EVALUATION OF SLOW SHUTDOWN SYSTEM FLUX DETECTORS IN POINT LEPREAU GENERATING STATION

II: Dynamic Compensation Error Analysis

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Abstract

CANDU reactors are protected against reactor overpower by two independent shutdown systems: Shut Down System 1 and 2 (SDS1 and SDS2). At the Point Lepreau Generating Station (PLGS), the shutdown systems can be actuated by measurements of the neutron flux from Platinum-clad Inconel In-Core Flux Detectors. These detectors have a complex dynamic behaviour, characterized by “prompt” and “delayed” components with respect to immediate changes in the in-core neutron flux. It was shown previously (I: Dynamic Response Characterization by Anghel et al., this conference) that the dynamic responses of the detectors changed with irradiation, with the SDS2 detectors having “prompt” signal components that decreased significantly.

In this paper we assess the implication of these changes for detector dynamic compensation errors by comparing the compensated detector response with the power-to-fuel and the power-to-coolant responses to neutron flux ramps as assumed by previous error analyses. The dynamic compensation error is estimated at any given trip time for all possible accident flux ramps. Some implications for the shutdown system trip set points, obtained from preliminary results, are discussed.

1. Introduction

The current In-Core Flux Detectors (ICFDs) at the Point Lepreau Generating Station (PLGS) are Straight Individually Replaceable (SIR) Platinum-clad Inconel self-powered detectors, housed in Helium Encapsulated SIR (HESIR) assemblies.

The objective of the work outlined here was to estimate detector dynamic compensation errors for each detector in the Regional Overpower Protection Trip (ROPT). This estimation is provided in the context of changes in the dynamic response parameters of SDS1 and SDS2 detectors in Point Lepreau that are outside the range of variation considered in the safety analysis report. The present work uses the same general set of conditions as the safety analysis report for Point Lepreau to characterize ROPT detector dynamic compensation errors. As the differences in detector response were found to be larger than the estimated error of each response, we used a more rigorous, and easily implemented analytical approach.

The compensation error can be estimated for different possible choices of electronic compensation adjustment. For overpower protection detectors, the signals are electronically compensated, with signal changes multiplied by an initial gain which decreases back to 1 via two exponentially decaying terms with time constants of 30 and 2500 seconds and amplitudes that may be adjusted. A ready-to-use assessment method may allow the safe margin to trip of the reactor to remain high as its core ages.

2. General Assumptions

2.1 Assumptions on Accident Flux Evolution

The detector dynamic compensation error is estimated by considering the response of detectors to a hypothetical of flux evolutions, starting from a variety of initial steady-state conditions:

a) The hypothetical set of flux evolutions is a set of flux ramps: $\phi(t) = \phi(0) + \alpha t$.

b) A probability distribution is given for the family of flux ramps, that is, a probability distribution function (PDF) depending on the initial flux and the ramp slope. A sketch of the PDF is shown in Figure 1.

