Improved ASI Control Method for Flexible Operation

Geon Hee Park* and Sung Ju Kwon
KEPCO NF 242, Daedeok-daero 989 beon-gil, Yuseong-gu, Daejeon, 34057, Republic of Korea
*geonhee@knfc.co.kr**

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1. Introduction

Flexible operation, which adjusts power in response to changes in power supply and demand based on grid load, is essential not only for domestic nuclear power plants but also for the international export market. However, when the power is adjusted without proper control, the axial power distribution in the reactor core may oscillate vertically. To ensure fuel integrity, plant operators make efforts to stabilize the axial power distribution during both normal and flexible operation conditions.

In typical CE (Combustion Engineering)-type reactor designs, the axial power distribution is often assessed using the Axial Shape Index (ASI). When the target ASI is determined for flexible operation, it requires excessive control rod insertions and withdrawals to maintain the target ASI consistently. Therefore, an upper and lower allowable range for the target ASI is designated to manage its variations. Once the ASI reaches these allowable limits, further control requires rapid control rod insertion or withdrawal, which is undesirable from both an operational and safety perspective.

In this study, a new control method that prevents deviations beyond the allowable ASI range with minimal control rod movement. The main focus is to determine the optimal timing for control before the ASI amplitude exceeds the allowable range. Control rod movement can be minimized by applying control at the appropriate timing. The effectiveness of this method is demonstrated through its application in an actual operational support system for the APR1400 core.

2. Methods

2.1. Limit ASI formula

The axial shape index (ASI) is commonly used as a factor to represent axial power shift and is defined by Eq. (1). ASI indicates the shift in power toward the upper or lower part of the core.

$$\mathrm{ASI}(t)=\frac{P_{bot}(t)-P_{top}(t)}{P_{bot}(t)+P_{top}(t)}. \tag{1}$$

where

$\mathrm{P}_{top}(t)$: The power in the top half of the core at time t,

$\mathrm{P}_{bot}(t)$: The power in the bottom half of the core at time t,

The ASI oscillates due to xenon oscillations occurring within the reactor core. Xe-135, a strong neutron absorber, continuously varies due to neutron capture and the decay of I-135, leading to power fluctuations. When power increases in a specific axial region, the neutron flux accelerates the depletion of Xe-135. The reduction of Xe-135 decreases neutron absorption, which increases local power. Subsequently, the decay of I-135 leads to the accumulation of Xe-135, increasing neutron absorption and thereby reducing local power. When this process occurs asymmetrically between the upper and lower regions of the core, the ASI oscillates periodically and can be expressed as a sine wave pattern over time, as shown in Eq. (2) [1].

$$\mathrm{ASI}(t)=\mathrm{ASI}_0\cdot e^{bt}\sin\left(\frac{2\pi t}{T}+t_0\right)+\mathrm{EASI}. \tag{2}$$

where

$\mathrm{ASI}(t)$: Time-dependent axial shape index,

ASI_0 : Amplitude of oscillation,

b : Xenon stability index,

T : Period,

t_0 : Phase shift,

EASI : Equilibrium axial shape index.

The EASI represents the long-term equilibrium value of the ASI in the steady-state condition of the reactor core. Since ASI control using control rods is performed within a time interval much shorter than the xenon oscillation period, the xenon stability index (b) can be assumed to be zero at the moment of ASI control. Let ASI_0 defined as a, be the allowable upper or lower limit, and let EASI be regarded as equivalent to the target ASI(T.A.). Based on theses considerations, Eq. (2) can be reformulated as Eq. (3).

$$\mathrm{ASI}(t)=\mathrm{a}\cdot\sin\left(\frac{2\pi t}{T}+t_0\right)+\mathrm{T.A.} \tag{3}$$

Equation (3) represents the most limited ASI wave that does not exceed the allowable range based on the target ASI. If the amplitude of ASI is smaller than that in Eq. (3), control is not required.

2.2. Limit of ASI Gradient

Figure 1 illustrates the slope cos(t) corresponding to the values of sin(t) with an amplitude of 1. This circular graph provides insight into the minimum and maximum possible slopes for a given value of sin(t).

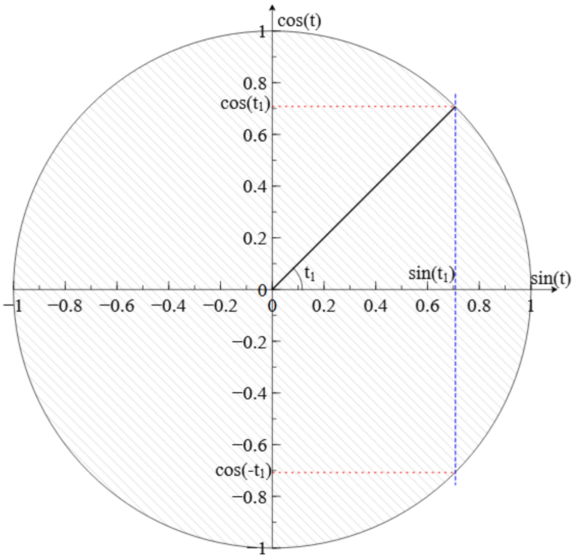

Fig. 1. The relationship between sin(t) and cos(t).

