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THE HIGHER ORDER FLUX MAPPING METHOD IN LARGE SIZE PHWRs

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Abstract

A new higher order method is proposed for obtaining flux map using single set of expansion mode. In this procedure, one can make use of the difference between predicted value of detector reading and their actual values for determining the strength of local fluxes around detector site. The local fluxes are arising due to constant perturbation changes (both extrinsic and intrinsic) taking place in the rector.

1. INTRODUCTION.

Large reactor systems, such as Indian 500 MW(e) PHWRs, are known to sustain power tilts following minor local perturbations. If these tilts are not controlled, they can lead to unacceptable power distribution. This can result in an economic penalty. Therefore it is essential to have in-core flux measurements, and to process these measurements to get accurate knowledge of the operating state of the reactor. With the help of the On-line Flux Mapping System (OFMS), a virtually continuous power regulating system, then, can maintain the core power distribution closer to the design values [1].

The Self powered Neutron Detectors (SPNDs) are employed to measure the point thermal fluxes in the reactors. The electrical signals generated by these detectors, on absorption of the neutron and followed by β^- decay, are fed as an input to the flux mapping procedure. In flux mapping, the instantaneous flux distribution is expressed in terms of finite number of λ modes (corresponding to the nominal operating state of the reactor), while the modal amplitudes are determined in such a way that, the least square error between the actual detector readings and synthesized flux values at detector sites is minimum.

It is apparent that there would be inherent errors present in the flux map, generated by OFMS due to following reasons : (1) Flux synthesis errors, as limited number of flux modes are used in obtaining the flux map. (2) The numerical truncation + round off errors in calculating the higher harmonics of the diffusion equation itself.(3) Random errors accompanying the online flux measurements, and their propagation to the estimated flux map.

In order to reduce the synthesis errors in the predicted flux map during the reactor operation under the perturbed conditions, the basis set (i.e. set of predetermined λ modes) is expanded by adding appropriate perturbation modes such as adjuster rod shim modes, control absorber modes, start up modes. A perturbed mode basis is said to have formed, when perturbation modes are added to standard mode basis [2].

Since each mode basis is stored on the online computer and depending upon the operating state of the reactor proper basis set is to be selected for getting the flux map, this procedure of flux mapping needs the operator intervention for selection of the particular basis set. This will definitely increase the administrative efforts. Furthermore in this procedure, only limited number of device perturbations modes corresponding to the predetermined patterns of devices are available for flux mapping. It is possible that this perturbed mode set might be grossly insufficient for determining the flux map in some prevailing operating conditions of the reactor. Therefore the best alternative is to carry out the flux mapping operations with the help of a single basis set. It is apparent that some sort of auxiliary procedure will be needed to improve the accuracy of the flux map for those core configurations which are having strong perturbations.

In this paper we are going to discuss the higher order method for obtaining the flux map using the single basic set for expansion with newly developed auxiliary method. We are also going to present analysis of this procedure.

2. LEAST SQUARE PROCEDURE FOR FLUX MAPPING

The basic assumption of the flux mapping software is that the instantaneous thermal flux inside the reactor can be represented by the linear combination of a set of predetermined modes.

$$\Phi(\bar{r}) = \sum_{J=1}^{S} A_J \Psi_J(\bar{r}) \quad (1)$$

where,

$\Phi(\bar{r})$ is the instantaneous thermal flux, and, $\Psi_J(\bar{r})$ higher modes / flux distributions which are normally encountered in an operating reactor.

The aim of the flux mapping procedure is to obtain the combining coefficients A_j (and therefore the flux profile) from the measured flux levels. Since the equation (14) is valid at all points inside the reactor, it is also valid at the detector sites, we can rewrite it in matrix form at the detector sites as,

$$\begin{bmatrix} D_d \end{bmatrix}_{Rx1} = \begin{bmatrix} M_{dj} \end{bmatrix}_{RxS} \bullet \begin{bmatrix} A_j \end{bmatrix}_{Sx1} \tag{2}$$

The flux equation at the selected points can also be written in a matrix form as follows,

$$\begin{bmatrix} F_n \end{bmatrix}_{Kx1} = \begin{bmatrix} N_{nj} \end{bmatrix}_{KxS} \bullet \begin{bmatrix} A_j \end{bmatrix}_{Sx1} \tag{3}$$

where,

R	Number of flux mapping detectors.
S	Number of modes / flux profiles chosen for the expansion.
K	Number of points at which flux map is required.
D_d	detector reading of the d^{th} flux mapping detector.
M_{dj}	j^{th} mode / flux distribution value at d^{th} flux mapping detector site.
A_j	combining coefficient for j^{th} mode.
F_n	flux map estimated at n^{th} flux mapping point.
N_{nj}	j^{th} mode / flux distribution value at n^{th} flux mapping point.

