An Approach to Evaluate Alternate AC Power Source Effects on SBO Events in Multi-Unit Nuclear Power Plants

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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 SBO event 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 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 event frequency of the first unit of the 2-unit site is quantified. The methodology suggested in the present paper is believed to be very useful in evaluating the SBO event 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.

1. Introduction

There have been many issues to be solved when performing probabilistic safety assessments (PSA) of multi-unit nuclear power plants [1,2]. One of them is a shared alternate AC (AAC) power source that supplies electric power to any one of the 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 [3] had been developed to evaluate the effects of the installation of the additional EDG, which is not based on fault tree technology.

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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 increases significantly proportionally to the number of 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 [4]. 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 AC electric power to the selected Class 1E bus of any one of the multiple units through the realignment of pre-selected breakers.

The SBO event 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 event 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 event 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

$P(X)$ = 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

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

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

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 event 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.

In this Section, the target unit of the probabilistic evaluation of the SBO event frequency is unit 1

and the conservative assumption is employed to avoid the underestimation of the SBO event 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 S_1 and S_3 in Table 2 are identical to the states S_{16} and S_{32} in Table 1, respectively, and the state S_2 in Table 2 represents the states S_{29}, S_{30}, and S_{31} in Table 1.

If a plant is in state S_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 S_2 or S_3 in Table 2. Hence, the SBO event frequency of unit 1 for the LOOP event at only unit 1 is

$$F(L_1) \times P(S_2 \vee S_3)$$
$$= F(L_1) \times P(FFS \vee FFF)$$
$$= F(L_1) \times P(FF\text{-})$$
$$= F(L_1) \times P(F_{AAC}F_1) \,. \tag{3}$$

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

$$F(L_{12}) \times P(S_1 \vee S_2 \vee S_3)$$
$$= F(L_{12}) \times P(SFF \vee FFS \vee FFF)$$
$$= F(L_{12}) \times P(SFF \vee FF\text{-})$$
$$= F(L_{12}) \times \{ P(S_{AAC}F_1 F_2) + P(F_{AAC}F_1) \} \,. \tag{4}$$

If the plant is in state S_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 S_2 or S_3.

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

$$F(SBO_1)$$
$$= F(L_1) \times P(F_{AAC}F_1) + F(L_{12}) \times \{ P(S_{AAC}F_1 F_2) + P(F_{AAC}F_1) \}$$
$$= \{ F(L_1) + F(L_{12}) \} \times P(F_{AAC}F_1) + F(L_{12}) \times P(S_{AAC}F_1 F_2)$$
$$= F(L_1 \vee L_{12}) \times P(F_{AAC}F_1) + F(L_{12}) \times P(S_{AAC}F_1 F_2)$$
$$= F(L) \times P(F_{AAC}F_1) + F(L_{12}) \times P(S_{AAC}F_1 F_2) \tag{5}$$
$$\leq F(L) \times P(F_{AAC}F_1) + F(L) \times P(S_{AAC}F_1 F_2) \tag{6}$$

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).

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

$$F(L_1) \times P(S_8 \vee \ldots \vee S_{15}) = F(L_1) \times P(FF\text{---}) \tag{8}$$

where the system state $FF\text{---}$ represents the 8 disjoint system states S_8 to S_{15}.

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

$$F(L_{12}) \times P(S_4 \vee S_5 \vee S_6 \vee S_7 \vee S_8 \vee \ldots \vee S_{15})$$
$$= F(L_{12}) \times P(S_4 \vee S_5 \vee S_6 \vee S_7 \vee FF\text{---}) . \tag{9}$$

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 S_4 to S_{15} in Table 3. If the system is in one of the system states S_4 to S_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 S_8 to S_{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 event frequencies for the simultaneous LOOP event at unit 1 and another unit (no LOOP event at the other units) are

$$F(L_{13}) \times P(S_2 \vee S_3 \vee S_6 \vee S_7 \vee S_8 \vee \ldots \vee S_{15})$$
$$= F(L_{13}) \times P(S_2 \vee S_3 \vee S_6 \vee S_7 \vee FF\text{---}) \tag{10}$$

$$F(L_{14}) \times P(S_1 \vee S_3 \vee S_5 \vee S_7 \vee S_8 \vee \ldots \vee S_{15})$$
$$= F(L_{14}) \times P(S_1 \vee S_3 \vee S_5 \vee S_7 \vee FF\text{---}) . \tag{11}$$

