Sensitivity Study of 1D/2D Power Synthesis Method for PWR Flexible Operation

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1. INTRODUCTION

The rapid expansion of renewable energy in South Korea has imposed new operational demands on nuclear power plants. To accommodate the intermittent nature of renewable sources, OPR1000 PWRs, which have traditionally operated as inflexible baseload units, are now being required to adopt flexible, load-following operation. This paradigm shift demands more dynamic control of reactor power and more frequent maneuverability of control rods, placing greater demands on the accuracy and responsiveness of the core monitoring system.

Conventional power distribution synthesis systems such as CECOR rely on pre-generated libraries produced during the core design phase. Under flexible operation, however, the actual operating history deviates substantially from the design-basis assumptions embedded in these libraries, potentially introducing significant errors in the synthesized power distribution. This underscores the need for a synthesis method that does not depend on pre-calculated design libraries and can respond accurately to dynamic operating conditions.

For real-time core surveillance of Korean NPPs, KNF (KEPCO Nuclear Fuel) developed OASIS (Operational Core Analysis and Simulation System), an advanced online core monitoring system that reconstructs the 3D power distribution on-the-fly from fixed in-core detector (ICI) signals using the 3D Power Connection Method (3DPCM) [1]. Subsequently, KNF has been developing SIMON, a next-generation online core monitoring system, in which the 3D power distribution synthesis function is also an essential component. Given the real-time nature of online monitoring, computational performance is a critical requirement.

The 3DPCM employed in OASIS has been shown to have two fundamental issues: inaccuracies in the Power Sharing Factor and a strong 3D coupling between assemblies that distorts the synthesized axial power distribution when predicted and measured distributions differ [2]. These problems are expected to be exacerbated under flexible operation. To resolve them, an improved 1D+2D Power Connection Method (1D+2D PCM) was proposed [2], which decouples the axial and radial reconstruction steps, eliminates spurious cross-assembly coupling, and is well-suited to parallel computation for real-time performance.

In this paper, the applicability of the 1D+2D PCM to OPR1000 flexible operation is assessed through sensitivity analyses, and the technical basis for its adoption is established.

2. NUMERICAL METHOD

To resolve both issues identified in the 3D PCM, an improved 1D+2D PCM was proposed [2]. The synthesis procedure is decomposed into two sequential and structurally independent steps.

The axial measured power distribution for each instrumented assembly is determined using only its own five detector signals, completely eliminating cross-assembly coupling. The basic 1D power connection equation is:

$$2\,P_i^m \cdot PCF_i = P_{i-1}^m + P_{i+1}^m \qquad (4)$$

where

PCF_i : pre-generated power connection factor at node i (from calculated distribution).

P_i^m : measured power at node i (unknown).

However, the basic formulation still assumes the intra-detector power shape follows the calculated distribution. To remove this assumption, an intra-detector power redistribution factor α_{d_k} is introduced as an additional unknown:

$$2\,PCF_i \cdot P_i^m = P_{i-1}^m + P_{i+1}^m + \alpha_{d_k} \cdot P_i^c \qquad (5)$$

where α_{d_k} is intra-detector power redistribution factor for the k-th detector (unknown). The detector power conservation constraint is imposed for each of the K detectors:

$$\textstyle\sum_{j\in d_k} P_j^m = P_{d_k}^m \qquad (6)$$

where $P_{d_k}^m$ measured power of the k-th detector (known from ICI signal).

For a single assembly with N axial nodes and K detectors, the combined system of N equations from Eq. (5) and K equations from Eq. (6) is solved simultaneously for the N node powers and K redistribution factors. The intra-detector power shape is therefore approximated without prescribing the calculated shape, resolving the PSF issue.

