A Dynamic PSA Framework Based on System Performance through Thermal-Hydraulic Simulation

Jong Woo Park [a], Seung Jun Lee [a*]
[a]*Department of nuclear engineering, Ulsan National Institute of Science and Technology, Republic of Korea*
[*]*Corresponding author: sjlee420@unist.ac.kr*

1. Introduction

Over the past decades, safety of nuclear power plants (NPPs) has been assessed by deterministic and probabilistic methods. Classic probabilistic safety assessment (PSA) is a quantitative assessment method, which has been widely used in safety analysis and risk assessment field. Classic PSA is also a comprehensive method to assess the risk from possible initiating events considering system failures and human errors. Also, it is a static approach basically, have limitation of analysis dynamic sequences caused by stochastic random events [1]. For that reason, classic PSA which based on assumption related to uncertainties, is conservative in general. Due to limitation of classic PSA, dynamic PSA has been introduced in recent decades. Unlike to classic PSA, dynamic PSA is integrated process to analyze time-dependent accident sequence, but also to calculate branch probabilities [2]. However, dynamic PSA has too many branches considering stochastic events, also it is hard to evaluate and simulate all generated branches. In this work, a dynamic PSA framework is proposed to assess dynamic accident sequences. It could reduce too many branches efficiently by using performance-based surrogate method which based on thermal-hydraulic (TH) simulation and analysis of system performance. In addition, large loss of coolant accident (LLOCA) is analyzed in case study using proposed framework.

2. Methods

2.1 Performance-based Surrogate Method

There are numerous branches could be generated if we consider all plant dynamic behavior. However, an NPP is one of complex systems, if we consider the various failure modes of all components with time-dependent behavior, the branches would be innumerable. Thus, it is hard to simulate numerous branches to perform DPSA. For that reason, it is necessary to reduce branches efficiently.

This paper proposes a performance-based surrogate method to reduce branches by grouping and categorizing. A Proposed method simulates all possible events related to accident scenarios such as operator error, recovery, component failure, etc., and groups to make surrogate method based on simulation result. To do that, physical performance factors such as *mass flow rate, volume flow rate, time, and velocity* are used to group to generate surrogate branches.

For example, when we analyze LLOCA scenario, related systems and action could be identified as safety injection tank (SIT), low-pressure safety injection (LPSI) system, and high-pressure safety injection (HPSI) system, operator back-up, etc. Then, stochastic components failures such as valve failure, pump failure, electric power failure, delayed time to backup, etc., to consider TH simulation to generate dynamic branches. And then, all branches could be analyzed physical performance factors. Therefore, surrogate branches represent all generated branches using by physical performance factors. For example, if scenario is safety injection signal is failed, but operator manually generated signal with delayed 10 minutes, and pump performed only 50%, then this scenario could be represented by 50% *mass flow rate* and 10-minute of delayed *time*. By using this performance-based surrogate method, scenarios that result similar performance, can be replaced with a single surrogate branch. This proposed method effectively reducing the number of branches while reflecting realistic plant dynamic behavior. Also, it could be reduced simulation time efficiently.

2.2 Integrated Dynamic PSA Framework

By using performance-based surrogate method, integrated dynamic PSA framework is proposed in this section. The process of integrated dynamic PSA framework is total 7 steps as follows.

1. Selection of initiating event
    - Selecting initiating event for analyzing accident sequence using dynamic PSA framework

2. Analysis of event tree (ET)
    - Analyzing accident sequences for selected initiating event
    - Analyzing possible stochastic failures such as system, component failures, and human errors

3. Analysis of fault tree (FT)
    - Analyzing system performance with performance factors

4. Generating possible scenarios (branches)
    - Generating dynamic branches based on ET and FT analysis

5. Grouping (reducing) scenarios using performance-based surrogate method
   - Reducing generated branches using performance-based surrogate method

6. Evaluate both probabilities and peak cladding temperatures for surrogate branches
   - For surrogate branches, evaluate probabilities. Also, TH simulating to decide that plant state is damaged or not