The SBO event 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

$$F(L_{123}) \times P(S_2 \vee S_3 \vee S_4 \vee S_5 \vee S_6 \vee S_7 \vee S_8 \vee \ldots \vee S_{15})$$

$$= F(L_{123}) \times P(S_2 \vee S_3 \vee S_4 \vee S_5 \vee S_6 \vee S_7 \vee FF\text{---}) \tag{12}$$

$$F(L_{124}) \times P(S_1 \vee S_3 \vee S_4 \vee S_5 \vee S_6 \vee S_7 \vee S_8 \vee \ldots \vee S_{15})$$
$$= F(L_{124}) \times P(S_1 \vee S_3 \vee S_4 \vee S_5 \vee S_6 \vee S_7 \vee FF\text{---}) \tag{13}$$

$$F(L_{134}) \times P(S_1 \vee S_2 \vee S_3 \vee S_5 \vee S_6 \vee S_7 \vee S_8 \vee \ldots \vee S_{15})$$
$$= F(L_{134}) \times P(S_1 \vee S_2 \vee S_3 \vee S_5 \vee S_6 \vee S_7 \vee FF\text{---}) . \tag{14}$$

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

$$F(L_{1234}) \times P(S_1 \vee S_2 \vee \ldots \vee S_7 \vee S_8 \vee \ldots \vee S_{15})$$
$$= F(L_{1234}) \times P(S_1 \vee S_2 \vee \ldots \vee S_7 \vee FF\text{---}) . \tag{15}$$

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

$$F(SBO_1)$$
$$= F(L) \times P(FF\text{---})$$
$$+ F(L_{14} \vee L_{124} \vee L_{134} \vee L_{1234}) \times P(S_1)$$
$$+ F(L_{13} \vee L_{123} \vee L_{134} \vee L_{1234}) \times P(S_2)$$
$$+ F(L_{13} \vee L_{14} \vee L_{123} \vee L_{124} \vee L_{134} \vee L_{1234}) \times P(S_3)$$
$$+ F(L_{12} \vee L_{123} \vee L_{124} \vee L_{1234}) \times P(S_4)$$
$$+ F(L_{12} \vee L_{14} \vee L_{123} \vee L_{124} \vee L_{134} \vee L_{1234}) \times P(S_5)$$
$$+ F(L_{12} \vee L_{13} \vee L_{123} \vee L_{124} \vee L_{134} \vee L_{1234}) \times P(S_6)$$
$$+ F(L_{12} \vee L_{13} \vee L_{14} \vee L_{123} \vee L_{124} \vee L_{134} \vee L_{1234}) \times P(S_7) \tag{16}$$

$$\leq F(L) \times P(FF\text{---}) + F(L) \times P(S_1 \vee S_2 \vee \ldots \vee S_7)$$
$$= F(L) \times P(FF\text{---}) + F(L) \times P(SFSSF \vee SFSF\text{-} \vee SFF\text{--}) \tag{17}$$
$$\leq F(L) \times P(FF\text{---}) + F(L) \times P(SF\text{--}F \vee SF\text{-}F\text{-} \vee SFF\text{--})\}$$
$$= F(L) \times P(F_{AAC}F_1) + F(L) \times \{ P(S_{AAC}F_1F_2) + P(S_{AAC}F_1F_3) + P(S_{AAC}F_1F_4) \} \tag{18}$$

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

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

and the system states S_1 to S_{15} are disjoint one another.

2.3. N-Unit Site

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

$$F(SBO_i) \leq F(L) \times P(F_{AAC}F_i) + F(L) \times \sum_{j \neq i} P(S_{AAC}F_i\,F_j) \tag{20}$$

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 the SBO event $CCDP_{SBO}$ to Eq. (20), the core damage frequency resulting from the SBO event could be conservatively evaluated as

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

3. Application

The SBO event 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 event frequency in Eq. (6) or (20) are developed as shown in Figs. 3 through 5. The basic fault trees and event data are from the Ulchin Unit 3&4 PSA report [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}
3. two CCF groups of 4 EDGs {DG1A, DG1B}, {DG2A, DG2B}

The CCF quantities are calculated using the multiple Greek letter (MGL) method. The MGL data for CCF of EDGs in Ref. [6] are used. 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 [7,8]. The results are summarized in Table 4. 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 is used. As shown in Table 4, 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 event 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 event 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 event frequencies of Cases 1 and 2.