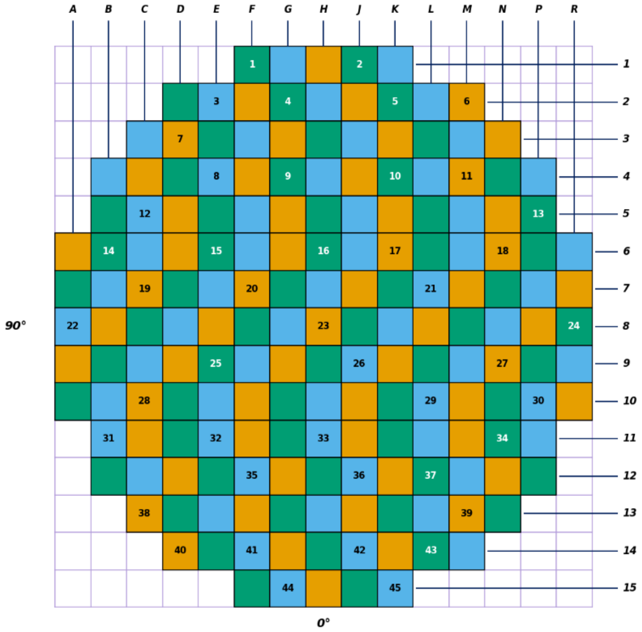

Fig. 1: *Detector radial locations*

Once the axial measured power distributions are established for all instrumented assemblies, the power distributions of uninstrumented assemblies are reconstructed using the radial power connection factor:

$$PCF_i = \frac{\sum_{r=1}^{N_{i,r}} P_{i,r}^c}{P_i^c \cdot N_{i,r}} \tag{7}$$

The measured power distribution for uninstrumented assemblies is then determined by satisfying the following system:

$$PCF_i \cdot P_i^u \cdot N_{i,r} - \sum_{r=1}^{N_{i,r}} P_{i,r}^u = \sum_{r=1}^{N_{i,r}} P_{i,r}^m \tag{8}$$

Because Steps 1 and 2 are structurally independent, they can be executed in parallel, which is highly beneficial for maximizing real-time computational performance in the online monitoring system.

3. NUMERICAL RESULTS

The target core for this study is the OPR1000 initial core operating at 50% full power (FP), which represents a typical steady-state load-following condition. To generate the Power Connection Factors (PCFs) required by the 1D+2D PCM, a reference flexible operation history is defined as follows: the reactor operates at 100% FP for 12 hours, ramps down from 100% to 50% FP over 6 hours, holds at 50% FP for 4 hours, and then ramps back up from 50% to 100% FP over 2 hours. All control rods are assumed to be fully withdrawn throughout the reference operation.

The PCFs are computed from the three-dimensional power distribution predicted by the neutronics code at the end of the 50% FP hold period of the reference flexible operation. These PCFs represent the theoretical basis against which the sensitivity of the synthesized power distribution is evaluated. It is important to note that this PCF generation procedure is entirely based on the reference (theoretical) operational history, and any deviation of the actual plant state from this reference directly affects the accuracy of the synthesized power distribution — this is precisely the quantity examined in the following sensitivity studies.

The first sensitivity study investigates the effect of a discrepancy between the operational power level at the time of core monitoring and the theoretical power level used for PCF generation (50% FP). In practice, the actual reactor power may differ from the reference level assumed during PCF calculation, and this difference can introduce errors in the synthesized 3D power distribution.

To quantify this effect, artificial measured power distributions are generated for power levels ranging from 40% to 60% FP with 2 percent intervals. For each power level, the core neutronics calculation is performed at the corresponding steady-state condition (with all control rods withdrawn and nominal inlet temperature for that power level), and the resulting assembly-wise power distribution is taken as the true reference distribution. The detector powers are then extracted from each of these distributions to serve as the artificial measured detector signals. A time step of one hour is assumed between consecutive power levels.

Using the fixed PCF set generated from the 50% FP reference flexible operation, and the artificially generated detector powers at each power level, the 1D+2D PCM synthesizes the 3D measured power distribution. The synthesized distribution is then compared with the true distribution at the corresponding power level. The calculation matrix is summarized in Table 1.

Table 1. Results of Synthesis Power Distribution at various Power level

Power (%)	RMS Error	2D Max. Error	3D Max. Error
40	0.30	0.66	1.09
42	0.24	0.55	0.89
44	0.18	0.40	0.71
46	0.12	0.28	0.46
48	0.07	0.14	0.28
50	0.00	0.00	0.00
52	0.07	0.14	0.27
54	0.12	0.26	0.45
56	0.17	0.36	0.63
58	0.22	0.48	0.84
60	0.27	0.60	1.04

After the evaluation of the sensitivity of the 1D+2D PCM reconstruction to operating-power mismatch using a fixed PCF set generated at 50% FP. As anticipated, the minimum error is observed at the reference condition (50% FP), where RMS, 2D maximum, and 3D maximum errors are nearly zero. Consequently, deviations from 50% FP result in a gradual, almost symmetric increase in all error metrics under both under-power and over-power conditions. At the largest mismatch considered (40% and 60% FP), RMS error remains below 0.30% while 3D maximum absolute error approaches 1.1%, hence indicating strong robustness of the synthesis method against moderate operational power deviations.