7. Evaluate conditional core damage probability (CCDP)
   - Based on previous evaluation, calculate CCDP totally

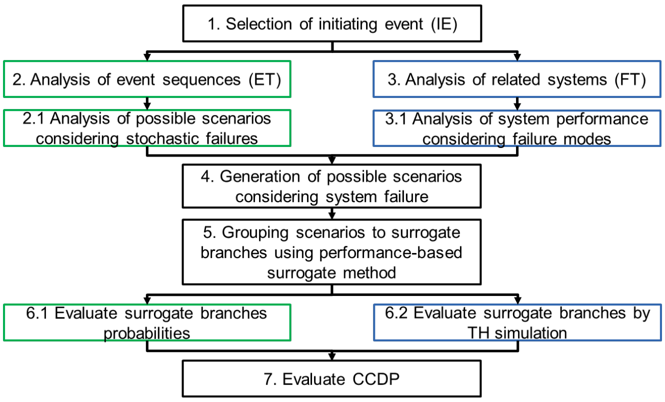

Fig. 1. The process of integrated dynamic PSA framework.

Figure 1 shows the process of integrated dynamic PSA framework in detail.

3. Case Study

3.1 LLOCA Scenario

To perform case study, LLOCA scenario was assessed in this case study. Figure 2 illustrates typical 4-loop PWR reactor coolant system (RCS) configuration in LLOCA scenario. When cold leg of reactor coolant system LLOCA initiating event happened as shown in figure 2, RCS inventory will decrease. Then, engineering safety features actuation system (ESFAS) generates safety injection actuation signal (SIAS) to actuate safety injection systems such as SIT, LPSI, and HPSI. They have set points for each, actuation and performance are time dependent. Once SIAS generated, isolation valves in SIT are opened. Then, SIT fills out the boric water at the set point of RCS pressure. However, the SITs stored limited water, it should be exhausted without isolation. For that reason, alternative systems to refill water are needed. LPSI and HPSI are active safety systems to refill the water from refueling water storage tank (RWT) in LLOCA scenario, which have set points at low pressure and high pressure, respectively.

In this case study, only ESFAS, SIT and LPSI (without HPSI) are selected to perform dynamic PSA. For that reason, simulation is performed only 3000 seconds which is exhausted time of water in RWT. Table 1 shows the details of timeline of LLOCA scenario.

Table I: Timeline of LLOCA scenario.

Time-line	description
0s	Steady state
200s	Break (6 inches for LLOCA) opened
210s	Reactor trip on low-primary pressure (12.8MPa) - SIAS is generated (SIT iso. valve (fully) opened) - Chemical volume control system, reactor coolant pump, main feed water system trip - Main steam isolation valve (fully) closed
240s	Aux feedwater system actuated by ESFAS (12.27MPa) - Aux feedwater delivered - Steam generator relief valves actuated on set point
330s	SIT injected by pressure difference
400s	LPSI actuated by ESFAS (1.42MPa)
3000s	Water in RWT is exhausted

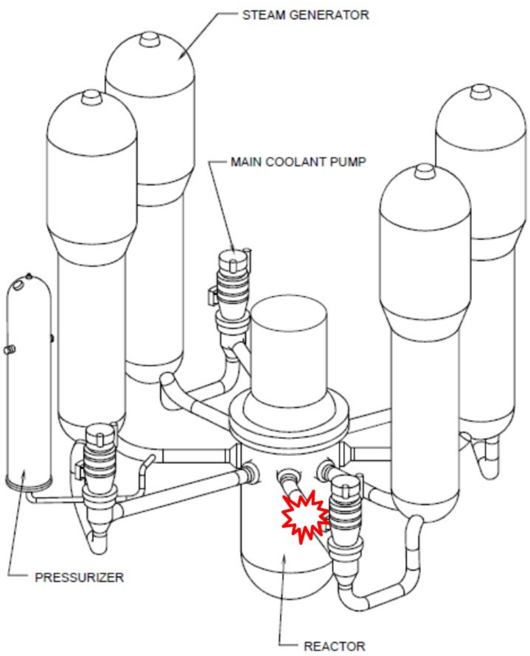

Fig. 2. Typical 4-loop PWR reactor coolant system configuration in LLOCA scenario.

3.2 Analysis of ET and FT

For the LLOCA scenario, ET and FT are analyzed. Figure 3 illustrate event sequences for LLOCA. As previous mentioned, when LLOCA occurs, mitigation systems such as SIT, LPSI, HPSI will be operated. Total branches of event tree of static PSA in figure 3 are 6. However, if we consider plant dynamic behavior due to stochastic failures such as valve failure, pump failure, signal failure, operator manual backup failure, etc., then, numerous dynamic branches would be generated.

