduces the SBO frequency. That is, it is the most effective way to reduce the potential SBO event in Case 3. Furthermore, Case 3 has the least total SBO frequency, $F(L) \times P(F_{AAC}F_1)$ and $F(L) \times P(S_{AAC}F_1F_2)$, approximately 15 percent of the SBO frequency of Case 1.

Even though Cases 1 and 2 have comparable total SBO frequencies, $F(L) \times P(F_{AAC}F_1)$ and $F(L) \times P(S_{AAC}F_1F_2)$ are dominant in Cases 1 and 2, respectively. Since the SBO frequency $F(L) \times P(S_{AAC}F_1F_2)$ of Case 3 is negligible, its probabilistic modeling and evaluation could be ignored. However, it should be quantified in Cases 1 and 2 since the total SBO frequency is underestimated if $F(L) \times P(S_{AAC}F_1F_2)$ is ignored.

If a plant has CCF group characteristics like Cases 1 and 2, the probabilistic evaluation of $F(L) \times P(S_{AAC}F_1F_2)$ should be performed. It is desirable that the CCF group such as Case 3 be obtained and maintained since it has a negligible $F(L) \times P(S_{AAC}F_1F_2)$ and the smallest amount of $F(L) \times P(F_{AAC}F_1)$.

Table 6. SBO frequencies (number/year)

Cases of CCF group	AAC			No AAC	Ratio	
	a	b	c	d	b/a	c/d
1. {DG1A,DG1B,DG2A,DG2B,AAC}	1.338E-05	1.533E-06	1.491E-05	4.881E-05	0.11	0.31
2. {DG1A,DG1B,DG2A,DG2B}	1.868E-06	9.642E-06	1.151E-05	4.881E-05	5.16	0.24
3. {DG1A,DG1B}, {DG2A,DG2B}	2.147E-06	3.563E-08	2.183E-06	4.789E-05	0.02	0.05

a. $F(L) \times P(F_{AAC}F_1)=F(L) \times P(FF\text{-})$

b. $F(L) \times P(S_{AAC}F_1F_2)=F(L) \times P(SFF)$

c. $F(L) \times P(F_{AAC}F_1)+F(L) \times P(S_{AAC}F_1F_2)=F(L) \times P(FF\text{-})+F(L) \times P(SFF)$

d. SBO frequency (no AAC)

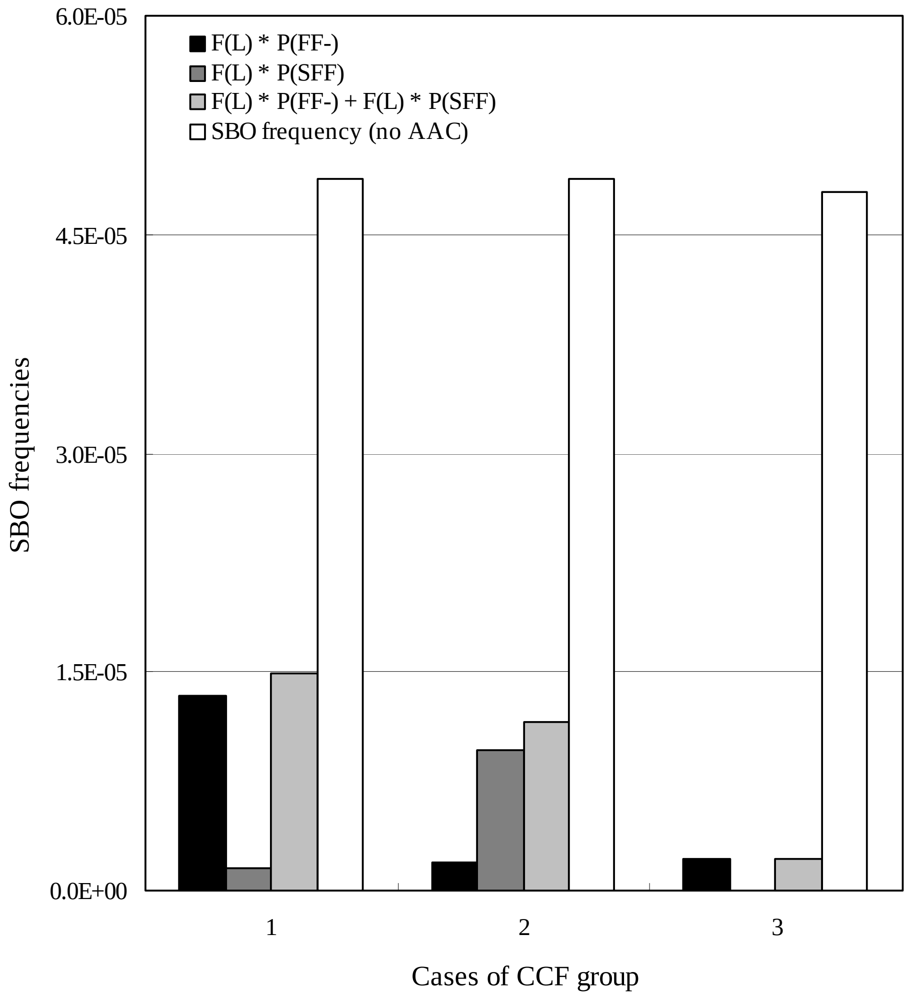


Fig. 6. SBO frequencies (number/year)

4. Conclusions

An approach has been developed in this study in order to describe the inter-unit behavior of the AAC power source of a multiple-unit site upon the simultaneous multi-unit LOOP event. The SBO frequency could be quantified by this approach that incorporates the complex inter-unit behavior of the shared AAC power source under multi-unit LOOP conditions. The effect of the inter-unit behavior of the shared AAC power source on the SBO frequency is not negligible depending on the CCF characteristics among AC power sources.

