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Effects of house load operation on PSA based on operational experiences in Korea

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ABSTRACT

House load operation (HLO) occurs when the generator supplies power to the house load without triggering reactor trips during grid disturbances. In Korea, the HLO capability of optimized power reactor 1000 (OPR1000) plants has prevented several reactor trips.

Operational experiences demonstrate the difference in the reactor trip incidence due to grid disturbances between OPR1000 plants and Westinghouse plants in Korea, attributable to the availability of the HLO capability. However, probabilistic safety assessments (PSAs) for OPR1000 plants have not considered their specific design features in the initiating event analyses.

In an at-power PSA, the HLO capability can affect the initiating event frequencies of general transients (GTRN) and loss of offsite power (LOOP), resulting from transients within the grid system. The initiating event frequencies of GTRN and LOOP for an OPR1000 plant are reduced by 17.7% and 78.7%, respectively, compared to the Korean industry-average initiating event frequencies, and its core damage frequency from internal events is reduced by 15.2%. The explicit consideration of the HLO capability in initiating event analyses makes significant changes in the risk contributions of the initiating events. Consequently, for more realistic at-power PSAs in Korea, we recommend incorporating plant-specific HLO-related design features when estimating initiating event frequencies.

1. Introduction

For a power plant, house load operation (HLO) is a mode in which the plant is not connected to the grid system, and a small part of the rated capacity is generated to power only the auxiliary loads of the plant. This mode of operation is usually triggered by a grid disturbance. The ability of a nuclear power plant (NPP) to reduce to house load operation allows the reactor to stay at power during temporary grid issues [1].

The HLO capability is generally implemented on conventional power plants worldwide. When the plants are isolated from the grid, they can be kept on standby. This capability enables fast reconnection, which allows for the prompt recovery from an unstable grid and benefits from the high availability of power plants. However, for NPPs, the requirements and practices differ from country to country; for example, most European NPPs have this capability, whereas no US NPP has it. In general, some grid codes (mostly European) impose the requirement for HLO capability on NPPs because it is favorable from a grid operation point of view. On the other hand, the HLO capability can generate instability in the voltage and frequency of the onsite electrical power system, which is potentially unfavorable from a reactor safety point of view. The 2006 Forsmark event, triggered by a switchyard short circuit with complications from related control system failures, highlighted certain shortcomings of NPP designs with HLO capabilities [2].

In case of an unplanned event that disconnects an NPP from the grid system due to a grid disturbance, the NPP can remain stable through a reactor trip. However, after a reactor trip, before resuming the operations of the NPP, the restarting of the reactor can be delayed by several days due to reactor dead time and the time it takes to acquire the approval of the regulatory authority after inspection. Moreover, a reactor trip may threaten the safety of the NPP through rapid changes in reactor power, pressure, and temperature, which impact its life span. Therefore, preventing reactor trips due to grid disturbances is preferable if the NPP could be made as available as possible without compromising its safety.

After the disconnection of an NPP from its grid system, to

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maintain its continuous operation without triggering a reactor trip, the turbine-generator needs to enable a continuous power supply for house loads (all the auxiliary electrical loads of the NPP). The HLO capability of an NPP is also beneficial from a safety perspective because it provides an alternative electrical power source for its auxiliary load separate from the grid system.

In a probabilistic safety assessment (PSA), the disturbance of the grid system connected to the NPP can be an initiating event whose contribution to risk is generally significant. If the NPP possesses HLO capability, the risk of the NPP can be reduced by preventing a reactor trip following the disturbance. In other words, the availability of the HLO capability in the NPP significantly affects the risk of the NPP. However, most PSAs for the NPPs that enable HLO did not give credit for the capability due to the operational instability problems of HLOs [3]. The abrupt load reduction during a transfer to HLO stresses several of the NPP systems and can lead to instability problems arising from the management of excess power and its mismatch [2].

In Korea, all NPPs have been operating in baseload mode at steady full power for as long as possible, to meet the demand for electricity. Thus, from a baseload supply perspective, most NPPs in Korea need to be capable of performing uninterrupted operations during reductions at any power level, including through a runback to house load for safety. The OPR1000 (optimized power reactor 1000) design [4], which was the first NPP design developed in Korea, therefore implemented the HLO capability. The design target of the HLO capability for OPR1000 plants was to resolve its instability issues. After its successful development, the HLO capability of OPR1000 plants was confirmed during the commissioning of the first plant of its kind, Hanul unit 3, in 1998 [5,6]. Therefore, the Korea Institute of Nuclear Safety (KINS) required no follow-up action stemming from the Forsmark event because the safety issues of HLO for the OPR1000 plants were resolved [7]. As of 2018, there have been a number of operational experiences in which OPR1000 plants have prevented reactor trips during grid disturbances through HLO.

However, in existing PSAs for Korean NPPs [8], the initiating event frequencies have been estimated using generic Korean nuclear industry data [9]. The ASME/ANS PRA standard [10] includes two supporting requirements, IE-C3 and IE-C6(c), concerning recovery actions for estimating the initiating event frequencies. The requirements for all three Capability Categories are as follows:

> “IE-C3: INCLUDE recovery actions as appropriate.
>
> IE-C6: USE as screening criteria no higher than the following characteristics (or more stringent characteristics as devised by the analyst) to eliminate initiating events or groups from further evaluation:
>
> (c) the resulting reactor shutdown is not an immediate occurrence. That is, the event does not require the plant to go to shutdown conditions until sufficient time has expired during which the initiating-event conditions, with a high degree of certainty (based on supporting calculations), are detected and corrected before normal plant operation is curtailed (either administratively or automatically).”