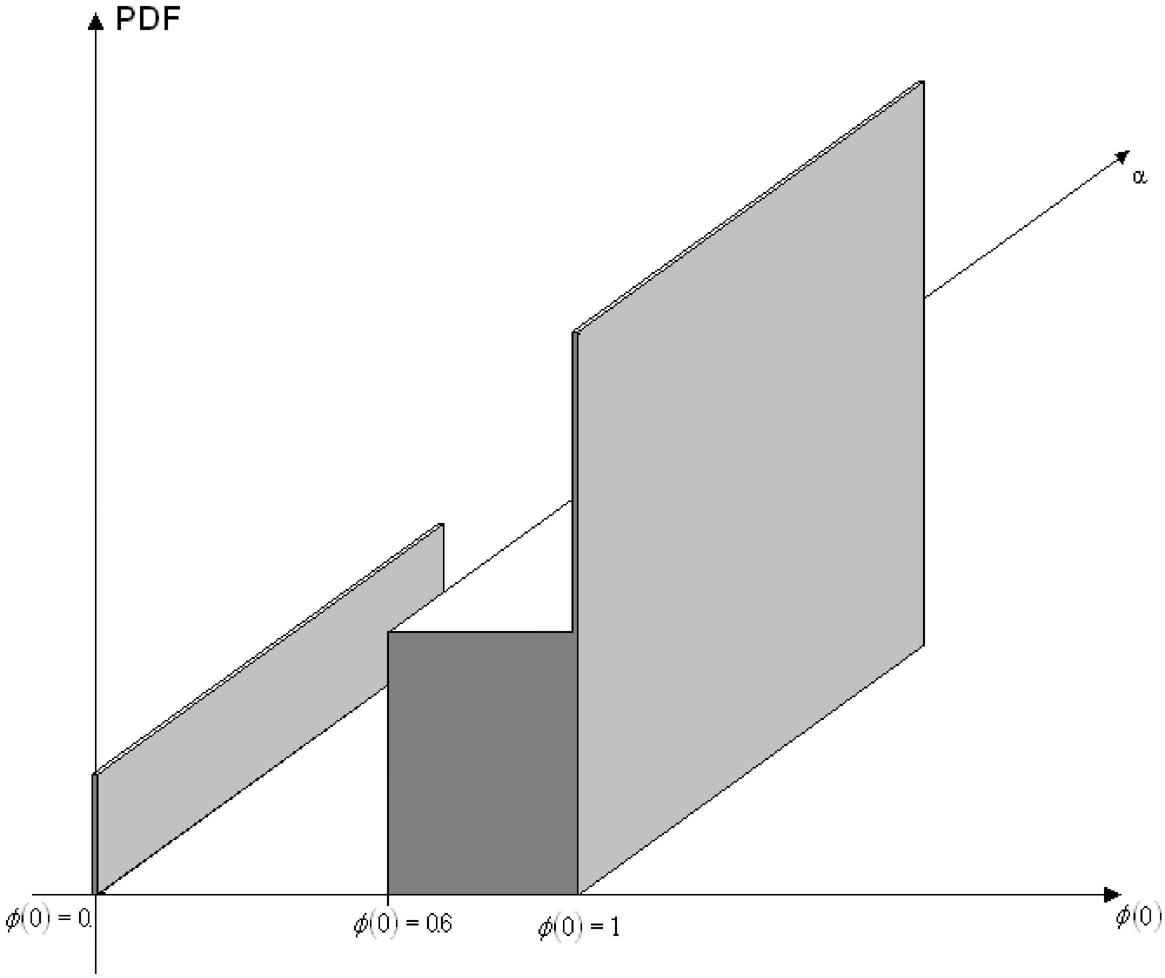

Figure 1 Sketch of the joint PDF $R(\phi(0), \alpha)$ for the initial flux $\phi(0)$ and ramp slope α . The thin "walls" indicate the infinite delta function PDF at $\phi(0) = 0$ and $\phi(0) = 1$.

These two hypotheses are the same as the hypotheses in the safety analysis report.

2.2 Detector Response Assumptions

The assumptions on the detector signal are the same as in the first part of this work, but are listed here for completeness and because they will allow to simplify the estimation of compensation error:

a) The response of the detector itself, *F*, to the neutron flux Φ is assumed to be linear, composed of a prompt response a linear combination of delayed fractions.

b) The lifetimes for all delayed fractions are the same for all detectors.

c) The delayed fraction amplitudes are estimated for each detector. The errors in estimation are not considered, because the errors are much smaller than the amplitude variation between detectors

The first two hypotheses are the same as the hypotheses in the safety analysis report, while the third is more restricted.

2.3 Fuel Power

The assumed fuel power response to a flux ramp is the same as in the safety report.

3. Calculation of the Detector Compensation Error

3.1 Definitions

A necessary condition for a reactor trip is that the signal from a detector reaches a critical value d_{trip}. t_{trip} it the time at which the reactor trips. The expression for compensation error is given in Equation1, and a representation in Figure 2.

The compensation error is defined in terms of the flux variation with time, $\phi(t)$, and the responses of the detector signal, $c(t)$, and the fuel power, $p_f(t)$, to then flux variation:

$$CompensationError(FPU) = \frac{c(t_{trip}) - p_f(t_{trip})}{\phi(t_{trip})} \quad (1)$$

