

A Preliminary Concept of Periodic Steady-State Xenon Reactivity Estimation in Load-Following Operation

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1. Introduction

As efforts toward carbon neutrality accelerate and the share of renewable energy continues to grow, the need for load-following operation (LFO) in nuclear power is receiving increased attention. So far in Korea, planned power-reduction operation has only been carried out during short periods of sharply reduced demands (e.g., holidays). This mode of operation lowers reactor power and holds it at a reduced level for a few days, timed to periods when electricity demand is expected to drop. Outside these periods, the reactor is essentially operated as a baseload source. However, Korea plans to expand renewable energy's share [1]. Such a shift of energy mix system would increase both the frequency and the burden of nuclear reactor operator actions related to reactivity control.

In the current mode of power-maneuvering operation, the reactor is simply held at reduced power for two days before power is restored. Because the concentrations of fission-product reach an equilibrium state during this two-day period, the plant essentially moves from one equilibrium core state to another, which makes transient behavior relatively easy to predict (see Fig. 1). However, if LFO becomes routine, the operator burden associated with boron concentration control and control rod would be expected to increase substantially, and this warrants safety review as a potential contributor to human error. Suppose the reactor holds power steady for some period after refueling and then begins daily LFO. Then the core would move from an equilibrium state directly into a transient one. Even if the power pattern identically repeats every day, produced fission products take more than 24 hours to reach equilibrium. Power will therefore change again before these concentrations fully converge. As a result, once daily LFO begins, the core may never reach a static equilibrium state at any point afterward. The conventional approach controls power only from an equilibrium core state. If this approach is retained under these conditions, daily LFO is expected to face real technical difficulty.

To address this limitation, this study preliminarily proposes the redefining core equilibrium not as a static state but through the concept of a periodic steady state (PSS). If the reactor's power pattern repeats on a daily cycle, the operator actions need to compensate for the time-dependent reactivity trajectories of the fission products. Such repeating operator actions cause the core

reactivity trajectory itself to converge into a repeating pattern as well. Such a condition, in which the state variables no longer settle to a constant value over time but instead recur with the same periodicity as the operating cycle, can be defined as a PSS. PSS is a concept already well established across various engineering fields for analyzing the behavior of periodically operated processes and systems [2, 3].

Based on the preliminary investigation, we propose two criteria for determining whether the reactor has reached a PSS. The first criterion combines the various measured quantities generated during daily LFO into a single state vector, and judges the reactor to have reached PSS once the cycle-to-cycle change in that state vector falls below a specified tolerance. The second criterion assumes that the variables relevant to the operator's control actions are already known, and judges PSS to be reached once the cycle-to-cycle change in these key variables fall below a specified tolerance. Using a simplified 100-50-100% LFO case study, this paper discusses the advantages and disadvantages of applying each of these two criteria.

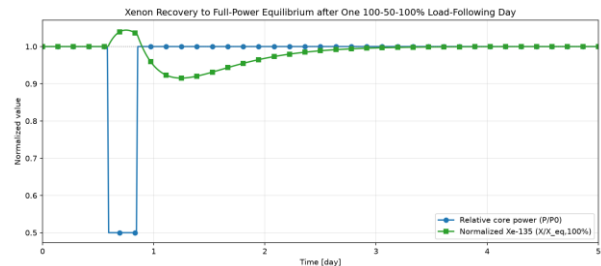


Fig. 1. Xenon recovery to full-power equilibrium after single cycle of 100-50-100% load-following operation.

2. Methods

2.1 Modeling Scope and Assumptions

As an exploratory investigation, this study establishes a quantitative framework by proposing two distinct criteria for determining whether a reactor has reached a PSS. Accordingly, rather than constructing a full point kinetics closed loop model that includes reactivity feedback and delayed neutron precursor behavior, the neutron flux ϕ is assumed to be a known, exogenous input that repeats identically every day. This formulation relies on the premise of ideal reactivity compensation, wherein operators or automated control systems

continuously adjust control rods and boron concentration to maintain the target power trajectory. Furthermore, this preliminary investigation focuses strictly on core-averaged global reactivity behavior, assuming that local spatial phenomena (e.g., axial xenon oscillation) are effectively suppressed. Based on these assumptions, linear relationship between core power P and φ can be expressed as follows:

$$P = E_f \sum_f V \varphi \quad (1)$$

where E_f is emitted energy per fission, V is volume of the core, and $\sum_f$ is the core averaged macroscopic fission cross section.