Even though Cases 1 and 2 have approximately similar total SBO event 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 event 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 event 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 $F(L) \times P(F_{AAC}F_1)$.

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 a simultaneous multi-unit LOOP event. The SBO event frequency could be quantified by the approach without losing any information.

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 paper could be employed with a little effort in evaluating the SBO event 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.

Acknowledgement

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

Index	AAC	DG1A	DG1B	DG2A	DG2B	AAC alignment (LOOP event at both units)	SBO event (LOOP event at both units)	AAC alignment (LOOP event at only unit 1)	SBO event (LOOP event at only unit 1)
S1	S	S	S	S	S	-	-	-	-
S2	S	S	S	S	F	-	-	-	-
S3	S	S	S	F	S	-	-	-	-
S4	S	S	S	F	F	2	-	-	-
S5	S	S	F	S	S	-	-	-	-
S6	S	S	F	S	F	-	-	-	-
S7	S	S	F	F	S	-	-	-	-
S8	S	S	F	F	F	2	-	-	-
S9	S	F	S	S	S	-	-	-	-
S10	S	F	S	S	F	-	-	-	-
S11	S	F	S	F	S	-	-	-	-
S12	S	F	S	F	F	2	-	-	-
S13	S	F	F	S	S	1	-	1	-
S14	S	F	F	S	F	1	-	1	-
S15	S	F	F	F	S	1	-	1	-
S16	S	F	F	F	F	2(a), 1(b)	SBO1(a), SBO2(b)	1	-
S17	F	S	S	S	S	-	-	-	-
S18	F	S	S	S	F	-	-	-	-
S19	F	S	S	F	S	-	-	-	-
S20	F	S	S	F	F	-	SBO2	-	-
S21	F	S	F	S	S	-	-	-	-
S22	F	S	F	S	F	-	-	-	-
S23	F	S	F	F	S	-	-	-	-
S24	F	S	F	F	F	-	SBO2	-	-
S25	F	F	S	S	S	-	-	-	-
S26	F	F	S	S	F	-	-	-	-
S27	F	F	S	F	S	-	-	-	-
S28	F	F	S	F	F	-	SBO2	-	-
S29	F	F	F	S	S	-	SBO1	-	SBO1
S30	F	F	F	S	F	-	SBO1	-	SBO1
S31	F	F	F	F	S	-	SBO1	-	SBO1
S32	F	F	F	F	F	-	SBO1, SBO2	-	SBO1

a AAC is aligned to unit 2 (conservative assumption)   S Success
b AAC is aligned to unit 1 (non-conservative assumption)   F Fail
SBOn Station blackout event at unit n   - Not applicable
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

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
S1	S	F	F	2(a), 1(b)	SBO1(a), SBO2(b)	1	-
S2	F	F	S	-	SBO1	-	SBO1
S3	F	F	F	-	SBO1, SBO2	-	SBO1

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

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
S1	S	F	S	S	F	4(a), 1(b)	SBO1(a),SBO4(b)
S2	S	F	S	F	S	3(a), 1(b)	SBO1(a),SBO3(b)
S3	S	F	S	F	F	4(a), 1(b)	SBO1(a),SBO3,SBO4(b)
S4	S	F	F	S	S	2(a), 1(b)	SBO1(a),SBO2(b)
S5	S	F	F	S	F	4(a), 1(b)	SBO1(a),SBO2,SBO4(b)
S6	S	F	F	F	S	3(a), 1(b)	SBO1(a),SBO2,SBO3(b)
S7	S	F	F	F	F	4(a), 1(b)	SBO1(a),SBO2,SBO3,SBO4(b)
S8	F	F	S	S	S	-	SBO1
S9	F	F	S	S	F	-	SBO1,SBO4
S10	F	F	S	F	S	-	SBO1,SBO3
S11	F	F	S	F	F	-	SBO1,SBO3,SBO4
S12	F	F	F	S	S	-	SBO1,SBO2
S13	F	F	F	S	F	-	SBO1,SBO2,SBO4
S14	F	F	F	F	S	-	SBO1,SBO2,SBO3
S15	F	F	F	F	F	-	SBO1,SBO2,SBO3,SBO4

