Synthesis of Axial Power Distribution Using 5-Level Ex-core Detector in a Core Protection System

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1. Introduction

In ABB-CE digital plants, Core Protection Calculator System (CPCS) is used for a core protection based on several online measured system parameters including 3-level safety grade ex-core detector signals. The CPCS provides four independent channels for the departure from a nucleate boiling ratio (DNBR) and local power density (LPD) trip signals to the reactor protection system. Each channel consists of a core protection calculator (CPC) and a control element assembly calculator (CEAC).

The cubic spline synthesis technique has been used in online calculations of the core axial power distributions using 3-level ex-core detector signals in CPC[1]. The pre-determined cubic spline function sets are used depending on the characteristics of the ex-core detector responses. But this method shows large power distribution errors for the extremely skewed axial shapes due to restrictive function sets and an incorrect SAM value. Especially thus situation is worse at a higher burnup.

To solve these problems, the cubic spline function sets are improved and it is demonstrated that the axial power shapes can be synthesized more accurately with the new function sets than those of a conventional CPC [2].

In this paper, synthesis of an axial power distribution using a 5-level ex-core detector is described and the axial power distributions are compared between 3-level and 5-level ex-core detector systems.

2. Method and Results

2.1 Cubic Spline Synthesis Method

The cubic spline synthesis assumes the core axial power distribution to be a sum of the splines[3].

$$\phi(z) = \sum a_i \mu_i(z) \qquad (1)$$

The various axial power distributions are classified depending on their characteristics, i.e., center peak, top and bottom peaked, saddle types. Figure 1 shows a schematic of the cubic spline synthesis for a 5-level ex-core detector system. Active core height is divided into 6 intervals. The cubic spline basis function is shown in Figure 2 and defined as follows:

$$\mu_i(z) = f_1(\eta_1) \qquad \text{for } z_{i-2} \leq z \leq z_{i-1}$$
$$\mu_i(z) = f_2(\eta_2) \qquad \text{for } z_{i-1} \leq z \leq z_i$$

$$\mu_i(z) = f_2(\eta_3) \qquad \text{for } z_i \leq z \leq z_{i+1}$$
$$\mu_i(z) = f_1(\eta_4) \qquad \text{for } z_{i+1} \leq z \leq z_{i+2}$$
$$\mu_i(z) = 0 \qquad \text{for } z > z_{i+2} \text{ or } z < z_{i-2}$$

where,

$$\eta_1 = (z - z_{i-2})/(z_{i-1} - z_{i-2}), \quad \eta_2 = (z - z_{i-1})/(z_i - z_{i-1})$$
$$\eta_3 = (z_{i+1} - z)/(z_{i+1} - z_i), \quad \eta_4 = (z_{i+2} - z)/(z_{i+2} - z_{i+1})$$
$$f_1(\eta) = 0.25 \cdot \eta^3, \quad f_2(\eta) = 0.25 + 0.75(\eta + \eta^2 - \eta^3)$$

Amplitude coefficients can be computed by performing a matrix multiplication. In the following equations, $\overline{H^{-1}}, \overline{B}$ are the inverse spline matrix and the vector of the detector responses including the boundary point powers, respectively. The spline matrix is determined depending on the spline nodal assignments in each spline zone(Intervals A to F in Fig. 1). An appropriate number of axial nodes should be assigned in each spline zone. Hence, the sum of the number of axial nodes in a function set must be equal to the total number of axial nodes.

Amplitude coefficients are found to satisfy the following conditions.

• Detector response
$$D_i = \int_i \phi(z) dz \qquad (2)$$
• Two empirical boundary point powers
$$\phi(0) = \alpha_1 \cdot D_5 + \alpha_2 \quad \text{(top)} \qquad (3)$$
$$\phi(H) = \alpha_3 \cdot D_1 + \alpha_4 \quad \text{(bottom)} \qquad (4)$$
• Two extrapolated boundary conditions
$$\phi(-\delta) = 0.0 \qquad (5)$$
$$\phi(H + \delta) = 0.0 \qquad (6)$$
• Amplitude coefficients of matrix form
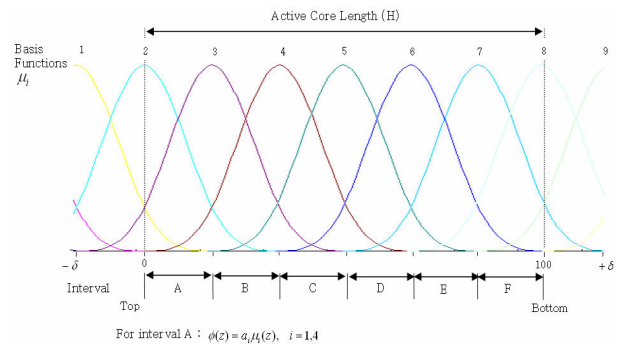$$\overline{A} = \overline{H^{-1}} \cdot \overline{B} \qquad (7)$$

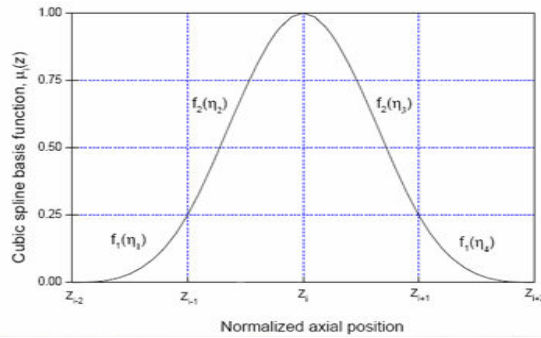Figure 1. Schematic of cubic spline synthesis for 5-level ex-core detector system.

