An Application of New Dynamic PSA Framework to Large Break LOCA Scenario

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1. Introduction

Since static PSA (probabilistic safety assessment) has been introduced to safety analysis for complex systems such as nuclear power plants (NPPs), it has been widely used in quantifying the risk, finding the weak points, and decision making based on risk information. Static PSA consists of fault tree and event tree analyses based on Boolean algebra logic. Also, static PSA is static in nature, it has limitations that considering the sequential events or time-dependent interactions between system-system or system-human [1]. For that reason, dynamic PSA has been emphasized to solve the limitations of static PSA. Dynamic PSA has many advantages such as increasing realism in the modeling of time-dependent interactions in quantifying risk, providing insights based on the integration of deterministic and static approach, and considering uncertainties in physical process and system responses [2]. However, dynamic PSA generates numerous branches because it considering many dynamic scenarios related to operators, components, and systems. Therefore, it is necessary to develop a new dynamic PSA framework that could assess the risk considering dynamic sequences while managing numerous dynamic scenarios properly. In this study, we will propose a new dynamic PSA framework and perform the case study using the proposed framework.

2. Framework

This proposed framework has 6 steps, figure 1 shows the process of the proposed dynamic PSA framework. The 6 steps to perform dynamic PSA as follows:

1. Selecting initiating event
   - Selecting initiating event for analyzing accident sequence using dynamic PSA framework
2. Analyzing event sequences and system failures
   - Analyzing accident sequences for selected initiating event
   - Analyzing possible stochastic failures in systems, components, and dynamic operation failures by human operators
   - Analyzing system performance with performance factors
3. Generating dynamic scenarios based on step 2
   - Generating dynamic branches based on ET and FT analysis
4. Grouping the scenarios based on performance
   - Reducing dynamic scenarios using the performance-based grouping method
5. Optimizing scenarios
   - Optimizing simulation branches to assess the risk
   - Simulating optimized branches using TH code to judge whether the reactor core is damaged or not