Over the time scale of a load-following cycle (e.g., 24 hours), the change in $\sum_f$ due to burnup progression is negligibly slow, so the product $E_f \sum_f V$ can be treated as constant within that cycle. Consequently, if the load pattern repeats identically every day, the neutron flux can likewise be treated as a known periodic function with the same period.

2.2 Influence of Fission Products to Reactivity

To keep the scope of the study manageable, only a limited number of fission products were considered. Many fission products are affected by changes in neutron flux, but xenon-135 has by far the largest influence, owing to its larger absorption cross section. Using φ as the exogenous input, the time-dependent concentrations of iodine-135 and xenon-135 during power maneuvering are governed by the following coupled differential equations:

$$\dot{I} = \gamma_I \sum_f \varphi - \lambda_I I \quad (2)$$

$$\dot{X} = \gamma_X \sum_f \varphi + \lambda_I I - \lambda_X X - \sigma_X X \varphi \quad (3)$$

where I and X are the concentrations of iodine 135 and xenon 135, γ_I and γ_X are their direct fission yields, λ_I and λ_X are their decay constants, and σ_X is the microscopic absorption cross section of xenon 135.

In the core criticality balance the xenon reactivity can be approximated as follows:

$$\rho_X \approx -\frac{\sigma_X X}{v \sum_f} \quad (4)$$

where v is the average number of neutrons released per fission.

The calculated concentrations of iodine and xenon are used to determine whether the reactor has reached PSS. The two criteria used for this determination are described in the next section.

2.3 Two Criteria for Determining PSS

A calculation was performed in which the same neutron flux pattern is applied repeatedly over successive

cycles, and PSS was judged using the following two criteria:

Criterion 1 (system level): The relative error between the state vector x_n during cycle n , then x_n can be defined as $[p_1, p_2, p_3, \dots]$. The p_k is time series data which is calculate by model. The specified tolerance must be lower than $\|x_n - x_{n-1}\|/\|x_{n-1}\|$.

Criterion 2 (parameter of interest): Let $y(t)$ denote such a parameter of interest (or, more generally, a set of such variables, selected because they are the ones actually referenced when the operator determines a required reactivity-control action). For each cycle n , the maximum cycle-to-cycle deviation of $y(t)$ within the cycle must be lower than specific tolerance.

3. Results

In this paper, the state vector was constructed by treating the concentrations of iodine and xenon as the representative variables of core state, and the cycle at which the criterion 1 PSS condition is satisfied was then identified. Next, it was assumed that the operator offsets the core-averaged xenon reactivity through boron concentration control and control rod movement. Xenon reactivity was accordingly taken as the variable used to evaluate the criterion 2 PSS condition.

The parameters required to construct Equations (1)-(4) were taken from Table 1 of Esteki et al. [4]. Fig. 2 shows the relative power of the core, concentrations of iodine and xenon, and xenon reactivity according to the time. This study assumed 100-50-100% LFO, the daily load-following cycle was configured with the reactor held at 50% rated for 6 hours and at full power for 18 hours, following the operating pattern reported by the OECD Nuclear Energy Agency [5]. Fig. 2 shows the calculated concentrations of iodine and xenon, and corresponding xenon reactivity, over successive cycles of 100–50–100% LFO.

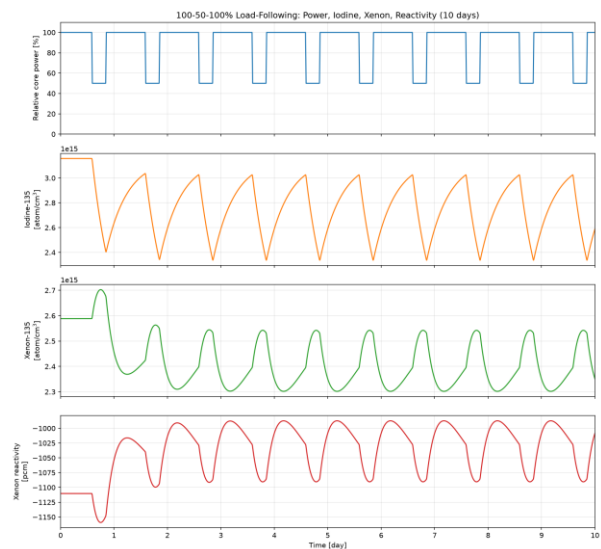


Fig. 2. Results of 100-50-100% load-following operation (power, concentrations of iodine and xenon, xenon reactivity for 10 days).