Figure 2. Cubic spline basis function.

Finally, core axial power distribution can be synthesized by the Eq. (1) using the amplitude coefficients vector and the cubic spline basis function.

2.2 Synthesis of Axial Power Distribution

In order to demonstrate the applicability of the improved 5-level ex-core detector signals, various axial power shapes are generated for the Yonggwang unit 3 cycle 1. The MASTER[4] code is used to generated the axial data for various plant conditions such as BOC, MOC and EOC at a 100% steady state power. Then calculated axial power distributions are converted into 5-level detector responses using Eq. (2).

From the above 5-level ex-core detector responses, axial power distributions are synthesized by using the cubic spline generation program and compared with the reference results which are simulated by the MASTER code.

Figure 3 shows the typical center-peaked axial power shapes at BOC. Synthesized power shapes with 3-level and 5-level ex-core detector signals agree well with the reference shape.
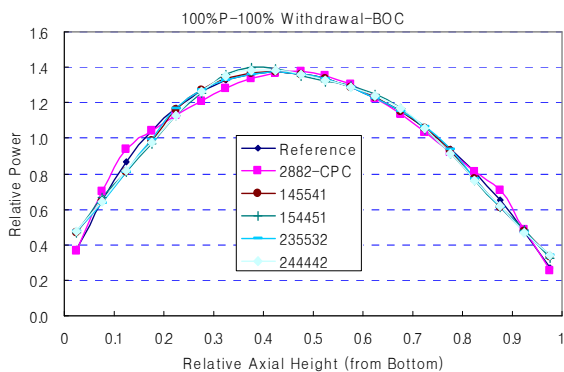

Figure 3. Synthesized center-peaked axial power shape.

However, for the bottom peaked axial shape, as shown in Figure 4, the synthesized shape with the 2837 function set shows a large difference from the reference axial shape. The 2837 function set is a currently used function set with a 3-level ex-core detector in a CPC for a categorized shape ($34 \leq P_2 < 40$ and $|P_1-P_3| > 35$). On the other hand, synthesized axial shapes with 5-level ex-core detector signals agree well with the reference shape.

For the various test results, the more the axial power distribution is skewed the more it can be synthesized more accurately with the 5-level ex-core detector system than with the 3-level system. After all, this result will lead to the improvement of a thermal margin by reducing the RMS error for an axial power distribution.
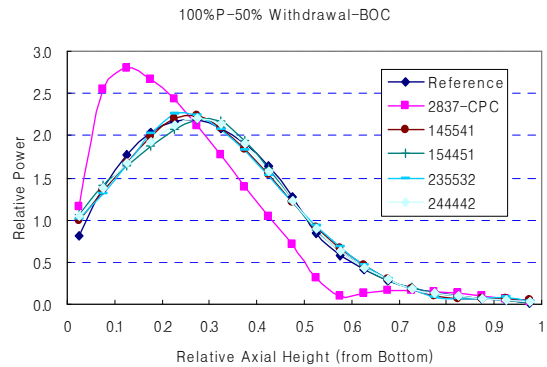

Figure 4. Synthesized bottom-peaked axial power shape.

3. Conclusion

For Yonggwang unit 3 cycle 1, various axial power distributions are simulated by applying the cubic spline method with 5-level ex-core detector signals. Then the synthesized axial shapes are compared with the neutronics code results and conventional 3-level detector results.

It proves that the synthesis of an axial power distribution using 5-level ex-core detector signals appears to be better than that of the conventional 3-level ex-core detector, especially for the strongly distorted shapes. From the above result, improvement of the thermal margin is expected because of a more accurate axial power distribution. However, more detailed study for the various power shapes is needed as a future work.

Acknowledgement

REFERENCES

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[2] B. S. Koo et al., Improvement of the Cubic Spline Function Sets for a Synthesis of the Axial Power Distribution of a Core Protection System, Transaction of KNS Autumn meeting, Gyeongju, November 2-3, 2006.
[3] W. K. In et al., "On-line Core Axial Power Distribution Synthesis Method from In-core and Ex-core Neutron Detectors", KAERI/TR-1415, 1999.
[4] J. Y. Cho et al., "MASTER 3.0 User's Manual", KAERI/UM-8, 2004.