ANALYTICAL EVALUATION OF THE UNCERTAINTY OF ON-LINE AXIAL POWER DISTRIBUTION MEASUREMENT WITH THE FOUR-SECTION EX-CORE DETECTOR

Jumpei Matsumoto, Kazuya Seki, Yasuo Komano
Mitsubishi Heavy Industries, Ltd.
Minatomirai, Nishi-Ku, Yokohama, Japan

Abstract

The four-section ex-core detector for PWRs has been developed for the advanced core monitoring and protection. This paper presents the study of the uncertainty evaluation of on-line axial power distribution measurement with the four-section ex-core detector. The study is analytically made for Advanced PWR (APWR) plants to determine the uncertainty. The results show that the four-section detectors monitor the axial power distribution with a good accuracy even in the anticipated transients and load follow operation and the measurement error can be kept sufficiently small for the core monitoring and protection by the adequate frequency of the in-core / ex-core calibration.

Introduction

The four-section ex-core detector for PWRs has been developed for the advanced core monitoring and protection. This ex-core detector has four neutron detectors which are axially arranged outside the reactor vessel, and makes on-line measurements of the axial core power distribution. Each detector monitors the power of the axial quarter with its centre at the same elevation as that of the detector's centre, and the axial power distribution is reproduced from the signals of the four detectors using the Fourier series fitting technique.

In the conventional PWRs, the axial imbalance (delta-I) between the upper half and lower one of the core can be only measured with the two-section ex-core detector which consists of two axially arranged detectors. In the case of the four-section detector system, however, the axial power distribution can be monitored and the local linear power can be calculated from the distribution. Therefore, the plant capability such as the plant operating margin can be considerably improved using the four-section detector system.

The uncertainty evaluation of the axial power distribution measurement with the four-section detector is important, because the improvement of the plant capability depends on the uncertainty of the measurement. The detailed study is analytically made for APWR plant on the measuring uncertainty of the axial power shape with the four-section detectors based on the following background.

- Analytical evaluation is essential for determining the uncertainty in the anticipated transients and the load follow operation which make the axial power peaking worse and never occurs during operational plant experiments at any domestic plants.

- Instrumentation error of the signal conditioning circuit for the ex-core detectors propagates in a complicated way and it can not be definitely said the most penalised case is observed in the operational plant experiments.

This paper, accordingly, presents the analytical evaluation of the measurement uncertainty of the axial power distribution with the four-section ex-core detector.

System description

The four-section ex-core neutron detector is composed of four neutron detectors axially installed in the biological shield outside the reactor vessel. The current output from each detector is converted to voltage, and from analog to digital, and inputted to a μ-processor. The axial power distribution, P(z), is then calculated in the μ-processor. The system configuration is detailed in Figure 1.

The axial power distribution is reproduced by fitting the Fourier series to the four axial quarter powers which are calculated from detector currents by the correction matrix. The distribution is corrected by the point-wise correction factors and normalised. Usually, the correction matrix is calibrated by the in-core / ex-core calibration, and the point-wise correction factor is calibrated by a monthly in-core flux mapping. This algorithm is presented as follows, and is described in detail in Ref. 1 & 2.

$$[Qj] = [Aij]^{-1}[Ii] \quad 1\ i,\ j\ 4$$
$$[P''k] = [Fkj]\ [Qj] \quad 1\ k\ M$$
$$[P'k] = [Ck * P''k]$$
$$[Pk] = [P'k / S]$$

where

$$S = \int_{k=1}^{M} P'k/M$$

[Ii]: Vector of the detector currents;

[Aij]: Correction matrix calibrated by an in-core / ex-core calibration, Aij represents the i-th detector response to the j-th axial quadrant power;

[Qj]: Vector of the axial quadrant powers;

[Fkj]: Fourier series fitting matrix determined by the geometry;

[Ck]: Vector of the point-wise correction factors at given core elevations calibrated by a monthly in-core flux mapping;

[P"k]: Vector of the point-wise core average linear power at given core elevations;

[P'k]: Vector of the point-wise core average linear power with point-wise correction at given core elevations;

[Pk]: Vector of the normalised core average linear power at given core elevations.

The error producing mechanism should be specified before the uncertainty of the measurement using the four-section system is evaluated. Here, the uncertainty is defined as the biggest deviation of the reproduced P(z) by the four-section system from P(z) measured by an in-core neutron detector system. The in-core measurement uncertainty is not included in the uncertainty evaluated here. The main error components are:

(1) Error associated with the Fourier series fitting method;

(2) Error due to the change of the axial power distribution;

(3) Error due to the change of the radial power distribution;

(4) Error due to instrumentation error.

