Dynamic Event Tree Construction of Small LOCA based on Simulation Optimization Framework

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1. Introduction

In recent decades, PSA (probabilistic safety assessment) has been introduced as one of the useful methods for the safety assessment of complex systems such as nuclear power plants (NPPs). PSA aims to quantify the risk and use risk-informed decision-making in finding weak points and reducing the risk [1]. To do so, PSA uses static-based event trees (ETs) and fault trees (FTs) to quantify the risk based on Boolean logic [2]. PSA is a static approach by nature, it considers dynamic scenarios, time-dependent interactions, and sequences by conservative assumptions [3]. For that reason, dynamic PSA has been introduced and studied to consider dynamic scenarios in risk assessment [4]. Dynamic PSA can both analyze the dynamic scenarios and evaluate the risk, it increases the realism and provides risk insights. However, dynamic PSA increases the massive number of dynamic scenarios to assess the risk realistically, it also increases the number of simulations. Therefore, it is necessary to introduce a simulation optimization framework to manage the number of simulations while assessing the risk of the dynamic scenarios. In this work, a simulation optimization framework for dynamic PSA is proposed, and a case study is conducted using the proposed framework. Also, a dynamic event tree is developed with risk quantification based on the results from the proposed framework.

2. Simulation Optimization Framework

A simulation optimization framework has 7 steps; 1) selecting an initiating event, 2) analyzing event sequences and system failures, 3) generating dynamic scenarios, 4) grouping based on performance, 5) optimizing via an algorithm, 6) constructing dynamic ET, 7) quantifying the risk.

Figure 1 describes the process of dynamic PSA using the proposed framework. Details of performance-based grouping, optimization algorithm, and construction of dynamic ET are addressed in the next.

2.1 Performance-Based Grouping

Performance-based grouping is a method to classify the dynamic scenarios based on the system performance factors as mass flow rate and time which determines peak cladding temperature in the reactor core. Various dynamic stochastic failures affect the performance of systems. For example, if pumps or valves in a high-pressure safety injection (HPSI) system fail to perform appropriately, the performance of HPSI is degraded as below of the designed flow.

Therefore, dynamic scenarios can be categorized into a few dynamic scenario groups according to mass flow rate and time. In addition, thermal-hydraulic models for simulations using TH code are developed based on the grouped scenarios. The simulations are

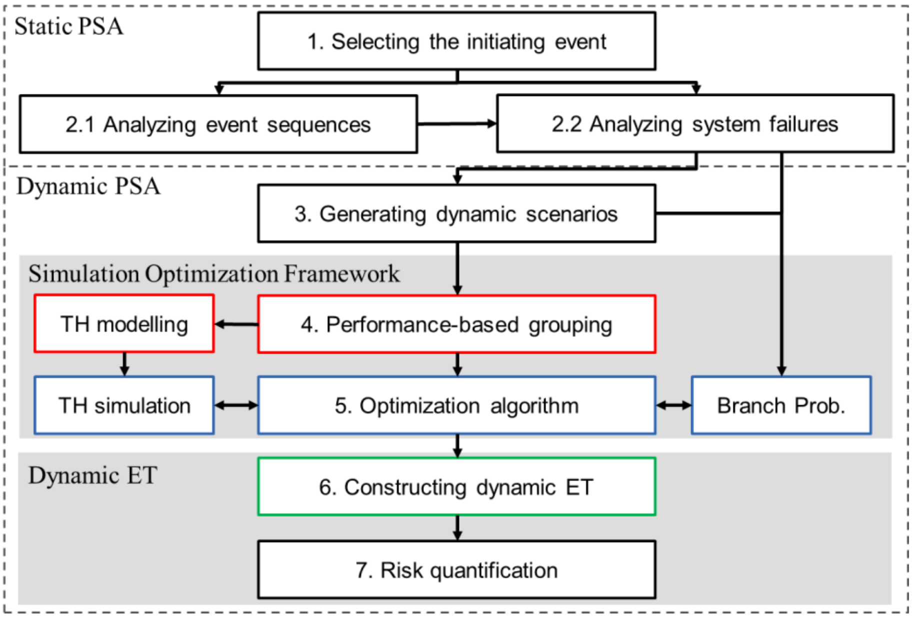

Fig. 1. The process of dynamic PSA using the simulation optimization framework.

required to determine that scenarios are core-damaged or not.