In accordance with these requirements, the initiating event frequencies related to grid disturbances need to be estimated depending on the HLO capability that can recover loss of auxiliary loads.

The HLO capability of OPR1000 plants affects various areas of NPP operation by preventing reactor trips after grid disturbances. In this study, we show the effects of the HLO capability on the risk of OPR1000 plants by reassessing the initiating event frequencies and the core damage frequency (CDF) from internal events based on the operational experiences of HLO in Korea. This study is not intended to perform the initiating event analysis itself. Rather, the estimation of the initiating event frequencies performed here are intended to improve the practice of the initiating event analysis in Korean PSAs. Section 2 presents an overview of HLOs in OPR1000 plants, covering system design, operator actions, and plant responses. Section 3 reviews the operational experiences of HLOs in OPR1000 plants and discusses the initiating events following the success and failure of HLOs. Section 4 describes the estimation of the initiating event frequencies in this study and examines their effects on the CDF. Section 5 presents the conclusions of this study and suggestions for more realistic PSAs in Korea.

2. Overview of house load operation in OPR1000 plants

2.1. Concept of house load operation

In Korea, OPR1000 plants are connected to two electrically separated sections of the grid system; one section is connected to the main transformer to transmit the power produced by the generator to the grid system during normal operations, while the other is connected to the standby auxiliary transformer (SAT) to serve as a standby electrical power source. Fig. 1 shows the conceptual diagram of the electrical power system in an OPR1000 plant. During normal operation, the generator supplies power to the offsite grid system through the main transformer and to house loads through the unit auxiliary transformer (UAT).

Once grid disturbances occur, the NPP cannot supply power to the offsite grid system because of the automatic opening of power circuit breakers (PCBs) in the power transmission lines. However, HLO enables the generator to continuously supply power to house loads through the generator circuit breaker (GCB) and the UAT, as shown in Fig. 2.

2.2. System design for house load operation

After opening the PCBs in the power transmission lines (transmission line 1 in Fig. 1), HLO is automatically initiated. Fig. 3 shows the linkages between the control systems involved in HLO. On the primary side of the NPP, the reactor power cutback system (RPCS) generates a signal for dropping selected control rods to decrease reactor power. The reactor regulating system (RRS) also creates a control rod insertion signal according to the primary and secondary power differences. The digital rod control system (DRCS) moves the control rods by receiving signals from the RPCS and the RRS. On the secondary side, the turbine control system (TCS) rapidly decreases the turbine power. The steam bypass control system (SBCS) balances the outputs between the primary and secondary sides.

During normal operations, the primary and secondary powers of the NPP are balanced at the rated level. Fig. 4 depicts the scenario in which the power transmission lines are disconnected and the operation mode is switched to HLO. On the primary side, the selected control rod drop by the RPCS can reduce power by approximately 25%. The RRS and other primary side systems can reduce by an additional 20%. Therefore, the total primary side power can be instantaneously decreased by 45%. Thus, if all the control systems operate successfully, the primary and secondary side power will equilibrate at 55% of the rated power after the initiation of HLO. On the secondary side, the SBCS can cover up to 50% of the full power level, and the turbine runback and setback can decrease 95% of the rated turbine power. The generator supplies 5% of the rated power for house loads.

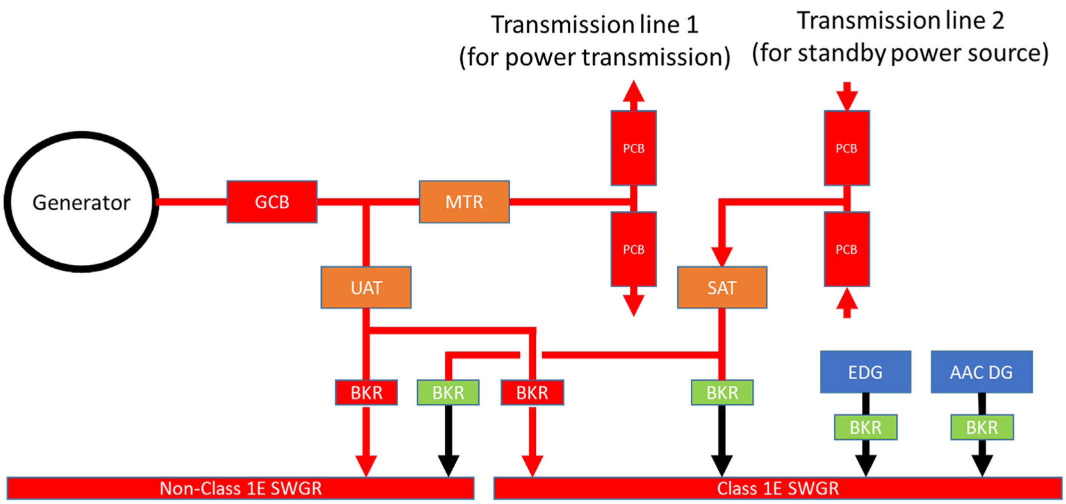


Fig. 1. On-site electrical power system for OPR1000 plants during normal operation. AAC DG, alternative ac diesel generator; BKR, breaker; EDG, emergency diesel generator; GCB, generator circuit breaker; MTR, main transformer; PCB, power circuit breaker; SAT, standby auxiliary transformer; SWGR, switchgear; UAT, unit auxiliary transformer.
Note: Red lines and black lines denote energization and de-energization, respectively. Red boxes denote closed breakers and green boxes denote opened breakers. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