The error (1) is generated by the Fourier series fittings. This error varies with the change in the axial shape due to the fuel depletion, the rod control and xenon oscillation.

The error (2) is generated by the change of the four detector responses from the calibrated ones. Each detector monitors the average quarter core power face to it, but the probability that the neutron produced in the core can reach the detector is different at core elevation. Therefore, if the axial power shape changes, the detector response changes.

The error (3) is generated by the reason that the ex-core detector monitors only some peripheral assemblies, not the core average axial power distribution.

The error (4) is generated because the instrumentation error propagates to the reproduced distribution. The instrumentation error includes that of I/E amplifiers, and that of analog-to-digital (A/D) converters.

These error components (1) ~ (3) are all dependent on conditions such as fuel depletion, the axial power distribution with the control rod movement. Therefore, the uncertainty evaluation should be made at several depletion points.

Uncertainty evaluation method

The uncertainty evaluation flow chart which includes all error components as described above is showed in Figure 2. The analytical evaluation is made as follows.

(1) Behaviour of the reactor core is simulated very accurately using a three-dimensional nodal diffusion code, ANC. Number of the core simulations for this evaluation are made varying the following.

   (a) Fuel burn-up (depletion);

   (b) Operational condition: base load operation, load follow operation, or anticipated transients.

The core relative power, delta-I, core average axial power distribution are calculated in the ANC, and radial mean power and axial power distribution of peripheral fuel assemblies which effect ex-core detector are also calculated.

(1) Ex-core detector currents are calculated as follows.

   (a) Neutron transport from the core to the reactor vessel is calculated through a simple point kernel expressed as

$$\mathrm{EXP}(-\Sigma \bullet r) \times 1/r$$

   where

   Σ: effective removal cross section in the reactor vessel
   r: distance from a point in the core to a point at the reactor vessel

   and considered are the contribution of all the peripheral fuel assemblies close to the ex-core detector calculated by the two-dimensional transport code, DOT. It is described in Ref. 2 & 3 that the neutron transport from the core to each detector section is simulated well by the point kernel method.

(b) Neutrons are assumed to be isotropically scattered at the surface of the reactor vessel. Using this point kernel method, ex-core detector currents are calculated with the axial power distribution of peripheral fuel assemblies.

(2) The core relative power, delta-I, axial power distribution are reproduced by the detector currents. Then, the uncertainty is evaluated comparing those of core average calculated by 3-D ANC.

(3) For all the simulation cases considered are all the possible sets of the instrumentation errors of the four detectors within the warranted accuracy.

(4) In that evaluation, the correction matrix is assumed to calibrate by in-core / ex-core calibration every three months, and the point-wise correction factor is assumed to calibrate by monthly in-core flux mapping. The core relative power is assumed to calibrate adequately.

Uncertainty evaluation results

The uncertainty evaluation is made for APWR plants.

The examples of the error by the change of core conditions is shown in Figures 3 & 4. Figure 3 shows that the errors of delta-I and Fz during the fuel burn-up is respectively less than 1% and 1.5%. Figure 4 indicates the results during load follow operation with Xe free condition which includes the transient condition, and shows that the errors of delta-I and Fz is less than 3%. So, the errors of delta-I and Fz at anticipated transients is expected less than 3%.

The instrumentation error propagated to Fz is evaluated 2% even in the anticipated transient conditions with a distorted axial shape. The example of the evaluation is shown in Figure 5.

The result of the uncertainty evaluation for APWR plants is summarised in Table 1. Table 1 shows that the uncertainty can be kept sufficiently small for the core monitoring and protection. The evaluation is made considering all possible core condition including anticipated transients which make the axial power peaking worse.

Table 1. The uncertainty of delta-I, Fz with the four-section detector system

Mechanism	Delta-I	Fz
Change of core conditions	3%	3% of measurement
Instrumentation error	1%	2% of measurement

Conclusion

The analytical uncertainty evaluation is made for APWR plants with four-section ex-core detector system. The results are;

(1) Four-section detectors monitor the axial power distribution with a good accuracy in PWR plants even in the anticipated transients and the load follow operation.

(2) Error of the axial power distribution measurements with the four-section detectors increases according to the fuel burn-up and the distortion of the axial power distribution, but it can be kept sufficiently small for the plant core monitoring and protection by the adequate frequency of the calibration with the in-core instrumentation.