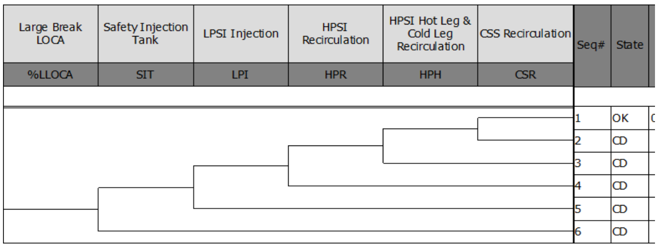

Fig. 3. Event tree of LLOCA scenario.

Figure 4 illustrates FT of SIT system considering valve and signal failure. Following the performance-based surrogate method, mass flow rate and velocity would be reduced or 0 if valve failed to open or stuck. In the same reason, time of injection would be delayed if signal to open valve is failed but operator manually generate signal with delayed time.

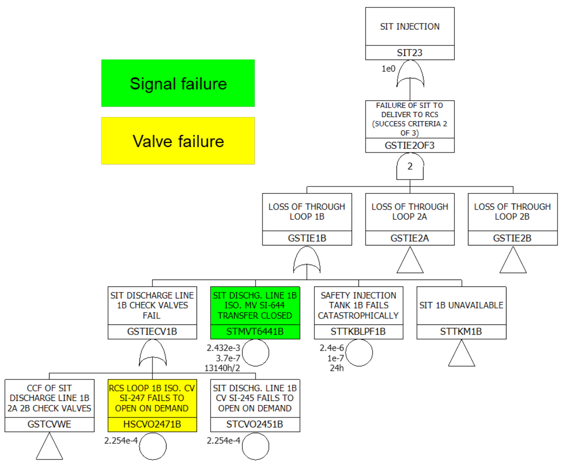

Fig. 4. Fault tree of SIT system considering possible failures.

3.3 Dynamic Scenarios

Based on analysis of ET and FT in previous section, possible failure modes of selected system for LLOCA scenario is analyzed as shown in table 2.

Table II: Possible failure modes of selected system for LLOCA scenario.

System	Possible failure modes
ESFAS	Delay 100, 300 seconds to generate SIAS
SIT	Fail to open isolation valve Partially (50%) open isolation valve
LPSI	Fail to open check valve Partially (50%) open check valve
	Fail to start pump Partially (83, 66, 50, 33, 16%) operated pump

In this analysis, there are several failure modes are considered that ESFAS failed to generate signal, SIT failed to inject by valve failure, and LPSI failed to perform caused by valve and pump failure. Based on mentioned failure modes, there are 4.78E+6 scenarios are generated.

3.4 Reducing branches by performance-based surrogate method

Applying performance-based surrogate method, selected systems could be grouped as follows.

1. ESFAS
   - There are 3 types of scenarios could be considered as;
     1) ESFAS generate signal at time normally
     2) ESFAS failed to generate signal, but operator manually generate signal in delayed time 100s
     3) ESFAS failed to generate signal, or operator manually generate signal in delayed time 300s+.
2. SIT
   - There are 3 types of scenarios could be considered as;
     1) SIT injected 100% mass flow rate as designed, normally
     2) SIT injected 50% mass flow rate due to valve failure
     3) SIT failed to inject (0%)
3. LPSI
   - There are 10 types of scenarios could be considered as; LPSI performed to inject coolant from 100% to 0% at 10% intervals.

As a result, total 4.78E+6 dynamic scenarios are reduced to 99 surrogate branches using performance-based surrogate method.