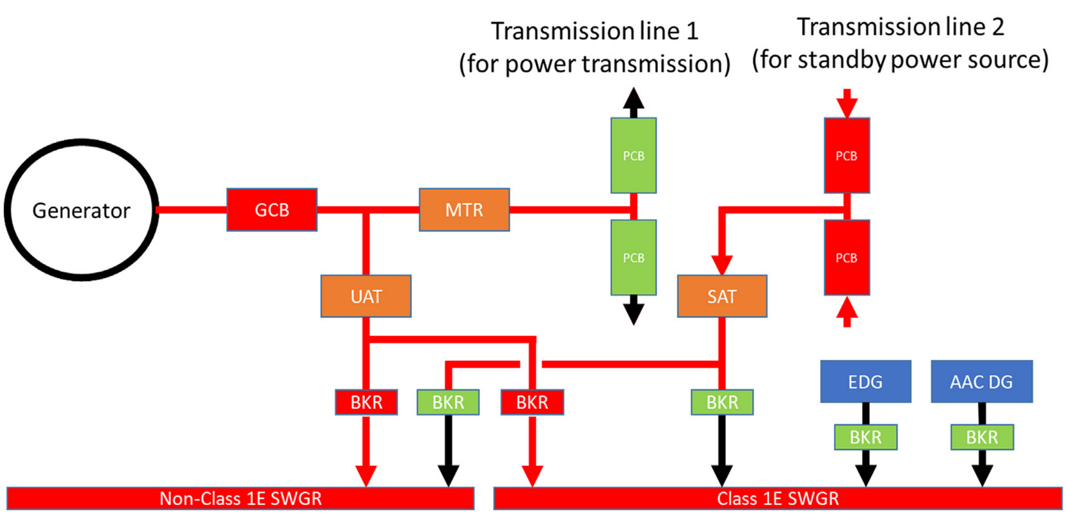


Fig. 2. On-site electrical power system for OPR1000 plants during house load operation.

If the control systems for HLO operate successfully, no operator intervention is required for at least 30 min after the initiation of HLO.

2.3. Operator actions in house load operation

Immediately after the initiation of HLO, the operator begins to perform an abnormal procedure for loss of loads [11]. If HLO is successful, neither the reactor nor the turbine-generator will be tripped and no other procedure is required. If HLO does not proceed as designed due to any issue, the reactor and turbine will be tripped automatically.

The main objectives of the abnormal procedure are to verify that the automatic control systems are operating as designed after the initiation of HLO by monitoring the information in the main control room, and to maintain reactor power. In the core, the concentration level of xenon increases due to the instantaneous power reduction associated with the initiation of HLO, and the reactor power automatically decreases over time. The abnormal procedure states that the reactor power should be kept above 18%, at which the control mode of the steam generator water level must be manually adjusted. Therefore, operator actions are required to maintain the reactor power level. If the reactor power decreases to below 18%, HLO cannot be maintained.

Fig. 5 shows the decrease in reactor power over time. Immediately after HLO initiation, the period during which the reactor power falls from 55% to 18% of full power is the window given to the operator to implement the abnormal procedure for HLO [11]. Based on the operational experience [12], the decrease rate of the reactor power is estimated to be 0.6% of full power per minute in the early stage of HLO. Assuming that the reactor power decreases linearly, the time it takes to reduce the reactor power by 37% points is approximately 60 min. Note that according to the operational experience [12], HLO can last for several hours without manual control. This shows that, unlike some NPPs with the HLO capability, which require operator actions for HLO within only a few tens of minutes [13], the time for actions to maintain HLO in OPR1000 plants is long enough to avoid human failure events associated with the operator actions.