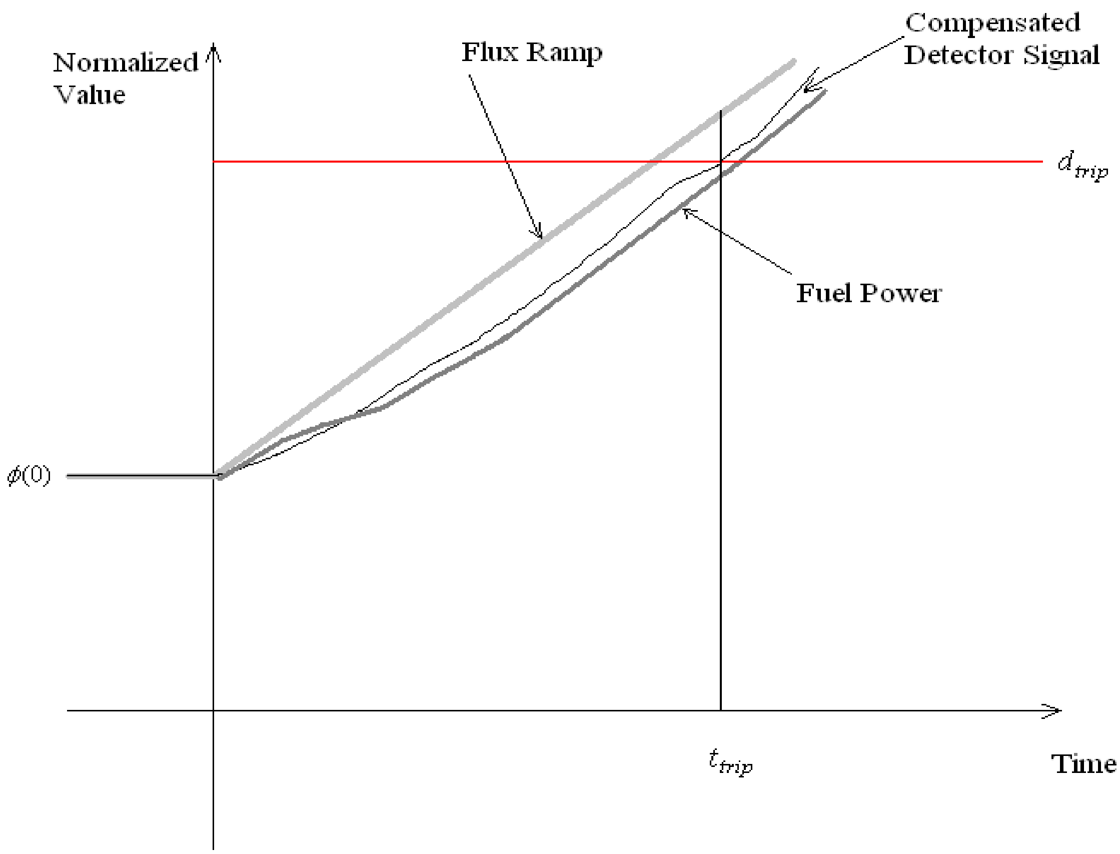

Figure 2 Sketch of the flux ramp, the compensated detector response and the fuel power response

3.2 Methods

The computational approach (see also Figure 3) can be described as follows:

a) For each detector, the delayed fraction amplitudes are given by a set of constants, i.e. the delayed amplitudes are assumed deterministic. It was found that the detector delayed fraction amplitudes vary significantly from detector to detector (order of percents). The detector-to detector variation is much larger that the estimated standard deviation for computed detector amplitudes (fractions of percent).

b) For each detector, the compensation error average and the compensation error root mean square deviation are computed by integrating analytically over the all the flux ramps at a given trip time and then integrating numerically over the trip time.

The detectors respond linearly to the neutron flux. $\phi(t) = \phi(0) + \alpha f(t)$ Looking at the trip condition when the detector signal reaches d_{trip}, we have the relation

$d_{trip} = \phi(0) + \alpha f(t_{trip})$, with $f(t)$ the detector response to a ramp t. Looking at the trip condition in the $(\phi(0), \alpha, PDF)$ space, it is found that it is represented as a vertical plane in the $(\phi(0), \alpha, PDF)$ space, as shown in Figure 4.

This plane cuts sections in the "volume" of the flux ramps PDF.