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

Table 4. SBO event frequencies

CCF group	AAC			No AAC	Ratio	
	a	b	c	d	b/a	c/d
{DG1A,DG1B,DG2A,DG2B,AAC}	1.338E-05	1.533E-06	1.491E-05	4.881E-05	0.11	0.31
{DG1A,DG1B,DG2A,DG2B}	2.189E-06	1.230E-05	1.449E-05	4.881E-05	5.62	0.30
{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 $F(L) \times P(F_{AAC}F_1) + F(L) \times P(S_{AAC}F_1F_2) = F(L) \times P(FF\text{-}) + F(L) \times P(SFF)$
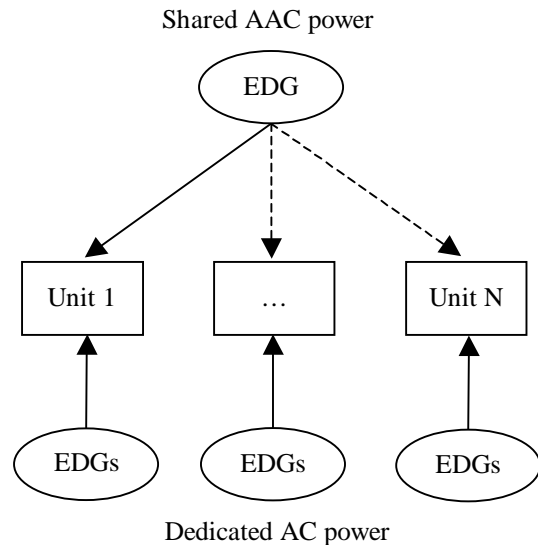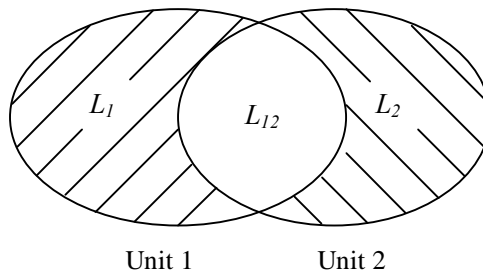
d SBO event frequency (no AAC)

Shared AAC power

EDG

Unit 1   …   Unit N

EDGs   EDGs   EDGs

Dedicated AC power

Fig. 1.   AC power supply configuration

L_1 L_{12} L_2

Unit 1   Unit 2

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
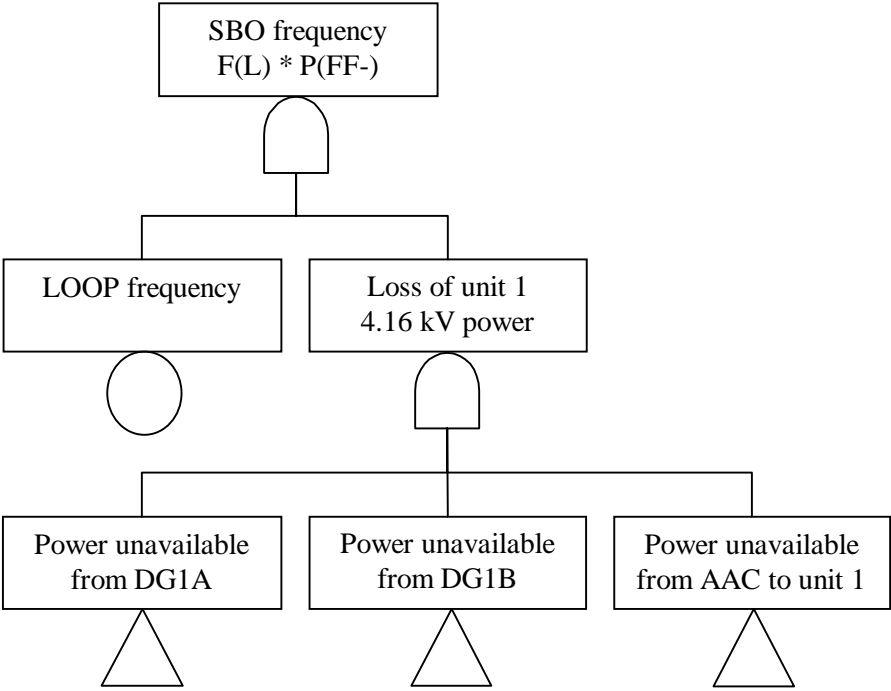
Fig. 2.   LOOP events for 2-unit site