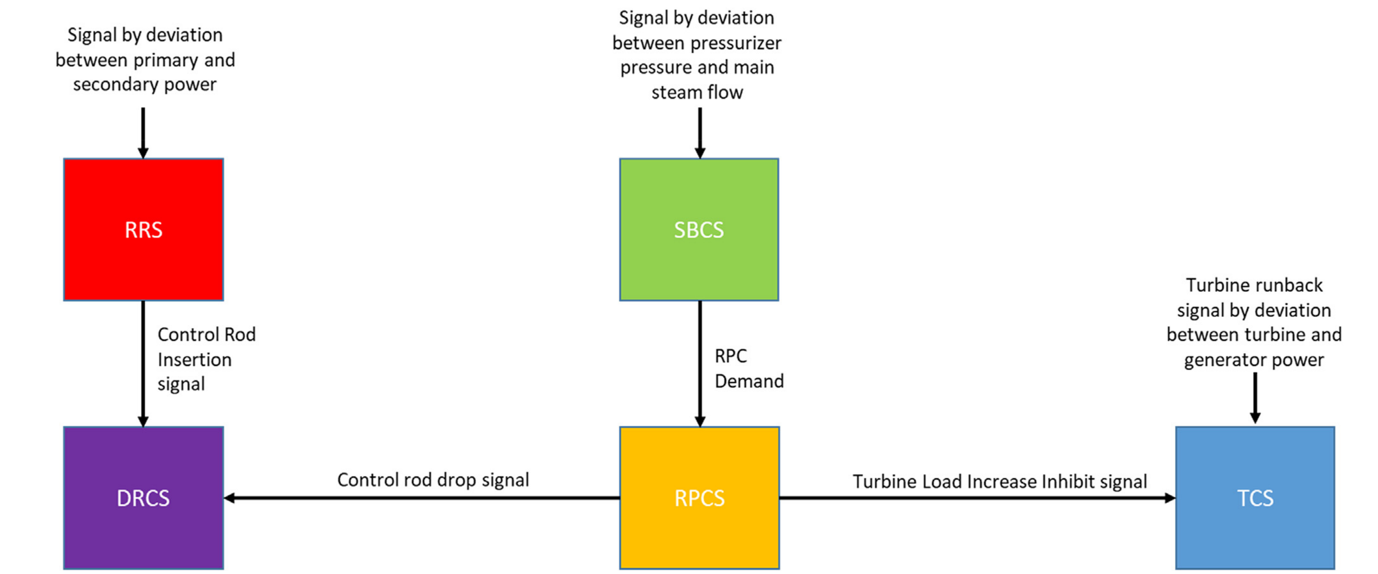


Fig. 3. Simplified schematic of the interrelated control systems for house load operation in OPR1000 plants. RRS, reactor regulating system; DRCS, digital rod control system; SBCS, steam bypass control system; RPCS, reator power cutback system; TCS, turbine control system.

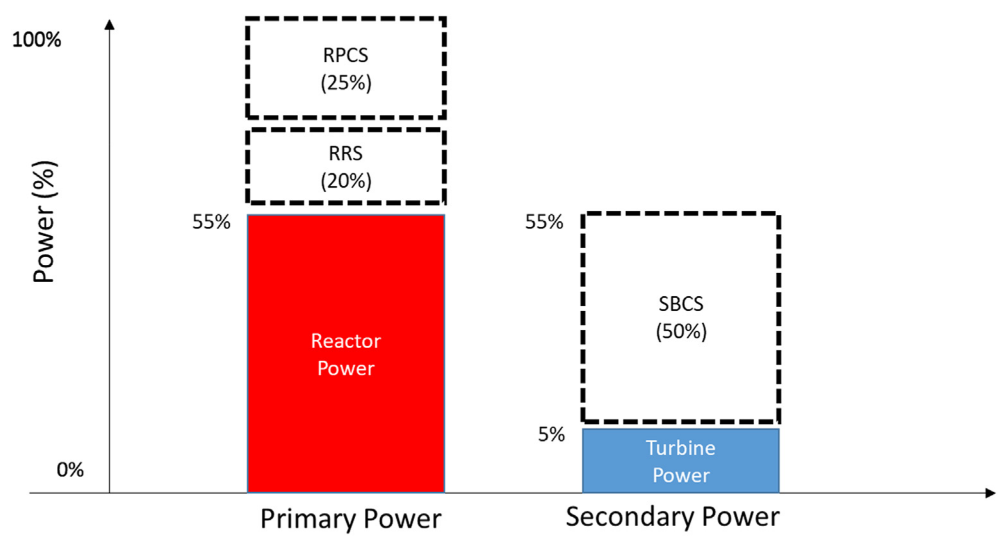


Fig. 4. Power balance between primary and secondary sides during house load operation.

After the recovery of the grid system is complete, the reactor power can be increased to return to normal operation, and the NPP can be reconnected to the grid system. If the recovery of the grid system is delayed, according to the technical specifications [14], the NPP will reach its limiting condition for the offsite power system at least 12 h after the initiation of HLO and then the reactor must be tripped manually.

2.4. *Effects of house load operation on OPR1000 response*

In OPR1000 plants, during normal operations, the UAT is connected to house load while the SAT is not connected to the onsite electrical power system. Even after transients of power transmission lines connected to the UAT, if HLO is successful, regardless of the status of transmission lines connected to the SAT, the NPPs can operate without reactor trip.

If the house load is not fed from the UAT, it can be automatically fed from the SAT via the fast bus transfer. Momentary power losses to the house load during the fast bus transfer result in a reactor trip.

If the fast bus transfer fails and the SAT fails to supply the house load, a loss of offsite power (LOOP) event occurs and the emergency diesel generators (EDGs) automatically start. If at least one EDG succeeds in supplying safety loads, the reactor can remain stable and safe. However, if all the EDGs fail, the alternative alternating current diesel generator (AAC DG) will start manually and supply safety loads. If the AAC DG fails, a station blackout[1] (SBO) event occurs, which is well known as one of the most serious events for NPPs.

Fig. 6 shows the response of an NPP following the loss of power transmission lines, as discussed above. The events that occur in response, such as HLO, the fast bus transfer, reactor trip, loss of

[1] In existing Korean PSAs [8], SBO is defined as loss of all alternating current (AC) power sources, including the AAC DG.