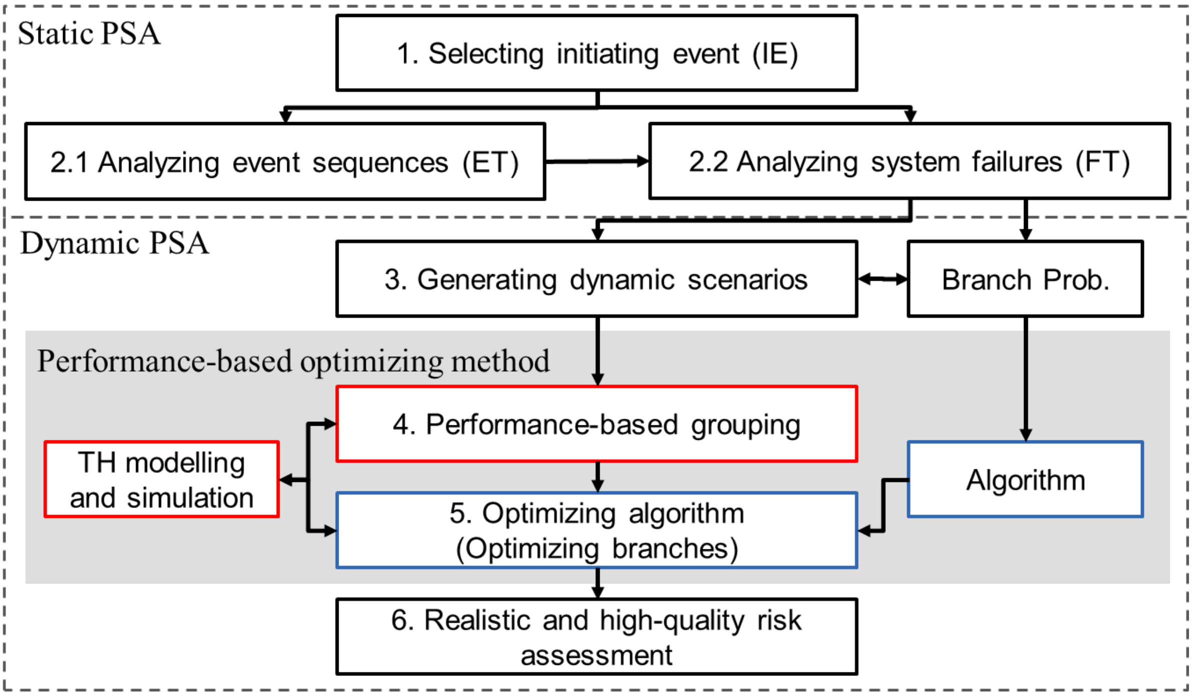

Fig. 1. The process of the proposed dynamic PSA framework

6. Quantifying the risk
   - Evaluating each branch probability, and calculating CCDP for all core damaged branches

In this framework, key methods are two. One is the performance-based grouping method, the other is the optimization algorithm. The details of the two methods will be addressed in the next section.

3. Method

3.1. Performance-based grouping

There are numerous dynamic scenarios are generated by considering stochastic failures of components such as valves and pumps, and operation failures by operators. Then, the performance of systems could be determined based on mass flow rate, time, etc. Therefore, it is possible to group the performance of each system for generated dynamic scenarios. Figure 2 shows the example of performance-based grouping of SIT (safety injection tank system) and LPSI (low-pressure safety injection system).

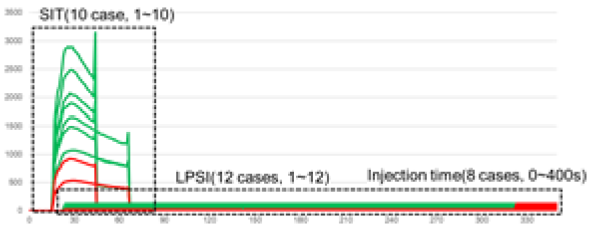

Fig. 2. The example of performance-based grouping of SIT, LPSI

3.2. Optimization algorithm

The optimization algorithm is to find not core-damaged scenario group (green box) which contains all not core-damaged scenarios (green points) with the minimum number of simulations for grouped scenarios. To finding all not core-damaged scenarios, this algorithm searching green points from best performance to worst performance diagonally. In this searching, the optimum scenarios are simulated by TH code to judge whether the core damaged scenario or not. After finding the green box, this algorithm validating it whether the box contains core damaged scenarios (red points) or not. This algorithm is to find all green boxes recursively for remain spaces. Finally, it is possible to find all green points and boxes with the minimum number of TH simulations, also, the number of simulations could be optimized to assess the risk with reasonable accuracy.