REFERENCES

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Figure 1. Axial geometry and system block diagram

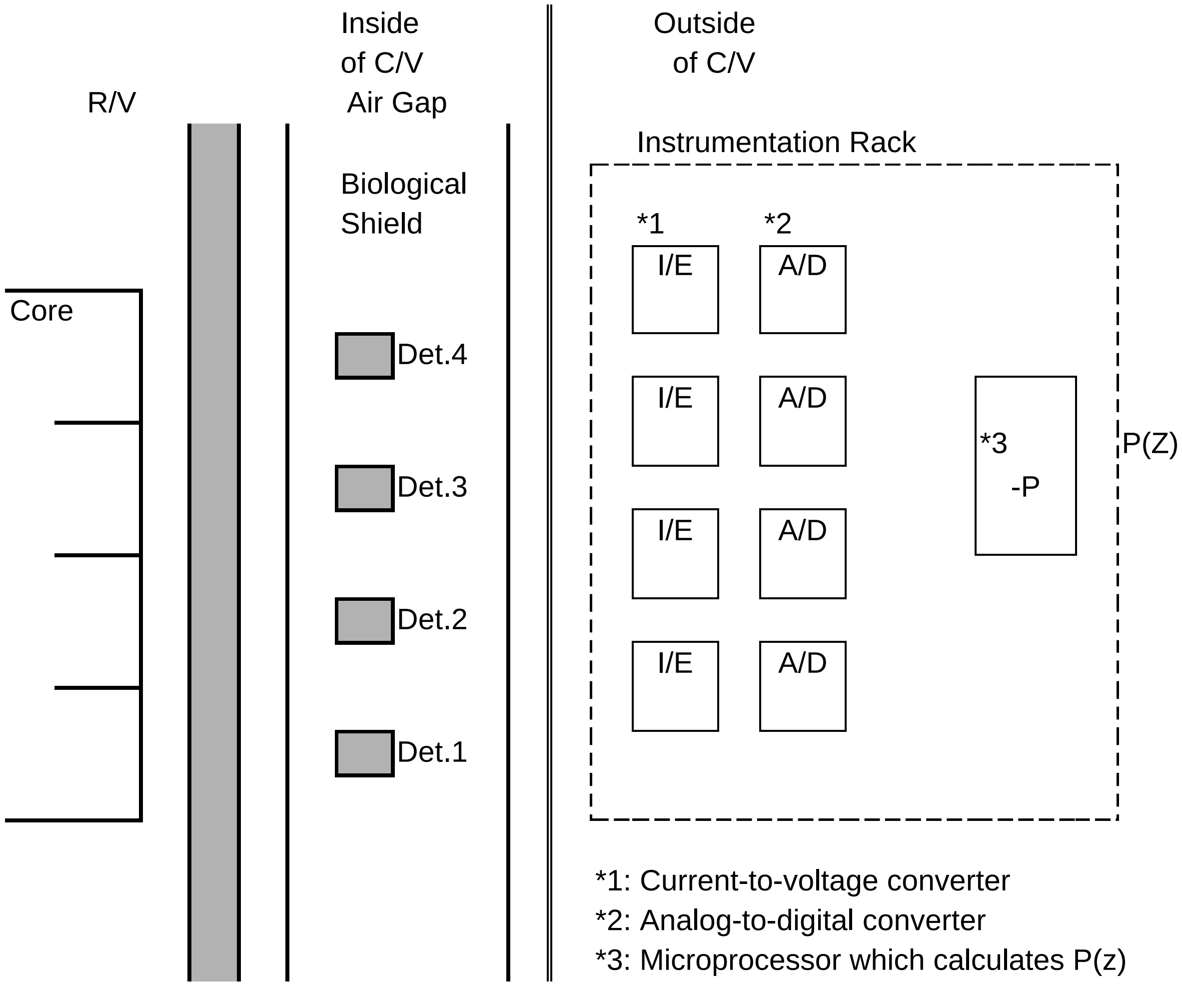