2.2 Optimization Algorithm

For the grouped scenarios and developed models, the optimization algorithm is proposed to manage the number of simulations to quantify an appropriate level of risk. This algorithm is a recursive process to search not core-damaged scenarios with the minimum number of simulations and validate it. 3 axes are determined by system performance according to the grouped dynamic scenarios in three-dimension space, diagonal searching is used to find not core-damaged scenarios. After that, the validation process is adopted to make and validate a box that contains only not core-damaged scenarios for the founded not core-damaged scenarios.

The number of applications of the algorithm is called "depth" in this work, the algorithm can find out more not core-damaged scenarios as depth increases even more simulations are necessary. That means, more realistic risk assessment is possible as depth increases. However, the number of simulations increases also. Therefore, it is required to adjust depth for efficient risk assessment by reducing the number of simulations.

2.3 Construction of Dynamic ET

From the results of the algorithm, it is possible to develop the dynamic event tree. The result of the algorithm is already defined as the 3 axes which represent the performance of the system according to dynamic scenarios, dynamic event tree can be developed based on the 3 axes. To quantify the risk, scenario probability should be evaluated or assumed additionally.

3. Case study

3.1. Small LOCA and reference model

In this case study, a small loss of coolant accident (LOCA) in an NPP was postulated. The reference plant was Zion NPP which is one of the retired NPPs that was designed as a typical Westinghouse 4-loop and 1000MWe as shown in Figure 2. Based on the reference model, TH physical model for simulations was developed. In this work, MARS-KS which is one of the general TH codes was used to simulate the scenarios [5].

Once a small LOCA occurs in NPP, a reactor trip is required. Then, the engineering safety feature and actuation system (ESFAS) generates an actuation signal to HPSI to inject the coolant. In a small LOCA, heat removal by the primary side in NPP is not enough to prevent core damage, the secondary side heat removal by the auxiliary feedwater system and atmospheric dump valves or main steam safety valves is necessary.

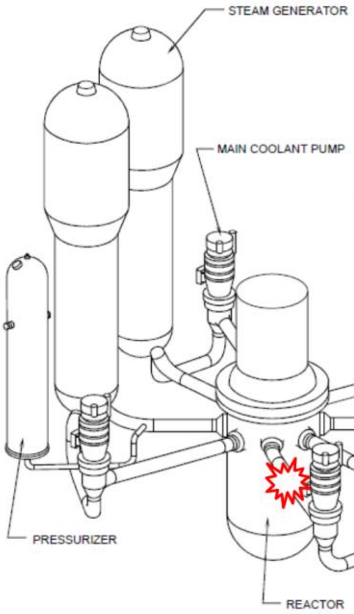

Fig. 2. Typical 4-loop PWR reactor coolant system configuration in large break LOCA scenario.

Figure 3 illustrates an ET of small LOCA in static PSA. In this work, only HPSI injection and secondary heat removal via ADVs were considered. In other words, it was assumed that the reactor is tripped, AFWS delivers feedwater to the secondary side, and MSSVs are unavailable when small LOCA in this case study.

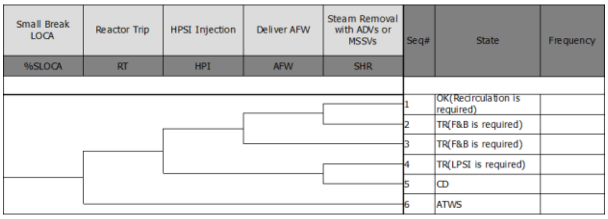

Fig. 3. ET of small LOCA in static PSA

3.2 Result of Simulation Optimization Framework

To generate the dynamic scenarios, the HPSI system and ADVs were considered. HPSI system has 4 redundant trains. And each train has three check valves, one motor-operated isolation valve, and a pump. In this work, pump partial failure which performs 66% and 33% were considered. Also, the 11 different delayed times of HPSI actuation and operations of ADVs by recovery of operators were considered as listed in Table 1, because operators can manually actuate the HPSI system if ESFAS failed to generate the signal, and operators can open ADVs for recovery if MSSVs failed to open.