By applying this to the ASI equation, we can determine the minimum and maximum slopes of ASI based on its current value relative to the target ASI under a given allowable range. Eq. (4) is obtained by differentiating Eq. (3) with respect to time t, representing the ASI slope over time.

$$\mathrm{ASI}'(t) = \frac{d\mathrm{ASI}(t)}{dt} = \mathrm{a}\frac{2\pi}{T}\cdot\cos\left(\frac{2\pi t}{T} + t_0\right) \qquad (4)$$

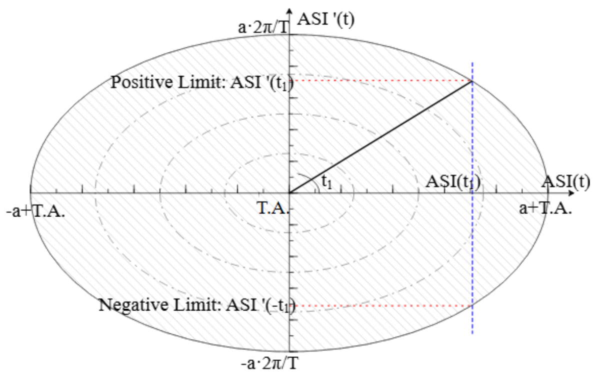

Fig. 2. The relationship between ASI(t) and ASI`(t)

Similar to Fig. 1, the relationship between ASI(t) and ASI′(t) can be represented in an elliptical shape, as shown in Fig. 2. Note that the shaded region in Fig. 2 can be considered as an area where control is not necessary. However, note that the other regions indicate areas where control is required, even if the ASI does not exceed the upper or lower allowable limits. If the slope of the maximum and minimum ASI in a specific ASI is known, it is possible to determine whether control should be applied. However, Eq. (4) is a time-dependent function, which presents the drawback of requiring calculations at each time step. Since obtaining an exact function from the continuously varying ASI is inherently inaccurate, this method is not suitable for determining the maximum and minimum slopes. By rearranging Eq. (3) and (4) in terms of sine and cosine, squaring them, and summing the results, ASI′(t) can be expressed in terms of ASI(t) as shown in Eq. (5). This equation enables the determination of the upper and lower bounds of the ASI slope, given only the ASI obtained at a specific time t.

$$\mathrm{ASI}'(t) = \pm\frac{2\pi}{T}\sqrt{\mathrm{a}^2 - \left(\mathrm{ASI}(t) - \mathrm{T.A.}\right)^2} \qquad (5)$$

2.3. ASI Control Logic

The primary control principle of ASI is to withdraw the control rods when ASI is increasing and insert them when ASI is decreasing. If ASI is outside the allowable range but its slope is directed toward the target ASI, control is not necessary. Additionally, as mentioned in Section 2.2, no control is required if ASI is within the graph shown in Fig. 2. This concept can be visualized in Fig. 3, which illustrates the insertion, withdrawal, and non-control regions of the control rods.

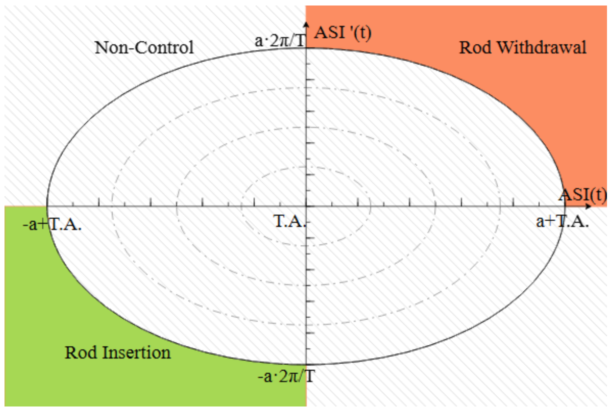

Fig. 3. Visualization of Control Areas

The suggested control algorithm follows these steps:

1. An arbitrary time t_1, adjust the control rods to bring ASI within the allowable range and obtain $ASI(t_1)$.
2. After a time interval Δt, maintain the same control rod position and obtain $ASI(t_2)$.