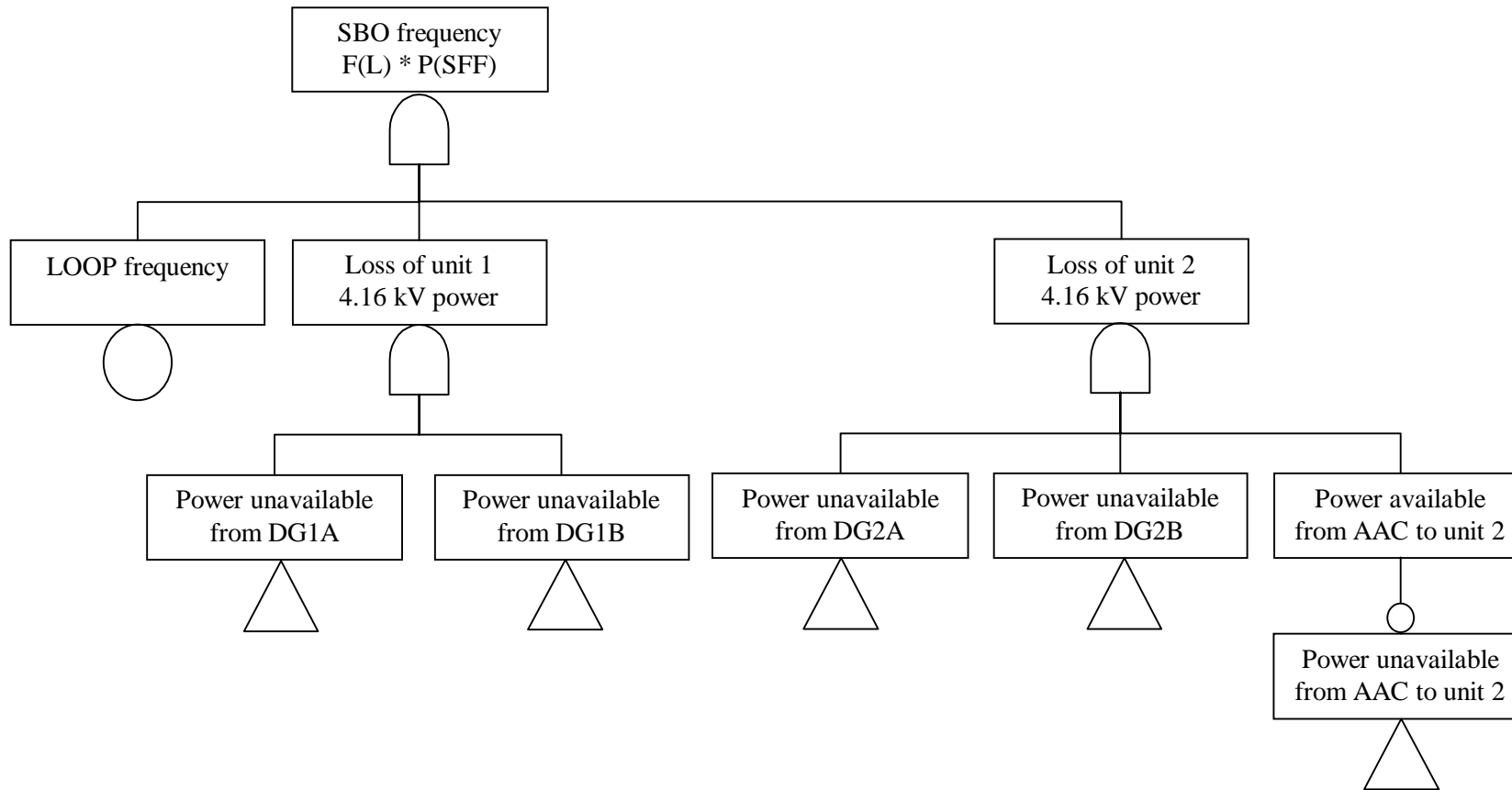**Fig. 3. Fault tree for SBO event frequency ($F(L) \times P(FF\text{-})$)**
