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Considering Variability in Battery Depletion Time for Conditional Core Damage Probability Calculation

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1. Introduction

Station blackout (SBO) is one of the most critical accident scenarios in probabilistic safety assessment (PSA) due to its high potential to cause core damage. SBO occurs when all emergency diesel generators (EDGs) become unavailable following a loss of offsite power (LOOP), making it impossible to supply emergency power. In such cases, alternative power sources are required to sustain decay heat removal through the secondary loop. The alternate alternating current diesel generator (AAC DG) and the turbine-driven pump (TDP) play essential roles in this process.

Among these, TDP operates using direct current (DC) power supplied by the Class-1E battery, a safety-related power source. Conventional PSA models typically assume a fixed battery depletion time (e.g., 4 hours) and set a predefined offsite power recovery time for scenario analysis [1]. However, this assumption does not fully account for the variability in battery depletion time caused by operator load-shedding actions, which can extend battery life by reducing power consumption.

To address this limitation, this study proposes a method for calculating the conditional core damage probability (CCDP) by treating operator load shedding time as a variable. The analysis is conducted in two stages. First, the non-recovery of AC power probability is estimated using a time-discretized approach. Then, a continuous probabilistic model is applied to represent the stochastic nature of operator actions better. Integrating operator actions into battery depletion modeling, this approach provides a more realistic model for CCDP estimation.

2. SBO scenario

Compared to other initiating events in PSA, SBO scenarios require a more time-dependent analysis due to various dynamic factors. As mentioned in the introduction, in conventional PSA approaches, the event tree/fault tree (ET/FT) methodology calculates the core damage frequency (CDF) by assuming a predefined AC recovery time. However, a more refined convolution approach considers the fail-to-start (FTS) and fail-to-run (FTR) probabilities of the AAC DG and TDP, leading to a more accurate estimation of the Conditional Core Damage Probability (CCDP) [2].

This study takes a further step by removing the assumption of a fixed battery depletion time, meaning that AC recovery time is not treated as a fixed value in the CCDP calculation. Instead, a probabilistic approach is applied to dynamically model the influence of operator actions on battery availability.

Figure 1 presents a simplified event tree (ET) that considers only the fail-to-start events of the AAC DG and TDP as an illustration before moving on to analysis. Figure 1's, T_c and T_{bd} represent the time until core damage occurs after both the AAC DG and TDP fail to start, and the time during which Class-1E DC batteries can supply DC power to the TDP, respectively. This study calculates the CCDP of sequence 3

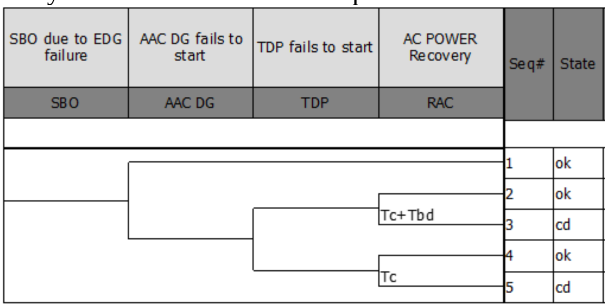

Fig. 1. Simplified SBO ET

3. Methodology for Dynamic Battery Depletion Modeling

For fail-to-run failures, a constant failure rate is assumed, implying that the corresponding time-to-failure is modeled by an exponential distribution. Under this assumption, the probability density function and cumulative distribution function can be represented as follows:

(1) $$f(t) = \lambda e^{-\lambda t}$$

(2) $$F(t) = \int_0^t f(\tau)d\tau = 1 - e^{-\lambda t}$$

The probability distribution for the non-recovery of AC power before t is assumed to follow a lognormal distribution as

(3) $$p_{NRAC}(t) = 1 - \int_0^t \frac{1}{\sqrt{2\pi}\sigma x} e^{-\frac{1}{2}\left(\frac{\ln x - \mu}{\sigma}\right)^2} dx$$

Where μ and σ are the mean and standard deviation of the natural logarithms of the date, respectively. The switchyard-centered LOOP data in NUREG/CR-6890 (2020 Update) [4,5] are used.

3.1 ET/FT approach

According to the ET/FT approach in conventional PSA, the mathematical formula for sequence 3 is given by [3]:

$$P_{AS,BD} = p_{AS} \cdot (1 - p_{TS}) \cdot \left(1 - F_{TR}(T_m)\right) \cdot p_{NRAC}(T_{bd} + T_c) \tag{4}$$

In equation (4), the subscripts AS, TS, TR, and BD denote the following failure conditions:

- AS: AAC DG fails to start
- TS: TDP fails to start
- TR: TDP fails to run
- BD: TDP is unavailable due to battery depletion

And T_m represents the mission time.