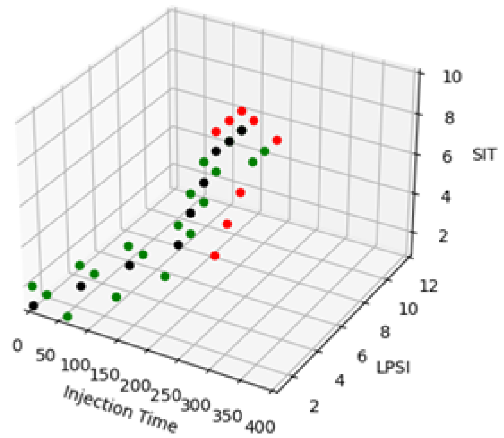

Fig. 3. The example of a diagonal search in the optimization algorithm

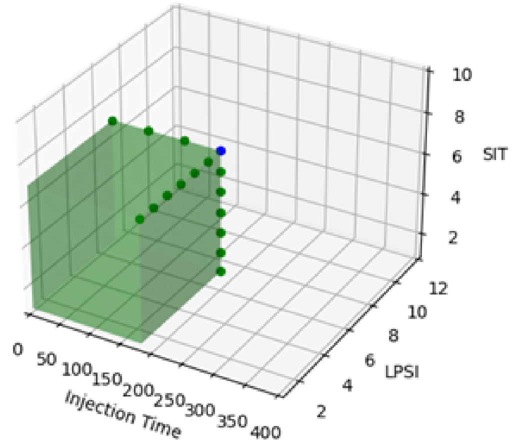

Fig. 4. The example of validation in the optimization algorithm

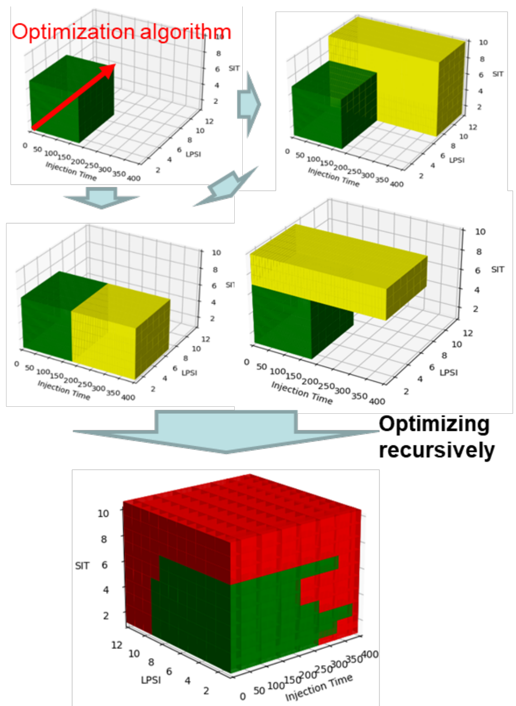

Fig. 5. The process of the optimization algorithm

4. Case study

To show the feasibility of proposed the new dynamic PSA framework, a case study was performed.

4.1. An initiating event

In this case study, a large break loss of coolant accident (LOCA) is selected as an initiating event. This initiating event is one of the extreme accidents, it postulated guillotine break. In this accident, coolant injection is essential because coolant is escaped rapidly. At the first, SIT is injected according to the set pressure. However, it is not enough to fill out to cover the core in large break LOCA. Therefore, LPSI should be injected at the proper time with an adequate flow rate.

For dynamic PSA, dynamic scenarios related to SIT and LPSI are considered. The scope of this case study is decided that from the beginning of break to the exhausting of RWST (refueling water storage tank) for LPSI.

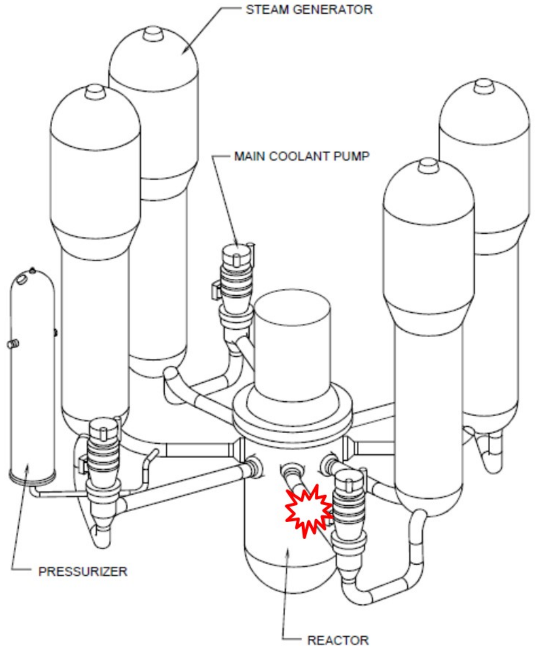

Fig. 6. Typical 4-loop PWR reactor coolant system configuration in large break LOCA scenario.

4.2. Dynamic scenarios

Based on ET (event tree) and FT (fault tree) analysis, possible dynamic failure scenarios are in table 1.

Table I: Possible dynamic failure scenarios for systems.

System	Possible dynamic failure scenarios
ESFAS	- ESFAS failed to generate SIAS - ESFAS failed to generate SIAS, but the operator recovered with a delay time
SIT	- Check valves ■ Valve failed to open - Isolation valves ■ Valve transferred to close ■ Valve partially (0 to 100%) opened
LPSI	- Check valves ■ Valves failed to open - Isolation valves ■ Valves failed to open ■ Valves partially (0 to 100%) opened ■ Valves failed to open, but recovered by operator - Pump ■ Pump failed to start ■ Pump partially (0 to 100%) performed

There are a total of 6.45 E+ 8 scenarios that are generated combining all possible dynamic failure scenarios including human operator backup scenarios.