Table I: Possible modes of the components for dynamic scenarios

System	**Component**	**Possible modes**
HPSI	Check valves and Motor-operated iso. valves	Valve area fraction 100, and 0%
	Pumps	Pump flow 100, 66, 33, and 0%
ESFAS/SHRS	ESF signal processors (considering operator manual backup)	Delayed time of 0, 6, 12, 18, 24, 30, 36, 42, 48, 54, and 60 min
	ADVs opened manually by operators	Delayed time of 0, 6, 12, 18, 24, 30, 36, 42, 48, 54, and 60 min

Based on the above assumptions, a total of 2.030E+09 dynamic scenarios were generated. For this dynamic scenario, the performance-based grouping was applied. As a result, the HPSI performance, considering valve failure, pump failure, the operator's manual backup with ESFAS failure, was classified as a total of 13 flow rates according to mass flow rate. For the actuation time of HPSI and operation time of ADVs, a total of 11 different delayed times were considered, respectively. In this study, HPSI flow rate, HPSI actuation time, and ADV actuation time were determined assuming the performance from failures that valves and pump and operator's recovery time. Thus, various flow rates and actuation times can be simulated by considering various failure modes of valves and pumps based on experiment or failure data, and various operator recovery times through simulation. As a results, the performance-based grouping method classified a total of 2.030E+09 dynamic scenarios into 1573 grouped scenarios.

For the grouped 1573 scenarios, the developed optimization algorithm was applied. The algorithm found all not core-damaged scenarios with 6 depths and 702 simulations (which is 45% of the total 1574 grouped scenarios). The results of the algorithm by depth are listed in Table 2. To optimize the number of simulations, it is possible to adjust the percentage of finding scenarios that are not core damaged. If we set the algorithm to find 60% and 87% of not core-damaged scenarios, only 3% and 20% simulations of all scenarios are required, respectively. Figure 4 visualizes the result of the algorithm for this case study. In Figure 4, three axes are defined as HPSI flow rate, HPSI actuation time, and ADV actuation time, green points and red points illustrate not core-damaged scenarios and core-damaged scenarios, green boxes show the set of green points.

Table II: The result of the simulation optimization framework

Depth	**# of not core-damaged scenarios (cum. %)**	**# of simulation (cum. %)**
1st	343 (62%)	46 (3%)
2nd	140 (87%)	263 (20%)
3rd	53 (96%)	107 (26%)
4th	16 (99%)	189 (39%)
5th	4 (100%)	93 (44%)
6th	0 (100%)	4 (45%)
total	556 (100%)	702 (45%)

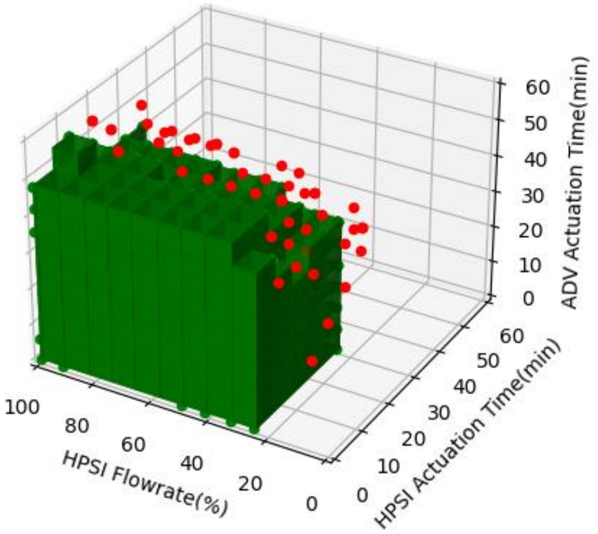

Fig. 4. The result of the simulation optimization framework for this case study

3.3 Construction of Dynamic ET

Based on the results of the algorithm, it is possible to construct a dynamic ET. This step is an approach to integrate dynamic and static PSA. Figure 5 shows the developed dynamic ET based on the result of the algorithm for 6 depths. Using the dynamic ET and the probabilities of the grouped scenarios, it is possible to evaluate the risk. In this work, conditional core damage probability (CCDP) was used as a risk metric. In static PSA, the CCDP of the small LOCA scenario performed in the case study was quantified as 3.08E-03. On the other hand, the CCDP was estimated as 2.92E-03 by using the proposed framework for dynamic PSA. The developed dynamic ET provides both quantitative and qualitative insights into the CCDP of each sequence, available time of HPSI and ADV operations, failure domain for each accident sequence, etc.

Fig. 5. Developed dynamic ET of small LOCA based on the results

4. Conclusion

This paper proposes a simulation optimization framework to manage the number of simulations for performing dynamic PSA efficiently. This framework includes the performance-based grouping method and the optimization algorithm. The proposed framework is possible to find all not core-damaged scenarios with a reduced number of simulations. Also, it optimizes the number of simulations for the appropriate level of risk by adjusting depths or the percentage of finding not core damaged scenarios of all. A case study for the small LOCA is performed. In the case study, dynamic ET for the small LOCA is developed, and the risk is quantified with CCDP.

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