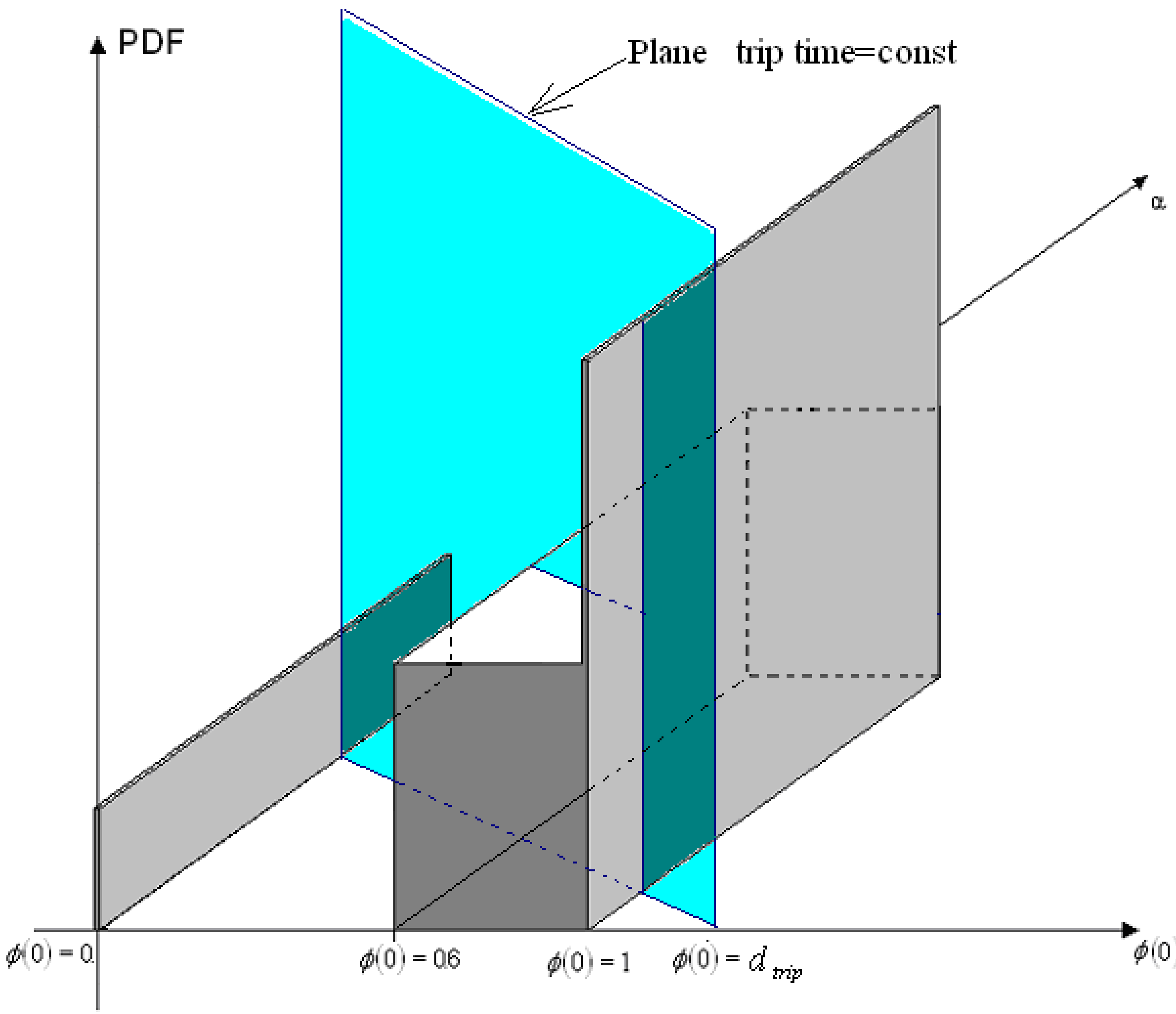

Figure 3 "Volume" of the joint PDF $R(\phi(0), \alpha)$ being cut by the plane that includes all trips that have the same trip time.

In general, the PDF issue can be outlined analytically as follows: Assume we have a PDF $R(\phi(0), \alpha)$ for the family of accidental flux ramps. Assuming the linear response of detectors, the PDF $S(\phi(0), t_{trip})$ in the space $(\phi(0), t_{trip})$ is:

$$S(\phi(0), t_{trip}) = R\left(\phi(0), \frac{\phi(0)}{f(t_{trip})}\right) \frac{d_{trip} - \phi(0)}{f^2(t_{trip})} f'(t_{trip}) d(\phi(0)) dt_{trip} \quad (1)$$

In these coordinates, the compensation error is a polynomial fraction in $\phi(0)$ and its products with the PDF can be integrated analytically over $\phi(0)$. Therefore the average and the root mean square deviation of the compensation error at a fixed t_{trip} are analytic functions of t_{trip}.