Figure 2. Flow chart of uncertainty evaluation

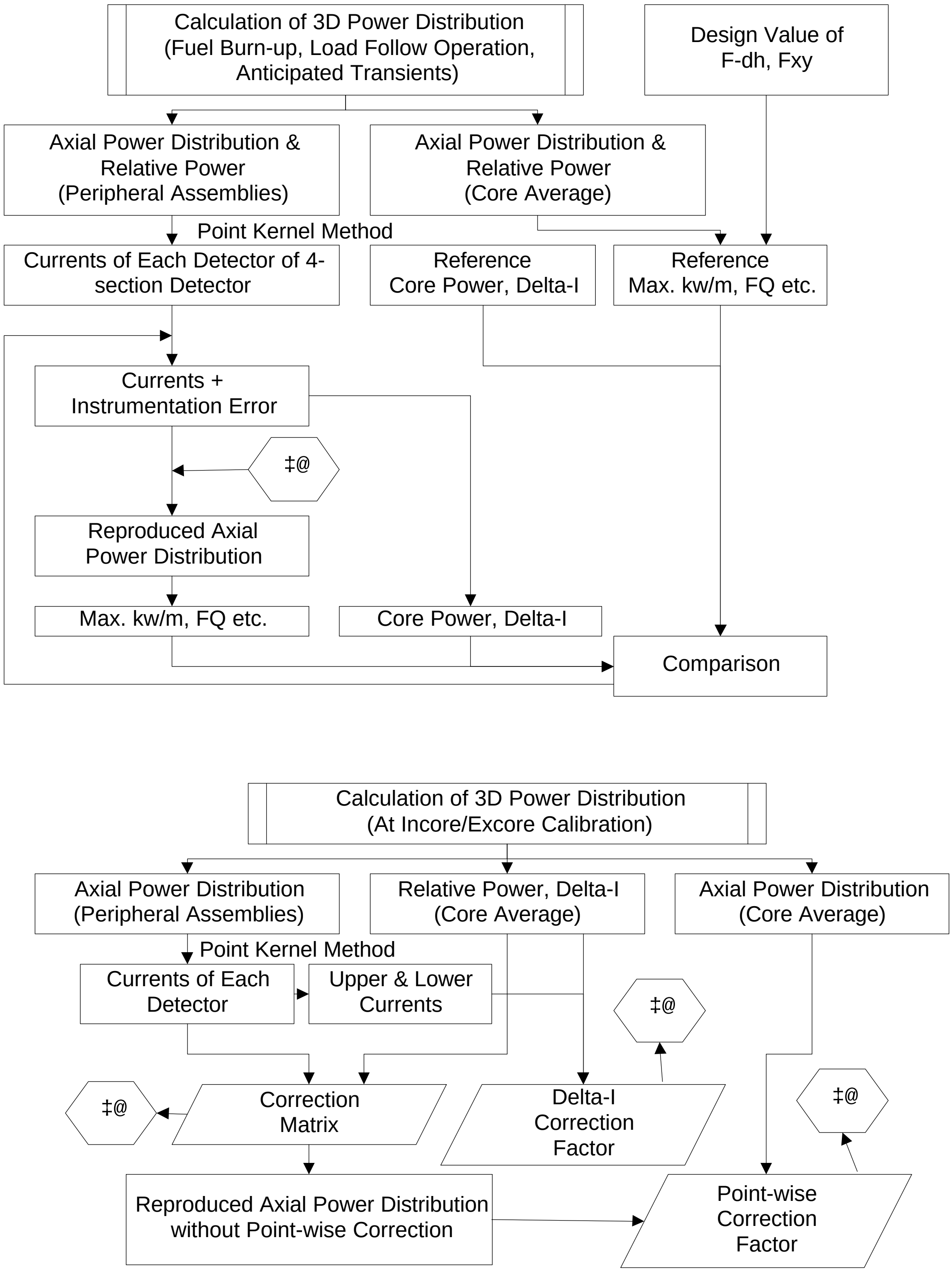

Figure 3. Uncertainty evaluation result during fuel burn-up (APWR equilibrium cycle)