The second sensitivity study examines the effect of a discrepancy between the actual control rod position during monitoring and the control rod configuration assumed during PCF generation (all rods out). In flexible operation, partial insertion of control rods is a primary means of power maneuvering, and it significantly alters the 3D power distribution shape. If the PCF was generated under a rod-out condition but the actual monitoring state involves partial rod insertion, the synthesized power distribution may deviate from the true distribution.

To quantify this effect, the lead control rod bank R5 is partially inserted till to the depths of 10% during the flexible operation. For each control rod position, the neutronics calculation yields the true 3D power distribution, from which the detector powers are extracted as artificial measured signals. The PCF set generated from the reference 50% FP rod-out condition is used unchanged for all cases.

The synthesized power distributions obtained by combining the rod-out PCFs with the partial-insertion detector powers are then compared against the corresponding true distributions.

Table 2. Results of Synthesis Power Distribution at various control rod positions

Rod Position	RMS Error	2D Max. Error	3D Max. Error
90	0.65	0.70	17.66
91	0.57	0.59	15.32
92	0.41	0.39	10.76
93	0.22	0.17	4.89
94	0.18	0.16	4.01
95	0.11	0.12	2.08
96	0.08	0.09	1.13
97	0.06	0.08	0.82
98	0.05	0.05	0.38
99	0.04	0.05	0.26
100	0.00	0.00	0.00

1D+2D PCM reconstruction shows physically consistent rod-position dependence: as R5 withdrawal increases from 90% to 100%, full-core error decreases. This behavior is expected because deeper rod insertion produces stronger local spectral and flux-shape distortion, increasing reconstruction difficulty, while near-withdrawn conditions approach an easier, weakly perturbed state. The contrast between low RMS and higher 3D maximum at lower rod positions indicates that most mismatch is spatially localized rather than distributed across the core. From an operational and safety-analysis standpoint, global reconstruction fidelity is strong across all cases, but the limiting condition is the localized peak-error tail in the 90-94% range, which should remain the primary focus for peaking-factor and uncertainty-margin assessments.

4. CONCLUSION

This paper has investigated the applicability of the 1D+2D Power Connection Method to the OPR1000 flexible operation through two sensitivity studies. The first study evaluated the effect of a mismatch between the operational power level and the theoretical power level used for PCF generation, by examining artificially measured power distributions over the range of 40% to 60% FP (10% power deviation) and the second study assessed the impact of partial control rod insertions (R5 lead bank, 10% power), where the PCF was generated under the rod-out condition while running the 100%-50%-100% flexible operation scenario.

The results indicate that the 1D+2D PCM method is weakly sensitive to moderate operating-power mismatch. Errors are minimized at the reference condition (50% FP), with near-zero RMS, 2D max, and 3D max values. As power deviates from 50% FP, errors increase gradually and near-symmetrically for under-power and over-power cases. Even at 40% and 60% FP, performance remains strong (RMS < 0.30%, 3D max about 1.1%), confirming robust reconstruction under practical power deviations. Reconstruction accuracy improves as rod withdrawal increases, consistent with reactor physics expectations: stronger insertion causes more localized spectral/flux distortion and is harder to reconstruct, while near-withdrawn states are less perturbed. The pattern of low RMS but relatively higher 3D max at lower withdrawal indicates mostly localized mismatch rather than broad core-wide error. Operationally, global fidelity is strong across all cases; the main limiting condition is the localized peak-error tail in the 90–94% withdrawal range, which should guide peaking-factor and uncertainty-margin evaluation. These findings provide a quantitative basis for the application of the 1D+2D PCM to real-time core monitoring under flexible operation conditions, and identify the dominant sources of synthesis error that should be accounted for as considering acceptable uncertainty in future development.

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