These analytic functions are the integrated numerically along to yield the compensation error and the root mean square deviation for each detector.

c) The average and the root mean square deviation for a population of detectors (for instance for SDS1 or SDS2) is then estimated from the already estimated individual detector time averaged quantities

4. Results

4.1 Averages over accident ramp population

The first item of interest resulting from integrating over the accidental flux ramp population is the PDF distribution of trip time for a given detector, of which an example is shown in Figure 5. This probability distribution is strongly peaked at short time (1 s or so).

During this analysis, it was found that in general the PDF of the t_{trip} has a “fat tail”, decreasing like $(t_{trip})^{-2}$ for large t_{trip}. This has no consequences for the analysis here, but may become important if one decides that the trip time distribution is important for safety analysis. Taking time a trip time average or RMS is not possible, as the PDF and has a fat tail that does not allow taking of averages. If a decision is made to use trip time in the future, it is recommended to use percentiles, as recommended in the IEEE standard [3].

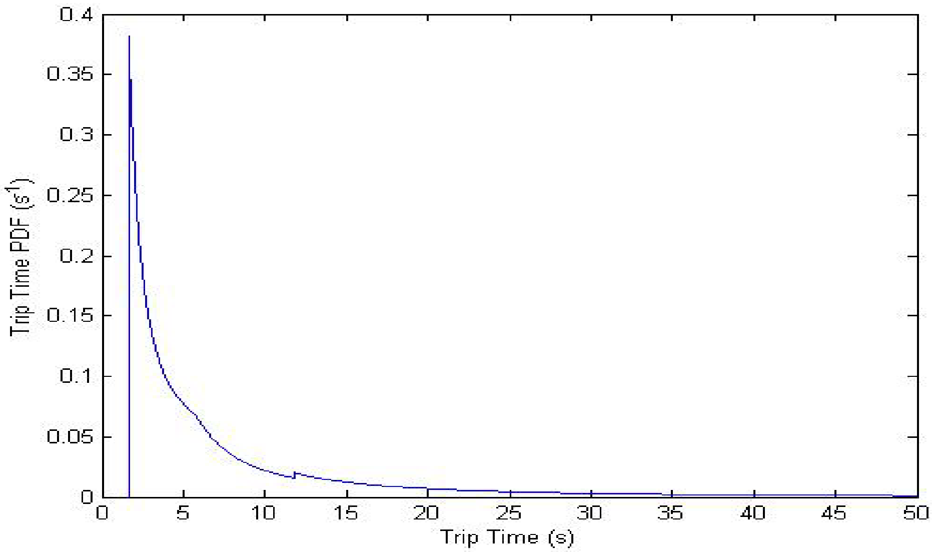

Figure 4 Trip time probability distribution function (PDF) resulting from averaging the PDF over accidental flux ramps

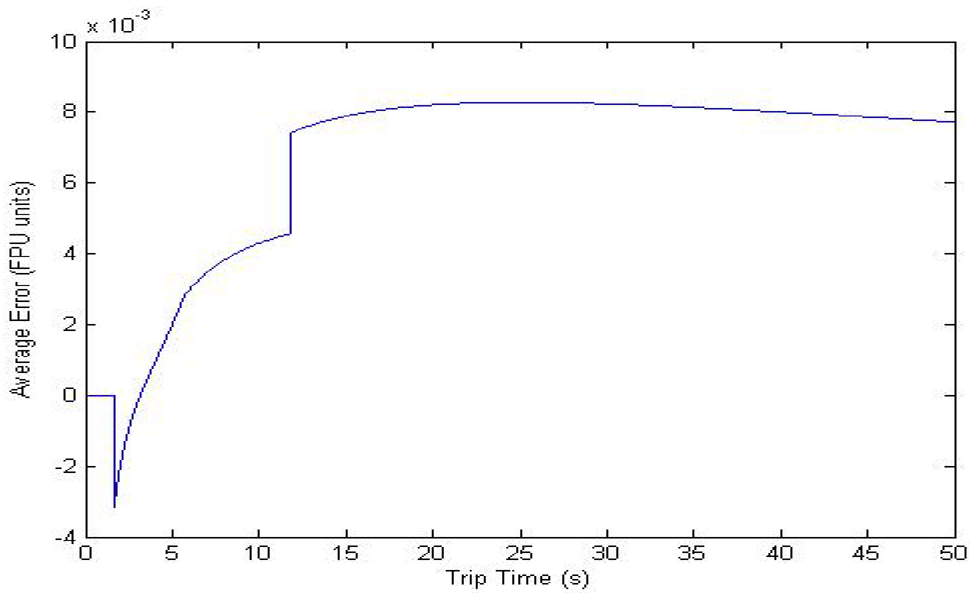

Figure 5 Example of Compensation Error Average versus Trip Time

The average of the compensation error over flux ramps at constant trip time for a single detector is shown in Figure 6. For most of the trip times shown, the average compensation error is positive, thus in the safe range.