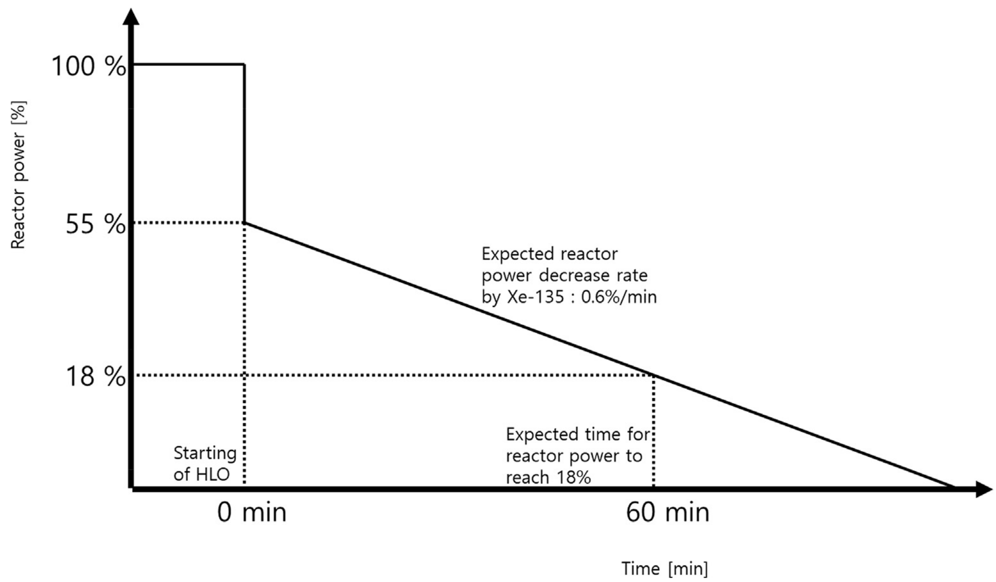


Fig. 5. Estimated reactor power decrease during house load operation.

power to the SAT, and onsite power supply to safety load, are associated with various initiating events in the PSA. The initiating-event conditions perturbing the steady-state operation of an NPP are caused by grid disturbances and can be recovered by HLO. Therefore, the HLO capability affects the occurrence of initiating events, such as general transients (GTRN), LOOP, SBO, and anticipated transient without scram (ATWS). In this paper, we focus on the effects of HLO on risk caused by the first three categories of events. An ATWS event is not considered in this study, as it is not directly related to the failure of HLO and does not significantly contribute to the CDF of OPR1000 plants [8].

3. Operational experiences of house load operation from a PSA perspective

3.1. Review of house load operation experiences

Table 1 shows the operational experiences of HLO in OPR1000 plants over the last decade (2009–2018) [15]. The total number of HLO experience cases is eight, excluding those involved with start-up tests. Of these eight cases, seven were designated successful HLOs and one was classified as a failure, according to the success criteria for HLO [16]. The failure probability of HLO in OPR1000 plants ($P_{HLO\ failure}$) can be estimated to be 0.125 (= 1 failure in 8 cases of HLO). Note that the HLO failure probability is in the range of 0.089–0.25 for some European NPPs, even though they possess different design characteristics for HLO, which require stressful manual control in the early stages of HLO [3,13].

3.1.1. Review of success case

In the case of a successful HLO, the NPP responses are basically identical. Of the seven successful cases presented in Table 1, the one from November 2013 is reviewed below as a representative case.

This case started with a grid disturbance due to a ground fault caused by lightning strikes; the PCBs were opened automatically. Immediately after the initiation of HLO, the operators implemented

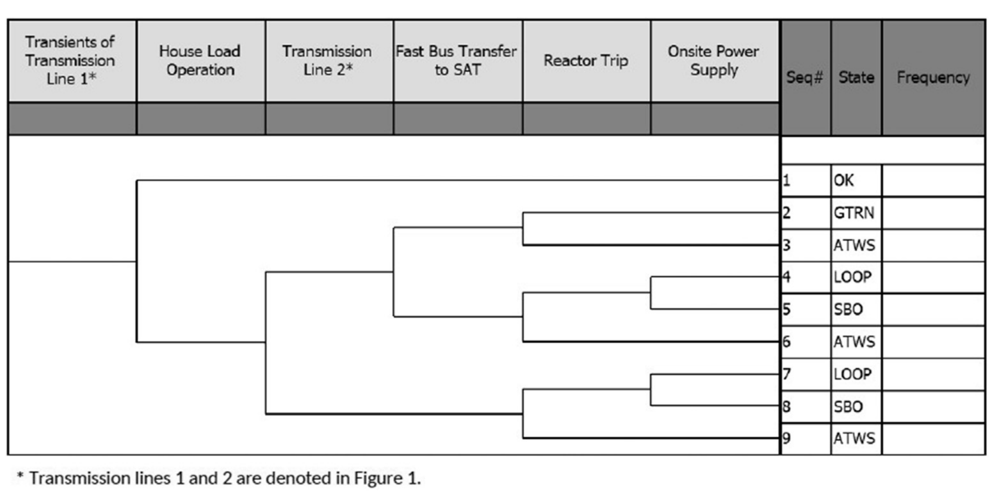


Fig. 6. Initiating events following grid disturbances.

Table 1
Experiences of HLO in the OPR1000 plants for 2009–2018.

