Improvement of the Cubic Spline Function Sets for a Synthesis of the Axial Power Distribution of a Core Protection System

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1. Introduction

Online digital core protection system(SCOPS) for a system-integrated modular reactor is being developed as a part of a plant protection system at KAERI. SCOPS[1] calculates the minimum CHFR and maximum LPD based on several online measured system parameters including 3-level ex-core detector signals.

In conventional ABB-CE digital power plants, cubic spline synthesis technique has been used in online calculations of the core axial power distributions using ex-core detector signals once every 1 second in CPC[2]. In CPC, pre-determined cubic spline function sets are used depending on the characteristics of the ex-core detector responses. But this method shows an un-negligible power distribution error for the extremely skewed axial shapes by using restrictive function sets.

Therefore, this paper describes the cubic spline method for the synthesis of an axial power distribution and it generates several new cubic spline function sets for the application of the core protection system, especially for the severely distorted power shapes needed reactor type.

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 and the axial power shape is determined as follows[3].

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

Where, $\phi(z)$ = Neutron flux at axial location z

a_i = Amplitude coefficients

$\mu_i(z)$ = Cubic spline basis functions

The various axial power distributions are classified depending on their characteristics, i.e., center peak, top and bottom peaked, saddle types. As shown in Figure 1, the active core height is divided into 4 intervals and an appropriate number of nodes for each interval is assigned based on the categorized axial power shapes. Figure 2 shows the cubic spline basis function.

Amplitude coefficients(a_i) could be computed by performing the matrix multiplication. In the following equation, H^{1}, B_j means the inverse spline matrix and the vector of the detector responses including the boundary point powers, respectively.

$$a_i = \sum_{j=1}^{5} B_j \cdot H^{-1} \quad (i = 2,3,\ldots,6)$$

The cubic spline method is needed to determine the boundary point power correlation coefficients(BPPCC) and the spline matrix H^{-1}. The BPPCC are empirically determined from the axial power distribution and the detector signals. The spline matrix is then determined depending on the spline nodal assignments in each spline zone. An appropriate number of axial nodes should be assigned in each spline zone. In other words, the number of nodes between the spline regions is chosen based on the relative detector signals such as the middle detector power integral and the magnitude of the top to bottom difference in the power integrals.

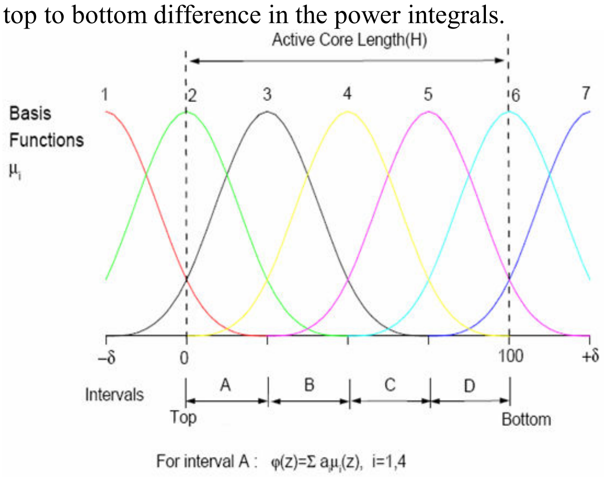

Figure 1. Schematic of cubic spline synthesis for 3-level ex-core detector system.

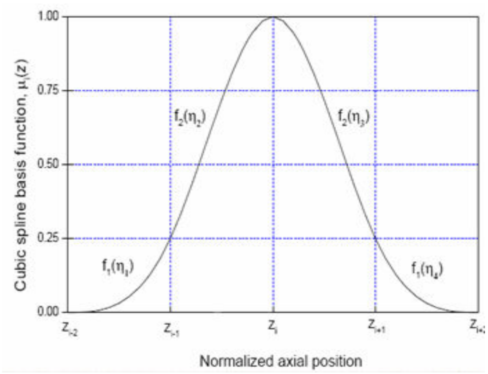

Figure 2. Cubic spline basis function.

A function set can be described conveniently as follows. In Figure 1, function set 2882 means that there are 2 nodes in interval A, 8 nodes in interval B, 8 nodes in interval C and 2 nodes in interval D. Hence, the sum of the number of axial nodes in a function set must be equal to the total number of axial nodes.

2.2 Function Set Evaluation

About 600 cases of axial power shapes were generated for the Yonggwang unit 3(cycle 1) by using the MASTER[4] code. For every case, 81 function sets were used to synthesize the axial power shapes. Where the sum of the nodes in two regions(Interval A+B or C+D) is restricted to 10, because there are too many possible combinations if this constraint is not considered.