3.5 TH simulation

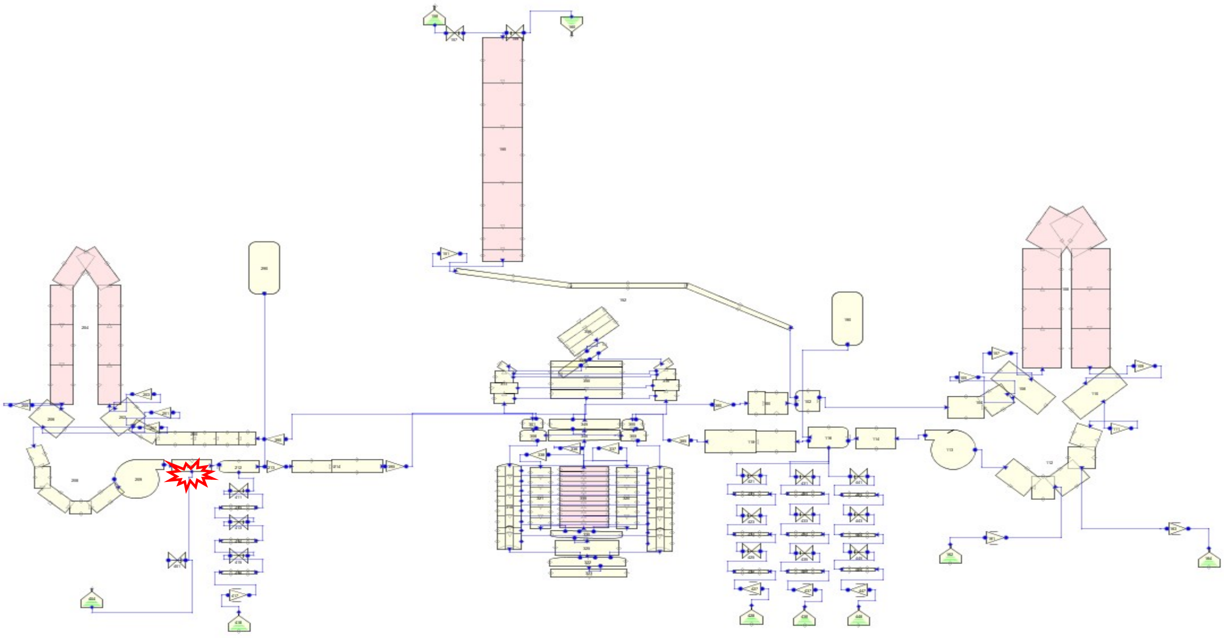

Fig. 5. Nodalization diagram of the TH simulation model

To simulate surrogate scenarios, TH model was developed for typical 4-loop PWR. Figure 5 illustrates developed model. TH simulation is performed using MARS (Multi-dimensional Analysis of Reactor Safety) code [3].

3.6 Branch probability calculation

Based on classic PSA reliability data, branch probabilities for surrogate branches are calculated. Table 3 shows probabilities for each possible failure modes of selected systems.

Table III: Possible failure modes and their probabilities for selected system.

System	failure modes	Probability
ESFAS	Delay 100s to generate SIAS	4.658.E-07
	Delay 300s (or more) to generate SIAS	4.192.E-06
SIT	Partially (50%) open isolation valve	2.432.E-04
	Fail to open isolation valve	2.189.E-03
LPSI	Partially (50%) open check valve	2.254.E-05
	Fail to open check valve	2.029.E-04
	Partially (83%) operated pump	6.120.E-05
	Partially (66%) operated pump	3.428.E-08
	Partially (50%) operated pump	6.400.E-12
	Partially (33%) operated pump	1.728.E-10
	Partially (16%) operated pump	1.555.E-09
	Fail to start pump	4.666.E-09

3.7 Calculation of CCDP based on TH simulation result

99 surrogate scenarios are simulated by TH code. To judge core damage or not, peak cladding temperature are analyzed in simulation results. Table 4 shows the CCDP with comparison between classic PSA and proposed dynamic PSA framework.

Table IV: Comparison between static and DPSA result for LLOCA scenario

Initiating event	SIAS (207s)	SIT (330s-550s)	LPSI (400s-3000s)	Result	
	SIAS generation time	SIT valve area fraction	LPSI mass flow rate	Static CCDP (3 scenarios)	Dynamic CCDP (99 scenarios)
%LLOCA	0	1	1 0.9 0.8 0.7 0.6	0.987 (OK)	0.995 (OK)
	+100 +300	0.5 0	0.5 0.4 0.3 0.2 0.1 0	1.26E-02 (CD)	4.01E-03 (CD)

4. Conclusions

In this paper, integrated dynamic PSA framework using performance-based surrogate method is suggested, and case study for LLOCA scenario is performed to apply proposed framework. By using a proposed framework and method, branches could be reduced efficiently while conditional branch probabilities could be evaluated realistically. Also, case study of application proposed dynamic PSA framework to LLOCA scenario is performed.

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.
[3] KAERI, (2006). MARS Code Manual Volume II: Input Requirements. Korea Atomic Energy Research Institute, KAERI/TR-2811/2004, Daejeon, Korea.