Date	Unit	Success/failure
Dec-2009	■■#5	Success
Dec-2009	■■#6	Success
Mar-2011	■■#3	Success
Nov-2012	▲▲#2	Success
Nov-2013	■■#5	Success
Oct-2014	▲▲#1	Failure
Oct-2014	▲▲#2	Success
May-2016	□□#4	Success

Note: The unit names in Table 1 are not disclosed because they represent confidential information of Korea Hydro & Nuclear Power Co., Ltd.

Table 4
LOOP events during at-power operation in Korea since 1978.

Unit	Date	Grid Disturbances	Failures in Electrical Power System
Kori 4	1986.08.28	Yes	
Kori 1	1987.07.16	Yes	
Kori 2	1987.07.16		Yes
Kori 3	1987.07.17		Yes
Kori 4	1987.07.17		Yes
Hanul 2	1997.01.01	Yes	
Kori 2	1998.09.27		Yes

the abnormal procedure [11] and successfully performed the operator actions required by the procedure. It took 1 h and 39 min to reconnect the NPP to the offsite power grid system after the recovery of the grid system.

3.1.2. Review of failure case

The case reviewed in this section occurred in October 2014 [17]. The PCBs were unexpectedly opened due to spurious signals from the control circuit of the 765 kV switchyard breaker and HLO was initiated automatically. Approximately 1 min later, the PCBs were automatically re-closed and the reverse power relay of the generator malfunctioned. As a result, the turbine-generator tripped and was unable to supply house loads through the UAT. In turn, a successful fast bus transfer resulted in a reactor trip. Although the direct cause was the malfunctioning of the generator reverse power relay, which is not part of the HLO systems, it was nevertheless classified as a failure of HLO because it did not satisfy the success criteria of HLO [7].

3.2. Operational experiences related to general transients

There are a total of 25 NPPs in Korea, including 12 OPR1000 plants. There are 6 Westinghouse (WH) plants that do not possess HLO capability. In addition, there are seven other NPP types that incorporate different system designs for HLO. In this section, the impact of HLO capability on PSAs is analyzed by comparing the operational experiences of HLOs in OPR1000 plants with those of WH plants without the HLO capability.

Based on the operation performance information system data [18] provided by the KINS, reactor trips in OPR1000 and WH plants from 2009 to 2018 were investigated. Table 2 shows the number of reactor trips counted in this study. There were 24 cases of reactor trips in OPR1000 plants. Of the 24 cases, one occurred due to grid disturbances, which corresponded to 4.2% of the total. During the same period, there were 20 reactor trips in WH plants. Of the 20 cases, four occurred due to grid disturbances, which corresponded to 20% of the total. The average number of reactor trips per unit is 0.08 for OPR1000 plants and 0.67 for WH plants. The average number of reactor trips per unit as well as the percentages of reactor trips caused by grid disturbances are quite different between the two types of plants.

Table 3 shows the impact of the HLO capability on OPR1000 plants. As mentioned above, the HLO capability in the 12 OPR1000 plants has prevented seven reactor trips over the past decade. If the capability was not available, the seven successful HLO cases would have been added to the total number of reactor trips. This would raise the number of reactor trips caused by grid disturbances to eight, corresponding to 25.8% of 31 cases. In addition, the number of reactor trips caused by grid disturbances per unit would be identical at 0.67 for both OPR1000 and WH plants.

As only one standardized grid system exists in Korea, the number of grid disturbances per unit should be similar across all types of Korean NPPs. Therefore, the difference between the incidence of reactor trips by grid disturbances between OPR1000 and WH plants can be attributed to the availability of the HLO capability rather than to any differences in grid system design and operation.

3.3. Operational experience review related to LOOP and SBO

In OPR1000 plants, even if an initiating-event condition corresponding to LOOP occurs, that is, the NPPs are disconnected from grid system by transients of both transmission lines shown in Fig. 1, reactor trips can be prevented by HLO. Table 4 shows the LOOP experiences of NPPs in Korea [18]. Over the last decade, there have been no LOOP events during at-power operations of Korean NPPs. In addition, of the eight cases of HLO experience listed in Table 1, there is no initiating-event condition corresponding to LOOP.

4. House load operation in at-power level 1 PSAs for OPR1000 plants

Based on the operational experiences of HLO as discussed above,

Table 2
Number of reactor trips by NPP type in Korea for 2009–2018.

NPP type	Number of units	Total number of reactor trips	Number of reactor trips due to transmission line transients
OPR1000	12	24	1
WH	6	20	4

Table 3
Change in number of reactor trips by house load operation capability in OPR1000 for 2009–2018.

Case	Number of reactor trips due to transmission line transients	Total number of reactor trips	Number of reactor trips due to transmission line transients per unit
OPR1000	1	24	0.08
OPR1000 without considering the HLO capability[a]	8	31	0.67

[a] Seven cases of HLO success are added into reactor trips due to transmission line transients.

Table 5
Reactor operating years by NPP type in Korea for 2009–2018. Note: Reactor operating years in this table were rounded after the summation of reactor operating years of each NPP.

Type of NPP		Reactor operating years (ry)
PWR plants	OPR1000 plants	84.24
	Other PWR plants	65.93
PHWR plants		28.39
All NPPs in Korea		178.55

Table 6
Number of reactor trips by grid disturbances during at-power operation for 1978–2018 in Korea.