The terms on the right-hand side of the equation, except for $p_{NRAC}(T_{bd} + T_c)$, are not affected by batter depletion time. Therefore, we will analyze the process and results of finding p_{NRAC} instead of calculating the entire equation to find CCDP.

3.2 Time-Discretization Approach

In this chapter, to consider the operator's load-shedding action time, the discrete variable t_{op} is introduced. And constant value T_{bd} is defined as a discrete variable $\boldsymbol{t_{bd}}$. In this time-discretization approach, p_{NRAC} can be calculated using the following formula:

$$P_{AS,BD} = p_{AS} \cdot (1 - p_{TS}) \cdot \sum p_{t_{op}} p_{NRAC}(t_{bd} + T_c) \tag{5}$$

Furthermore, the relationship between the load-shedding time and battery depletion time is assumed to be based on interpolation and extrapolation of sample results obtained from thermal-hydraulic analysis, and these results are shown in the following Table 2 [6]. Assuming a probabilistic distribution for t_{bd} with a mean value of 30 minutes, the probability distribution table is given in Table 3.

Table 2: Time variables for calculation

$\boldsymbol{t_{op}}$(Load shedding time) [h]	0.25	0.375	0.5	0.625	0.75
Battery depletion time [h]	1	2	3	4	5
$\boldsymbol{t_{op}}$(Load shedding time) [h]	0.875	1	1.125	1.25	1.375
Battery depletion time [h]	7	6	8	9	10

Table 3: probability distribution of t_{op}

t_{op} [h]	0.25	0.375	0.5	0.625	0.75
$p_{t_{op}}$	0.165	0.228	0.247	0.202	0.116
t_{op} [h]	0.875	1	1.125	1.25	1.375
$p_{t_{op}}$	0.041	5e-6	4e-6	3e-6	2e-6

3.3 Continuous-time Approach

Now, t_{bd} is considered as a continuous variable. We can set the formula as follows:

$$P_{\mathrm{AS,BD}} = p_{\mathrm{AS}} \cdot (1 - p_{TS}) \cdot \int_{t_{min}}^{t_{\max}} f_{bd}(t_{bd}) p_{NRAC}(t_{bd} + T_c) dt \tag{6}$$

$$t_{bd} = g(t_{op}) \tag{7}$$

Although the formulations for the continuous variable approach are developed, insufficient information about the relationship between variables and the probability density function of variables makes it difficult to derive meaningful computational results. Therefore, in the next chapter, the comparison focuses on the first two approaches.

4. Comparison of results

In this chapter, the results of the ET/FT approach and the time-discretization approach will be compared. Table 3 provides information about the data to be used in calculations. Table 4 shows the result of the two approaches.

Table 3: The notation's description and its value

Notation	Description	Value
μ	The mean of the natural logarithm	0.44
σ	The standard deviation of the natural logarithm	1.66
T_{bd}	Constant battery depletion time	4 [h]
T_c	The time to core damage after the failure of the AAC DG and TDP	1 [h]

Table 4: The result of the two approaches

	ET/FT approach	Time-discretization approach
p_{NRAC}	0.241	0.148

The result in Table 4 indicates that considering variability in battery depletion time due to the load shedding time makes CCDP lower. Therefore, it supports the need for a dynamic modeling approach when evaluating SBO risk.

Additionally, the finding in this study aligns with Kim (2023) [2] and Kim (2023) [3], which are precious studies of this study, reinforcing the importance of a dynamic approach.

5. Conclusion

SBO scenario involves complex time-dependent interactions among multiple components and events. In this study, the battery depletion time affected by the load shedding time is considered as a time-dependent element. Thus, instead of constant battery time, T_C, we introduced t_c to a variable. The conventional ET/FT method, which assumes a fixed depletion time, tends to be more conservative, potentially overestimating risk. In contrast, the time-discretization approach incorporates operator actions dynamically, making a more realistic assessment.

The continuous-time probabilistic model was formulated. However, the lack of sufficient data on probability distributions and the relation between load-shedding time and battery depletion time made proper assumptions hard thus, making calculations challenging. Future work should aim to address this limitation.

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