Minimization of the energy loss of nuclear power plants in case of partial in-core monitoring system failure

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Abstract. In this paper we consider the optimization problem minimize of the energy loss of nuclear power plants in case of partial in-core monitoring system failure. It is possible to continuation of reactor operation at reduced power or total replacement of the channel neutron measurements, requiring shutdown of the reactor and the stock of detectors. This article examines the reconstruction of the energy release in the core of a nuclear reactor on the basis of the indications of height sensors. The missing measurement information can be reconstructed by mathematical methods, and replacement of the failed sensors can be avoided. It is suggested that a set of ‘natural’ functions determined by means of statistical estimates obtained from archival data be constructed. The procedure proposed makes it possible to reconstruct the field even with a significant loss of measurement information. Improving the accuracy of the restoration of the neutron flux density in partial loss of measurement information to minimize the stock of necessary components and the associated losses.

1. Introduction

The safe and efficient operation of a nuclear reactor requires the continuous monitoring of the reactor core state. One important task is the control of neutrons flux density. The control is necessary because a critical power ratio can vary greatly with small fluctuations of process parameters. Special sensors of in-core monitoring system (ICMS) [1] located along the core height are used to obtain information about the flux density. Pressurized water reactors VVER have assemblies of seven self-powered neutron detectors (SPNDs) [2], distributed uniformly over the core height. In the practice of operating nuclear reactors there may occur situations when some sensors fail. If a sensor fails, then the use of its indications is ‘prohibited’, e.g. assembly of SPNDs in VVER reactors is banned if three or more sensors fail [3]. Failure of the ICMS increases error of the neutron flux determination [4]. In such cases it is necessary either to reduce the power of the reactor, or to replace the failed part of the ICMS. The replacement is possible only when the reactor is stopped, moreover, for this purpose at the plant should be a certain reserve of necessary components. There is an opportunity to increase the assembly operation time. The missing measurements information can be restored by mathematical methods and premature replacement of the failed sensors can be avoided, which is also expedient economically. For this, it is proposed that missing sensor indications be calculated by approximation the known points. Harmonic functions are used for the recovery of neutron flux density distribution, but these functions are not optimal. Approximation is suggested to be made as an expansion to the series of functions,
adjusted in a certain way using the archive data. The proposed technique enables to use accumulated data from an archive to restore the neutron field even after a serious loss of measurement information.

2. Minimization of the energy loss

Consider the simple situation for VVER, when the moment of failure is random. Until the maximum burnup fuel assembly located in the reactor core for several campaigns. Thus, the campaign is determined by the reactivity margin. It is therefore possible extension of the campaign through the use of reactivity temperature effect [5]. In this case either the reactor power is reduced by a predetermined amount by the operator, or is transferred to block spontaneous power reduction mode. For simplicity we consider the first option. Then it is possible to estimate losses due to shut down the reactor for replacement of the failed part of ICMS and by reducing the power. This makes it possible to calculate the boundary point in time $t_b$, after which advantageously reduces power:

$$ t_b = T - \frac{\tau W + \Delta W (T - T_{low})}{\delta W} $$

$T$ – the estimated time of the reactor campaign; $T_{low}$ – the time of the planned power reduction at the end of the campaign; $\tau$ – downtime required for replacement; $W$ – nominal reactor power; $\Delta W$ – the value of power reducing to work at the end of the campaign; $\delta W$ – value of the required power reduction in case of partial failure of the ICMS.

![Figure 1. Loss in case of shutdown and in the case of reducing power.](image)

This value can be regarded as a time for the unit should be stored ICMS stock components. Most often a nuclear power plant is equipped with the same type of units. Therefore, at the moment $t_b$ for the first reactor stock can be transferred to another reactor. Then it is possible to plan the start-up of reactors with time $t_b$ offset. This approach is justified, because a separate reserve for each block leads to economic losses. Estimate what stock to have on station of the $N$ reactors of type VVER in order to minimize losses. The minimum number of spare sets will be equal to $\lceil Nt_b/T \rceil + 1$, where $\lceil x \rceil$ is the integer part of $x$. It is seen that the smaller $t_b$, the smaller the reserve needed for operation of nuclear power plants. The reduction $t_b$ allows to lower losses. And to reduce $t_b$ it should be possible to reduce $\delta W$ which depends on the accuracy of the neutron flux density restoration in partial loss of measurement information.