Years	Reactor trips due to grid disturbances	LOOP due to grid disturbances
1978–2008	27	3
2009–2018	7	0

we considered the effects of HLO on PSAs in the calculation of initiating event frequencies of GTRN, LOOP, and SBO for OPR1000 plants. To calculate the initiating event frequencies based on the last decade of operational experiences in this study, reactor operating years (ry) for the years 2009–2018 were estimated using yearly availability factors for NPPs in Korea [19]. Table 5 shows these estimations across all NPPs in Korea.

4.1. Effects of HLO on GTRN frequency

The GTRN frequency is calculated by dividing the number of GTRN events by reactor operating years. The GTRN frequency for OPR1000 plants was 0.285/ry. However, if these plants did not possess HLO capability, the GTRN frequency would instead be 0.368/ry. The difference between these two figures, 0.083/ry, shows the effect of the HLO capability on GTRN frequency.

In existing PSAs in Korea, the GTRN frequency is estimated based on industry-wide operational experiences.[2] There have been 52 reactor trips categorized as GTRN over the last decade. Thus, the Korean industry-average GTRN frequency for all PWR plants is 0.346/ry, which is comparable to the GTRN frequency for OPR1000 plants without considering the HLO capability. This shows that the Korean industry-average GTRN frequency does not reflect the HLO capability in OPR1000 plants and is not suitable for OPR1000-specific PSAs.

4.2. Effects of HLO on LOOP frequency

4.2.1. Assumption on LOOP events reflecting the effects of HLO

To analyze the effect of the HLO capability on LOOP frequencies in PSAs, we estimated the number of potential transients, corresponding to LOOP initiating-event conditions, based on the characteristics of the Korean grid system as discussed in section 3.2.

Based on these characteristics, this study assumed that power transmission line transients occur in a similar fashion across all NPP types. From 1978 to 2008, there were 27 reactor trips triggered by grid disturbances [18], of which three were categorized as LOOP, as listed in Table 6. The fraction of the potential transients to the total number of reactor trips due to grid disturbances is 0.111 (= 3/27). This ratio is assumed to be consistent with that over the last decade.

However, if the HLO capability is available in NPPs, the reactor trips categorized as LOOP are matched with the potential transients corresponding to LOOP initiating-event conditions because the HLO capability can prevent reactor trips following the transients. Power transmission line transients have triggered seven reactor trips in the last decade. In addition, for OPR1000 plants, seven reactor trips were prevented by HLO. Thus, there were a total of 14 power transmission line transients. Based on the assumption above, the number of potential occurrences of LOOP initiating-event conditions due to grid disturbances across all Korean NPPs over the last decade is calculated as 1.56. For OPR1000 plants, by considering the ratio of reactor operating years of OPR1000 plants and all across Korean NPPs, the number of potential transients corresponding to LOOP initiating-event conditions due to grid disturbances is 0.734. Table 7 summarizes the above calculations.

4.2.2. Calculation of LOOP frequency

The LOOP frequency is calculated by dividing the number of LOOP events by reactor operating years. In OPR1000 plants, reactor trips by LOOP can only occur if HLO fails. The number of potential LOOP events following the failure of HLO is 9.17E-2, and the LOOP frequency is calculated to be 1.09E-3/ry. However, if these plants did not possess HLO capability, the LOOP frequency would instead be 8.71E-3/ry. As in existing Korean PSAs, if the LOOP frequency is estimated for all NPPs in Korea, the number of potential LOOP events over the last decade is 0.913, excluding reactor trips prevented by HLO in OPR1000 plants. Thus, the LOOP frequency is 5.11E-3/ry.

4.2.3. Calculation of SBO frequency

According to the PSAs of OPR1000 plants, SBO events are transferred from the sequences in LOOP event tree when the safety load supply fails following LOOP. The SBO frequency can be calculated as the product of the LOOP frequency and the failure probability of safety load supply following LOOP. Thus, in this study, the ratio of the SBO frequency to the LOOP frequency is assumed to be the failure probability of safety load supply following LOOP.

Based on the PSA of a representative OPR1000 plant [8], this ratio was found to be 2.86E-3. In this study, the SBO frequency for OPR1000 plants was calculated to be 3.11E-6/ry. If there were no HLO capability in OPR1000 plants, the SBO frequency would instead be 2.49E-5/ry. If LOOP frequency for estimating the SBO frequency is replaced by the Korean industry-average LOOP frequency, the SBO frequency is 3.49E-7/ry.

The estimated results in this study show that the HLO capability significantly reduces the initiating event frequencies of GTRN, LOOP, and SBO. Table 8 summarizes the changes in initiating event frequencies after incorporating OPR1000-specific operational experiences.

[2] There are four pressurized heavy water reactor (PHWR) plants, Wolsong units 1–4, in Korea. All other plants are pressurized water reactor (PWR) plants. In existing Korean PSAs for PWR plants, PHWR-specific events, such as GTRN, are not included in the initiating event analysis while the events of LOOP were included in the analysis.

Table 7
Estimation of LOOP frequency for 2009–2018.