In Fig. 3, the blue line shows the number of cycles required to satisfy PSS when the criterion 1 tolerance is set to $1\text{E-}3$. The red line shows the number of cycles required when the cycle-to-cycle change in xenon reactivity is held to a tolerance of 5 pcm, following criterion 2. Under criterion 1, the reactor is found to reach PSS starting from the fourth cycle. Under criterion 2, however, the cycle-to-cycle change in xenon reactivity at the fourth cycle still slightly exceeds the tolerance (by less than 1 pcm), so PSS is not reached until the fifth cycle. It is worth noting that the minor fluctuations observed at higher cycle counts beyond the convergences (on the order of $1\text{E-}8$ for criterion 1 and $1\text{E-}5$ for criterion 2 in Fig. 3). Such fluctuations reflect the numerical round-off precision limit of the integration scheme.

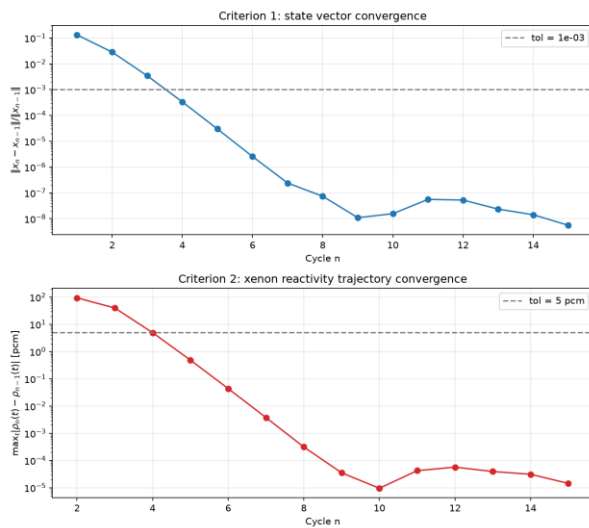


Fig. 3. Results of periodic steady state for criteria 1 and 2.

4. Discussion and Conclusion

The two PSS criteria proposed in this study each carry distinct advantages and disadvantages. Criterion 1 is general in that it can broadly judge whether the reactor has reached PSS without knowing in advance which variables actually influence the operator's reactivity control decisions during LFO. However, combining multiple state variables into a single state vector risks diluting the influence of the one variable most directly tied to reactivity control, since it gets averaged together with the others. This showed up in the case study itself: criterion 1 judged PSS to be reached at the fourth cycle, while criterion 2 did not register PSS until the fifth cycle, because the cycle-to-cycle change in xenon reactivity still slightly exceeded its tolerance. This suggests that criterion 1 can declare PSS somewhat earlier than criterion 2.

Criterion 2, in turn, ties its PSS judgement directly to the variable operators actually use for reactivity control, giving it a clearer interpretation and a more conservative safety margin. Its limitation is that it can only be applied once the relevant variable, the one that actually drives operator actions, has been identified in advance. In more complex situations, where several variables affect

reactivity control at once, even identifying that variable of interest may become difficult.

Future work can extend this study in several directions. First, since neutron flux was treated here as an exogenous input, the PSS concept should be re-examined using a closed-loop point-kinetics model that includes reactivity feedback and delayed neutron precursors. Second, a hybrid criterion that combined criteria 1 and 2 is worth investigating. Third, the information of critical variables (e.g., axial offset, xenon oscillation) must be additionally involved for the judgement of PSS. A thermal-hydraulic code coupled with neutronic calculation is desirable for incorporating such variables into the further analysis. Finally, future study should quantitatively verify whether achieving a PSS effectively reduces the potential for human error. Through these extensions, the PSS concept is expected to develop into a technical basis for standardizing reactivity-control procedures during LFO.

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