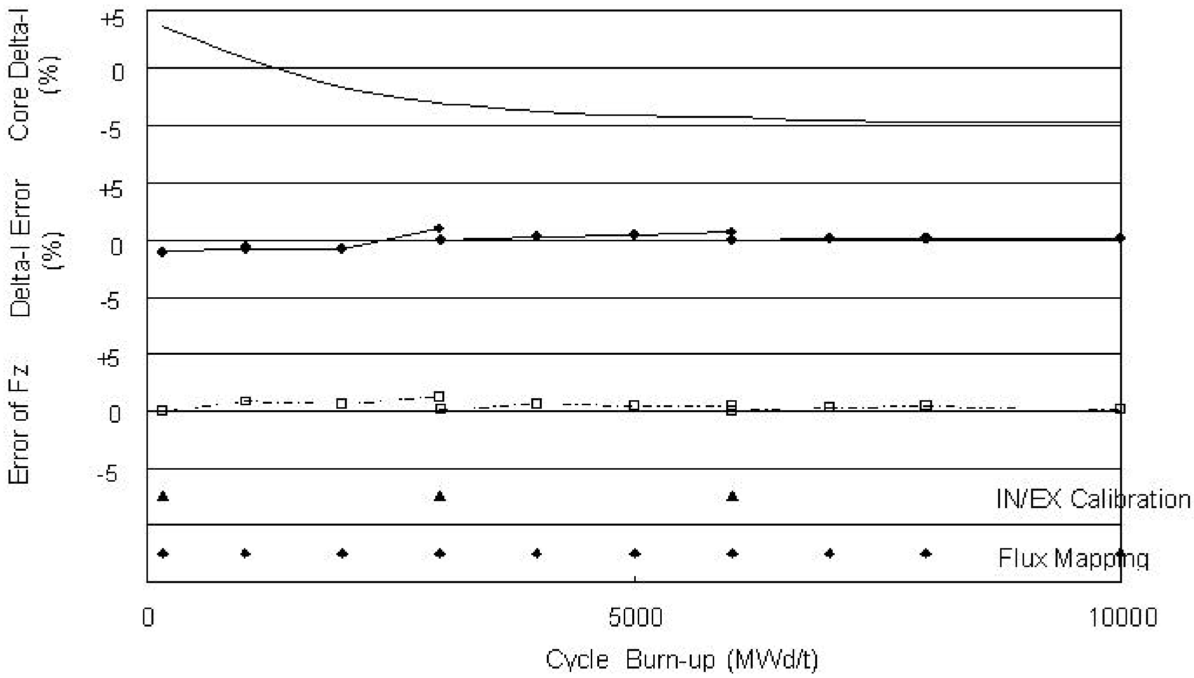

Figure 4. Uncertaintly evaluation during load follow operation with Xe free (APWR equilibrium cycle)

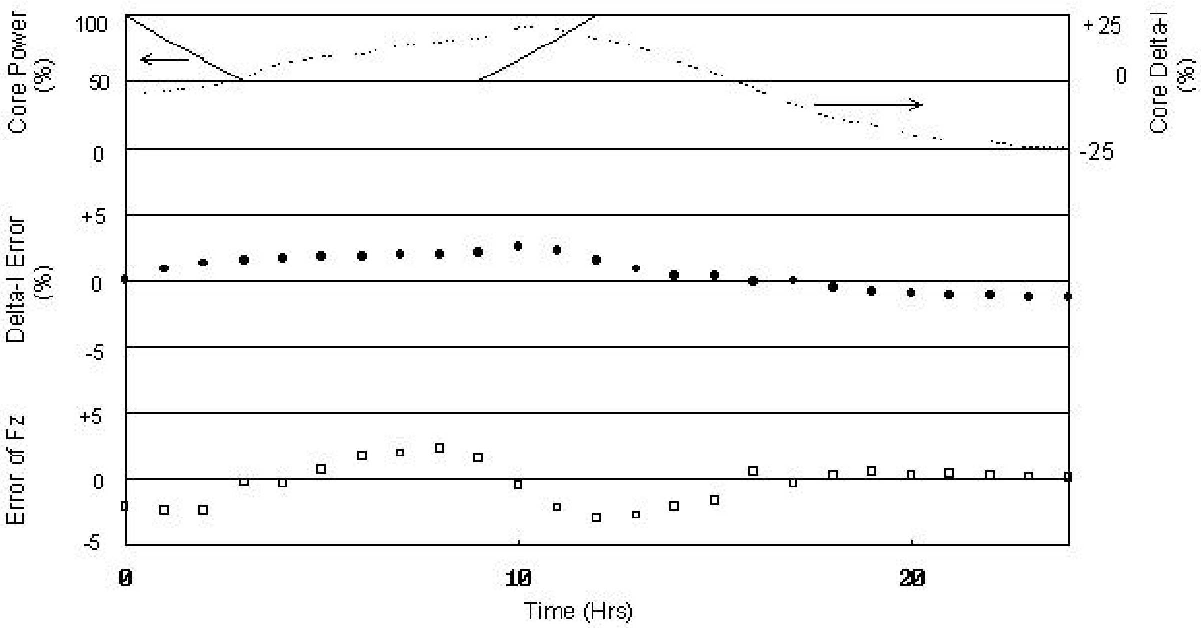

Figure 5. Distribution of error with Fq reproduction by 4-section detector system (APWR equilibrium cycle)