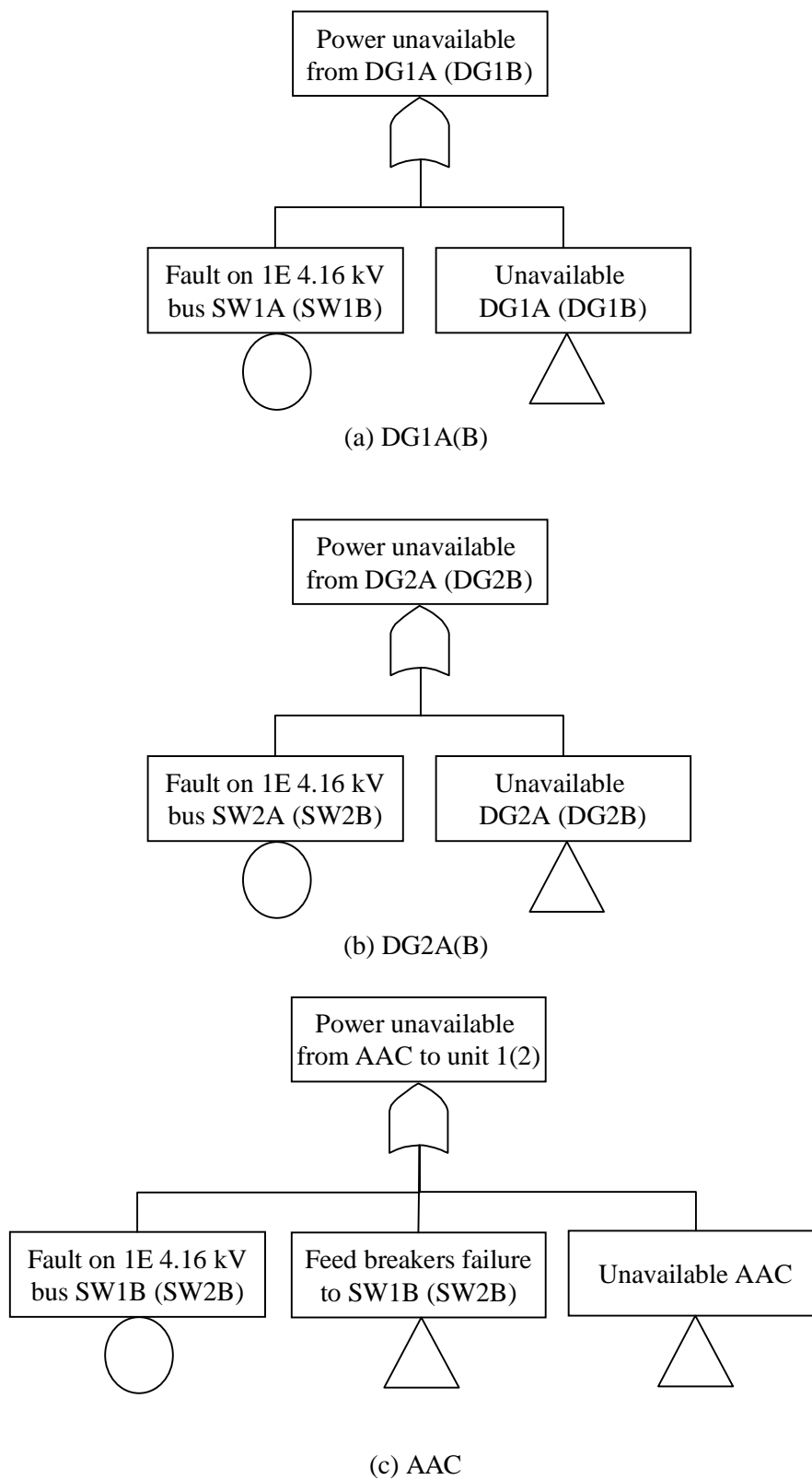
Fig. 4. **Fault tree for SBO event frequency** (***F(L)×P(SFF)***)

Fig. 5.   Fault trees for AC power sources