   $t_2 = t_1 + \Delta t$

3. Calculate the slope between the two time points:

$$\text{Slope} = \frac{\text{ASI}(t_2) - \text{ASI}(t_1)}{t_2 - t_1}$$

4. Use Eq. (5) to determine limit slopes of $ASI(t_1)$.
5. Check whether the slope obtained in step 3 falls within the range determined in step 4.
6. If the condition in step 5 is not met, determine which region in Fig. 3 the ASI falls into.
7. If ASI is in the control region, move the control rods one step and obtain the new $ASI(t_2)$.
8. Repeat steps 2 to 6 until ASI enters the non-control region.

3. Results

Flexible operation was conducted using ASI control methods, and a comparative analysis was performed by applying both the conventional method, which moves the control rods only when ASI reaches the allowable boundary, and the suggested method. To evaluate behavior under high-amplitude conditions, the analysis was conducted at EOC, where xenon oscillations are more pronounced. The calculation conditions are tabulated in Table I.

Table I. Condition of flexible operation

Item	**Value**
Reactor	APR1400
Burnup [MWD/MTU]	18,000
Power [%]	100-70-100
Rod Insertion Priority	Bank P
Rod Withdrawal Priority	Bank 5
ASI Allowance	$\pm$0.03, $\pm$0.01
Flexible Operation Scenarios 1. 100%, 10 hours, Target ASI: ESI 2. -3%/h, 10 hours, Target ASI: 0.00 3. 70%, 100 hours, Target ASI: 0.00 4. 3%/h, 10 hours, Target ASI: 0.00 5. 100%, 20 hours, Target ASI: ESI	

Figure 4 illustrates the differences in ASI control between the conventional and suggested methods when the ASI allowable ranges are set to ±0.01 and ±0.03. The solid line represents the suggested method (Mod.), while the dashed line represents the conventional method (O.G.). In the conventional method, when the ASI reaches the boundary of the allowable range, rapid movement of the control rods occurs, resulting in sharp behavior of the ASI. And it is evident that the suggested method effectively maintains ASI within the allowable range without exceeding the limits. Additionally, the control rod movement is minimized. In particular, when the ASI allowable range is set to ±0.03, the difference in control rod movement is clearly observed.

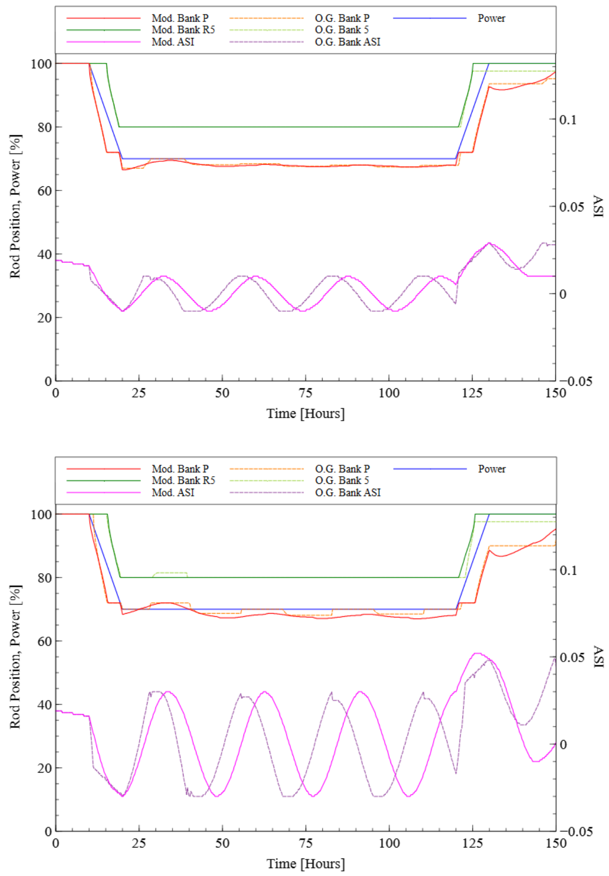

Fig. 4. Comparison of ASI control method at $\pm$0.01 (top) and $\pm$0.03 (bottom) ASI allowance

4. Conclusion

In this study, a new ASI control method was suggested for flexible operation with minimized control rod manipulation. The suggested method was implemented in an operational support system and compared with conventional ASI control methods. With suggested ASI control method, unnecessary control rod movements were reduced while maintaining ASI stability. Comparative analysis demonstrated that the suggested method effectively controlled ASI with fewer rod adjustments, even under significant xenon oscillations. It is noted that the suggested ASI control method enhances the operation efficiency and stability with reliable ASI management for the flexible operation.

REFERENCES

[1] W.S. Kim, et al., "An Automated Calculation Program for the Axial Xenon Stability Index," *Trans. KNS*, Gyeongju, Korea, Oct. 29 - 30, 2009 (2009).