It is strongly recommended that the desirable CCF characteristics among AC power sources such as Case 3 in Section 3 be obtained and maintained through the design, installation, test, and maintenance process of EDGs.

The methodology in the present report could be employed with a little effort in evaluating the SBO frequency and the SBO related core damage frequency. Furthermore, it could be applied to the probabilistic evaluation of the other shared systems in a multi-unit nuclear power plant.

Appendix A. Delete-term procedure

The quantification of the fault tree that has negates is a very time consuming work. If an example fault tree is expressed as

$$TOP = G_1\overline{G}_2$$
$$G_1 = ABC + ACD + BCD$$
$$G_2 = AB + AC \ ,$$

then the solution is

$$\begin{aligned} TOP &= (ABC + ACD + BCD)\overline{(AB + AC)} \\ &= (ABC + ACD + BCD)(\overline{A} + \overline{B})(\overline{A} + \overline{C}) \\ &= (ABC + ACD + BCD)(\overline{A} + \overline{A}\overline{B} + \overline{A}\overline{C} + \overline{B}\overline{C}) \\ &= (ABC + ACD + BCD)(\overline{A} + \overline{B}\overline{C}) \\ &= (ABC + ACD + BCD)(\overline{A} + \overline{B}\overline{C}) \\ &= \overline{A}BCD \end{aligned}$$

where DeMorgan's law is applied when expanding the Boolean equation $\overline{(AB + AC)}$, $\overline{A}\overline{B}$ and $\overline{A}\overline{C}$ are deleted at the intermediate stage since they are subsets of $\overline{A}$, and impossible states such as $A\overline{A}BC$ and $AB\overline{B}C\overline{C}$ are also deleted at the final stage.

Instead of the complex Boolean algebra, the delete-term procedure as a simple approximation method is used in the conventional PSA. The top event is on the assumption of the failed gate G_1 and the successful gate G_2 ($TOP = G_1\overline{G}_2$). Cut sets ABC and ACD of the failed gate G_1 make G_2 failed ($G_2 = AB + AC$). Since the two cut sets violate the assumption of the successful gate G_2, they are deleted. Finally, the cut set BCD remains as follows:

$$TOP = (ABC + ACD + BCD)\overline{(AB + AC)} \cong BCD \ .$$

Thus, cut sets of the failed gate are deleted if they violate the assumption of the successful state of the other gate.

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서 지 정 보 양 식

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연구자 및 부서명	양준언 (종합안전평가부)

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초록

공유 대체교류전원(Shared alternate AC (AAC) power source)을 가진 다중호기 원전의 발전소정전사고(Station blackout, SBO) 빈도를 적절히 평가하기 위해, 여러 호기에서 동시에 외부전원상실사고(Loss of offsite power, LOOP)시 호기간의 대체교류전원의 복잡한 상호의존성을 고려할 수 있는 방법을 개발하였다. 2호기와 4호기를 가진 원전 각각에 대한 발전소정전사고 빈도 계산 방법을 유도하였고 N호기를 가진 다중호기 원전에 대한 일반식을 유도하였다. 또한 2호기의 경우에 대해 발전소정전사고 빈도 계산을 수행하였다.

다중호기간의 상호의존성이 적절히 모델되지 않을 경우 발전소정전사고 빈도가 저평가 될 수 있고, 공유 대체교류전원과 비상전원의 비상디젤발전기들 사이의 공통원인고장(Common cause failure, CCF)의 특성에 따라 이 상호의존성이 발전소정전사고 빈도에 크게 영향을 미칠 수 있음을 본 연구에서 보여주었다.

공유 대체교류전원을 가진 다중호기 원전의 발전소정전사고 빈도와 이에 의한 노심손상 빈도를 본 연구의 방법으로 효율적으로 계산할 수 있다. 또한 본 연구의 방법은 다중호기의 일반 공유기기의 신뢰도 평가에 확대 적용될 수 있다.

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Abstract					

In order to evaluate accurately a station blackout (SBO) event frequency of a multi-unit nuclear power plant that has a shared alternate AC (AAC) power source, an approach has been developed which accommodates the complex inter-unit behavior of the shared AAC power source under multi-unit loss of offsite power (LOOP) conditions. The approach is illustrated for two cases, 2 units and 4 units at a single site, and generalized for a multi-unit site. Furthermore, the SBO frequency of the first unit of the 2-unit site is quantified.

The SBO frequency at a target unit of probabilistic safety assessment (PSA) could be underestimated if the inter-unit dependency of the shared AAC power source is not properly modeled. The effect of the inter-unit behavior of the shared AAC power source on the SBO frequency is not negligible depending on the common cause failure (CCF) characteristics among AC power sources.

The methodology suggested in the present report is believed to be very useful in evaluating the SBO frequency and the core damage frequency resulting from the SBO event. This approach is also applicable to the probabilistic evaluation of the other shared systems in a multi-unit nuclear power plant.

Subject Keywords	Alternate AC power source, Station blackout, Loss of offsite power, Multi-unit nuclear power plant