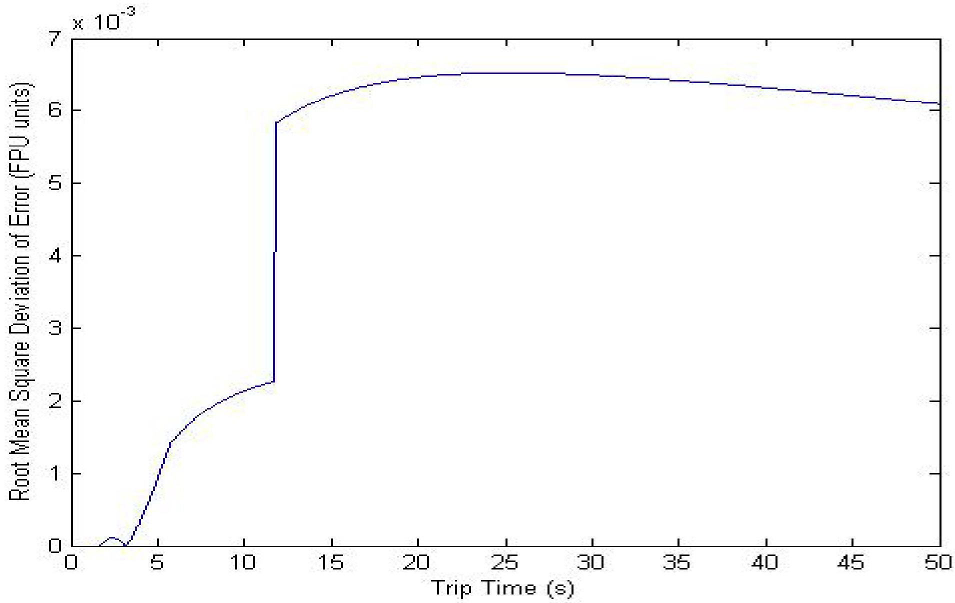

Figure 6 Example of Compensation Error Standard Deviation versus Trip Time

Figure 7 shows that the magnitude of the standard deviation of the compensation error is comparable to the average of the compensation error.

4.2 Averages over time

When the time averages of the compensation error at trip and the RMS of mean square deviation of the compensation error at trip are take for each detector, it is found that the average compensation errors for the SDS2 detectors are all negative (see Figure 7) and that the RMS of the compensation error are about twice as large for SDS2 compared to SDS1 (see Figure 8).