Since in general the number of detectors are more than the number of modes chosen for the instantaneous flux expansion,the equation (15) is a set of inconsistent equations Therefore to solve these equations a Least Square (LS) approximation is employed. Defining

$$\begin{bmatrix} P_{jd} \end{bmatrix}_{SxR} = \begin{bmatrix} M_{dj} \end{bmatrix}^{-1}_{RxS}$$

$$\begin{bmatrix} P_{jd} \end{bmatrix}_{SxR} = \begin{bmatrix} \begin{bmatrix} M_{jd} \end{bmatrix}^{T}_{SxR} * \begin{bmatrix} M_{dj} \end{bmatrix}_{RxS} \end{bmatrix}^{-1} * \begin{bmatrix} M_{jd} \end{bmatrix}^{T}_{R} \tag{4}$$

$\begin{bmatrix} P_{jd} \end{bmatrix}_{SxR}$ is called as generalized inverse of $\begin{bmatrix} M_{dj} \end{bmatrix}_{RxS}$

Using equation (17), the equations for $\begin{bmatrix} A_j \end{bmatrix}_{Sx1}$ and $\begin{bmatrix} F_n \end{bmatrix}_{Kx1}$, become

$$\left[A_J\right]_{Sx1} = \left[P_{Jd}\right]_{SxR} \bullet \left[D_d\right]_{Rx1} \tag{5a}$$

$$\left[F_n\right]_{Kx1} = \left[N_{nJ}\right]_{KxS} \bullet \left[A_J\right]_{Sx1} \tag{5b}$$

Equations (5a) and (5b) are the working equations for flux mapping procedure.

3. HIGHER ORDER METHOD.

A novel refinement of the modal expansion method of flux mapping involves use of local flux correction functions. The total flux at any flux mapping site is assumed to separable into global component and a local component. The global component of the perturbed flux describes the propagation of perturbed flux due to neutron multiplication effects in the core, while the local flux describes the propagation of the perturbed flux due to the cross-sectional changes in the core. The local effect thus depends only on the cross-section at the site of perturbation and is attenuated by the absorption outside the perturbation region without propagation due to the neutron multiplication. Therefore the local flux effect in not present in the modes generated, since these modes have been generated for the unperturbed reference core. The local flux effect are modeled from an approximation to the solution of the local flux changes in source / sink model [3]. They appear as incremental flux change at the site of perturbation through the local multiplication factor. This increment flux extends beyond the region of perturbation to the surrounding region. It is assumed that any perturbation in the core is simulated by affecting the proper changes in the absorption cross-section of the thermal group in the perturbation zone. This will lead to the changes in flux level at the perturbation site. The diffusion equation for the perturbation site is

$$\begin{bmatrix} \nu\Sigma_{f1} & \nu\Sigma_{f2} \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \phi_1 + \Delta\Phi_1 \\ \Phi_2 + \Delta\Phi_2 \end{bmatrix} - \begin{bmatrix} -D_1\nabla^2+\Sigma_{r1} & 0 \\ -\Sigma_{12} & -D_2\nabla^2+(\Sigma_{a2}+\Delta\Sigma) \end{bmatrix} \begin{bmatrix} \phi_1 + \Delta\Phi_1 \\ \Phi_2 + \Delta\Phi_2 \end{bmatrix}$$

$$= \begin{bmatrix} \nu\Sigma_{f1} & \nu\Sigma_{f2} \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \Delta\Phi_1 \\ \Delta\Phi_2 \end{bmatrix} \tag{6}$$

After certain rearrangement of terms, we get

$$\begin{bmatrix} \Sigma_{r1} & o \\ -\Sigma_{12} & \Sigma_{a2} + \Delta\Sigma \end{bmatrix} \begin{bmatrix} \Delta\Phi_1 \\ \Delta\Phi_2 \end{bmatrix} = - \begin{bmatrix} o & o \\ o & \Delta\Sigma \end{bmatrix} \begin{bmatrix} \Phi_1 \\ \Phi_2 \end{bmatrix} \tag{7}$$

which gives the incremental fast flux $\Delta\Phi_1 = o$, and incremental thermal flux as,

$$\Delta\Phi_2 = \frac{\Delta\Sigma}{\Sigma_a + \Delta\Sigma} \Phi_2 \tag{8}$$

The attenuation of this incremental flux to other region is determined by the source calculation.