Case	Number of occurrences of condition corresponding to LOOP	Number of reactor trips prevented by HLO	Number of potential LOOP events	LOOP frequency (/ry)
OPR1000 plants	7.34E-1 (A)	6.42E-1 (B)	9.17E-2	1.09E-3
OPR1000 plants without considering the HLO capability	7.34E-1 (A)	0	7.34E-1	8.71E-3
All NPPs in Korea	1.56 (C)	6.42E-1 (B)	9.13E-1	5.11E-3

A. $C \times \frac{\textit{reactor operating years of OPR1000 plants for } 2009-2018}{\textit{reactor operating years of all NPPs in Korea for } 2009-2018}$
B. $A \times (1 - P_{HLO\ failure})$; $P_{HLO\ failure} = 0.125$ *in section* 3.1
C. $\frac{\textit{number of LOOP events due to grid disturbances for } 1978-2008}{\textit{number of reactor trips for } 1978-2008} \times \textit{number of grid disturbances for } 2009-2018$

Table 8
Comparison of initiating event frequencies for OPR1000 plants.

Initiating event	OPR1000 Initiating event frequency (/ry) (A)	OPR1000 (without considering the HLO capability)		Korean industry average (in this study)	
		Initiating event frequency (/ry) (B)	Change (%) $(\frac{A-B}{B})$	Initiating event frequency (/ry) (C)	Change (%) $(\frac{A-C}{C})$
GTRN	2.85E-1	3.68E-1	−22.6	3.46E-1	−17.7
LOOP	1.09E-3	8.71E-3	−87.5	5.11E-3	−78.7
SBO	3.11E-6	2.49E-5	−87.5	1.46E-5	−78.7

4.3. Effects of HLO on CDF

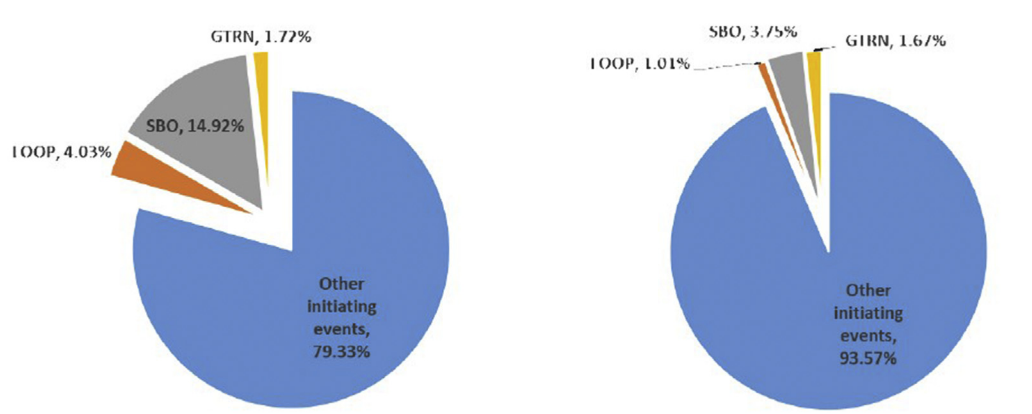
To analyze the effects of the HLO capability on CDF, the CDFs for GTRN, LOOP, and SBO were calculated as the product of the initiating event frequency and the conditional core damage probability (CCDP) of the initiating event because the CCDP is a variable independent of HLO capability. The CDFs for other initiating events are independent of HLO capability and therefore were not calculated in this study.

Here, the CDFs for LOOP, SBO, and GTRN were calculated for the representative OPR1000 plant [8] by multiplying the initiating event frequencies for OPR1000 plants and the CCDPs corresponding to the initiating events. The calculation results are shown in Fig. 7 as CDF contributions by initiating events. The overall internal event CDF for the representative OPR1000 plant is decreased by 15.2% when the HLO capability of OPR1000 plants is explicitly considered, compared to the CDF applying Korean industry-average initiating event frequencies.

5. Conclusions

HLO is a mode of operation in which power is supplied to the house load through the generator without tripping the reactor when it is in a transient condition due to grid disturbances. In Korean NPPs, OPR1000 plants have developed complete HLO capability by incorporating it during the design stage and verifying its stability during the operation stage. The HLO experiences of OPR1000 plants over the last decade show only one failure out of a total of eight HLO cases. In this regard, the HLO capability can be a reliable source of power for OPR1000 plants. However, in existing PSAs for Korean NPPs, HLO experiences have not been considered explicitly as plant-specific data in initiating event analyses.

This study, following the ASME/ANS PRA standards, estimated the frequencies of plant-specific initiating events related to the transients of the grid system, using the HLO experiences of OPR1000 plants over the last decade. Compared to the Korean industry-average initiating event frequencies of GTRN, LOOP, and SBO, those specifically for OPR1000 plants were significantly lower.



(a) Korean industry-average GTRN, LOOP, and SBO frequencies (b) OPR1000 specific GTRN, LOOP, and SBO frequencies

Fig. 7. Comparison of CDF contributions by initiating events.

In addition, this study examined the effects of the HLO capability on the internal event Level 1 PSA results for OPR1000 plants. The at-power internal event CDF dropped by approximately 15.2%, mainly due to a significant decrease in LOOP and SBO frequencies, compared to the CDF employing Korean industry-average initiating event frequencies. The CDF contributions from each initiating event also changed accordingly.

These results imply that initiating event frequencies differ when considering the HLO capability explicitly in the initiating event analysis. The inherent risk characteristics of NPPs also vary depending on the existence of HLO capabilities. Therefore, it is necessary to consider them in PSAs as plant-specific characteristics for more effective risk management. As such, future work should be directed toward updating existing Korean NPP PSAs based on plant-specific operational experiences that realistically reflect the effects of HLO.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.net.2020.05.018.

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