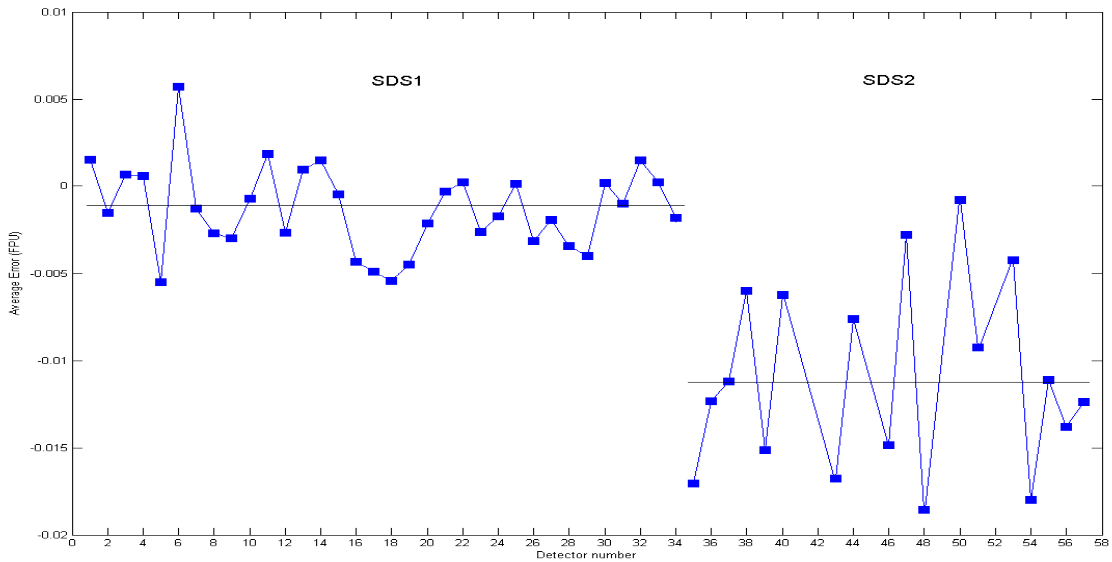

Figure 7   Compensation error average over trip time for individual detector parameters determined by data from a reactor trip in 2007. Difference-compensated detectors are not shown.

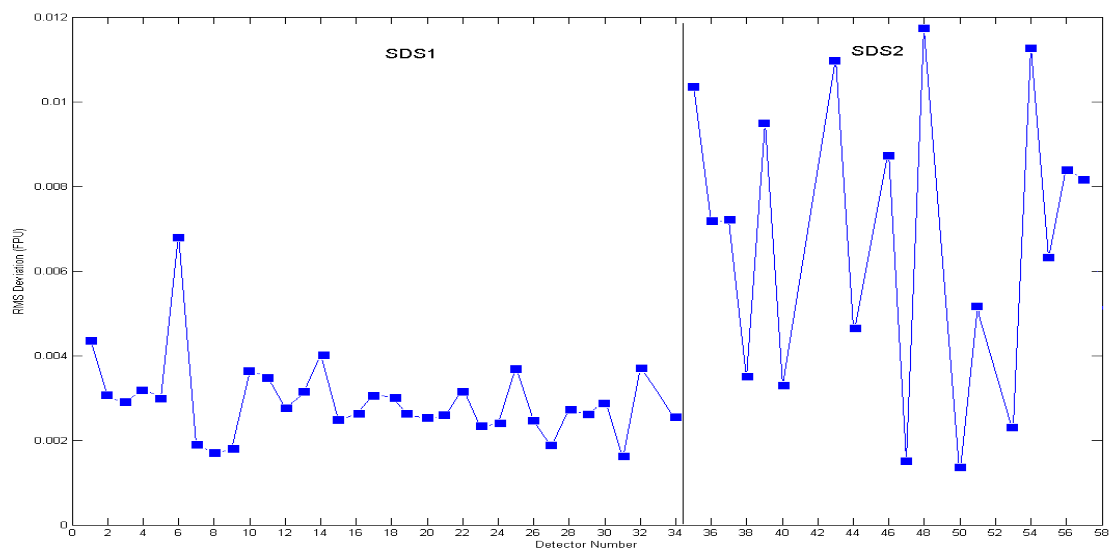

Figure 8   Compensation error standard deviations over trip time for individual detector parameters determined by data from a reactor trip in 2007. Difference-compensated detectors are not shown.

5. Conclusions

This work on an analytical method to evaluate the dynamic compensation of the SDS1 and SDS2 detectors led to the following conclusions:

a) All the quantities of interest for analyzing the compensation of detector signals can be computed analytically and with deterministic numerical algorithms.

b) It was found that, for the SDS2 detectors, the compensation error averages and the compensation error standard deviations fluctuate from detector to detector about 2 times more than in the SDS1 case. The amplitudes for the SDS1 and SDS2 detectors used in this estimation were computed using amplitudes estimated from data collected during a SDS2 in 2007.

c) It was found that a uniform compensation change over the whole SDS1 detector set could work well.

d) A uniform compensation change may have a relatively small effect on the SDS2 amplifiers, due to the large variation of the average compensation error from SDS2 detector to SDS2 detector mentioned above.

6. References

[1] C. M. Bailey, R. D. Fournier, and F. A. R. Laratta, “Regional Overpower Protection in CANDU Power Reactors”, International Meeting on Thermal Nuclear Reactor Safety, Chicago, Illinois, 1982 August 29 - September 2.

[2] C. M. Bailey, M. Nguyen, B. Sur, “A Proposed Method for Assessing In-Core Flux Detector Dynamic Compensation Adequacy...“, Proceedings of the 22nd Annual Conference of the Canadian Nuclear Society, Toronto, Ontario, Canada, 2001.

[3] ANSI/IEEE, “IEEE Guide for General Principles of Reliability Analysis of Nuclear Power Generating Station Safety Systems”, ANSI/IEEE Std 352-1987.