Thus the local flux effect functions are used for accounting the local flux changes induced due to the material configuration changes around the detector locations. As seen above the local flux effects are dependent only on the cross-sectional changes and are attenuated by absorption without propagation through the neutron multiplication. These changes are obtained from the flux distribution prevalent in the reactor due to fictitious neutron source kept around the detector [4]. The local flux change at the detector site is $\Delta\Phi_2(r_d)$ is dependent on the strength of the fictitious source around the detector site and the strength of the source is determined from the error between the actual detector reading and the predicted flux map at the detector site. It is further assumed that the local flux effect from all detector readings can be superimposed. Therefore this method of flux mapping would be as follows :-

The preliminary flux map is obtained using only the standard mode set (set of λ modes) for any operating condition of the reactor. The errors between actual and predicted values of detector readings are determined. These errors are used to estimate the local flux effects and further the corrections in the flux map.

4. GENERATION OF MODE DATA.

Higher modes are generated by the code MONICA [5] for their use in flux mapping procedure. These modes are corresponding to the nominal operating state of the reactors which means :

1) Reactor is in equilibrium burnup state.
2) No poison in moderator.
3) Adjuster rods fully in.
4) Zone controller are filled on an average 42 % .
5) All shut off rods are out.

In Table 1 we are giving the modes and their eigenvalue as obtained by code MONICA. We found that these modes are adequate for the purpose of flux map simulations.

5. GENERATION OF DETECTOR READINGS.

The most important input component of the flux mapping procedure is the FM detector readings. Since the online detector readings would become available only from an operating reactor, at present these readings have been estimated numerically from the power profile obtained during the simulation of our fuel management code TRIVENI [6]. The procedure adopted for obtaining the detector readings is discussed below in brief.

TRIVENI simulation is done for the desired Reactivity Device (RD) and burnup configuration for which the flux map is sought. TRIVENI calculates the average fluxes in uniform parallelepiped meshes. The detector tubes are inserted vertically. Since their distance from axial midplane is not normally a integral multiple of the fuel bundle length, the detector readings are derived from TRIVENI fluxes in two steps. Mean fluxes in three consecutive axial points adjoining the given detector location is found first as the average of the surrounding four radial meshes. Then the flux at the detector location is obtained by a parabolic interpolation [7].

6. RESULTS & DISCUSSION.

The detector readings were obtained numerically for the following core configurations, without superimposing the random errors. :

(A) Fresh fuel core configuration with burnup distribution generated from standard Pattern Age approximation and the RD positions are as follows,

1) No poison in moderator.
2) Adjuster rods fully in.
3) Zone controller are filled on an average 42 % .
4) All shut off rods are out.

(B) The core configuration as in case (A) plus Bank-1 of adjuster rods is withdrawn.

(C) The core configuration as in case (A) plus Bank-1 and Bank-2 of adjuster rods are withdrawn.

(D) The core configuration as in case (A) plus Bank-1 Bank-2 and Bank-3 of adjuster rods are withdrawn.

(E) The core configuration as in case (A) plus all banks adjuster rods are withdrawn.

The flux map is obtained for all above configurations using normal as well as higher order flux mapping procedure.

For assessing the predictions of the flux map, 500 flux points distributed uniformly throughout the core were chosen. Table 2 gives the comparisons of predicted flux map and TRIVENI fluxes in terms of maximum and rms errors for 102 detector sites as well as the 500 selected flux sites. It was found that the RMS errors in all 500 points was found to be 2.6 % for normal procedure and 2.3 % for higher order method. It is clear that since the detector readings are exactly matched in higher order procedure, there would be no spread in their predicted value of the flux map. The Maximum error value remains same indicates that the local flux effect dies down from all detectors before reaching at that point.

Table 3 give comparisons of predicted flux map with moderately strong perturbations such withdrawal of number of adjuster banks. As in case of nominal equilibrium case the maximum errors (both under predicted and over predicted) remain unchanged due the the fact that the local flux does not affect their prediction in the present model.

Table 4 gives the flux map comparisons of core follow up studies from fresh core up to 140 Full Power Days (FPDs) using normal and higher order flux mapping method. It can be seen the flux map prediction are better in case of higher order method.