Since the time of the failure is a random variable, we can estimate the average losses for both cases.

$$ \overline{Q} = \int_0^T Q(t)f(t)dt $$

$$ Q_1 = \begin{cases} 
\tau W, & t < T_{low} \\
\tau (W - \Delta W), & t > T_{low}
\end{cases} $$
\[ Q_2 = \begin{cases} \delta W (T_{\text{low}} - t) + (\delta W - \Delta W)(T - T_{\text{low}}), & t < T_{\text{low}} \\ 0 + (\delta W - \Delta W)(T - T_{\text{low}}), & t > T_{\text{low}} \end{cases} \] (4)

\(\overline{Q}\) – average losses, \(Q_1\) – losses during sensor replacement, \(Q_2\) – losses as a result of the power reduction, \(f(t)\) – probability density function.

Take as \(f(t)\) is a uniform density. Then we obtain the following estimates:

\[
\overline{Q}_1 = \alpha T \left[ W \frac{T_{\text{low}}}{T} + (W - \Delta W) \left(1 - \frac{T_{\text{low}}}{T}\right) \right] \]

(5)

\[
\overline{Q}_2 = \alpha \left[ \delta W \frac{T_{\text{low}}}{2T}^2 + (\delta W - \Delta W)(T - T_{\text{low}}) \right] \]

(6)

It is seen that \(\overline{Q}_1\) does not depend on \(\delta W\), and \(\overline{Q}_2\) depends on \(\delta W\) is linear, then there is a value \(\delta W\), where the average in case of failure of any component of ICMS, to replace is unprofitable. This fact confirms that in case of failure of part of the ICMS should be possible to accurately restore the field to minimize the value \(\delta W\). Thus, it is important to improve the recovery algorithms of the flux density of neutrons with partial loss of measurement information.

3. Recovering of missing height-sensor readings

Harmonic functions are used for the recovery of axial neutron flux density distribution, because they are eigenfunctions of one-dimensional nuclear reactor. The maximum number of harmonics is equal to the number of running sensors. However, these functions are not optimal for the reactor. The actual distribution of the neutron field may not be described by a superposition of these functions. In actual operation, for a neutron-physical and thermophysical feedbacks, displacement of the control rods, and others the distribution of the multiplying properties varies in time and space and is not uniform. The data used in the research was derived for the period from June 9 to August 17, 2011 of 4 measuring channels of unit 1 Tian Wan NPP (China) with VVER-1000 reactor. Using these data, we obtain a matrix of the correlation coefficients. Analysis of the matrix obtained on the basis of archives of power-generating units operating in the nominal regime showed that, as a rule, the matrices are not diagonal. This means that there exists a correlation between the fitting coefficients. In other words, the neutron flux density as a random function is represented in the form of a superposition of harmonic functions with correlated random coefficients. This fact confirms the bad choice of functions for approximation. There is the possibility to find the system of functions, which would have non-correlated coefficients in expansion. According to the theory of random functions [6], the convergence of an expansion of a random function in the series can always be improved by an identity transformation to a canonical expansion of the random function. The procedure for transforming to the canonical expansion is reminiscent of the Gram–Schmidt procedure for orthogonalizing vectors or the method of principal components [7]. The coefficients will be expressed in terms of the correlation moments of the random quantities. We obtain an approximate canonical expansion of the random function. This approach claims that new functions called ‘natural’ functions are linear combinations of initial harmonic functions (see figure 2). Therefore the solution of the approximation problem does not become more complex.
The following numerical experiment confirms the efficacy of a ‘natural’ fit to the axial distribution of the neutron flux. The sensors were prohibited fictitiously and the values of the sensor currents were reconstructed using harmonic functions and the ‘natural’ functions. The results of the experiment show that the correct choice of functions increases the accuracy of the fit. The advantage of the ‘natural’ functions is that each one contains several harmonics. For this reason, using fewer of them for the fit gives a smaller error than a large number of harmonic functions.

Obviously, the increase of the number of failed sensors affects the error [8]. However, VVER reactors have assemblies of seven SPNDs. The proposed technique enables to use accumulated data from an archive to restore the neutron field even after a serious loss of measurement information. Since the natural functions are found by processing archival information, their form must depend on the volume and character of the processed archival information. The simulation results [9] show that by using the archive data of 100 readings [10], lost reading may be recovered by special functions with an accuracy of about 2.5%. However, such a high accuracy is due to not only a good choice of functions but also the fact that the energy-release field in VVER type reactors operating in a stationary regime does not change strongly.

4. Conclusions

It is preferable to use ‘natural’ functions to reconstruct the height distribution of the energy release in the event of partial loss of measurement information. This choice of a basis makes it possible to reconstruct the field by using fewer functions on average with an order-of-magnitude smaller reconstruction error than with the use of harmonic functions. The reason is that information on the possible height distribution of the neutron flux density in the process of reactor operating is used to construct a new basis. Moreover, in essence, an approach to monitoring the energy release where its algorithm adapts during the operation of the reactor was proposed as an example of a solution to this problem.

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