Pre-calculated axial power distributions were used for the generation of 3 detector responses. Detector responses were determined by a core volume weight average. Thus, for the 20 node 3-level ex-core detector system used here, the general equation becomes,

$$P_1 = 0.05\left(\frac{2}{3}FZ_{14} + \sum_{i=15}^{20} FZ_i\right)$$
$$P_2 = 0.05\left(\frac{1}{3}FZ_7 + \sum_{i=8}^{13} FZ_i + \frac{1}{3}FZ_{14}\right)$$
$$P_3 = 0.05\left(\frac{2}{3}FZ_7 + \sum_{i=1}^{6} FZ_i\right)$$

From the above detector response, axial power distribution was synthesized by using the cubic spline method and compared with the reference results simulated by neutronics code. Figure 3 shows the comparison of the center-peaked axial power shape which is a typical shape at BOC. The synthesized power shapes agree well with the reference shape. However, as shown in Figure 4, axial shape by the 2837 function(currently used function set in a CPC for the categorized shape($34 \leq P_2 < 40$ and $|P_1-P_3| > 35$) shows a large difference with the reference shape. This means that some of the currently used spline function sets are not good for the special cases(for example, extremely skewed shapes) and therefore an additional function set should be considered to reduce the difference. 600 axial power shapes using 81 function sets were categorized and an appropriate function set was selected as shown in Table 1. Finally the selected function sets are summarized in Table 1. Where, a function set which satisfies the symmetric condition(nodal assignment) was only chosen for the top-peaked and bottom-peaked power shape.

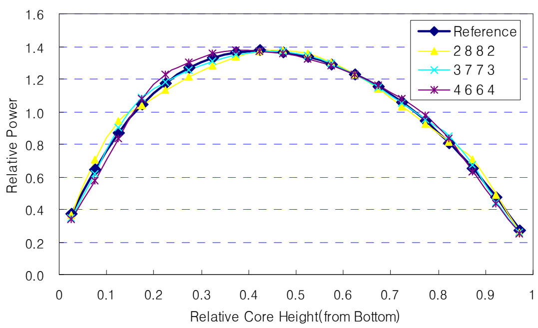

Figure 3. Comparison of center-peaked axial power shape.

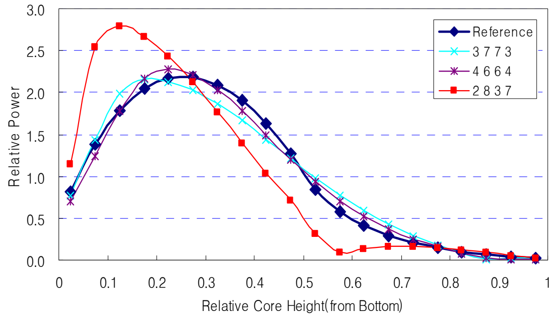

Figure 4. Comparison of bottom-peaked axial power shape.

Table 1. Summary of spline function sets for 3-level detector systems.

k	Shape	P_2(%)	$\Delta = \|P_1-P_3\|$	Function sets
1	Center peak	> 40	< 12	3773
2	Center peak	> 40	$12 \leq \Delta < 30$	2882
3	Center peak	> 40	$30 \leq \Delta < 40$	3773
4	Center peak	> 40	$40 \geq$	4664
5	Flat	$34 \leq P_2 < 40$	< 25	2882
6	Flat	$34 \leq P_2 < 40$	$25 \leq \Delta < 35$	3773
7	Flat	$34 \leq P_2 < 40$	≥ 35	3773
8	Saddle	< 34	< 20	2882
9	Saddle	< 34	$20 \leq \Delta < 40$	3773
10	Saddle	< 34	≥ 40	3773

3. Conclusion

Axial power distribution was calculated by applying the cubic spline method and compared with the neutronics code results. In addition, several new cubic spline function sets were generated for the drastically distorted axial shapes for an application to a core protection system. It demonstrates that the newly generated function sets appear to be better than that of the conventional CPC from the aspect of an axial power synthesis particularly for the much distorted shapes. However, more detailed analysis for the various power shapes is needed as a future work.

Acknowledgement

This research has been performed under the nuclear R&D program supported by the Ministry of Science and Technology of Korean Government. I wish to express my personal thanks to Dr. Wang-Kee In for the supporting of cubic spline generation program.

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