4.3. Performance-based grouping

About the generated scenarios, they were grouped by the performance-based grouping method. 216 scenarios related to SIT were grouped into 10 groups based on mass flow rate and injecting time. Also, LPSI related 373,248 scenarios were grouped into 12 groups based on mass flow rate. ESFAS related 8 scenarios were grouped into 8 groups based on injection time. Therefore, a total of 6.45 E+ 8 scenarios were grouped to a total of 960 represent scenarios.

4.4. Optimization algorithm

For grouped scenarios optimizing algorithm was applied recursively. By repeatedly applying the algorithm six times, all 315 green points were found out of 960, and the number of simulations required for the finding was 292, and only 30% of the total was simulated.

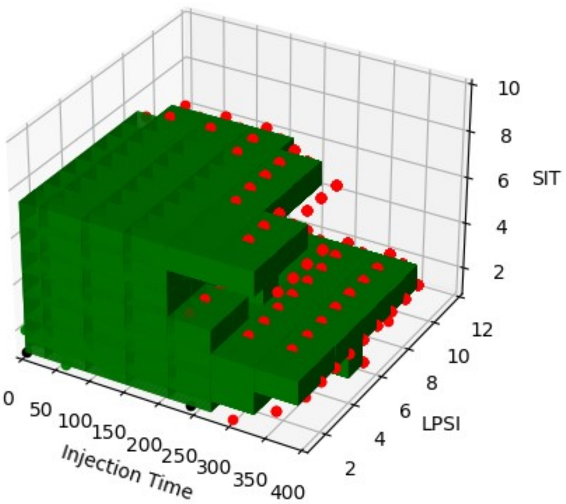

Fig. 7. The result of the optimization algorithm for this case study

4.5. Result

Finally, the risk was evaluated using CCDP (conditional core damage probability), estimated CCDP was 5.004E-4. Table 2 shows the result and comparison among the static PSA, proposed dynamic PSA, and general dynamic PSA. By using the performance-based grouping method, the number of scenarios is reduced dramatically compared to the general dynamic PSA. However, still, 960 simulations are needed to get the exact CCDP.

Even with the once use of the algorithm, 62% (196) of green points were found only with 5% (50) simulation of the entire scenarios, and the CCDP was evaluated as 5.804E-5. If 6 times use of the algorithm recursively, it was possible to find all green points and exact CCDP within only 30% (292) of simulations.

5. Conclusion

In this paper, a new dynamic PSA framework and methods were proposed for assessing accurate risk while managing the number of scenarios effectively, and a case study for large break LOCA was performed. Also, by using this proposed framework and methods, it is possible to optimize the number of simulations for estimating reasonable risk. In future work, we expect that it is possible to assess the risk realistically for many initiating events considering more various dynamic scenarios.

REFERENCES

[1] Marseguerra, M., Ricotti, M. and Zio, E., (1995). Approaching system evolution in dynamic PSA by neural networks. Reliability Engineering & System Safety 49, 91-99
[2] Verma, A.K. et al., (2016). Reliability and Safety Engineering. Springer Series in Reliability Engineering.

Table Ⅱ: Result comparison among static PSA, proposed dynamic PSA framework, and general dynamic PSA.

<table>
<tr><th rowspan="3"></th><th rowspan="3">Static PSA</th><th colspan="4">Proposed Dynamic PSA framework</th><th rowspan="3">Dynamic PSA</th></tr>
<tr><th colspan="3">Performance-based grouping + Optimization algorithm</th><th rowspan="2">Performance-based grouping</th></tr>
<tr><th>1 time</th><th>…</th><th>6 times</th></tr>
<tr><td>Number of simulations (total scenarios)</td><td>3</td><td>50</td><td>…</td><td>292</td><td>960</td><td>6.45 E+ 8</td></tr>
<tr><td>Number of green points (not core-damaged scenarios)</td><td>-</td><td>196</td><td>…</td><td>315</td><td>315</td><td>-</td></tr>
<tr><td>CCDP</td><td>9.931 E-4</td><td>5.804 E-4</td><td>…</td><td>5.005 E-4</td><td>5.005 E-4</td><td>Less than 5.005 E-4</td></tr>
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