7. CONCLUSIONS.

From present analysis, it can be concluded that the fundamental + 18 higher λ modes are sufficient for obtaining the flux map in case of small perturbations. In case of larger perturbations like movement of adjuster banks, the predictability of the flux map can be improved by making use of higher order flux mapping method. It can be noted that the basis set is not expanded by adding the perturbation modes correspond to the movement of adjuster rod banks. It can be possible to refine this technique to predict the flux map within the tolerated accuracy with this expansion mode set.

Table 1

Modes used for expansion of flux & precursor concentration

NO	NAME OF THE MODE	EIGENVALUE
1	FUNDAMENTAL MODE	1.00537
2	FIRST AZIMUTHAL (1)	0.99036
3	FIRST AZIMUTHAL (2)	0.98934
4	SECOND AZIMUTHAL (1)	0.96671
5	SECOND AZIMUTHAL (2)	0.96566
6	THIRD AZIMUTHAL (1)	0.93782
7	THIRD AZIMUTHAL (2)	0.93334
8	SECOND AXIAL	0.95154
9	FIRST RADIAL	0.93831
10	SECOND AXIAL * FIRST AZIMUTHAL (1)	0.92742
11	SECOND AXIAL * FIRST AZIMUTHAL (2)	0.92573
12	FIRST AXIAL	0.98364
13	FIRST AXIAL * FIRST AZIMUTHAL (1)	0.96705
14	FIRST AXIAL * FIRST AZIMUTHAL (2)	0.96586
15	FIRST AXIAL * SECOND AZIMUTHAL (1)	0.94222
16	FIRST AXIAL * SECOND AZIMUTHAL (2)	0.94154
17	FIRST AXIAL * THIRD AZIMUTHAL (1)	0.91377
18	FIRST AXIAL * THIRD AZIMUTHAL (2)	0.90860
19	FIRST AXIAL * FIRST RADIAL	0.92914

Table 2

Flux shapes comparisons between
TRIVENI fluxes and predicted flux map
for the equilibrium case.

	102 Detector sites		500 flux map sites	
	Normal	Higher	Normal	Higher
1). % rms error.	1.8	---	2.6	2.3
2). % maximum under prediction error.	-6.9	---	-10.4	-10.4
3). % maximum over prediction error.	2.5	---	2.5	2.5
4). Number of points having errors between ± 2 %	80	102	334	372

$$\% \text{ error} = \frac{(\text{Predicted})-(\text{TRIVENI})}{(\text{TRIVENI})} \times 100$$

Table 3

Flux shapes comparisons between TRIVENI fluxes and predicted flux map

	Case B	Case C	Case D	Case E
A) 102 Detector sites				
% rms error	1.7	3.9	3.6	5.9
% max error (under prediction)	-7.2	-14.9	-17.2	-23.2
% max error (over prediction)	3.1	6.3	6.1	14.2
number of points (closely predicted)	89	71	45	44
B) 500 Flux map sites				
% rms error	2.7	4.0	4.8	7.8
% max error (under prediction)	-8.8	-15.4	-14.2	-22.7
% max error (over prediction)	8.1	8.6	9.4	17.2
number of points (closely predicted)	330	252	188	114
C) 500 Flux map sites				
% rms error	2.4	3.8	4.5	7.2
% max error (under prediction)	-8.8	-15.4	-14.2	-22.7
% max error (over prediction)	8.1	8.6	9.3	16.8
number of points (closely predicted)	355	295	226	152

A	Normal procedure.
B	Normal procedure
C	Higher order procedure.

Table 4

Flux Map Comparisons during Core follow up

FPDs	Flux Map Comparisons Normal procedure			Flux Map Companions Higher Order procedure		
	% rms err	% max err	pts	% rms err	% max err	pts
0	2.58	10.4	334	2.36	10.4	371
10	2.49	9.4	333	2.27	9.4	375
20	2.68	10.5	323	2.45	10.5	364
30	2.72	10.8	338	2.47	10.8	364
40	2.44	9.5	350	2.21	9.5	384
50	2.22	8.3	368	2.01	8.3	397
60	1.99	7.0	380	1.80	7.0	406
70	1.67	5.3	413	1.51	5.3	428
80	1.42	5.2	428	1.29	5.3	443
90	1.29	5.1	449	1.18	5.1	456
100	1.33	5.0	440	1.23	5.0	453
110	1.59	4.9	401	1.43	4.9	425
120	1.93	5.2	347	1.71	5.2	386
130	2.32	6.0	301	2.04	6.0	350
140	2.74	7.6	253	2.39	7.6	317

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